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**Human Visual Navigation:  
Effects of Visual Context, Navigation Mode, and Gender**

A thesis  
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by  
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## Abstract

This thesis extends research on human visual path integration using optic flow cues. In three experiments, a large-scale path-completion task was contextualised within highly-textured authentic virtual environments. Real-world navigational experience was further simulated, through the inclusion of a large roundabout on the route. Three semi-surrounding screens provided a wide field of view. Participants were able to perform the task, but directional estimates showed characteristic errors, which can be explained with a model of distance misperception on the outbound roads of the route. Display and route layout parameters had very strong effects on performance. Gender and navigation mode were also influential.

Participants consistently underestimated the final turn angle when simulated self-motion was viewed passively, on large projection screens in a driving simulator. Error increased with increasing size of the internal angle, on route layouts based on equilateral or isosceles triangles. A compressed range of responses was found.

Higher overall accuracy was observed when a display with smaller desktop computer monitors was used; especially when simulated self-motion was actively controlled with a steering wheel and foot pedals, rather than viewed passively. Patterns and levels of error depended on route layout, which included triangles with non-equivalent lengths of the two outbound roads. A powerful effect on performance was exerted by the length of the *approach segment* on the route: that is, the distance travelled on the first outbound road, combined with the distance travelled between the two outbound roads on the roundabout curve. The final turn angle was generally overestimated on routes with a long approach segment (those with a long first road and a 60° or 90° internal angle), and underestimated on routes with a short approach segment (those with a short first road or the 120° internal angle). Accuracy was higher for active participants on routes with longer approach segments and on 90° angle trials, and for passive participants on routes with shorter approach segments and on 120° angle trials. Active participants treated all internal angles as 90° angles.

Participants performed with lower overall accuracy when optic flow information was disrupted, through the intermittent presentation of self-motion on the small-screen display, in a sequence of static snapshots of the route. Performance was particularly impaired on routes with a long approach segment, but quite accurate on those with a short approach segment. Consistent overestimation of the final angle was observed, and error decreased with increasing size of the internal angle. Participants treated all internal angles as 120° angles.

The level of available visual information did not greatly affect estimates, in general. The degree of curvature on the roundabout mainly influenced estimates by female participants in the Passive condition. Compared with males, females performed less accurately in the driving simulator, and with reduced optic flow cues; but more accurately with the small-screen display on layouts with a short approach segment, and when they had active control of the self-motion.

The virtual environments evoked a sense of presence, but this had no effect on task performance, in general. The environments could be used for training navigational skills where high precision is not required.

## Acknowledgments

The PhD process is often described as a journey. This metaphor seems especially apt for a thesis about navigation, by an author who has spent many years travelling. But while travel is always fascinating, reaching the destination on this particular journey is welcome: it is a place which has often seemed elusive. And what a ride it has been! I have sometimes felt like a learner driver at the wheel of a Ferrari.

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# **Chapter 1. Introduction**

## **1.1 Human Navigation**

The ability to navigate through an environment is an essential human skill. For most people, daily life revolves around a series of routine journeys between known locations in familiar environments: for example, between home and other important places, such as a workplace, educational establishment, shops, and entertainment venues. However, we sometimes venture out of familiar surroundings into unknown territory. We then need to explore, and learn about, completely new environments: we need to find our way around them, remember their layout in order to reliably locate important places, and discover how to return home. The motivation behind such forays may once have been the need to seek new food sources, as it often is for other animals; nowadays, however, humans are more likely to visit new places for leisure pursuits, shopping, entertainment, or holidays. We may also relocate more permanently, for example, for work or study, and have to familiarise ourselves with a new area.

This thesis is concerned with how we learn our way around a new environment, and build up a cognitive representation of its layout that enables us to carry out whatever activities we need to do there. Path integration is one strategy, performed by many diverse animals, which contributes to this process. It has been extensively studied in other animals (Tolman, 1948; Gallistel, 1990; Mittelstaedt & Mittelstaedt, 1980; Etienne, Maurer, & Séguinot, 1996; Collett & Collett, 2000; Müller & Wehner, 1988). An increasing number of researchers have begun to focus on human path integration, making use of new experimental techniques such as virtual reality, which can overcome some of the problems associated with real-life studies; and brain imaging. This study adds to research on human path integration, and on the use of virtual reality techniques to study it. The findings have practical implications for the use of virtual environments in spatial training contexts.

## **1.2 Overall Aims of the Study**

Human path integration ability in authentic virtual environments will be investigated, with a focus on some of the factors which may affect its accuracy: specifically, aspects of the visual environment, such as optic flow and depth cues; navigation mode, including active, passive and intermittent; and gender.

The central issue of interest concerns the impact of a high level of ecological validity on human path integration performance in virtual environments: enhanced accuracy is expected, in comparison with previous studies of path integration, especially when optic flow is derived in a more realistic context. Ecological validity will be increased in several ways. A version of the commonly-used triangle-completion task will be used, which will simulate real-world navigational experience as closely as possible, within the constraints of limited funds and technical capability; but which will simultaneously retain the high level of experimental control which is a feature of virtual reality. The task will require participants to make directional estimates of the start point of a triangular route, after they have travelled along it and reached its end.

Previous studies of path integration conducted in virtual reality have generally examined triangle-completion performance in small-scale environments, using routes with short straight outbound paths, and small degrees of turning; optic flow is often simulated through the use of abstract random-patch textures (Kearns, Warren, Duchon, & Tarr, 2002) or limited texture (Péruch, May, & Wartenberg, 1997). In order to make the virtual experience more realistic, participants in this study will perform the triangle-completion task by driving along longer complex routes (paths), which will include a long curved section around a large roundabout (traffic circle), within authentic large-scale virtual environments.

The standard triangle-completion task will, therefore, be embedded in a typical everyday context which is commonly encountered in the real world, and based on a real-world navigational task, that is, driving around a roundabout. The intention is to replicate everyday driving experiences, where roundabouts are common, so that the triangle-completion task becomes similar to normal everyday navigational activity. The error observed in participants' performance of the task under such conditions will be examined, and compared with the error which has been found in previous studies.

The use of roundabouts in a triangle-completion task is unique among path integration studies. Their inclusion on the routes in this study is a novel method to introduce an element of realism to the task, by contextualising the rotational component. In addition, the roundabouts provide a large gradual degree of rotation, which is intended to minimise the potential for cybersickness symptoms: these are a common experience of participants in virtual environments, and could be exacerbated by rotation. Gradual rotation has been included in few previous path integration studies.

In this study, the contribution of visual information to path integration will be examined within four authentic virtual environments, which will be presented on a three-screen display in order to provide a wide field of view. Visual cues will be derived from realistic contexts: that is, from naturalistic textures, typical of those

found in the real world, and detailed architectural structures. The relative level of structural detail provided by visual features will vary in each environment, and, thus, the environments will differ from each other in visual appearance, along a continuum ranging from very sparse to very structured. This will enable manipulation of the availability of visual information from both optic flow, resulting from the textures, and from depth cues, arising from the structures. The effects of optic flow, with and without additional depth cues, on participants' performance will be assessed.

Some researchers have noted that the role of optic flow could be better understood by studying human path integration under certain conditions: for example, conditions in which unrestricted optic flow is available from both self-rotation and self-translation (Loomis, Klatzky, Golledge, & Philbeck, 1999); and in which ecological validity results from the use of large environments with complex paths that, for example, include gradual curvature (Cornell & Bourassa, 2007). These conditions have been replicated in the virtual environments used in this study.

Directional estimates will be measured in this study: these do not involve scaling, unlike distance estimation, and so could be considered a reasonably direct measure of human behaviour. A consistent tendency for distance underestimation in virtual environments has been clearly established, through extensive research (Frenz & Lappe, 2005; Sun, Campos, & Chan, 2004; Thompson et al., 2004; Loomis & Knapp, 2003; Witmer & Kline, 1998); rotational estimates in virtual environments are more intriguing, however. Findings across studies have been inconsistent. Highly inaccurate rotational performance has been observed in some studies (Péruch et al., 1997; Bakker, Werkhoven, & Passenier, 2001, 1999); whilst extremely accurate performance has been found in others (Riecke, van Veen, & Bühlhoff, 2002, 2000; Gramann, Müller, Eick, & Schönebeck, 2005). Considerable variability, together with compression towards stereotyped responses, is typical. However, many different display devices and fields of view have been used in these studies.

It has been shown that humans can use optic flow to perceive and control translational self-motion with high accuracy, even if no landmark information is available (Bremmer & Lappe, 1999). In contrast, human estimation of self-rotation from optic flow alone has generally been found to be very inaccurate (Bakker et al., 1999, 2001; Péruch et al., 1997; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Chance, Gaunet, Beall, & Loomis, 1998; Sadalla & Montello, 1989). Riecke et al. (2002, 2000), on the other hand, found considerably greater accuracy when a large half-cylindrical projection screen with a field of view of 180° was used, together with realistic virtual environments: in fact, performance was almost perfect.

Angular estimates may be more difficult than translational estimates. Péruch et al. (1997), for example, observed that participants found it much harder to extract

directional information from optic flow than distance information, while performing visual path integration in a virtual environment.

The overall aim of this study is to obtain psychophysical evidence of human path integration abilities within authentic virtual environments. If path-completion can be performed with higher accuracy, compared with previous studies, under the more realistic conditions simulated here, then the thesis will have very practical real-world applications. Well-developed path integration skills are required in professions such as firefighting and search-and-rescue, and it may be possible to enhance these skills through training in virtual environments. If factors which promote improved performance can be identified, they could then be incorporated in the design of virtual environments and methodology for training. Potential barriers to the use of virtual reality for training real-world spatial tasks would need to be addressed: for example, their effectiveness and cost would need to be compared with other methods.

### **1.3 Navigation Strategies Used by Humans**

Navigation is a complex cognitive ability, requiring both perceptual and cognitive input. Humans can use several strategies when navigating in new environments: these are based on various sources of information, and perceived through different sensory modalities. One such strategy, path integration, is the focus of this study.

Effective navigation depends on several skills, including the ability to update one's position and orientation in an environment during travel: a process known as *spatial updating*. It is also necessary to develop a mental representation of the environment as it becomes more familiar, which can be used to plan further travel (Loomis et al., 1993): this has been termed a *cognitive map* (Tolman, 1948).

Humans have various cues available for spatial updating (Gallistel, 1990), which can be classified according to the type of information used: position, velocity or acceleration (Loomis et al., 1993). Navigation based on positional cues is known as *piloting*, or recognition-based navigation; whilst navigation based on velocity or acceleration is referred to as *path integration*, or dead-reckoning (Gallistel, 1990). These strategies generally work together in everyday life. However, some are more suited to particular environmental conditions, as will be discussed below.

#### **1.3.1 Piloting**

This is a strategy whereby navigators use external signals to determine their current position and orientation in the environment (Etienne, 1992). Thus, it is position-based

navigation. In known environments, position and orientation can be directly perceived by recognising visible reference points, such as familiar landmarks or landscape features (Billinghurst & Weghorst, 1995). Any distinctive, stationary, and salient object (such as a particular building, intersection, or street sign) can function as a landmark. Very distant features, such as the sun, may also provide an azimuthal reference (Gallistel, 1990; Maurer & Séguinot, 1995; Mittelstaedt, 1985).

Determining one's current location, that is *position-fixing*, can be achieved by, for example, computing one's position in relation to distances and bearings to either a single landmark or to multiple landmarks (Loomis, Klatzky, Golledge, & Philbeck, 1999). In human visual navigation, piloting predominates: typically, navigation with reference to salient landmarks is preferred when these are available. Piloting allows for correction of errors in perceived position and orientation through reference points, and is thus suited to large-scale navigation (Riecke, van Veen, & Bülthoff, 2002).

### 1.3.2 Path Integration

This is the simplest navigational strategy (Etienne & Jeffery, 2004). It is a process by which navigators continuously update their position and orientation (heading) in an environment, using velocity and acceleration information derived from self-motion via various sensory modalities (Etienne, 1992; Mittelstaedt & Mittelstaedt, 1982; Wehner & Wehner, 1986). Navigators obtain ongoing current estimates of their location and heading, through the continuous cumulation of successive estimates of position changes due to self-motion (Ellmore & McNaughton, 2004; Loomis et al., 1999b). Information on the distance and direction travelled, that is, translations and rotations, is continuously gathered and combined (Etienne & Jeffery, 2004). Translational and rotational displacements from the starting position of a route are determined by integrating velocity signals, or by sensing and doubly integrating acceleration signals (inertial navigation), or both (Loomis et al., 1993).

Human navigators can perform path integration by using sensory information about velocity and turn rate, which they obtain from external (allothetic) inputs, including *optic flow*, that is, the constantly changing pattern of light which is projected onto the retinae in response to self-motion through an environment (Gibson, 1950). Humans can also use internal (idiothetic) cues, including afferent proprioception, that is, sensory feedback from muscles, joints, or tendons, and motor efferent commands (Mittelstaedt, 1985); and inertial cues, that is, information about linear and angular acceleration and rotational velocity, provided by the vestibular system, that is, the otoliths and semicircular canals (Loomis et al., 1993). Proprioceptive signals could include muscle effort to maintain a constant speed (Riecke et al., 2002), for example.

Internal self-motion cues may be especially important for orientation when visual cues (such as distant landmarks) are restricted or blocked (Riecke et al., 2002; Riecke, van Veen, & Bühlhoff, 2000). Inertial signals from the semi-circular canals play a specific role in assessing angular motion, by providing information about turn rate, which indicates a navigator's instantaneous speed and direction of travel. Integration of turn rate over time enables navigators to determine the turn since the last known heading (Loomis et al., 1999b). During active walking, proprioceptive and further cues from locomotion complement vestibular information. Vestibular and kinaesthetic cues are thought to be particularly important for rotational self-motion (Riecke et al., 2002).

In familiar environments, navigators can obtain information which enables them to maintain a continuous record of their direction of travel, by using stable distal landmarks of known orientation as directional references (Jeffery, 1998); or by measuring rotations since the last known heading, with or without an external reference (Etienne & Jeffery, 2004). The most commonly-used environmental spatial references are visual cues (O'Keefe & Nadel, 1978). When these are not available, other types of external information can be relied on, together with self-motion cues

Thus, navigators calculate a position vector, which they then update through the continual updating of estimations of location and orientation, from the perception of self-motion (Etienne & Jeffery, 2004). The position vector may specify distance and direction from their current position to a single reference point, such as the origin of travel (a "homing vector"), or a more elaborate representation of the travelled path (Loomis et al., 1999b; Loomis et al., 1993; Kearns, Warren, Duchon, & Tarr, 2002; Cornell & Heth, 2004; Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999). Current position may be represented by the resultant vector of the summation of all the intermediate short-range (or infinitesimal) vectors, processed since the departure from the home position (Etienne & Jeffery, 2004). Path integration enables navigators to return to the starting point of a journey, through continuous estimation of their position with respect to the starting point.

Path integration is, thus, distinct from piloting, as it enables navigation without reference to prominent positional cues (such as landmarks) in an environment. It is, therefore, a useful strategy for travel in conditions where landmarks are absent or perceived as unreliable, such as in large-scale unfamiliar environments without any recognisable landmarks or other features: for example, in darkness, during a heavy snowfall, when flying through clouds, or in novel undifferentiated expanses of sea or snow. Path integration is a complementary process to piloting.

Under natural conditions, external references, such as landmark information and self-motion cues, usually interact continuously during navigation and can be

used to complement each other. Environmental and self-motion estimation information is integrated, with preference given to one or other type of information, depending on its salience or reliability. This is beneficial for navigators, as it enables them to use the most appropriate source of information at any time for a particular purpose. When very precise navigation is required, for example, path integration alone is too inaccurate to be relied upon because of the errors which progressively accumulate, due to the recurrent computational process it involves; and so the use of external landmarks is also required. Landmarks are not always available: during this time, path integration can be used for more accurate navigation. Drift in the path integration process can be corrected by stable landmarks when they are available: navigators establish their current location and orientation through a position fix, that is, through perception of external references.

However, path integration is a noisy process, as with any physical system. It is susceptible to individual random errors, which accumulate, thereby causing the representation of position to “drift”, that is, to become increasingly inaccurate (Ellmore & McNaughton, 2004; Etienne, Maurer, & Saucy, 1988; Etienne & Jeffery, 2004). Errors increase exponentially with travelled distance (Riecke et al., 2002; Loomis et al., 1999b). This applies especially when rotations are estimated independently of an external reference (Benhamou, Sauv e, & Bovet, 1990). As path integration is an incremental recursive process, in which changes in the current estimate of the position are added to the position vector of the previous step, errors during the integration of successive estimates of translational and rotational displacements are inevitable, even if each individual estimate is quite accurate.

The term *path integration* is based on an assumption that the process involves cumulation of successive small increments of movement along a path, which are added to a continually updated representation of direction and distance from the starting point (Mittelstaedt & Mittelstaedt, 1982; Mittelstaedt & Mittelstaedt, 1980). *Integration* reflects the hypothesis that, if one’s location and orientation at time  $t$ , together with one’s linear and angular speed and elapsed time, are known, then it is possible to calculate one’s position and orientation at time  $t + \Delta t$  (Ellmore & McNaughton, 2004). Historically, path integration was known as dead reckoning, a reference to deduced (“ded”) reckoning, which was used by sailors to navigate across featureless open sea (Etienne & Jeffery, 2004; Gallistel, 1990).

It is not yet known exactly how position vectors are computed by the nervous system. Mittelstaedt and Mittelstaedt (1982) proposed that position is updated in Cartesian coordinates; and that each rotation is separated into its two orthogonal components (sine and cosine), which are then integrated (summed up) over the total path. Although it remains unknown exactly how these processes of summation or

integration are performed by the nervous system, and exactly what is added up, or integrated, the series of neural computations required are analogous to those of vector addition and subtraction (Etienne & Jeffery, 2004). The computations involved in path integration can be formally specified by trigonometric rules. However, this does not imply that navigators perform explicit trigonometric operations (Klatzky, Loomis & Golledge, 1997; Etienne & Jeffery, 2004). The combining of direction and distance to yield a vector implicates information processing that is isomorphic with trigonometry, but not necessarily identical to it (Gallistel, 1990). Thus, it is unlikely that humans mentally apply formal trigonometric rules during path integration.

Several models have been proposed to explain the computations which underlie path integration, that is, the continuous calculation of momentary changes in location and orientation. One influential set of models centre on error-based algorithms. As these algorithms are derived from empirical data, they generate precise, and therefore verifiable, predictions of how particular parameters are computed, and therefore a navigator's behaviour in a specific situation. These models have been used to explain the similar systematic error patterns which are exhibited by many species when homing, that is, attempting to return to the starting point on the final leg of a triangular route (Müller & Wehner, 1988): the return vector tends to be fairly, but not very, accurate (although performance is above chance), as participants typically misperceive the degree of rotation and distance required.

The similarity of the observed error across a variety of unrelated species, such as hamsters (Séguinot, Maurer, & Etienne, 1993), ants (Müller & Wehner, 1988), dogs (Séguinot, Cattet, & Benhamou, 1998) and humans (Loomis et al., 1999b), suggests a common path integration algorithm. Benhamou et al. (1990) explained the cumulative errors, which occur during rotational and translational estimates, by adding an explicit representation of Gaussian noise to a trigonometric formulation of path integration. However, Müller and Wehner (1988) argued that noise alone cannot account for the systematic error in homing, and that it indicates, instead, the use of an approximate, but reasonably efficient, algorithm to compute the starting position. They proposed a recursive arithmetical algorithm of path integration to explain this error pattern in the homing response in ants. The observed biases are, thus, assumed to indicate how direction and distance are calculated.

However, error-based algorithm models, while useful, may not have general validity, as they can not describe all homing trajectories which have been observed, such as those on more convoluted routes (Séguinot et al., 1993; Maurer & Séguinot, 1995). Another group of influential models adopts a neural networks approach (Hartmann & Wehner, 1995; McNaughton et al., 1996; Samsonovich & McNaughton, 1997; Maurer, 1998; Arleo & Gerstner, 2000; Stringer, Trappenberg, Rolls, & de

Araujo, 2002). In network (or connectivist) models, the complementary nature of path integration and external references is usually acknowledged.

Path integration has also been described in terms of arithmetical models (Fujita, Loomis, Klatzky, & Golledge, 1990), and flow diagrams (Mittelstaedt, 2000).

### 1.3.3 Cognitive Maps and Path Integration

As well as updating position and orientation, navigators also usually need to access a more comprehensive and detailed representation of the whole environment through which they are travelling, which provides an overview of its layout (Loomis et al., 1999b). It has been proposed that navigators develop an internal representation of this kind through experience with the environment, that is, a *cognitive map* (Tolman, 1948), which becomes part of long-term memory. O'Keefe and Nadel (1978) further proposed that the location of the mammalian cognitive map is in the hippocampus.

A network of neural structures underlying spatial cognition has been identified in rats (Maguire et al., 1998), and it appears to be similar in humans. There is now general agreement that spatial representation is one function of the hippocampus. The representation of local large-scale space appears to depend on both the hippocampus and nearby structures (O'Keefe & Nadel, 1978; Morris, Garrud, Rawlins, & O'Keefe, 1982; O'Keefe, Burgess, Donnett, Jeffery, & Maguire, 1998), which are required in various navigational tasks.

It has been further proposed that the cognitive map is represented by the collective activity of *place cells*: these are neurons in the hippocampus, which fire at a high rate in response to an animal's specific location in an environment, known as the cell's *place field* (O'Keefe & Nadel, 1978; Nadel, 1999; Wilson & McNaughton, 1993; O'Keefe & Dostrovsky, 1971; Muller, 1996). Place cells also obtain information about direction, probably from the head direction system, a network of structures near the hippocampus: *head direction cells* fire when an animal's head faces a specific direction within an environment (Taube, Muller, & Ranck, 1990; Taube, 1998). Place cells may represent an internal map, and head direction cells an internal compass (Etienne & Jeffery, 2004).

Path integration in mammals may also be mediated by the hippocampus and its associated structures, together with the head direction system. The hippocampus may, thus, function as both a map and a path integrator. It is possible that place cells constitute the mammalian path integrator: they are influenced by signals derived from translational and directional self-motion, and may be where distance and direction information from various sensory modalities is integrated (O'Keefe & Nadel, 1978; McNaughton et al., 1996; Samsonovich & McNaughton, 1997; Whishaw, McKenna, &

Maaswinkel, 1997). It is generally agreed that the representation of position can be updated by the ensemble firing of place cells from moment to moment, using self-motion cues that indicate direction (Jeffery, Donnett, Burgess, & O'Keefe, 1997) and distance (Gothard, Skaggs, & McNaughton, 1996), as well as landmark information (O'Keefe & Speakman, 1987). However, it is not known whether these signals are relayed to the hippocampus via a mediating structure, or arrive there directly and are then combined by the place cells: and thus, whether a mediating structure, or the hippocampus itself, is indicated as a path integrator (Etienne & Jeffery, 2004).

Place representation and path integration have a close relationship and are mutually reinforcing. Path integration may play a key role in the development of a navigator's map (Gallistel, 1990; McNaughton et al., 1996; Etienne, 1998): and may, in turn, be influenced by the representation of current surroundings provided by the map (Etienne & Jeffery, 2004). As path integration involves estimating distances and angles traversed during navigation, it may facilitate the acquisition of some metric details for inclusion in the cognitive map, such as approximate distances and angles between places (Kearns et al., 2002; Foo, Warren, Duchon, & Tarr, 2005).

An important function of path integration is to enable navigators to venture into unfamiliar terrain. During exploration of a novel environment, ongoing estimates of current position, provided by path integration, facilitate the gradual integration of the isolated perspective views encountered into a cognitive map of the layout of the environment, which supports subsequent piloting (Gallistel, 1990; Loomis et al., 1999b). Cognitive maps also support flexible navigation in familiar environments through more sophisticated behaviour, such as by facilitating detours and novel shortcuts to locations other than the starting point (Loomis et al., 1993): this requires a representation of the environment in which locations are interconnected, by either Euclidian or topological relationships (Etienne & Jeffery, 2004).

## **1.4 Experimental Considerations**

### **1.4.1 Path Completion Tasks: Triangle-Completion**

Experimental studies of human path integration typically employ path-completion tasks, such as return-to-origin tasks, in which participants are led along the outbound legs of a path, usually consisting of a small number of straight segments (legs) which are separated by turns, and then asked to return unaided to the origin by the most direct route (that is, to complete the path). Alternatively, participants can indicate the direction of the origin from the end point of the path, by turning to face it (Klatzky, Loomis, Beall, Chance, & Golledge, 1998), by reorienting a viewpoint in a virtual

environment (Péruch, May, & Wartenberg, 1997), or by pointing to it using a dial or protractor (Sadalla & Montello, 1989; Sholl, 1989). The task is conducted in the absence of piloting information, so that participants must use information from their self-motion to update estimates of their position and orientation along the path.

In attempting to return to, or to indicate, the origin, participants demonstrate their knowledge of the relationship between the origin and the end point, on the basis of path integration along the intervening path (Loomis, Klatzky, Golledge, & Philbeck, 1999). This type of task, therefore, assesses the ability of participants to keep track of their position in space as they move through it, without reference to landmarks: it requires only keeping track of the origin with respect to self. It is the most direct way of assessing path integration ability (May & Klatzky, 2000; Loomis et al., 1993; Klatzky et al., 1990; Worchel, 1951).

A commonly-used paradigm for path integration, and for other navigation tasks which do not depend on landmarks, is a return-to-origin task known as *triangle-completion*, or *homing*. In this task, participants are led by an experimenter along the two outbound segments of a triangular path, and through the angle between them; then, from the end of the second leg, they attempt to complete the third segment by heading directly back to the origin of the route, or home position, thereby closing the triangle (Loomis et al., 1993; Klatzky, Loomis, & Golledge, 1997; Péruch et al., 1997; Kearns, Warren, Duchon, & Tarr, 2002; Riecke, van Veen, & Bühlhoff, 2000, 2002; Riecke, von der Heyde, & Bühlhoff, 2001; Klatzky et al., 1990; Sadalla & Montello, 1989). Triangle-completion tasks use the simplest non-trivial combination of translations and rotations (Riecke et al., 2000, 2002; Kearns et al., 2002). Typically, input from one or more sensory sources is withheld, in order to assess the relative contribution of the remaining sense(s) to path integration.

Triangle-completion tasks have been widely used to study human path integration: in real-world studies of path integration performed without vision, that is, on the basis of vestibular and / or proprioceptive information (Loomis et al., 1993; Klatzky et al., 1990; Sholl, 1989); and to examine path integration performed in virtual environments, based purely on optic flow cues (Péruch et al., 1997; Riecke et al., 2000, 2002; Gramann, Müller, Eick, & Schönebeck, 2005). Triangle-completion tasks have also been used, in both real and virtual environments, to compare the relative contributions of visual, vestibular and proprioceptive information (Kearns et al., 2002; Klatzky et al., 1998; Chance, Gaunet, Beall, & Loomis, 1998). Humans display a limited ability to perform the task (especially compared with some other species), but responses are generally well above chance (May & Klatzky, 2000; Loomis et al., 1993; Klatzky et al., 1990; Worchel, 1951).

Triangle-completion is a suitable paradigm for the analysis of elementary spatial information about distances and directions (Wartenberg, May, & Péruch, 1998). It is a simple and well-defined task, which is also ecologically valid, since humans, like most other mobile species, often need to find their way back to specific places: for food, shelter, or social purposes. The results are usually clear and relatively easy to interpret. More complex navigation behaviour can be decomposed into elementary translations and rotations, which are, indeed, often studied in conjunction with triangle-completion experiments (Riecke et al., 2000, 2002).

### **1.4.2 Virtual Environments**

In order to distinguish experimentally between piloting and path integration, and to examine one type of spatial updating cue in navigation studies, other types of cue need to be excluded. Visual cues for path integration can be excluded experimentally by blindfolding participants, allowing a focus on the contribution of proprioceptive and vestibular information. It is more difficult to eliminate body-based cues, in order to examine the role of visual information. However, virtual environments provide a methodological means to present visual cues alone: self-motion can be simulated and physical participant movement excluded, enabling isolation of visual cues from proprioceptive and vestibular cues (Riecke et al., 2002; Wartenberg et al., 1998).

Implicating path integration requires the exclusion of any possibility of navigation based on piloting: it is important to confirm that participants did not have access to any external references, such as landmarks (Etienne & Jeffery, 2004). This can be accomplished experimentally by eliminating all potential positional cues, such as landmarks, from the environment (Loomis et al., 1999b; Etienne & Jeffery, 2004). Conversely, the elimination of all velocity and acceleration information, through presentation of a series of still images (as in a slide-show), excludes path integration.

The prevention of position-based spatial updating can be challenging, due to the dominant role of landmarks in normal navigation (Riecke et al., 2002). However, virtual environments can be used to render piloting difficult or impossible, and to ensure that participants rely on path integration only, by reducing the potential for visible objects to function as landmarks. This can be achieved methodologically by displaying only visual features which elicit optic flow, such as a great number of identical objects, which can be tracked over only a short distance.

Another advantage of using virtual environments to study navigation is that they can provide a simultaneously high degree of both experimental control and realism. Their use enables researchers to avoid the pitfalls of using either real-world environments, in which extraneous variables (such as traffic, or weather conditions)

cannot be controlled; or simplified laboratory simulations, which are unrealistic and may eliminate too many variables (Tarr & Warren, 2002; Loomis, Blascovich, & Beall, 1999; Bühlhoff & van Veen, 1999; Péruch & Gaunet, 1998; Hettinger & Haas, 2003; Christou & Bühlhoff, 2000a). Identical participant experience can, thus, be ensured. This methodology further allows the environment to be tailored to particular research questions, and the visual input to be rigorously controlled (Bühlhoff & van Veen, 1999; Péruch & Gaunet, 1998). Thus, the use of virtual reality supports controlled realism.

The flexibility of virtual environments enables novel environments, of varying levels of complexity, to be created (May, Péruch, & Savoyant, 1995); as well as rapid alternation between various environments, which are identical except for the experimental variables (Christou & Bühlhoff, 2000a; Péruch & Gaunet, 1998; Wilson, 1997; Bühlhoff & van Veen, 1999). Virtual worlds can provide sensory realism in experiments: for example, through the display of complex scenes with 3D graphics, which simulate visual cues in the real world; and through the use of spatial cognition tasks which closely reflect real-world tasks, and are performed in naturalistic contexts (van Veen, Distler, Braun, & Bühlhoff, 1998; Christou & Bühlhoff, 2000a).

Virtual reality may, thus, support a more ecologically valid approach to laboratory-based research within psychology (Hettinger & Haas, 2003). Many psychologists, in accordance with Gibson's ecological theory (Gibson, 1966, 1979), have argued for greater ecological validity in psychological research. Wann and Rushton (1995), for example, stressed the importance of using an ecological context and naturalistic optic array for studying self-motion.

### **1.4.3 Directional Estimates**

Participants in the current study will indicate the estimated direction of the starting point of the route with a virtual dial, which will be displayed on the computer screen at the end of each trial. Thus, directional estimates will be the dependent variable.

Estimates of path distance in the final response will not be measured. Having participants actually return to the start point of the route by the shortest path within the virtual world (as is common in path integration studies) is precluded. Neither the driving simulator nor the small-screen display permit physical movement, as both types of apparatus are non-immersive (unlike, for example, a head-mounted display). However, these methods are less invasive and less generally nauseogenic than more immersive equipment.

It is also impractical for participants to return to the start point using simulated self-motion, since this would involve travelling through buildings, especially in the urban environments: such behaviour would disturb the naturalness of the task, and

the authenticity of the environments. The study of path integration under ecologically valid conditions is an important aim of the experiments. Requiring participants to return to the start point would also introduce a further degree of rotation, which would be variable between participants.

Finally, giving participants the means to manipulate the point of view within the virtual world, so that they can change their heading direction to face the start point, and then initiate simulated movement towards it, would add unnecessary complexity to the task. Such a manoeuvre would require rotation of scenes in 3D space, which may be difficult for participants with no previous experience, and also add further variability between participants.

## **1.5 Previous Research on Human Path Integration**

Sensory information used in human path integration can include visual cues, such as optic flow, when the flow conveys information about a navigator's velocity (Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001); and non-visual cues, such as vestibular signals and / or proprioception (Loomis, Klatzky, Golledge, & Philbeck, 1999). The contributions of these potential inputs to path integration have been assessed in several previous studies, using path-completion tasks. The overall findings of these studies are discussed below. Some of the issues raised by this research will be further considered in this study.

### **1.5.1 Path Integration Performance Under Non-visual Conditions**

Human path integration performance using vestibular and proprioceptive cues, in the absence of vision, is not very accurate; neither is it greatly inaccurate, however, as it is generally well above chance (Loomis et al., 1993; Klatzky et al., 1990; Sholl, 1989; Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999). A systematic pattern of errors has been observed in path-completion studies in which participants walked without vision along paths with short (2, 4, or 6m) straight segments: this is thought to reflect systematic biases in path integration (Philbeck et al., 2001; Loomis et al., 1999b).

Distance and turn responses towards the origin tend to be stereotyped, showing a compression of the range of responses relative to the correct values: that is, a regression towards the mean of the set of values used. Typically, participants undershoot the correct response values when relatively large turn angles ( $> 90^\circ$ ) and long path distances are required; and overshoot them when relatively small turn angles ( $< 90^\circ$ ) and short path lengths (within 4m) are required. The point at which

errors change from overshoot to undershoot is not reliably close to the mean of the response range (Philbeck et al., 2001). There is limited sensitivity to differences in outbound path lengths, and in the turn angle between them: on triangle-completion tasks, responses are biased toward equilateral triangles, regardless of actual triangle layout. Performance becomes less accurate with increases in outbound path length and number of path segments. There is considerable between-participant variation.

Accuracy deteriorates further on longer (20-120m) curved outbound routes, especially those with a larger gradual curve (Cornell & Greidanus, 2006; Cornell & Bourassa, 2007). Participants tend to underestimate the degree of curvature, and to confuse straight and curved paths, showing a bias to straighten curved segments. The degree of rotation (that is, turn versus curve) may, thus, be important.

## **1.5.2 Path Integration Performance Under Visual Conditions**

### **1.5.2.1 Optic Flow**

The advent of virtual reality in experimental research has facilitated an examination of the role of vision in human navigation, by enabling the total, or almost total, exclusion of other sensory inputs; previously, this was difficult to achieve. In virtual environments, optic flow can be easily separated from non-visual cues, as well as from other visual information (such as landmarks): this supports the study of path integration based on visual cues such as optic flow. The amount of available visual and other sensory information can also be varied.

A critical requirement for navigating through an environment is the ability to estimate one's own self-motion (Perrone & Stone, 1994; Warren & Hannon, 1988; Warren, Morris, & Kalish, 1988; van den Berg, 1992; Cutting, Springer, Braren, & Johnson, 1992; Stone & Perrone, 1997; Turano & Wang, 1994; Warren, Mestre, Blackwell, & Morris, 1991; Rieger & Toet, 1985). Human perception of both rotational and translational self-motion seems to depend predominantly on vision. A compelling illusion of self-motion (vection) can be elicited by a purely visual stimulus which moves coherently, and occupies a large portion of the visual field, that is, by optic flow, in the absence of any physical movement (Dichgans & Brandt, 1978).

Optic flow is the dynamically changing pattern of image motion across the retinae, resulting from a navigator's self-motion through an environment (Gibson, 1950): a constantly fluctuating pattern of light projected onto the retinae, which is generated by images of surrounding moving objects. The image flow field results from a combination of the observer's translation and rotation relative to a 3D scene

(Hildreth & Royden, 1998). The properties of the flow field depend on both direction of travel and direction of gaze.

The optic flow experienced by humans during self-motion is essential for visual navigation, as it provides important information for the control of locomotion through the environment, such as speed and heading direction (Gibson, 1950, 1966, 1979). Humans can recover heading information from the combined translational and rotational components of optic flow (Rieger & Toet, 1985; Stone & Perrone, 1997), and are able to estimate heading quite accurately from optic flow during both linear (Warren & Hannon, 1988; Warren et al., 1988; van den Berg, 1992; Cutting et al., 1992), and curvilinear or circular (Stone & Perrone, 1997; Turano & Wang, 1994; Warren et al., 1991) self-motion.

Optic flow cues support human path integration, enabling both distance (Lappe, Jenkin, & Harris, 2007; Frenz & Lappe, 2005; Redlick, Jenkin, & Harris, 2001) and angular displacement (Ellmore & McNaughton 2004) to be estimated fairly accurately. Humans can judge 3D motion accurately, when presented with only sparse image features within a narrow field of view (Hildreth & Royden, 1998). 3D information, derived from visual motion, is integrated with that from other visual cues such as texture, and with extra-retinal information about eye and head movements.

Studies examining the visual contribution to path integration typically use moving patterns to generate optic flow in virtual environments: these range from dots moving in space, to replications of floor, wall and ceiling textures which simulate movement through more natural spaces, such as tunnels (Gramann, Müller, Eick, & Schönebeck, 2005) or urban space (Riecke, van Veen, & Bühlhoff, 2000, 2002).

It has been shown that humans can perceive self-motion, and estimate both the angles they have turned and distances they have travelled, from pure optic flow information (Bremmer & Lappe, 1999; Ellmore & McNaughton, 2004; Warren, Kay, Zosh, Duchon, & Sahuc, 2001; Warren & Wertheim, 1990). Angular speed and direction of rotation are specified by the rate of optic flow from the surrounding visual field (Warren, 1995). Optic flow also specifies the direction and speed of translation (Warren et al., 1988). This study examines human perception of self-motion, and estimation of angles and distances, from optic flow cues which are contextualised within realistic environments.

### ***1.5.2.2 Studies of Path-Completion in Virtual Environments***

Studies of human path integration based on optic flow information have typically utilised path-completion (especially triangle-completion) tasks conducted in virtual environments (Péruch, May, & Wartenberg, 1997; Wartenberg, May, & Péruch, 1998;

Riecke, van Veen, & Bühlhoff, 2000, 2002; Kearns, Warren, Duchon, & Tarr, 2002; Gramann, Müller, Eick, & Schönebeck, 2005). In general, the results of these studies (Riecke et al., 2000, 2002; Gramann et al., 2005; Kearns et al., 2002) indicate that humans can use optic flow for path integration with a level of accuracy similar to that found in non-visual studies (Klatzky et al., 1990; Loomis et al., 1993). Some of these studies also suggest that information from the body senses is preferred to visual information when it is available (Péruch et al., 1997; Kearns et al., 2002).

Péruch et al. (1997) and Wartenberg et al. (1998) examined human path integration ability on the basis of optic flow cues, using a triangle-completion task in simple virtual environments, which were presented on a flat projection screen. The results were broadly similar to those of Loomis et al. (1993) for non-visual path integration, but more pronounced. Performance was not very accurate, especially for rotation: it was less accurate, overall, than non-visual path integration performance, suggesting that optic flow alone cannot compensate for the absence of vestibular and proprioceptive cues. A consistent effect of triangle layout was observed: namely, a regression towards stereotyped responses in the final turning angles and distances, especially for isosceles triangles. In contrast with many other triangle completion-experiments (such as Loomis et al., 1993), the final turn response towards the origin showed strong systematic undershooting, particularly with the longest distances and largest turn angles on the outbound path.

However, there was minimal optic flow in the experiments by Péruch et al. (1997) and Wartenberg et al. (1998), due to a lack of textured surfaces and an absence of a ground plane in the virtual environments. Accuracy was higher in experiments in which optic flow cues were available from more extensive texture (Kearns et al., 2002; Riecke et al., 2000, 2002; Gramann et al., 2005): visual path integration performance was equal or superior to non-visual path integration. In the studies by Riecke et al. (2000, 2002) and Gramann et al. (2005), rotations, in particular, were found to be extremely accurate. Self-motion cues were available through optic flow only in these studies.

The experiments by Riecke et al. (2000, 2002) and Gramann et al. (2005), challenge the findings of some previous path-completion studies conducted in virtual environments, which indicated that optic flow information by itself is insufficient for accurate path integration, particularly during turns (Bakker, Werkhoven, & Passenier, 2001, 1999; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Chance, Gaunet, Beall, & Loomis, 1998). In the earlier studies, path integration performance was found to be more accurate when idiothetic (vestibular and proprioceptive) cues were available to participants in addition to optic flow, rather than just optic flow, suggesting that idiothetic cues are essential for updating heading and position,

especially for rotational changes. Participants tended to underturn (Bakker et al., 1999) or overturn (Bakker et al., 2001; Klatzky et al., 1998) when they had access to optic flow only. A large variability in performance was also found, both within and between participants (Bakker et al., 2001, 1999).

Kearns et al. (2002) used more textured virtual environments to compare the relative contributions of information available from optic flow and the body senses (such as vestibular, proprioceptive, and efferent cues) to human path integration. Participants performed a triangle-completion task, actively walking in environments in which the amount of information available from simulated optic flow was varied. Either rotational or translational flow alone was promoted, through inclusion of texture on the walls, or on the floor, respectively; both types of optic flow together were elicited through inclusion of both wall and floor texture; or no optic flow cues were provided, by completely dispensing with texture.

Optic flow provided sufficient information to enable participants to perform path integration, with a level of accuracy similar to that found in previous studies (Loomis et al., 1993; Péruch et al., 1997). Performance was most accurate in the richly-textured environment containing both wall and floor texture, as participants could benefit from both rotational and translational optic flow. Reduced translational flow increased variability in path length, whilst reduced rotational flow reduced turning accuracy, in the final response. When only optic flow was available, participants showed a strong tendency to turn too far for small (acute) angles and not far enough for large (obtuse) angles, whilst generally overshooting shorter path lengths and undershooting longer ones. This pattern is consistent with that found in studies of path integration performed with vision only (Péruch et al., 1997) and without vision (Loomis et al., 1993). Participants were not very sensitive to triangle layout: they tended to produce stereotyped (very similar) responses across different layouts when returning to the origin of the path, regardless of the actual layout. There was a tendency for participants to respond as though all triangles were equilateral, even though many were not: this suggests that performance did not entirely depend on sensory information, and may also have been biased towards equilateral triangles.

Performance was dominated by information about self-motion from the body senses, when this was available in addition to optic flow, suggesting that humans preferentially rely on non-visual cues for path integration. Accuracy was highly similar regardless of whether optic flow was available or not (that is, when both wall and floor texture were present, or when no texture was present), indicating reliance on other information. Performance was no more accurate than with vision alone but exhibited a pattern of systematic overturning (overshooting of the origin), in both turn angle and path length. Response variability also decreased when both types of cue

were available. Similarly, Sun, Campos, and Chan (2004) found that, while both optic flow and proprioceptive cues contribute to speed estimation, and either cue alone is sufficient, when the two types of cue are in conflict, proprioceptive cues dominate.

The influence of optic flow, relative to the body senses, during path integration may have been reduced in the experiments by Kearns et al. (2002), due to the use of a head-mounted display with a restricted field of view (60° horizontal x 40° vertical). However, the differential performance found, depending on the availability of texture in the environment, suggests that optic flow can be used for path integration even with such a limited field of view. Péruch et al. (1997) also found no significant effect of varying geometrical field of view between 40° and 80° (with a fixed actual field of view of 45°) on the accuracy of visual path integration.

The studies by Riecke et al. (2000, 2002) emphatically demonstrated that optic flow information is sufficient by itself to support human path integration, and indicated that proprioceptive and vestibular cues are not required for self-rotations. Participants performed a triangle-completion task with very small systematic errors and variance (much smaller than for non-visual turning), especially for rotations; they thereby showed that they were able to accurately integrate velocity and acceleration information, derived from optic flow, to estimate the angles turned and distances travelled.

Riecke et al. (2000, 2002) did not find the strong bias towards stereotyped turn responses (a regression towards mean responses), which has been observed in similar triangle-completion experiments in virtual environments (Péruch et al., 1997; Kearns et al., 2002), and in active walking (Loomis et al., 1993). The findings contrast sharply with the results from turning experiments by Bakker et al. (1999) and by Péruch et al. (1997), which demonstrated systematic undershooting of turning angles and large variability for rotations based on purely visual information. However, distances were compressed towards stereotyped responses, showing a bias towards the mean response, which is a common finding in virtual environments.

Riecke et al. (2000, 2002) attribute the high turning accuracy they observed to several factors, including the use of non-immersive (desktop) virtual environments, which were presented on a half-cylindrical 180° projection screen. The screen provided both a large field of view, which has been shown to facilitate navigation (Arthur, 2000); and a spatial reference frame, which, the authors argue, may have aided estimations of egocentric angles by suggesting a polar coordinate system. Riecke et al. (2000, 2002) also emphasise the methodological strengths of using virtual environments: as possible navigation mechanisms had been limited to path integration, the sufficiency of purely visual cues in a triangle-completion task could be demonstrated. The use of realistic and detailed virtual environments, in particular,

has been advocated (Bülthoff & van Veen, 1999): their use here may have led to more accurate performance.

Importantly, however, performance may also have been partly influenced by the inclusion of additional learning aids in the experiments: during training, participants were provided with feedback on the accuracy of their performance (Riecke et al., 2000), or a visual overview of the route (Riecke et al., 2002). Bakker et al. (2001) also found more accurate path integration performance based on rotational optic flow when participants received feedback. The influence of other variables, such as the use of a wide field of view and a curved projection screen, may also have been confounded by the learning aids. In the present study, no feedback will be given to participants about the accuracy of their performance during the experiments; and no navigational aids, such as an overview of the route, will be available.

Gramann et al. (2005) further demonstrated that optic flow cues can, by themselves, provide sufficient information for human path integration. Participants navigated through a virtual tunnel presented on a desktop display, and adjusted a homing vector indicating their end position relative to the origin of the path. Self-motion provided information on translational and rotational changes through the rate of optic flow only, which was derived from floor and wall texture: there were no accompanying proprioceptive or vestibular cues. Path integration performance was relatively accurate, even with a high number of turns. In common with previous studies, stereotyped responses were observed across tunnels with different numbers of turns: a general tendency to overestimate end positions of low eccentricity and underestimate those of high eccentricity, reflecting a tendency towards the middle values. Sparse optic flow information was sufficient for accurate path integration performance, indicating that even the simple virtual environment provided by the tunnel task enabled participants to develop a spatial representation that was accurate enough to support path integration.

The optic flow cues in the studies by Kearns et al. (2002) were available from random-patch texture patterns, rather than realistic textures; similarly, the optic flow in the tunnel study by Gramann et al. (2005) was presented through non-realistic texture. Urban environments have been used in a few studies, but these have tended to be greatly simplified, with a few well-defined buildings in a vast expanse of empty space, or featureless grey city blocks (Kirschen, Kahana, Sekuler, & Burack, 2000; Riecke et al. 2000; 2002). In the current study, realistic textures will be used.

The relative importance of visual versus vestibular and proprioceptive cues may also depend on the task, and on interface fidelity (that is, how realistically the users' interactions with the virtual environment are simulated, such as changes in their position and orientation during self-motion, including changes in velocity and

acceleration (Waller, Hunt, & Knapp, 1998). Lathrop and Kaiser (2005) found that a head-mounted display facilitated path integration performance on a simple target-search task, but not on a more complex task, which required maintaining orientation (Lathrop & Kaiser, 2005).

## **1.6 Path Integration and Navigation Mode**

This study will extend previous research on the effects of navigation mode on path integration. Firstly, the effects of active and passive navigation will be compared: participants will either control their own simulated self-motion along the routes, or watch a pre-recorded sequence of simulated motion along them. Secondly, the effect of making the information from self-motion available only intermittently, thereby disrupting the optic flow cues, will be examined: participants will navigate by observing a series of sequentially-presented static images of each route.

Several studies of human path integration have compared performance under active versus passive navigation conditions; and under conditions of dynamic versus intermittent presentation of visual information. The findings have been inconsistent. Péruch, Vercher, and Gauthier (1995) found that active navigation facilitated path integration; whilst others have found no difference between the effects of active and passive navigation (Gaunet, Vidal, Kemeny, & Berthoz, 2001; Wilson, Foreman, Gillett, & Stanton, 1997; Wilson, 1999). Similarly, some studies have found that path integration does not require continuous presentation of visual information (Gaunet et al., 2001; Péruch et al., 1995; Mestre, 1988); however, Kirschen, Kahana, Sekuler, and Burack (2000) observed that smooth optic flow promoted more accurate path integration, compared with intermittent optic flow resulting from a low-frequency refresh rate. This suggests that the quality of the optic flow presented in the visual stimulus may be important.

Gaunet et al. (2001) examined the effect of navigation mode on visual path integration in a large-scale urban virtual environment, presented in a driving simulator. Participants explored the environment in one of three modes: actively, by controlling their self-motion along a route with a joystick, according to directions; passively, by watching a pre-recorded route; or intermittently, by observing a series of still snapshots of the route, presented sequentially from every 4m along it.

Accuracy of directional estimates (pointing towards the route origin) was not affected by exploration mode, indicating that path integration did not require active self-motion or continuous presentation of visual information; participants may have relied, instead, on either integration of duration of self-motion or a frame of reference. Participants were able to perform path integration in the snapshot condition, which

suggests that even exploration of such an environment via intermittent views allows tracking of position with respect to the route origin. This may be because the availability of many salient landmarks in the structured environment provided sufficient visual information to support task performance; or because the inter-stimulus interval was not long enough to prevent perception of motion, allowing integration of the separate views of the path.

Similarly, Mestre (1988) found that participants were able to successfully control a large virtual ship, keeping it within the boundaries of a simulated channel, using visual information from a perspective view of the channel, which was presented as a sequence of static frames, that were updated every 3s. Performance improved when secondary displays were presented (such as a turn-rate indicator).

However, intermittent optic flow had a detrimental effect on purely visual path integration performance in virtual city-block environments, in a study by Kirschen et al. (2000). Participants were able to locate a remembered target position more accurately after navigating through the complex environments with “fluid” optic flow, than with “choppy” optic flow (conditions in which the display was updated 50 times versus just twice, respectively, during movement along equal-length segments of the route, evoking distinctly different impressions of self-motion). This indicates a facilitative effect of optic flow in the absence of other (e.g., vestibular) cues. Pauses of different lengths between successive updates ensured that the time taken to travel along segments was equivalent in the two conditions. Other visual cues were eliminated: for example, the textures on the floors, wall, and ceilings were modified to create a homogeneous environment of random-luminance squares. Participants used a keyboard to control realistic simulation of self-motion. In a previous experiment, participants had learned to navigate virtual T-junction mazes faster when optic flow cues were available than when they were not, but had relied on visual landmarks at maze junctions instead when these were available (Kirschen et al., 2000).

Péruch et al. (1995) found that participants learned the layout of a small-scale simple virtual environment, presented on a large display screen, better after active exploration (self-initiated movement and the ability to change viewpoints with a joystick) than passive observation (a pre-recorded tour viewed either dynamically during transportation along the path, or as a series of static scenes from successive points of view along it). Following exploration, active participants were faster and more accurate in reaching a specified target, not visible from the starting point, by the shortest path. However, dynamic and static passive conditions yielded equivalent performance. All participants found the active condition easier to perform than the passive conditions; most participants also reported that the static passive exploration was more difficult, and required more attention, than the dynamic passive condition.

Wilson et al. (1997a), however, using a simple desktop virtual environment, modelled on the one used in the Péruch et al. (1995) study, found no difference between participants who had actively explored the environment, and those who had passively observed it, in their ability to later find target objects. No effect was found of either psychological activity (directing the course of exploration), or physical activity (interacting with the computer). Wilson et al. (1997a) concluded that any effects of active exploration on spatial learning are small and difficult to detect. However, passive participants were yoked to an active participant in this study, so their performance could have depended on the ability of their partner to explore actively.

## **1.7 Navigation and Gender in Virtual Environments**

Differences in preferred navigational strategies may impact on men's and women's path integration performance. Various studies have shown a preference by females for landmark information, and by males for metric information, in navigation generally (Galea & Kimura, 1993; Sandstrom, Kaufman, & Huettel, 1998). As path integration is based on (possibly Euclidian) distance and angular information in the absence of landmarks, it could be expected that males might have an advantage, whilst females may be negatively affected. Some research also suggests that females are disadvantaged in studies conducted in virtual environments (Lawton & Morrin, 1999; Tlauka, Brolese, Pomeroy, & Hobbs, 2005). It might be expected, therefore, that females would show less accurate performance than males in path integration studies carried out in virtual environments.

Few studies as yet have specifically examined gender effects on path integration, but those which have (Fortenbaugh, Chaudhury, Hicks, Hao, & Turano 2007; Kearns, Warren, Duchon, & Tarr, 2002) present a somewhat mixed picture (as discussed below). The current study will extend previous research on gender effects on path integration in virtual environments. A large sample of both males and females will be included in the experiments, enabling detailed comparisons across conditions. Some studies, such as Kearns et al. (2002), have found that simulator sickness particularly affects female participants, thereby reducing the size of the female sample through attrition. As women may be more likely to experience such symptoms and withdraw from the study, efforts will be made to reduce the probability of cybersickness in these experiments. In view of the unpleasantness of symptoms, this will be beneficial for participants of both genders.

### 1.7.1 Path Integration and Gender

Kearns et al. (2002) found gender differences in visual path integration performance based on optic flow alone, assessed by triangle-completion. Females showed greater variability in their final turn angle and path leg responses than males, and they were less affected by the amount and type of optic flow information available in the environment, showing less dependence on optic flow. Thus, females may not have relied primarily on optic flow while performing path integration, instead using some other strategy to perform the task, such as timing or static information. Males tended to perform randomly in an environment with minimal texture, indicating greater reliance on optic flow for path integration, rather than static visual information.

However, these findings were complicated by an overall insensitivity to triangle shape among all the participants (that is, the widely-observed tendency to produce stereotyped responses across all triangle layouts), which suggests that responses were not entirely dependent on sensory information, and that path integration performance may also have reflected a bias towards equilateral triangles. Furthermore, the sample size in this study was very small. Kearns et al. (2002) advise caution in interpreting the results, in view of a high attrition rate for women due to simulator sickness; they suggest that sensory conflict may have led to a higher rate of sickness symptoms in women who relied on optic flow, and, hence, that those who completed the experiment may have been less visually dependent.

Women also turned further than men when only optic flow was available, and less than men when both optic flow and physical cues were available, which resulted in more accurate turns by women in both conditions. Thus, gender differences in path integration performance were not straightforward in this task: the use of different strategies did not appear to provide a clear advantage for either gender in path integration. This is consistent with previous research on navigation, showing both male and female advantages in different contexts (Galea & Kimura, 1993; Moffatt, Hampson, & Hatzipantelis, 1998).

Some other aspects of this study may have had gender implications, although these were not explicitly addressed, such as the limited field of view, immersive apparatus, and simulation of optic flow through abstract random textures in non-realistic environments. Several studies have found enhanced female performance in realistic virtual environments, and when a wider field of view is used. Thus, changing some of the experimental parameters may have beneficial effects on female performance. In the present study, a wide field of view, non-immersive apparatus, and simulation of optic flow through the presentation of realistic textures and environments, are expected to enhance female performance. Few previous studies of gender differences in navigation have focused exclusively on visual information.

Female dependence on non-visual cues for human path integration was also found by Fortenbaugh et al. (2007). Gender differences in performance were exhibited when participants walked without vision to previously seen targets in virtual rooms with either minimal or photorealistic textures. Men generally demonstrated more accurate path integration performance than women. Differences were also found in the type of sensory information used for spatial updating: men and women paid attention to different types of cues. In the presence of a salient visual cue, men were able to ignore misleading auditory cues; which suggests that men pay more attention to visual cues. However, gender effects were not only due to differences in cue preference: women were not able to use visual cues effectively to perform the task, whereas men were able to use both visual and non-visual (auditory) cues. Men tended to use auditory cues when texture was minimal, and visual cues when photorealistic texture was available, suggesting that the level of detail of visual cues was important in determining whether men relied more on these, or on auditory cues.

### **1.7.2 Virtual Environments and Gender**

Gender differences have been reported in studies of human navigation conducted in virtual mazes. Moffatt et al. (1998) found that males learned a novel route through a virtual maze (with no landmarks) more quickly and accurately than females. Lawton and Morrin (1999) observed that, while accuracy in pointing to the route origin in virtual mazes declined with number of turns for both genders, men were consistently more accurate than women, regardless of maze complexity. Similarly, Foreman, Sandamas, and Newson (2004) found that, while both genders underestimated distances to target objects in a real corridor, following simulated movement along a virtual corridor, males were more accurate than females.

Waller, Hunt, and Knapp (1998) found that women were less able than men to apply spatial knowledge acquired during training in a virtual maze to a real-world maze. However, comparable performance was observed after training in a real maze, suggesting that performance differences were probably due to gender differences in interacting with virtual environments, rather than in acquisition of spatial knowledge. Virtual environments may be more challenging for women: Waller, Knapp, and Hunt (2001) found a tendency for women to become more disorientated than men in virtual mazes. Waller (2000) showed that gender influenced spatial knowledge acquisition from a desktop virtual environment, primarily through its association with navigational interface proficiency; when this is factored out, the contribution of gender *per se* to spatial knowledge acquisition from virtual environments is not so great.

Tlauka et al. (2005) observed that gender also influenced acquisition of spatial information in more complex virtual environments: large-scale virtual shopping centres. Following exploration, compared with males, females were less efficient in navigating back to the start location; required more time to travel from start to finish locations and to make directional estimates; and made more incorrect navigational decisions while following a route.

However, several studies conducted in more realistic and ecologically-valid virtual environments (such as those containing more landmarks) have reported no gender effects: for example, Wilson, Foreman, and Tlauka (1997), in tasks that tested spatial knowledge acquired in a virtual multi-storey building; Rossano and Moak (1998), following exploration of a virtual university campus; and Darken and Sibert (1996) in a search task through virtual worlds. Inconsistencies in reported gender effects may therefore be related to differences between the virtual environments used (Tlauka et al., 2005): the majority of studies which have found gender effects used relatively abstract environments, such as featureless mazes (Astur, Ortiz, & Sutherland, 1998; Moffat et al., 1998; Sandstrom et al., 1998).

Females and males may also use different navigation strategies. Several studies, using various paradigms, have demonstrated a tendency for women to rely on landmarks (for example, memorising landmarks along the route and relations between these), and for men to depend on Euclidian geometric properties of the environment (such as cardinal directions and metric distances), when navigating (Dabbs, Chang, Strong, & Milun, 1998; Galea & Kimura, 1993).

Gender differences in navigation tasks may, therefore, be related to the number of landmark cues available, reflecting a male advantage in tasks that provide primarily Euclidian directional cues. Superior navigational performance by males is more apparent in tasks that favour a Euclidian strategy, because of limited or unreliable landmark cues (Astur, Tropp, Sava, Constable, & Markus, 2004; Moffat et al., 1998; Sandstrom et al., 1998). In tasks that rely on positional (landmark) cues, women perform as well as, or better than, men (Astur et al., 2004; Levy, Astur, & Frick, 2005; O'Laughlin & Brubaker, 1998; Saucier et al., 2002); while in maze navigation tasks where such cues are absent, shifted, or removed during testing, female performance is impaired to a greater extent than that of males (Moffat et al., 1998; Sandstrom et al., 1998). Saucier et al. (2002) found that men performed better than women when they were required to navigate using Euclidian information, but showed impaired performance, compared with women, when the task required the use of landmark information.

## 1.8 Virtual Environments

### 1.8.1 Sense of Presence

#### 1.8.1.1 *Immersion and Presence*

In this study, it is important that the virtual experience of driving around roundabouts simulates its real-life equivalent for participants, as closely as possible. An authentic virtual experience is expected to enhance the immersiveness of the virtual world, which will, in turn, aid performance on the triangle-completion task: partly through stimulating participants sense of *presence*, that is, the feeling of being located inside the virtual world, rather than in the physical world outside it. This is an especially important consideration, in view of the absence of several features which are thought to increase immersiveness in virtual environments, including sound, stereopsis and head-tracking; and the limited availability of others, such as photorealism and interactivity. Presence is thought to be closely associated with how immersive the virtual reality system is for participants. Researchers agree that higher levels of presence result from environments which are experienced as more immersive.

The concept of presence is important for understanding path-integration performance in virtual environments, particularly in those which closely replicate the real world. The relevance of presence to understanding users' experience of virtual environments is generally accepted (Waller & Bachmann, 2006); it can affect task performance, for example (Welch, 1999). The effectiveness of virtual environments is also commonly viewed in terms of how well they evoke a sense of presence for users (Witmer & Singer, 1998). Thus, incorporating design features, which are likely to enhance presence, is important in replicating triangle-completion studies in a realistic context.

A widely-accepted definition of presence is that it is the subjective experience of being physically situated in one environment, but feeling that one is actually in another: a psychological perception of being immersed in ("being in" or "existing in") a virtual environment, rather than in the external environment in which it is located (Witmer, Jerome, & Singer, 2005; Slater, 1999; Witmer & Singer, 1998; Held & Durlach, 1992; Sheridan, 1992; Sadowksi & Stanney, 2002; Barfield & Hendrix, 1995; Slater & Usoh, 1993; Heeter, 1992; Steuer, 1992; Barfield, Zeltzer, Sheridan, & Slater, 1995). Witmer and Singer (1998) refer to presence as a perception of "being there". It is thought to be multi-dimensional (Schubert, Friedmann, & Regenbrecht, 1999, 2001; Kalawksy, 1999; Welch, Blackmon, Liu, Mellers, & Stark, 1996).

Presence depends on the virtual environment overriding the physical one, with participants responding to events in the virtual world, rather than to those in the real world. A heightened sense of presence in the virtual world, thus, requires a simultaneously low level of presence in the real world, and vice versa (Slater, Usoh, & Steed, 1994). An important consequence of presence is that a virtual experience can evoke the same reactions and emotions in participants as a real experience: ducking to avoid a flying virtual object, for example, or exhibiting physiological symptoms of fear on a virtual cliff, or when crossing a narrow virtual suspension bridge over a virtual valley (Slater, 1999; Schubert et al. 2001; Regenbrecht, Schubert, & Friedmann, 1998; Bülhoff & van Veen, 1999).

A perception of being separate from the outside world is also necessary for a sense of presence in virtual environments (Witmer & Singer, 1998; Slater & Wilbur, 1997). Witmer and Singer (1998) suggest that this is, typically, more effectively achieved by viewing a virtual environment with a head-mounted display, than it is, for example, by viewing it on a desktop 2D flat-screen display. It is also important that participants experience and remember the virtual environment as a *place*, rather than as a series of computer-generated images (Slater, 1999).

### **1.8.1.2 Enhancing Presence in the Current Study**

A sense of presence, resulting from feeling immersed in a virtual world, can be evoked by a combination of three elements: the technological components of the system, the design features of the virtual environment(s), and user control over the virtual experience. The use of these elements, together, is usually intended to replicate the features of real-world environments, and of real-life interaction with them: the experience may be less immersive when some, or all, of them are missing.

Technological components may include the use of a head-mounted display and head tracking, multisensory stimulation, stereopsis, fast update rates, realistic displays with high visual resolution and a wide field of view, and realistic interface devices (Witmer & Singer, 1998; Slater & Usoh, 1993; Slater & Wilbur, 1997; Slater, 1999; Hendrix & Barfield, 1996; Snow & Williges, 1998; Barfield & Hendrix, 1995; Prothero & Hoffman, 1995).

Design features may include photorealism and rich visual detail (Welch et al., 1996), such as that resulting from texture (Stanney et al., 1998; Welch et al., 1996; Witmer & Singer 1994), which possibly enhance presence by improving depth cues (Darken & Sibert, 1996): judging 3D depth in virtual environments can be difficult (Barfield et al., 1995; Slater, 1999; Sutcliffe & Kaur, 2000). Pictorial and social realism may also arise from scene content, resolution, and field of view: real-world

content is not necessary, but events in the virtual world should be consistent with real-world events, and sensory information should be presented consistently within the virtual world (Witmer & Singer, 1998; Slater & Wilbur, 1997; Slater & Usoh, 1993).

User control includes interactivity and autonomy, that is, the ability to interact with the virtual world, and to modify its form and content in real time, via input devices which allow manipulation (Witmer & Singer, 1998; Slater, 1999; Slater & Wilbur, 1997; Slater & Usoh, 1993; Bystrom, Barfield, & Hendrix 1999; Steuer, 1992; Welch et al., 1996).

Inclusion of these elements also adds to the cost of virtual reality systems. However, it may be possible to compensate for their absence, and to create a more immersive virtual experience, through the use of alternative, less expensive design features; and thereby enhance participants' sense of presence. Lessiter, Freeman, Keogh, and Davidoff (2001) note that, as presence results from various determinants, it is likely that tradeoffs exist between them. Smets and Overbeeke (1995) observed that participants could solve a virtual picture puzzle with a visual resolution of 18 x 15 pixels, when they had active control over the camera's movements: this indicates that convincing virtual reality is achievable with a very low visual resolution, when other features are present. Stanney, Mollaghasemi, Reeves, Breaux, and Graeber (2003) suggest that particular techniques can be used to compensate for a lack of visual realism in virtual environments: such as fostering natural user interaction with the tasks, and removing as many real-world sensations as possible.

Other features have been shown to influence immersion and presence. These include a meaningful virtual experience for the user (arising from, for example, a motivating and / or salient task, or virtual environments that capture attention); a perception of realistic self-motion; non-intrusive displays and interface devices; and realistic depth cues (Witmer & Singer, 1998; Slater & Usoh, 1993; Hendrix & Barfield, 1996; Snow & Williges, 1998; Prothero & Hoffman, 1995; Barfield & Hendrix, 1995; Wilson, Nichols, & Haldane, 1997; Darken & Sibert, 1996).

Some of the system design features in the current study may lower feelings of immersion and presence, with possible effects on path integration performance. As the virtual environments are presented purely visually, some types of sensory input are lacking, such as sound and touch; whilst interactivity is severely limited, and physical participant movement, such as head movement, and object manipulation within the virtual world are precluded. There is also limited visual fidelity, as the virtual environments are not highly photorealistic.

In order to increase presence, several compensatory alternative features will be employed, involving manipulations of the display, interface, task, and visual stimulus. Firstly, a display with three screens, which partially surround the user, will

create both an inclusive and enclosing space; as well as a wide field of view, thereby enabling peripheral visual information to be presented. Large projection screens will add to these effects in the first experiment. Secondly, ecological validity will be enhanced in the design of the interface and task, through the inclusion of a “driving” metaphor, and complex routes with a roundabout, which will provide a lifelike context for path completion. Thirdly, the authentic virtual environments will include simulated local scenes and textures adapted from photographs. Contextualised visual self-motion cues (optic flow and depth) will increase the saliency of the task information.

## **1.8.2 Display Systems**

This study will examine the effect on path integration performance of presenting the virtual environments on three screens, arranged so that they partially surround the user. The display parameters will be further manipulated, in order to compare the effect of presenting the visual information on large screens in a driving simulator, and on smaller desktop computer screens.

### ***1.8.2.1 Immersive and Non-immersive Displays***

In immersive systems, the observer is perceptually surrounded by the virtual environment: by viewing it, for example, on a head-mounted display, used in conjunction with a head tracker; and by interacting with it, using, for example, datagloves. Depth perception can be enhanced by head-mounted displays, which display the virtual environment on two screens, through the stereoscopic image which results from binocular disparity (Wilson, 1997; Loomis, Blascovich, & Beall, 1999; Péruch & Gaunet, 1998; Sharples, Cobb, Moody, & Wilson, 2008). Similarly, in CAVE systems (Cruz-Neira, Sandin, Defanti, Kenyon, & Hart, 1992), computer-generated images are projected on the walls, floor and ceiling of a cubicle, which surrounds the participant (Tarr & Warren, 2002; Wilson, 1997; Loomis et al., 1999a; Sharples et al., 2008).

In non-immersive systems, virtual environments are displayed on a standard desktop computer monitor, or projected onto a larger screen (Wilson, 1997; Loomis et al., 1999a; Tarr & Warren, 2002; Péruch & Gaunet, 1998; Sharples et al., 2008). In driving and flight simulators, for example, virtual environments are presented on large projection screens; and the display is updated in response to realistic controls, such as a steering wheel and dashboard, or an instrument panel. These vary in their degree of immersiveness, ranging from a front-mounted screen, to several screens surrounding the user; realistic images and sounds, as well as physical forces exerted

on the body, can be reproduced in more sophisticated systems (Wilson, 1997; Tarr & Warren, 2002). Flight simulation can be especially realistic: a pilot may emerge from a simulated near-crash shaking and sweating (Wilson, 1997).

Immersive systems allow participant movement, thereby providing vestibular and proprioceptive information; and their displays occupy a wider functional visual angle than desk-top systems, as head movements are possible (Bülthoff & van Veen, 1999; Péruch & Gaunet, 1998). However, drawbacks include a restricted field of view, in the case of head-mounted displays (much less than the 200° of the normal human visual field); generally poor resolution and image quality; and delays between tracking of the user's head movements and updating of screen images (Péruch & Gaunet, 1998; Wilson, 1997; Bülthoff & van Veen, 1999; Hettinger & Haas, 2003).

Immersive characteristics of virtual environments may also induce symptoms of cybersickness or discomfort (Hettinger & Haas, 2003), especially in users of flight simulators and head-mounted displays (Wilson, 1997). Participants experience higher average levels of simulator sickness symptoms after exposure to head-mounted displays, compared with desktop computer displays (Sharples et al., 2008; Deisinger, Cruz-Neira, Riedel, & Symanzik, 1997; Wilson, 1997; Garris-Reif & Franz, 1995). 60-70% of participants experienced severe simulator sickness, after viewing a visually detailed virtual environment on a head-mounted display and on a projection screen (Sharples et al., 2008).

Projection-screens and desktop displays, typically, have a higher screen resolution than head-immersion systems (Wilson, 1997). Deisinger et al. (1997) found that viewing computer monitors was also much more acceptable to participants than viewing head-mounted display and screen-projection systems, as participants were usually familiar with using desktop computers. However, desktop monitors also have a limited field of view, restrict participants' movement, and lack the tactile and motor feedback that accompanies movement in real life: self-motion is typically effected by a joystick or similar device, and a user's head remains still during navigation (Bülthoff & van Veen, 1999; Wilson, 1997; Christou & Bülthoff, 2000a). Peripheral cues, which are usually absent in these systems, may be particularly important in providing self-motion information (Wilson, 1997).

Whilst projection-based displays are not stereoscopic, their size may promote immersion, through a sense of physical enclosure in the virtual world (Sharples et al., 2008). Deisinger et al. (1997) observed that inexperienced users found viewing a screen-based projection system more immersive than viewing a computer monitor screen or head-mounted display, and also preferred using the former to using the latter. Panoramic systems (Waller, Loomis, & Haun, 2004) heighten immersion by

covering the whole visual field with computer-generated imagery; however, they are also very expensive (Bülthoff & van Veen, 1999).

### **1.8.2.2 Large Displays**

There is evidence that navigational performance is enhanced through presentation of virtual environments on large displays. This may be due to an increased sense of immersion and presence, even in the absence of other features typically thought to stimulate presence, such as head-mounted displays and interactivity. Alternatively, it may be because large displays enhance visual information, such as optic flow cues.

Tan, Gergle, Scupelli, and Pausch (2003, 2004, 2006) found that the use of physically large projected wall displays enhanced performance on virtual navigation tasks, such as path integration, compared to standard desktop monitors; even when the two were viewed at identical visual angles (which were held constant by adjusting the viewing distance to each display). The researchers attributed the beneficial effect, partly, to the more immersive quality of large displays engendering a greater sense of presence, which led to the use of more efficient strategies to perform the tasks. The effects of physical display size were found to be independent of other factors that may induce immersion, such as interactivity within the virtual world.

Tyndiuk, Lespinet-Najib, Thomas, and Schlick (2007) also found that large displays (versus desk-top monitors) positively affected performance on navigation tasks in virtual environments. This effect was linked to users' satisfaction and visual attention abilities: users who preferred the large displays, and those with low-level attention abilities, took more advantage of the large displays. The study focused on the display (physical) field-of-view (DFOV), that is, the angle subtended from the eye to the edges of the display screen; rather than on the software field-of-view (that is, the angle subtended from the virtual camera to the sides of the viewing frustrum). The authors comment that a better understanding of how users perform virtual tasks may assist the design and construction of improved virtual reality interfaces, which optimise users' satisfaction and performance.

Patrick et al. (2000) observed that users were better able to acquire a cognitive map of a virtual environment while navigating through it on a large projection display, compared with a desktop monitor: this may have been partly due to the large display stimulating a heightened level of presence, which compensated for the lack of immersion. No difference in performance resulted from the use of a head-mounted display versus a large projection display, however; and large displays were an effective substitute for head-mounted displays.

A wider field of view may be especially effective when used together with very large displays, especially for females. Improved navigation performance, particularly by female participants, resulted from the use of a 36-inch semi-curved display, which provided both a large physical field of view, and a large virtual field of view of 75° (Czerwinski, Tan, & Robertson, 2002); similarly, enhanced female path integration performance was observed when a 43-inch wide curved surface was used, which provided a physical field of view of about 120° (Tan, Czerwinski, & Robertson, 2003).

Czerwinski et al. (2002) attributed the enhancement of female navigational performance to the display parameters supporting reliance on landmarks, rather than on the construction of a cognitive map. This is a strategy believed to be preferred by, and to benefit, females. Tan et al. (2003) argued that the effect results from the enhancement of optic flow cues by wider fields of view on large displays. These findings suggest that gender differences in navigation performance in virtual environments can be reduced, through appropriate manipulation of design factors.

### **1.8.2.3 Field of View**

In the current study, a large field of view will be provided through the use of a three-screen display. A larger field of view tends to make virtual environments more immersive (Slater, 1999). Kalawsky (1993) determined that a field of view of 100° or more is required; but that it may be more important to establish the field of view needed, in order to perform the tasks for which the system is designed. Lawson, Graeber, Mead, and Muth (2002) observe that, whilst a larger field of view of a moving visual display often enhances performance, it also increases the probability of experiencing side effects and discomfort. Decreasing the field of view in a virtual environment (and, thus, lag in updating the visual display) can reduce this.

Experimental findings, which indicate that humans cannot use visual information for accurate path integration, have come from studies in which optic flow was presented on visual displays with a limited field of view, compared with real environments. The natural field of view of the human eye is close to 200°. However, studies in virtual environments have generally used a physical field of view which is well below this, to present self-motion visually. Péruch, May, and Wartenberg (1997) used a projection screen with a field of view of 45° (horizontal) by 37° (vertical). The field of view of the head-mounted display used by Kearns, Warren, Duchon, and Tarr (2002) was 60° (h) x 40° (v). Bakker, Werkhoven, and Passenier (1999, 2001) used head-mounted displays with a field of view of 24° (h) x 18° (v), and 48° (h) x 36° (v), respectively. Finally, the head-mounted display used by Klatzky, Loomis, Beall, Chance, and Golledge (1998) had a field of view of 44° (h) by 33° (v).

On the other hand, when a wider field of view (180°) and curved projection screen were used, participants were able to perform path integration more accurately, based on optic flow in the absence of non-visual cues (Riecke, van Veen, & Bühlhoff, 2000, 2002). The positive influence of a larger field of view on motion perception has also been shown in other studies (Hendrix & Barfield, 1996).

Klatzky et al. (1998) and Kearns et al. (2002) both note the possibility that the restricted field of view of the display in their studies may have reduced the influence of optic flow, relative to the body senses, during path integration. Whilst Péruch et al. (1997) found no significant effects of varying geometrical field of view on path integration, all the fields of view they used were very restricted (40° to 80° with a fixed actual field of view of 45°).

Schulte-Pelkum, Riecke, von der Heyde, and Bühlhoff (2004) argue that differences between display devices are more critical than the field of view for the perception of self-rotations. They found no effect of reducing the field of view on human ability to control simulated self-rotations based solely on visual information from optic flow. However, there was a strong influence of display type: performance was enhanced through the use of a curved projection screen, and drastically reduced when a head-mounted display was used. In a comparable study, Riecke et al. (2002) obtained almost perfect performance in a similar task, using a 180° half-cylindrical projection screen.

The fields of view of different display types may also affect the kind of errors observed. In two similar experiments, participants tended to undershoot instructed angles when a horizontal field of view of 24° was used (Bakker et al., 1999); but to overshoot them with a horizontal field of view of 48° (Bakker et al., 2001). When self-motion was presented visually on a head-mounted display, participants displayed insensitivity to triangle geometry, producing the same mean response across different path layouts (Kearns et al., 2002); this effect was not found with projection screens, however (Riecke et al., 2000, 2002; Péruch et al., 1997).

### **1.8.3 Ecological Validity**

#### ***1.8.3.1 Virtually Real or Really Virtual?***

Path integration performance in virtual environments may be affected by the fidelity, both of the environments, and of the interface: that is, by how closely the virtual world resembles the real world, and by how convincingly the interface device simulates interactions with the world, such as self-motion or manipulation of objects (Waller, Hunt, & Knapp, 1998).

Virtual environments are usually designed to be as realistic as possible, unless costs prohibit this (Stappers, Overbeeke, & Gaver, 2003; Durlach et al., 2000), as high overall fidelity is assumed to increase their effectiveness (Waller et al., 1998). Realism is usually achieved by incorporating photorealistic graphics (Christou & Bulthoff, 2000a), and interface devices which replicate realistic self-motion (Bowman, 2002). It is considered especially important that virtual environments elicit a strong sense of presence (Stappers et al., 2003; Welch, Blackmon, Liu, Mellers, & Stark, 1996; Welch & Sampanes, 2008), for which realism is thought to be instrumental.

A compelling, visually-induced perception of self-motion (vection) can be engendered in virtual environments, through pictorial realism and visual complexity (Welch et al., 1996). Texture, for example, provides observers with speed and trajectory information, which are associated with vection (Hettinger, 2002). However, as vection is elicited by moving visual fields, it may also induce discomfort or cybersickness symptoms in participants, such as dizziness, headache, and eyestrain (Kolasinski, 1995; Hettinger & Riccio, 1992). Cybersickness may also result from the slower refresh rates, and increased visual lags, associated with more complex virtual environments with extensive texture (Stanney et al., 1998). Adverse effects may hinder performance. The level of visual complexity, thus, needs to be balanced with the level of system responsiveness required, for optimal user task performance (Watson, Walker, Hodges, & Worden, 1997). Sense of presence has been found to be positively correlated with feelings of vection (Lawson, Graeber, Mead, & Muth, 2002), and negatively correlated with simulator discomfort (Witmer & Singer, 1998).

The design of realistic virtual environments is supported by the availability of comprehensive 3-D modelling and rendering software tools, such as 3D Studio Max™ (from Autodesk), and techniques such as texture-mapping (the application of realistic textures to virtual objects): these facilitate the creation and rendering of complex models (descriptions) of real-world environments (Bülthoff & van Veen, 1999; Ayaz, Allen, Platek, & Onaral, 2008).

The purpose of a virtual environment is important in deciding the level of realism to model. There are advantages and disadvantages in attempting to replicate real environments. The benefits of realism may include enhanced user experience, through, for example, increased immersion and sense of presence (Bowman, 2002), and through easier performance of tasks which are based on principles familiar from daily life. Realistic environments can be useful in the context of training (Durlach et al., 2000), especially when, for example, they are used to train tasks which will later be performed in real life (Bowman, 2002).

Christou and Bülthoff (2000b) advocate the use of both realistic virtual environments and problem-solving tasks, to study spatial cognition. They recommend the provision of as much visual detail as possible (even to the point of redundancy), in order to facilitate realistic learning under highly controlled conditions; rather than making any prior assumptions about the kinds of information needed for a task.

In line with this approach, Riecke, Schulte-Pelkum, Avraamides, von der Heyde, and Bülthoff (2006) demonstrated that perception of vection was enhanced by the use of a realistic 3D virtual environment, partly through its ability to evoke a sense of presence. The believability of the virtual environment was increased by the inclusion of coherent pictorial depth cues, together with the spatial reference frame provided by a curved projection screen with a wide field of view (of 54° x 45°). Thus, manipulation of higher cognitive mechanisms, such as ecological validity and presence, can provide a relatively simple and cost-effective means to make virtual environments more convincing, and to increase the effectiveness of self-motion simulations. Effective path integration and cognitive mapping, based on purely visual information, was demonstrated by van Veen, Riecke, and Bülthoff (1999), in high-fidelity virtual environments, in which the availability of optic flow and landmarks was manipulated.

On the other hand, there are various drawbacks to using realistic virtual environments, which may outweigh the benefits. Endeavouring to recreate realism is immensely challenging: some idea of the difficulties involved can be gleaned from comments in the literature. Stanney, Mollaghasemi, Reeves, Breaux, and Graeber (2003) refer to it as “an overwhelming challenge for system designers” (p. 455); whilst Loomis, Blascovich, & Beall (1999) comment that “specification of the stimulation becomes formidable” (p. 560). Newman et al. (2007) describe it thus: “one walks the tight rope of experimental control versus realism and generalizability” (p. 251). Stappers et al. (2003) speak of the effort inherent in designing convincing virtual environments as “forcing the designer to do metalwork sweating at a forge” (p. 108).

Developing virtual 3D environments, especially very complex and / or large-scale ones, is an extremely time-consuming and laborious process. In order to produce a convincing environment, the computer must rapidly render a sequence of images consisting of a vast number of objects, each of which has been modelled with simple polygons by the designer, using 3D modelling and rendering software (Wilson, 1997; Ruddle, Payne, & Jones, 1997; Durlach et al., 2000; Huang & Alessi, 1998; Ayaz et al. 2008; Loomis et al., 1999a; Bullinger, Roessler, & Mueller-Spahn, 1998; Bülthoff & van Veen, 1999). This sophisticated software can be daunting: 3D Studio Max™, for example, is a powerful program with a plethora of functions, and requires

considerable programming expertise for effective use (Ayaz et al. 2008; Huang & Alessi, 1998).

In modelling the real world, it must be carefully considered which objects to include, and at what level of detail; and which to omit. This depends on factors such as the overall number and size of objects, ease of programming, and the importance of particular objects. Selectively limiting the total number of objects in a virtual environment reduces development time and increases rendering speed (Sebrechts, Lathan, Clawson, Miller, & Trepagnier, 2003; Wilson, Eastgate, & D’Cruz, 2002).

Creating detailed replicas of all the objects is a painstaking process, requiring decisions about geometry (e.g., dimensions) and texture (e.g., colours, patterns); and collection of relevant information, through, for example, observation, measurement, photography, internet research, and official documents (Wilson et al., 2002; Kessler, 2002; Durlach et al., 2000). Many details of the physical world, which are usually taken for granted, must be made explicit. As Huang and Alessi (1998) observe, “high degrees of realism can be modelled, but require high degrees of work” (p. 64).

Visual realism can be enhanced through the application of texture maps, that is, digitized photographic images, to the polygons (Wilson, 1997). A large number of textures are produced, however, and the real-time management of these can be difficult (van Veen, Distler, Braun, & Bülthoff, 1998). Image quality may be at the expense of update rates, resulting in time lag.

Finally, the enormous number of objects needed, in order to create realistic 3D virtual environments, which also behave as they would in the real world, places great demands on computer processing resources (Kessler, 2002; Lampton, Bliss, & Morris, 2002). The update rate for real-time interaction in a virtual environment is directly affected by the number of polygons used to model it, with more complex environments resulting in a slower update rate (Henry & Furness, 1993). In general, a more accurate representation requires more polygons (Kessler, 2002).

### ***1.8.3.2 Trade-offs Between Realism and Other System Features***

Participants tend to expect virtual environments to have ecological validity (Cobb et al., 1999); they are sensitive to even slight irregularities, such as distortions or lags in the update of visual images, even in highly realistic virtual environments (Kalawsky, 1999). Participants may notice artefacts of the simulation, such as all the trees in a landscape having a similar appearance. Bülthoff and van Veen (1999) found that, after they had gone to great lengths to create a visually realistic virtual model of the city of Tübingen in Germany, at least one participant commented on the absence of appropriate height differences between the streets, which exists in the real world.

Virtual environments tend to be simpler and less detailed than real ones, despite the effort required to create them, due to the impossibility of completely replicating the real world. Some loss of ecological validity is inevitable, because of both the complexity and the limitations of technology (Sebrechts et al., 2003; Stappers et al., 2003; Bühlhoff & van Veen, 1999; Loomis et al., 1999a; Hettlinger & Haas, 2003; Waller et al., 1998). Virtual worlds often have sensory and sensorimotor deficiencies: such as discordant sensory information, inadequate or misleading visual cues, and limited interaction (Welch, 2003; Welch & Sampanes, 2008).

Limitations of the visual display may include low spatial resolution; a restricted field of view, resulting in the absence of peripheral cues; optical distortions; and fixed accommodative distance. Also common are a slow rate of graphics updating and image rendering, resulting in a poor simulation of continuous self-motion; and delays in reflecting changes in participants' behaviour on displays, due to the processing time required. Such limitations result in virtual environments which can be easily distinguished from real ones, partly because they are less immersive and inhibit a sense of presence. Visual display limitations can also lead to confusion, misperceptions, disorientation, inappropriate behaviour, and sickness (Loomis et al., 1999a; Péruch & Gaunet, 1998; Bühlhoff & van Veen, 1999; Cobb, Nichols, Ramsay, & Wilson, 1999; Wilson, 1997; Welch, 2003; Welch & Sampanes, 2008).

The level of realism modelled in virtual environments is also related to cost. The technical limitations of most virtual reality systems, of all levels of sophistication, typically result in trade-offs between cost and other factors. These include processing power and memory; visual display quality, such as frame rate, stereoscopy, time delay, field of view, level of visual detail, and resolution; and the complexity (sensory richness) of the virtual world. Trade-offs may also involve factors such as interactivity, for example, the number of objects that can be manipulated in real time, and the methods for effecting this; and the richness and realism of the interface, for example, how convincingly self-motion is achieved (Durlach et al., 2000; Kalawsky, 1999).

Higher fidelity, especially of visual imagery, can be expensive, in terms of computational processing power, and also financially: it is usually achieved at the expense of system responsiveness and / or a higher probability of simulator sickness (Waller et al., 2001). Typically, compromises are made between visual fidelity (such as the level of complexity and / or realism in the appearance of virtual environments) and functionality (such as the degree and speed of interactivity): high-quality graphics usually result in updating lags, for example. Very realistic virtual environments can become too complex to update quickly (Sebrechts et al., 2003; Wilson et al., 2002). Thus, the value of developing highly realistic virtual environments for a particular purpose needs to be established. As it is usually necessary to simplify and prioritise

different system components, it is important to identify which features are essential for performance, and which may be dispensed with (Sebrechts et al., 2003; Waller et al., 1998; Durlach et al., 2000; Welch, 2003; Welch & Sampanes, 2008).

A high level of fidelity may not be necessary for task performance. In this case, more processing resources could be allocated to task-relevant information, rather than to photorealistic graphics. This requires specification of the level of complexity needed in a particular virtual world. An explicit visual horizon, for example, is a computationally cheaper alternative to photorealism, which provides useful information for the perception of distance and scale (horizon scaling) in virtual environments; and it sometimes creates a more convincing spatial impression than texture maps (Stappers et al., 2003).

A moderate level of realism can also be quite convincing; and even virtual environments with a quite simple or impoverished visual appearance, and lacking natural interaction, can be effective. Realistic graphics and self-motion may actually be counter-productive, as they use valuable resources and slow down rendering, often with no appreciable benefits (Welch, 2003; Welch & Sampanes, 2008; Stappers et al., 2003; Wilson et al. 2002; Kessler, 2002; Bowman, 2002; Huang & Alessi, 1998; Sebrechts et al., 2003).

Users are often unaffected by poor display quality, especially when they are engaged in goal-directed activity (Wilson, 1997): for example, participants were able to solve a virtual picture puzzle with very low visual resolution (Smets & Overbeeke 1995). Visual fidelity of virtual environments may be less important for cognitively-controlled tasks, which require conscious attention (such as learning the layout of an environment), than it is for perceptually- or motor-driven tasks (Waller, Knapp, & Hunt, 2001). Poor fidelity may even be preferable to near-perfect fidelity: Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley (1989) found a higher incidence of simulator sickness symptoms in simulators which users rated as very high in fidelity.

## **1.9 Overview of the Current Study**

In this study, human path integration performance will be examined: specifically, path integration which is based on visual cues (optic flow and depth), in the absence of both non-visual information and landmarks. Three experiments will be presented, in each of which a complex path-completion task will be conducted within four large-scale authentic virtual environments, which are based on real-life locations. Visual information will be presented realistically, in lifelike contexts. The availability of optic flow and depth cues will be manipulated in each environment, through variations in the level of realistic textures, and through the inclusion or omission of additional

structures. The path layouts will be modelled on local routes, and will include a large two-lane roundabout (traffic circle), with four exit roads. The routes will, thus, provide a more realistic rotational component than the standard triangle-completion task.

In all three experiments, the influence of three variables on human path integration performance will be examined. These are visual information, specifically, optic flow and depth cues; gender; and presence. In each experiment, the effects of other specific variables will also be examined. These are, firstly, display type and size; secondly, route layout parameters, that is, the length of the outbound paths (roads), and the internal angle between these; thirdly, navigation mode, that is, active control versus passive observation of the simulated self-motion; and, finally, presentation of intermittent versus continuous simulated self-motion.

Experiment 1 will examine the effects of presenting the virtual environments on three large projection screens, which partially surround participants, in a driving simulator; and the effects of path layout, that is, three values of the internal angle.

Experiment 2 will test the influence of several variables, including the effects of presenting the virtual environments on three partially-surrounding small-screen desktop computer monitors; as well as the effects of a variety of route layouts, in which the length of the approach and exit roads, and the value of the internal angle, will be manipulated, through the inclusion of three combinations of the road-lengths, together with three values of the angle. The effects of participants' mode of navigation, that is, active versus passive, will also be examined.

Experiment 3 will examine the impact of presenting visual information intermittently, thereby disrupting smooth self-motion through the environments, and, hence, limiting the availability of optic flow information for performance of the task. Participants will observe a sequence of static scenes of the routes, similar to watching a slide show made up of a series of still photographs.

Performance on routes with and without a roundabout will also be compared in the second and third experiments, in order to examine the effect of the complex rotation, which results from the large gradual curve. The novel rotation stage will provide a realistic setting for the rotation, but it is not clear how a curved segment of the route will affect task performance.

Ethical approval has been obtained for the experiments. The experimenter has undertaken to inform participants of the possibility of experiencing symptoms of sickness or discomfort from the simulated motion, especially during the rotations, and particularly in the driving simulator, and of the appropriate action to take should this occur; and to carefully monitor participants' health, before, during and after each experiment. Participants will be encouraged to take breaks from the task between trials, especially if they experience any such symptoms.

## Chapter 2. Data Analysis

### 2.1 Directional Estimation: Response Measure

The participant's task in each trial was to estimate the heading direction to the start position of the route, from the final position at the end of the second road, from where it was no longer visible. Participants used a virtual dial on the display screen to point to the start position. The participant's directional estimate was recorded at the end of each trial, and the angle between the two heading directions was calculated in degrees, by the computer. The participant's forward heading at the final position on the route was taken as the zero (or reference) direction  $0^\circ$ .

Thus, for each trial, the directional estimate was quantified as the angle between the participant's forward heading at the end of the route (taken as  $0^\circ$ ) and the measured heading (indicated with the pointer) towards the start point,  $\theta_m$ , as illustrated in figure 2.1.

### 2.2 Error

Error in the response measure was calculated as the difference between the *measured* angle  $\theta_m$  (the participant's directional estimate), and the *correct* angle  $\theta$ , on each trial: that is,  $\theta_m$  minus  $\theta$ . Thus, it represents the deviation of the measured heading direction (the participant's estimate), from the correct heading direction, on each trial. The correct angle  $\theta$  is given by  $180 - \beta$  (see figure 2.2).

This procedure yields two separate error measures: an absolute value, or magnitude; and a signed value, which depends on whether the participant's heading estimate is to the left, or to the right, of the correct direction.

Angular error was analysed in terms of both absolute and signed error. Thus, the effect of the experimental variables on both of these performance measures was examined. Patterns and magnitudes of error were analysed.

#### 2.2.1 Absolute Error

*Absolute error* refers to the absolute value of the error in a participant's estimate: the absolute difference between the participant's response and the correct response, separately from whether the estimate is on either side of the correct heading direction. Thus, absolute error represents an underestimation or overestimation of the correct angle. Absolute error in directional data indicates the probability of a participant

pointing within a range around the correct answer on any given trial of performance (Montello, Richardson, Hegarty, & Provenza, 1999). It can be considered as a measure of accuracy, or precision, in the response.

### 2.2.2 Signed Error

In addition to its absolute value, the error can be given a *signed* value, in terms of the direction of the error. This is defined by whether participants pointed to the left, or to the right, of the correct heading direction in physical space; that is, whether they turned the pointer too far, or not far enough, in terms of the degree of rotation required. The signed error, thus, indicates whether the estimate underestimates or overestimates the corresponding angle.

The signed error, in this study, indicates underestimation or overestimation of the degree of rotation required to face the start point (the correct heading), with a measured angle which is smaller or larger than the correct one. It can be considered as a measure of variability or bias in the response (Montello et al., 1999).

A response which underestimates the correct degree of required rotation results in a *positive* error. This occurred when participants did not turn the pointer on the dial far enough: it indicates underestimation of the required angle ( $180 - \beta$ ), and, hence, overestimation of angle  $\beta$ . A positive error suggests that the internal angle is perceived as larger than it is, and that the required degree of rotation is perceived as smaller than it actually is.

Conversely, a *negative* error results from a response which overestimates the correct degree of rotation required. This occurred when participants turned the pointer on the dial too far; and it indicates overestimation of the required angle ( $180 - \beta$ ), and, thus, underestimation of angle  $\beta$ . In this case, the internal angle is perceived to be smaller than it is, and the required degree of rotation to be larger.

An example is shown in figure 2.3: the correct response at vertex 2 for the internal angle  $\alpha = 90^\circ$  would be  $135^\circ$  (that is, a rotation of  $135^\circ$  is required to face the start position of the route). If a rotation of  $120^\circ$  only is made, then this is not turning far enough and the error is positive ( $135^\circ - 120^\circ = 15^\circ$ ). On the other hand, if a rotation of  $145^\circ$  is made, then this is turning too far, and the error is negative ( $135^\circ - 145^\circ = -10^\circ$ ).

Analysis of the signed error will reveal any differences in angular estimates (that is, consistent biases) with respect to the direction of error (underestimation or overestimation) across the different environments; as well as between males and females, and between participants in the active and passive modes; and according to turn type (roundabout curve versus intersection turn).

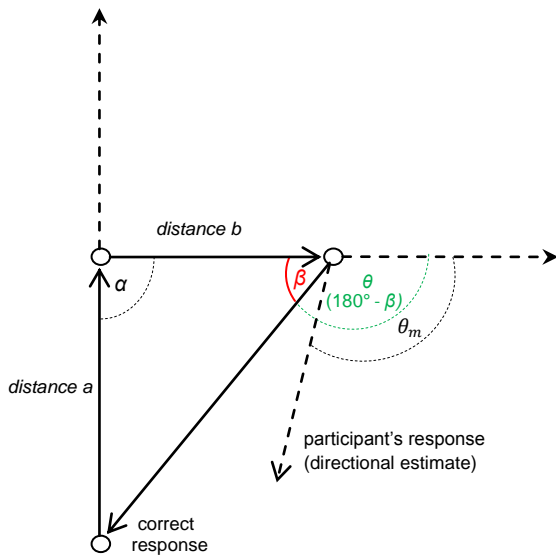


Figure 2.1. Error measure calculated from participant response  $\theta_m$

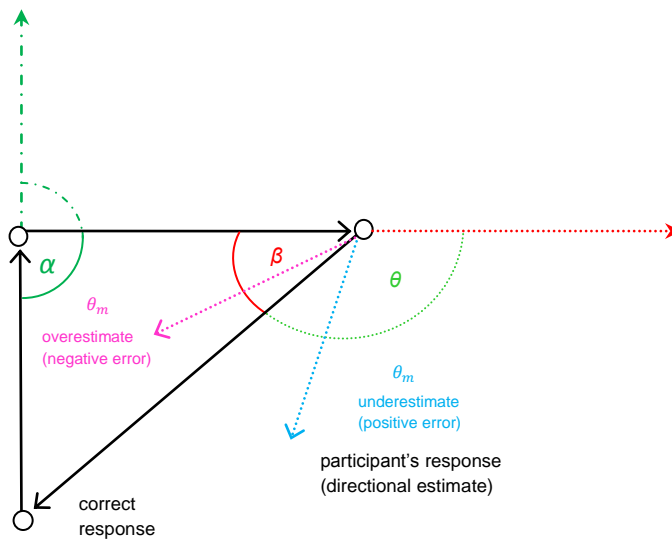


Figure 2.2. Response error: underestimate and overestimate

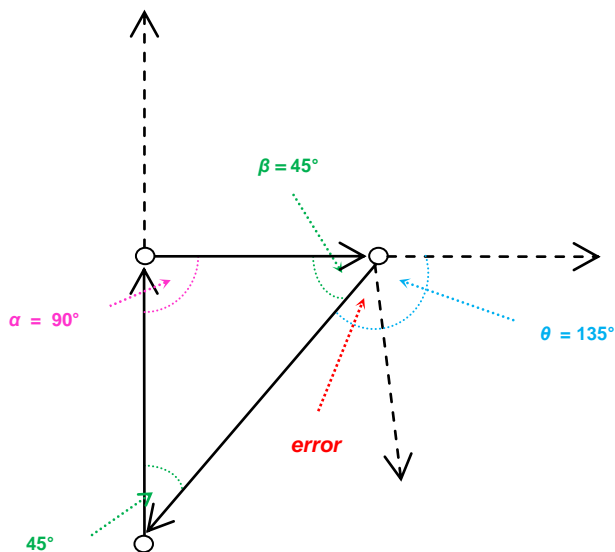


Figure 2.3. Example of response for an equilateral (L-L) triangle with  $\alpha = 90^\circ$  showing positive error

### 2.3 Identification and Elimination of Outliers

A criterion was established, in order to identify any outliers among the participants, and consequently eliminate their data prior to the analysis. A participant was defined as an outlier if their angular estimates fell more than three standard deviations from the mean of the sample for a particular condition, on more than six trials overall. This prompted a complete removal of their data from all subsequent analysis.

### 2.4 Analysis of Directional (Angular) Variables

In studying path integration, the observation and statistical analysis of directions is required. Directions are measured by angles ranging from  $0^\circ$  to  $360^\circ$  or, equivalently, from 0 to  $2\pi$  radians (Batschelet, 1981). Heading direction, for example, is measured in angular units (Berens & Velasco, 2009). Angles measuring directions are cyclic and, therefore, called *circular variables*. They behave differently from *linear variables* (for example, not like numbers on a number line), and the algebra of angles differs from the rules governing linear quantities (Batschelet, 1981).

Berens and Velasco (2009) note that the characteristics of directional data create various challenges for its analysis: for example, designation of the zero (or reference) direction is arbitrary; and any point on the circle can be designated as zero. The designation of high and low values is also arbitrary, unlike on a linear scale.  $0^\circ$  and  $360^\circ$  are identical angles. Thus, for example, whilst  $5^\circ$  and  $355^\circ$  are numerically far apart, they are close in physical space (Montello et al., 1999); so that  $180^\circ$  is not an appropriate mean.

Commonly-used (linear) statistical techniques are, therefore, not generally appropriate for the analysis of directional data, due to its circular nature: they tend to provide wrong or misleading results (Berens, 2009; Batschelet, 1981).

Instead, directions (represented as vectors) are more appropriately dealt with using techniques from circular statistics. These methods are appropriate for use with circular variables, that is, with those that consist of directional responses in  $360^\circ$  (Montello & Frank, 1996), and so are suited to the analysis of data measured on an angular scale such as directional data (Berens, 2009; Berens & Velasco, 2009). The use of circular statistics renders a study more precise when their use would be more appropriate than linear statistics. Several measures can be used, which are directly analogous to measures used in linear statistics.

Circular statistics can be used, for example, to compute the average heading direction; to assert the prevalence of a common heading direction for a group (of human participants or birds, for example); and to compare the average heading directions of two or more groups (Berens, 2009). Their use is, thus, appropriate in this study.

Specialised statistical methods for the analysis of directional data have been developed over the last fifty years (Fisher, 1953; Batschelet, 1981; Fisher, 1995; Zar, 1999; Jammalamadaka & Sengupta, 2001). However, few software packages are available that offer a comprehensive set of circular statistics methods, particularly ones which are easy to use. These methods are, in fact, still under development (Berens, 2009; Berens & Velasco, 2009).

Statistical methods available in the MATLAB Circular Statistics Toolbox (Berens, 2009; Berens & Velasco, 2009) were applied to the analysis of circular data in the current study. The CircStat2009 toolbox is a specialised add-on software package (that is, toolbox) which has been developed for use with MATLAB (The MathWorks, Inc., 2007, 2008), a commonly-used computational software programme for statistical analysis. It provides a set of functions for performing both descriptive, and some inferential, statistical analysis of directional data.

## **2.5 Data Analysis Using Circular Statistics in the Current Study**

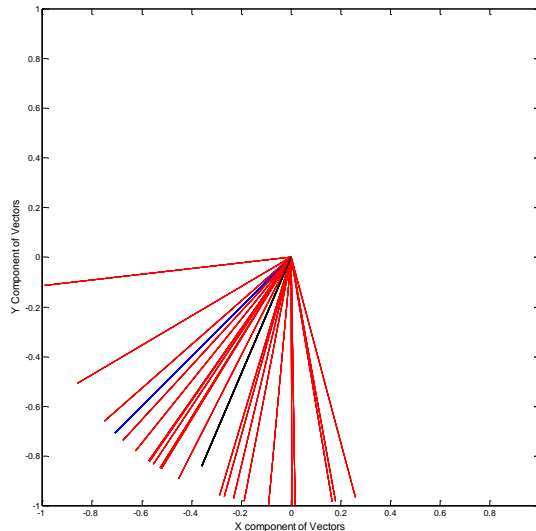
The following sections describe the particular statistical tests which were performed on the directional data obtained in the current study, using the MATLAB CircStat toolbox (Berens, 2009; Berens & Velasco, 2009).

### **2.5.1 Descriptive Statistics for Circular Data**

Using functions available in the CircStat toolbox, circular statistical methods (Batschelet, 1981) were used to calculate descriptive measures for the samples of angular data (that is, participants' directional estimates) obtained in each experiment. The data were first plotted on circular graphs. Measures of central tendency included the mean vector direction / mean angle (0, 360°); whilst measures of spread included the resultant vector length and angular variance, and the mean angular deviation. These measures are the circular counterparts of the mean, standard deviation, and variance in linear statistics; and they are equally important, in circular statistics, in the initial exploration and summarising of pertinent aspects of the directional data.

### **2.5.2 Graphical Representation of Directional Data**

For each experimental condition, the sample of participants' directional estimates were first represented graphically, as unit vectors on circular plots with radius 1.0, together with the resultant vector of the sample, and the vector representing the correct heading direction. This enabled the distribution of the directional data to be examined. The concentration of the sample points around the mean direction was determined, together with the angular variance, that is, the spread of the unit vectors around the circle. An example is shown in figure 2.4. The directional estimates are represented by the red lines, whilst the correct heading direction is depicted by the blue line. The solid black line indicates the direction and magnitude of the mean resultant vector. A large value of the resultant vector length indicates a tightly clustered bundle of vectors with small spread, as is shown in the example; whilst a small value of the resultant vector length indicates a dispersed group of vectors with large spread.



*Figure 2.4.* Example of a radial plot showing concentration of unit vectors (red lines) around the mean vector (black line) and angular variance, together with the correct response vector (blue line)

### 2.5.3 Measure of Location: The Mean (Vector) Direction / Mean Angle

The mean direction (or angle) of a sample of several directions, given by various angles, indicates a preferred direction (Batschelet, 1981). It is not appropriate to obtain a mean direction, or a mean angle, by calculating the arithmetic mean of the angles (Batschelet, 1981; Berens, 2009), as this will be incorrect: slightly, for vectors which are fairly close together; considerably, if the vectors are widely distributed around the circle (Montello et al., 1999). For example, the arithmetic mean of the two angles  $10^\circ$  and  $350^\circ$  would be  $180^\circ$ , whilst the correct mean should be zero, and  $180^\circ$  would point in the opposite direction (to the other side of the circle). Similarly, the arithmetic mean of a set of three angles  $10^\circ$ ,  $30^\circ$ ,  $350^\circ$  would be  $130^\circ$  (pointing southeast), whilst all data samples, in fact, point north, again towards  $0^\circ$  (Berens, 2009).

Instead, the mean direction, or the mean angle, for a set of directions is appropriately calculated by using circular statistics, based on the mean vector of the sample (Batschelet, 1981). A sample of directions in physical space is represented by unit vectors in the two-dimensional plane: summing these unit vectors gives the resultant vector, and dividing the length of the resultant vector by  $n$  gives the mean vector of the sample (Batschelet, 1981). This is transformed, using the four quadrant inverse tangent function, to yield the mean angular direction (Berens, 2009; Berens & Velasco, 2009). The process essentially involves splitting each directional estimate

into its sine and cosine, calculating the mean of each of these separately, and then retransforming them back into a vector.

#### **2.5.4 Measures of Dispersion (1): Mean Resultant Vector Length (0, 1)**

The length of the mean resultant vector is also an important measure of dispersion in circular statistics: that is, the average of all the unit vectors which represent the directions (here, the directional estimates). The closer the mean resultant vector length is to 1, the more concentrated the data sample around the mean direction. It decreases from 1 to 0, as concentration of the sample points around a mean direction decreases, and dispersion increases (Berens, 2009; Batschelet, 1981). With maximum concentration (that is, when all the sample data point in the same direction), it equals 1; and when there is no concentration around a single direction, it equals 0.

The mean resultant vector length is closely related to the angular variance (equivalent to the variance in linear statistics): this also indicates the circular spread of a sample of data, and is important for several hypothesis testing procedures. Unlike the variance on a linear scale, which can have any positive value, the circular variance ranges from 0 to 1 inclusive. If all samples point in the same direction, the mean resultant vector length is close to 1 and the circular variance is correspondingly small. If samples are spread out evenly around the circle, the resultant vector length is close to 0 and circular variance is close to 1 (Berens, 2009; Batschelet, 1981).

#### **2.5.5 Measures of Dispersion (2): Mean Angular Deviation**

The mean angular deviation, which is equivalent to the standard deviation in linear statistics, indicates the extent to which the sample values are clustered around the mean (Batschelet, 1981; Berens, 2009; Berens & Velasco, 2009). The mean angular deviation increases, as the mean vector length decreases. It equals 0 when all directional estimates are identical, and reaches a maximum of just over  $80^\circ$  when directional estimates are maximally distributed around  $360^\circ$ , that is, when there is no agreement between participants (Montello et al., 1999; Montello & Frank, 1996).

The mean angular deviation is obtained by taking the square root of the angular variance. This is calculated for each item, by averaging the absolute values of the differences between each participant's response, and the mean direction for all participants on that item within a given condition (Montello et al., 1999).

The mean angular deviation is a measure of between-case variability

(sometimes called variable error) in performance, that is, inconsistency or disagreement across responses, or precision of estimation across trials (Montello et al., 1999; Montello & Frank, 1996). It is measured in radians, but can be converted back into degrees by multiplying by  $180^\circ/\pi$  (Batschelet, 1981). The mean angular deviations in degrees are shown in the tables in this thesis.

### **2.5.6 Inferential Statistics for Circular Data: Two-sample and Multi-sample Tests**

Some inferential statistics are available for use with angular data. Methods for two- or multi-sample analysis, concerning the mean direction with one or two factors, were used in this study. Functions in the CircStat toolbox (Berens, 2009; Berens & Velasco, 2009) were used to perform circular equivalents of two linear ANOVAs: the Watson-Williams test (equivalent to the one-factor ANOVA) and the Harrison-Kanji test (equivalent to the two-factor ANOVA).

#### ***2.5.6.1 The Watson-Williams Test (One-factor ANOVA)***

The Watson-Williams two- or multi-sample test (Watson & Williams, 1956) assesses whether the mean directions (or mean angles) of two or more samples are the same (Berens, 2009; Berens & Velasco, 2009; Batschelet, 1981). Rejection of the null hypothesis (a significant result) provides evidence, only, that not all of the groups share a common mean direction; but not whether all groups have pairwise differing mean directions, or which groups significantly differ from each other (Berens, 2009; Batschelet, 1981). It is, therefore, important to plot the data and inspect the graphs, in order to interpret possible causes of significance (Batschelet, 1981).

#### ***2.5.6.2 The Harrison-Kanji Test (Two-factor ANOVA)***

The Harrison-Kanji test for circular data (Harrison, Kanji, & Gadsden, 1986; Harrison & Kanji, 1988) tests for the potential effects of two factors simultaneously, as well as their interactions, on population means (Berens, 2009).

### **2.5.7 Limitations of Circular Statistical Analysis**

The Watson-Williams and Harrison-Kanji tests are the most robust statistical tests currently available for circular data. Thus, the use of inferential statistics for circular

data is somewhat limited, since the most powerful test available for comparison of means is the two-way ANOVA equivalent. Their use in this study sometimes required several variables to be conflated during analysis.

For this reason, both signed and absolute errors were analysed, using circular and linear statistical techniques as appropriate for the type of data, in order to examine the effects of various variables in combination at a more powerful level. This enabled the limitations of both kinds of tests to be overcome, allowing a higher level of precision, and, thus, a more accurate picture of effects in the data to be obtained.

Batschelet (1981) notes that not all angles are circular variables. If the measurement of angles is restricted in advance (for example, if the angles range from 0° to 180°), then these angles behave like linear variables, and they can be appropriately treated by linear statistical analysis. In this study, the signed error was constrained to 180° on either side of the correct heading direction, and, thus, the use of linear statistics was appropriate for the analysis of these data.

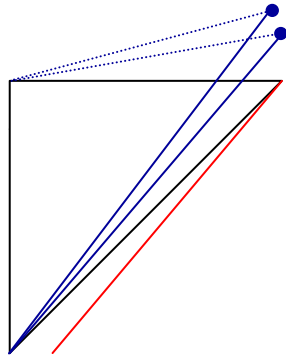
## 2.6 Models and Predictions

The experimental manipulations in this study are expected to increase the accuracy of human path integration performance, compared with the level of accuracy typically observed in similar studies conducted in virtual environments (Péruch, May, & Wartenberg, 1997; Wartenberg, May, & Péruch, 1998; Kearns, Warren, Duchon, & Tarr, 2002): that is, a mean signed error rate of between approximately  $\pm 7^\circ$ -  $24^\circ$ .

In performing the path (triangle) completion task, error in the response (the directional estimate at the end of the second outbound leg) could potentially result from two kinds of misperception. Firstly, it is possible that the participants will correctly perceive the distance that they have travelled along the outbound path, but misperceive the degree of rotation that they have experienced when turning between the first leg and second leg. This will lead to either underestimation or overestimation of the degree of rotation required, at the end of the second leg, by some percentage, assuming that the participants make the correct response towards the start position from their *perceived* final position: as their *actual* position is different from where they believe it to be. These cases are illustrated in figure 2.5 (top row). The blue dots indicate a participant's *perceived* final position at the end of the second leg. The solid blue line represents a hypothetical correct response (correct directional estimate to the start point) from the *perceived* final position. The dotted blue line indicates the *perceived* second leg. The red line represents the directional error which would result if such a response were made from the *actual* position at the end of the second leg.

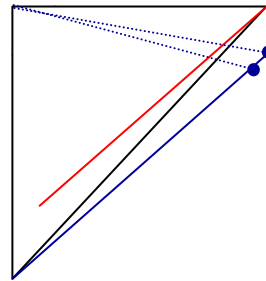
## Distance perceived correctly

a) Positive error (underestimation)



Rotation underestimated by some percentage

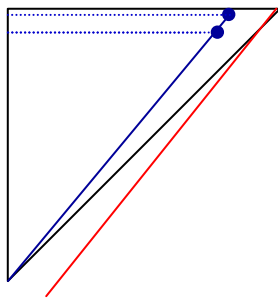
b) Negative error (overestimation)



Rotation overestimated by some percentage

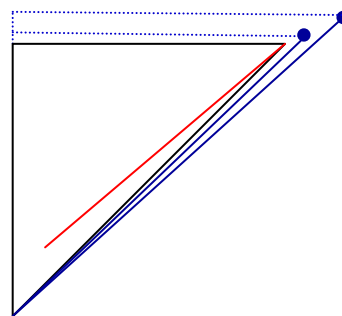
## Rotation perceived correctly

c) Positive error (underestimation)



Distance underestimated by some percentage

d) Negative error (overestimation)



Distance overestimated by some percentage

- perceived (erroneous) location
- correct response from erroneous position
- error (parallel response from correct position)

Figure 2.5. Potential response errors at vertex 2 (hypothetical example)

Conversely, it is possible that participants will correctly perceive the degree of rotation that they have experienced at the end of the first leg, but misperceive the distance that they have travelled along the outbound path. This will also result in participants either underestimating or overestimating the degree of rotation required, at the end of the second leg, by some percentage, if they make the correct response towards the start position from their *perceived* final position: which differs from their *actual* position. These situations are also illustrated in figure 2.5 (bottom row).

Thus, two classes of error are possible. The error is predictable, depending on where participants believe their final location to be. It is assumed, in both cases, that participants are able to make the correct response towards the final position from the end of the second leg; and that the error, therefore, lies in the perception of either distance or rotation on the outbound legs, rather than in execution of the response. It is also assumed, in the case of correct perception of rotation, that participants (correctly or incorrectly) perceive the lengths of the first and second legs to be equal. A tendency for participants to assume equal-length legs, regardless of actual triangle geometry, has been found in previous studies (Kearns et al., 2002).

The position of the red error line on the figures indicates where the data lie relative to the correct direction, and so it indicates a particular class of error: that is, underestimation of either the angle or the distance, if it is below the blue correct line; or, if it is above the blue line, overestimation of either the angle or the distance.

Thus, *positive* errors, that is, underestimation of the required final angle (when participants do not turn the pointer on the dial far enough), could potentially result from *either* underestimation of rotation (together with correct perception of distance), as shown in figure 2.5a; or from underestimation of distance (combined with correct perception of rotation), as shown in figure 2.5c. This is shown by the position of the red line (representing error) *below* the blue line (representing the correct response) in the figures.

Similarly, *negative* errors, that is, overestimation of the required final angle (when participants turn the pointer on the dial too far), could be produced through *either* overestimation of rotation (in conjunction with correct perception of distance), as shown in figure 2.5b; or through overestimation of distance (along with correct rotation perception), as shown in figure 2.5d. This is shown by the position of the red line *above* the blue line in the figures.

It is not possible to discriminate between the rotational error and distance error models, on the basis of the data obtained in this study. The experiments were designed with the aim of obtaining psychophysical evidence of human path integration performance in virtual environments, rather than to test competing

explanatory models. However, one of the two possible explanations is considered to be more likely to be able to account for the error data.

On the basis of previous evidence, from studies of visual path integration and distance estimation, error in estimating the final turn angle is considered to be likely to result from misperception of the distance travelled along the outbound path; rather than from misperception of the degree of rotation which has been turned through, between the two outbound legs of the route. Misperception of distance in virtual environments is a well-documented effect, which has been observed in a large number of previous studies, across a variety of tasks and conditions. Both underestimation (Frenz & Lappe, 2005; Frenz, Lappe, Kolesnik, & Bührmann, 2007; Lappe, Jenkin, & Harris, 2007; Bakker, Werkhoven, & Passenier, 1999) and overestimation (Redlick, Jenkin, & Harris, 2001; Lappe et al., 2007; Kearns et al., 2002; Bakker, Werkhoven, & Passenier, 2001) of distance have been reported. Lappe et al. (2007) have proposed a leaky path integration model to account for both patterns of error.

The effects of self-rotation on visual path integration, on the other hand, are less clear. Path-completion studies conducted in virtual environments have shown conflicting results. Some studies of visual path integration have indicated impaired updating of heading during turns (Bakker et al., 1999, 2001; Kearns et al., 2002; Klatzky, Loomis, Beall, Chance, & Golledge, 1998). However, Riecke, van Veen, and Bühlhoff (2000, 2002) found excellent turning accuracy; as did Gramann, Müller, Eick, and Schönebeck (2005), even with a high number of turns. Kaiser, Montegut, and Proffitt (1995) note the small magnitude of rotational displacements that usually occur during motion parallax. The image-plane (Euclidian) displacement for a given angle is far smaller for the rotational component than for the translational component. It may be more difficult to assess the effects of rotation.

It will, therefore, be assumed that error in the final turn is attributable to misperception of the distance on the outbound path: the analysis of the results will be conducted in line with this assumption. It is acknowledged, however, that the models predict that the same class of error could be produced in two ways. The error could also be explained by a mixture of the two models: simultaneous underestimation or overestimation of both rotation and distance. However, further development of the models, and psychophysical experiments to test them, would be required in order to provide a more definitive account.

Thus, even though these types of misperception produce equivalent outputs, the distance underestimation model will be emphasised in this thesis, due to the prevalence of observed distance underestimation in the literature.

## 2.7 The Virtual Experience

### 2.7.1 Presence and Immersion in the Virtual Environments

The degree of presence experienced by participants in virtual environments, and the influence of possible contributing factors, is generally measured with subjective rating scales, which require participants to reflect on their virtual experience after it has finished. Questionnaires in common use include the Presence Questionnaire (PQ) and Immersive Tendencies Questionnaire (ITQ), developed by Witmer and Singer (1998); the ITC Sense of Presence Inventory (ITC-SOPI), devised by Lessiter, Freeman, Keogh, and Davidoff (2001); and others, by, for example, Slater, Steed, McCarthy, and Maringelli (1998), and Schubert, Friedmann, and Regenbrecht (1999). Participants are generally required to rate the extent to which they felt physically located in the virtual environment, sensed that it had become more “real” to them than the physical world, and perceived the event as one that they had actually experienced, rather than as just a simulation (Lessiter et al., 2001).

These self-report measures have been found to be sensitive, non-intrusive, and convenient (Sadowski & Stanney, 2002). However, they can be prone to errors, since they measure presence after it has occurred. The results can also be difficult to validate, and the potential for response bias can make them unreliable (Mania & Chalmers, 2001). Caution is, therefore, advisable in interpreting the results.

A modified version of the ITC-Sense of Presence Inventory (ITC-SOPI) (Lessiter et al., 2001) was used to measure the sense of presence experienced by participants in the present study. This is a cross-media state questionnaire, which measures users' subjective experiences of, and responses to, various media, without reference to objective system parameters (that is, the physical properties) of the technology used. It is designed to apply to a wide range of systems, from standard broadcast displays to advanced fully immersive virtual environments (Lessiter et al., 2001). The questionnaire was given to participants immediately after the simulation. Participants were not specifically told that the questionnaire was intended to measure presence.

This questionnaire was selected because of its simplicity and user-friendly design. Items are phrased simply and unambiguously, and the same five-point Likert scale is used as the response option for all items, making it easy for respondents to complete the questionnaire and for the responses to be scored. It is completed with immediate responses to items, and takes only about 5-7 minutes to complete. As the questionnaire is easy to use and understand, the possibility for participants to tick the

wrong answer by mistake was reduced; and as it does not take long to complete, it was not too tedious for participants to answer, after doing the simulation.

This measure was also chosen because it included items about ecological validity and naturalness, as well as about the adverse effects of virtual environment exposure. It also provided a convenient way to collect demographic information within one questionnaire.

Lessiter et al. (2001) identified four main factors driving presence through exploratory factor analysis, based on responses to the ITC-SOPI by more than 600 people following an experience across a range of (predominantly noninteractive) media. These are: *spatial presence*, *engagement*, *ecological validity / naturalness* and *negative effects*. These factors are generally similar to those identified by other researchers (for example, Schubert et al., 1999; Witmer & Singer, 1998), but the inclusion of negative effects of exposure to media (Sadowski & Stanney, 2002) is unique. Witmer and Singer (1998) reported that presence and simulator sickness are negatively related. Each completed questionnaire, thus, results in 4 factor scores (the mean of all of the completed items contributing to the factor) for each participant.

The *spatial presence* factor is made up of 19, items which indicate participants' sense of being present in the virtual environment (rather than in the outside world), and of being able to interact with it. It is mainly determined by fidelity, field of view, photorealism, and the ability to physically control and manipulate aspects of the displayed environment. Items include: *I felt I could interact with the displayed environment*, *I felt I was visiting the places in the displayed environment*, *I had a sense of being in the scenes displayed*, and *I felt I could have reached out and touched things (in the displayed environment)*.

Six items concerning sound, other people, and object manipulation were removed from the *spatial presence* factor of the original questionnaire. The design of the virtual environments in this study had deliberately excluded such elements, in order to avoid possible confounding effects, and to focus on participants' experience in the absence of such components; as well as to consider possibilities for creating immersion by other means.

The *engagement* factor comprises 13 items, which measure participants' psychological involvement and interest in the virtual environments, and their general enjoyment of the virtual experience. Items include: *I vividly remember some parts of the experience*, *I felt involved (in the displayed environment)*, *I lost track of time*, and *I enjoyed myself*.

The *ecological validity / naturalness* factor consists of five items, which indicate whether participants perceive the virtual environments to be realistic and believable. Items include: *The displayed environment seemed natural*, *the content*

*seemed believable to me, I felt that the displayed environment was part of the real world, and the scenes depicted could really occur in the real world.*

The *negative effects* factor has six items, describing adverse physiological reactions, such as *I felt disoriented, I felt dizzy, I felt I had eyestrain, I felt nauseous and I felt I had a headache.*

Results for each factor are analysed individually, and cannot currently be combined into one overall “media experience” score: it is not clear whether the four factors all contribute to a sense of presence, and, if so, whether this occurs additively or in a more complex manner. Lessiter et al. (2001) recommend that each ITC-SOPI scale is analysed separately, as each is expected to be differentially sensitive to manipulations of particular determinants of presence.

The ITC-SOPI also has a single open-ended question for further comments: answers to this question were grouped broadly in terms of the four factors, as far as possible.

### **2.7.2 Authenticity of the Virtual World**

After completing the ITC-SOPI, participants completed a short questionnaire, developed by the researcher, in which they were asked to indicate the features of the virtual environments that they felt contributed to authenticity; and to suggest which features they would change (by addition or omission), in order to create more authentic environments.

The qualitative data were analysed using a series of *structural frames* (Kitchin & Blades, 2002; Kitchin, 1997), in order to reveal patterns within the data: that is, categories which were defined by the researcher, on the basis of relevant information expressed by the participants. Several sets of frames (categories of design features) were first established, through identification of commonly-occurring responses, and then used to organise the data. Every feature identified was recorded into a frame. Recurring themes among the responses were identified, and responses with similar themes grouped together, in order to reduce the large amount of data into a small set of conceptual categories, which encapsulated the main themes.

An example is the category of *countryside / rural areas*. This includes a wide range of related responses, such as *fields, pasture, paddocks, plains, open spaces, grass, grass areas, grassland, farmlands, rural scenery, settings, landscape, or environment.*

This approach has various shortcomings, some of which also apply to the use of the ITC-SOPI. As information about participants’ impressions was sought after they had left the virtual environments, the responses may not all have been accurate:

for example, some impressions may have been forgotten. However, it was assumed that, when reflecting on an experience, the most memorable aspects would easily come to mind, which would indicate the features that had made a strong impression. In other words, if something could be easily remembered, then this suggests that it was particularly salient in some way.

Caution is required in the use of qualitative methods, generally, to investigate cognitive processes: participants may have only a limited insight into their own cognitive processes, and may not have the ability to comment on them. It is also an introspective method, which assumes that the concepts under consideration (here the authenticity of design features) can be consciously expressed. Furthermore, in analysing such data, patterns are imposed on it by the researcher, who also makes subjective decisions about the division of the information into appropriate units of analysis. Reliability may also be an issue: participants may not provide consistent comments, for example.

Nevertheless, qualitative data can provide useful information in navigational research, which can complement the information gained from quantitative methods. The findings need to be treated with caution, but they do, however, provide some general insights into participants' thinking, albeit of a naive kind. Such methods also allow participants to express their ideas, and to give feedback, quite freely, which can be informative in an indirect way.

## Chapter 3. Experiment 1

### 3.1 Aims

The aims of this experiment were to examine the effects of several variables on path integration performance within large-scale virtual environments. The variables were: presentation of the environments on three large projection screens, which partially surrounded the participant; contextualisation of the visual information (optic flow and depth cues) within authentic virtual environments; variations in the value of the angle between the two roads on the outbound path (route layout); and gender.

It has been shown that large projection displays, especially curved screens, can increase the accuracy of path integration performance (Tan, Gergle, Scupelli, & Pausch, 2003, 2004, 2006; Tyndiuk, Lespinet-Najib, Thomas, & Schlick, 2007; Patrick et al., 2000); particularly the rotational element (Schulte-Pelkum, Riecke, von der Heyde, & Bülthoff, 2004; Riecke, van Veen, & Bülthoff, 2000, 2002); and especially by females (Czerwinski, Tan, & Robertson, 2002; Tan, Czerwinski, & Robertson, 2003). The beneficial effects may result from enhanced saliency of the visual information, such as optic flow, depth cues, or landmarks, due to the large field of view and increased peripheral visual information which such displays provide. It could also be because large displays engender a heightened sense of immersion and presence, especially when they surround or partially surround the user.

This experiment considers whether the same effect on path integration performance can be achieved with three large flat screens which partly surround the participant. The display was intended to provide a wide field of view, enabling peripheral visual information and more overall depth to be presented; and to evoke a sense of immersion and presence, in the absence of other immersive features. The experiment was conducted in a driving simulator. However, the simulator was not used interactively (that is, the participants did not actually “drive”): instead, the screen was viewed passively, as a pre-recorded simulated motion (“driving”) sequence along the route was presented. The aim was to test the visual effects of the display, and using the simulator was a convenient way to do this, since it is permanently set up with the three large screens. The principle could be extended to any large-screen display. Use of a real car added to the authenticity of the experience, however, by providing a driving metaphor.

The large displays were used in conjunction with manipulations of the optic flow and depth cues. Increased accuracy of visual path integration performance has also been observed in virtual environments in which optic flow cues were available from more extensive texture, again with particularly beneficial effects on rotation

(Riecke et al., 2000, 2002; Kearns, Warren, Duchon, & Tarr, 2002; Gramann, Müller, Eick, & Schönebeck, 2005; van Veen, Riecke, & Bühlhoff, 1999). The optic flow cues in these previous studies were generally available from abstract random texture patterns (Kearns et al., 2002), sometimes together with more naturalistic scenes (Riecke et al., 2000, 2002); or from other non-realistic textures (Gramann et al., 2005).

In this study, textures were presented within more natural contexts, as they would appear in real life: for example, complex combinations of textures from buildings; or simpler textures from the ground, or from natural elements such as grass and trees. The amount of visual information available (from optic flow and depth cues) was controlled and varied, through the presentation of simple versus complex environments. Saliency of the task information was increased, through the contextualisation of the visual self-motion cues, both optic flow and depth.

Kearns et al. (2002) observed that performance was particularly accurate in a richly-textured virtual environment, with wall and floor texture, which evoked both rotational and translational optic flow; whilst turning accuracy was reduced when rotational flow was reduced. Gramann et al. (2005) found that participants performed path integration relatively accurately, even in a simple virtual environment with quite sparse optic flow information, including on routes with a high number of turns. Optic flow was elicited by self-motion through a virtual tunnel, which provided information on translational and rotational changes through the rate of optic flow only, from floor and wall texture.

In order to stimulate participants' sense of presence in the virtual world, an enhanced immersive virtual experience was created: through manipulations of the visual stimulus, interface, task, and display (Witmer & Singer, 1998, 1994; Slater & Usoh, 1993; Slater & Wilbur, 1997; Slater, 1999; Slater, Steed, McCarthy, & Maringelli, 1998; Hendrix & Barfield, 1996; Snow & Williges, 1998; Prothero & Hoffman, 1995; Barfield & Hendrix, 1995; Wilson, Nichols, & Haldane, 1997; Darken & Sibert, 1996; Stanney et al., 1998; Welch, Blackmon, Liu, Mellers, & Stark, 1996; Stanney, Mollaghasemi, Reeves, Breaux, & Graeber, 2003). Enhanced ecological validity was achieved, through the use of authentic, moderately detailed virtual environments, which simulated real-world local scenes, textures, and depth cues. These were presented on a display with high visual resolution and fast update rates. The inclusion of a driving metaphor heightened the meaningfulness of the virtual experience for participants, by providing a realistic context for the path-completion task: a steering wheel and pedals, together with simulated self-motion along complex routes with roundabouts (traffic circles).

The convincingness of virtual environments, and the effectiveness of simulated self-motion, can both be increased through greater ecological validity: this enhances the perception of vection, partly by stimulating a heightened sense of presence (Riecke, Schulte-Pelkum, Avraamides, von der Heyde, & Bühlhoff, 2006).

Female performance, in particular, may be positively influenced by authentic environments, and by a more ecologically valid presentation of optic flow, in inducing an illusion of vection. Lessiter, Freeman, Keogh, and Davidoff (2001) differentiate between media *form* variables (objective physical properties of the display) and media *content* variables (the overall theme or narrative / story depicted via a display system). It is possible that women are especially affected by content variables.

Research on visual path integration in virtual environments suggests that females may pay less attention than males to optic flow; and more attention to static visual information, such as landmarks (Kearns et al., 2002; Fortenbaugh, Chaudhury, Hicks, Hao, & Turano, 2007). Females may also use completely different strategies to perform path integration, such as timing. Males appear to be able to switch from the use of visual cues to other, non-visual, cues, more easily than females, when the visual cues are less informative, such as in environments with minimal texture.

Gender effects found in navigation studies, particularly those conducted in virtual environments, may be, at least partly, due to the nature of the stimulus. The use of relatively abstract environments (with few features and random patch textures) seems to disadvantage females (Astur, Ortiz, & Sutherland, 1998; Moffatt, Hampson, & Hatzipantelis, 1998; Sandstrom, Kaufman, & Huettel, 1998); whilst studies employing more realistic and ecologically-valid virtual environments, such as a multi-storey building or a university campus, have reported no gender effects (Wilson, Foreman, & Tlauka, 1997; Rossano & Moak, 1998; Darken & Sibert, 1996).

There is some evidence that females become more easily disoriented, and require more time to perform some navigational tasks, in virtual environments, compared with males (Waller, Knapp, & Hunt, 2001; Waller, Hunt, & Knapp, 1998; Tlauka, Brolese, Pomeroy, & Hobbs, 2005; Lawton & Morrin, 1999); this may be the reason for reported gender differences, rather than differences in navigational ability. Comparable navigational performance between men and women has been found after real-world training (Waller et al., 1998).

The experimental task was kept simple, by limiting the set of path layouts to three values (60°, 90°, and 120°) of the first turn, that is, the internal angle between the two outbound roads; and by using equal-length straight segments, resulting in only equilateral or isosceles triangle layouts. The overall structure of the route was quite complex, however, due to the novel inclusion of a roundabout, which provided

an added degree of rotation through a large gradually curving road segment on the path layout.

*Hypotheses:*

1. Higher accuracy of path integration performance would result from the use of a large display, compared with previous studies
2. Accuracy would differ as a function of the internal angle
3. Accuracy would depend on the levels of realistically-presented optic flow and depth cues in the environments
4. The 3-screen semi-surrounding display, realistic visual information, and authentic environments, together, would increase participants' sense of presence and engagement, by making the experience more immersive, in the absence of other immersive features
5. A heightened sense of presence and engagement would result in more accurate path integration performance
6. Female performance would be particularly enhanced by the effects of the large screens, authentic environments, realistic visual information, and increased presence; leading to reduced or minimal gender differences, compared with previous studies

## **3.2 Method**

### ***Participants***

24 participants took part in this experiment, 12 of each gender, who were aged between 16 and 43, with a mean age of 28.7 years. Ten of the participants were first year undergraduate psychology students at the University of Waikato, who had been recruited through the course website, and who received course credit for their participation. Of the other participants, six were postgraduate students and five were staff members at the University of Waikato, two were high school students, and one was an employee from outside the university. These participants had been recruited through either word of mouth or personal recommendation by other participants. They all received their choice of either a petrol voucher or book token worth \$20, in return for their participation. All participants had normal or corrected to normal vision.

Most of the participants (18) had no previous experience in a motion simulator. Five of the six participants with such experience reported less than five hours participation in total, and one person had spent between 5-50 hours in a

simulator. Their reported experience had been either for entertainment (4) and/or previous psychology experiments in the University of Waikato driving simulator (2). One participant reported professional (engine operations) training in a Boeing 737 flight simulator.

### ***Apparatus***

The experiment was performed in the University of Waikato driving simulator, using an Intel Core Duo with three 3D graphics cards to generate the virtual environments, and three colour projectors. This is shown in figures 3.1 and 3.2.

The driving simulator consisted of a complete full-size BMW 314i car, positioned between three projection screens. The participant sat in the passenger seat, beside a “driver” (the experimenter, or an assistant). The car was facing a central projection screen, which was located 2.42m from the passenger seat, and between two side-screens, which were connected to the central screen at an angle of 62°. The image displayed on the central screen measured 2.64m wide by 2.10m high, at a resolution of 1280 by 1024 pixels, and each of the two images displayed on the peripheral projection screens measured approximately 2.65m wide by 2.00m high, with an XGA (extended graphics array) resolution of 1024 by 768 pixels.

The three projection screens, together, provided a 175° (horizontal) by 41° (vertical) forward view of the virtual environment from the participant’s position. The entire projection surface was tilted back away from the car, with a 14° difference between the bottom and the top of the screen, the bottom being closer to the participant in the car. The sloping screens are a feature of the University of Waikato driving simulator and are intended to enhance the 3D illusion, through the change in accommodative focus of the eyes which is required at different distances from the screen. The update rate of the projected images and vehicle model was 100 Hz.

Engine and road sounds were turned off. The participants (passengers) watched simulated observer motion through the environment. The “driver” (the experimenter or an assistant) appeared to drive the car, by ostensibly controlling the vehicle’s smooth motion through the virtual environments, with a steering interface consisting of a steering wheel and accelerator and brake pedals. The steering wheel provided 6-turn lock-to-lock (full lock left / full-lock right) steering with no dead zone, so it gave a realistic appearance of steering.

In reality, the images the participants saw displayed on the screen were of a pre-recorded simulated motion sequence, along a route driven previously by another driver. The “driver” attempted to mimic, in the car, the expected steering movements



Figure 3.1. Exterior views of the driving simulator car, showing the three screens

that would accompany driving along the route viewed on the screen, in order to give participants the impression that she was actually driving (rather than pretending to drive). This was intended to maintain some naturalness in the situation, as though the participant were really a passenger, and to simultaneously ensure identical participant experience.

The vehicle dynamics model (usually configured as a car with automatic transmission, 3 litre engine, and power steering) was disabled, as the simulated driving rendered it unnecessary.

A Logitech Trackman Marble trackball was mounted on the passenger side of the dashboard. Participants used this trackball to move the pointer on a virtual dial, which automatically appeared on the central screen at the end of the route in each trial, in order to indicate the estimated heading direction to the origin of the route; and they pressed a button on the trackball to enter their decision into the computer.

The virtual dial was represented as a circular frame (similar to a hoop, but smaller) with an arrow-like pointer mounted on top, extending from the centre to the circumference. It was presented as an object inside the virtual world, but intended to look as much as possible like a real object, which the participant could hold. It appeared in the middle of the screen, superimposed upon the scene, above the virtual ground, and in the middle of the virtual road in front of the participant (as if the participant were looking down at it, at around hand-height). The pointer could be moved 360° around the dial. The pointer was positioned randomly on the dial when it first appeared on each trial (but never pointing in the correct direction), in order to avoid influencing participants into thinking that it provided any directional information.

The dial was modelled on the real-world circular dials which were used in previous studies by Montello, Richardson, Hegarty, and Provenza (1999), and by Sadalla and Montello (1989); but it was larger, so that it was easy to see on the screen. It was also based on the onscreen virtual dial (“graphical object pointer”) used by Bakker, Passenier, and Werkhoven (2003). Montello et al. (1999) required participants to make directional estimates manually, by pointing with a circular dial made of smooth cardboard, using a rotating pointer: this had a single radius line, and a rotatable radius wire on the top face, which could be rotated to indicate direction.

The simulation software recorded participants’ directional estimate at the end of each trial, and calculated the angle representing the degree of rotation between the participant’s heading, at the end of the route, and the measured heading.



*Figure 3.2.* Interior views of the driving simulator car, with view of the screens

### ***Virtual Environments (Display Conditions)***

The experiments were performed in four 3D virtual environments, which were created with 3D Studio Max™ (from Autodesk) modelling and rendering software. The environments were large-scale, that is, the whole layout was not visible from any one position, reflecting environments typically encountered in real life navigation.

Each of the four environments consisted of a ground plane with four straight roads linked by a single large roundabout, surrounded by mountains, with a cloudless sky overhead. Two urban and two rural virtual environments were developed. Views of two of the virtual environments are shown in figure 3.3. Texture-maps were used to create lifelike ground surface textures (tarmac, gravel, grass). A texture-map, adapted from a photograph of a local mountain, created an effect of a mountain range in the distance: a single image was repeated, to prevent the mountain being used as a landmark for piloting by the participants. An effect of dusk falling was derived from a texture-map of an early evening sky: this helped to circumvent problems of artificially-bright colours and a lack of shadows, by giving an appearance of daylight but without harsh sunlight.

The degree of visual complexity of the environments was varied, by manipulating the amount of structure in each environment. The urban environments were modelled on a local suburb, with a rich, complex structure provided by a large number of texture-mapped buildings. The rural environments, also modelled on local areas, had a simpler, more basic structure. The physical features in the environments had all been adapted as texture-maps from photographs of real places, and relevant real-world architectural and engineering conventions had been observed, as far as possible (for example, in the relative dimensions of buildings and roads).

The roads in the urban environments were lined with similar-looking houses. Each house had an attached garage, and a high fence which obscured most of the house, leaving only the front door and garage door visible: this reduction of detail allowed computational power to be saved. Texture-maps had been applied to polygons representing the houses: these had been adapted from photographs of real roofs, fences, hedges, house-fronts, and garages, to foster a realistic appearance.

Although the houses shared the same basic design, they were not identical, as different textures had been applied to the features of each house, in order to create some degree of naturalness. At the same time, the houses were fairly indistinguishable, as the textures were randomly selected from a small set, and so the same fences and hedges, front doors, and garage doors appeared repeatedly at various intervals throughout the environment. Participants, therefore, had to rely on path integration, as no single house or its features could easily be used as a salient landmark for piloting.



*Figure 3.3.* Straight section of the route in a rural and an urban environment

These environments, with their repeated pattern of indistinguishable houses, were designed to create a compelling feeling of self-motion (vection) using optic flow. The repetitive textures provided a high level of optic flow and depth information, as participants travelled along the roads.

The rural environments contained mainly fields. Most of the texture was derived from largely featureless expanses of grass and road surfaces, which provided a lower level of optic flow and depth information during participants' self-motion along the roads.

Figures 3.4 and 3.5 show a view of the same position on the route in each of the four environments.

### ***Path Layouts***

The path layouts all had a constant length of the two straight segments (a distance of 300m); the internal angle of the exit-road from the roundabout in relation to the first road was varied (between  $\alpha = 60^\circ$ ,  $\alpha = 90^\circ$ , and  $\alpha = 120^\circ$ ) (see table 3.1). The distances are measured in *virtual metres* (that is, they are measurements within the virtual environments). The length of the curved segment of road, around the roundabout, depended on the value of the internal angle between the two outbound roads. The three path layouts were broadly based on a subset of the triangles used by Loomis et al. (1993) in their study of path integration in non-visual conditions, and in several studies of visual path integration (Wartenberg, May, & Péruch, 1998; Péruch, May, & Wartenberg, 1997; Kearns, Warren, Duchon, & Tarr, 2002; Riecke, van Veen, & Bühlhoff, 2000, 2002); they included the same angles, and pathways with equal-length straight segments. However, the layouts also differed from these previous studies, as the pathways were not strictly triangular, due to the addition of the curved section of road on the roundabout. The curved segment was included in order to provide a realistic rotational component, similar to that which is found in the real world: driving around roundabouts is a common everyday task for most people. Thus, the task was embedded within a real-life context. Participants navigated the paths in four environments, under four different optic flow conditions (see tables 3.2 and 3.3).

### ***Visual Information Available to Participants***

The amount of visual information available to participants was varied in the four virtual environments. There were two versions of both the urban and rural environment.

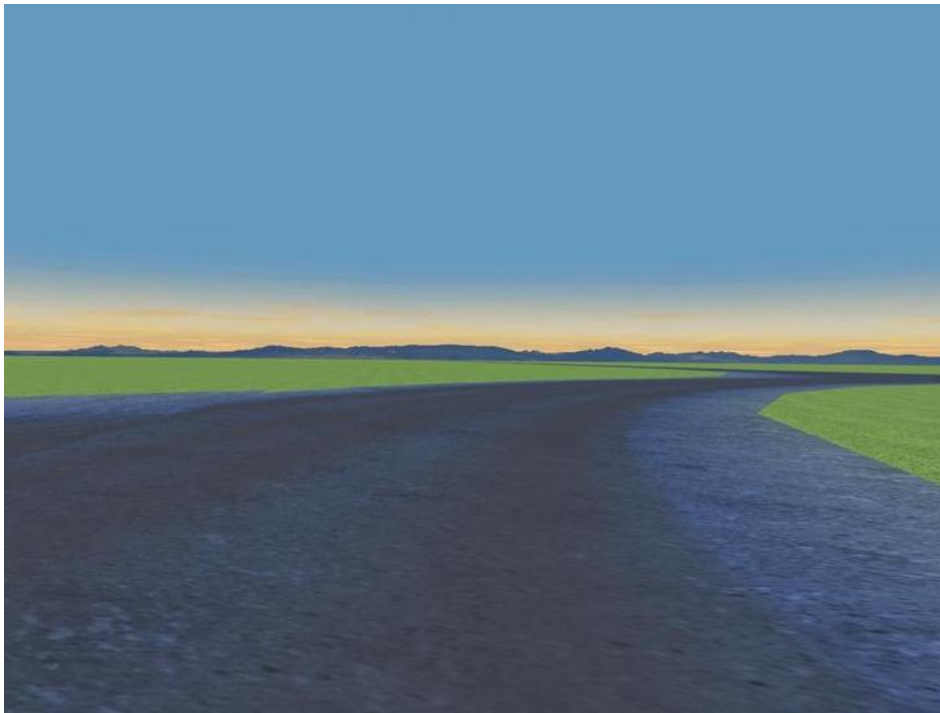


Figure 3.4. Rural environment with (above) and without (below) added structures

Table 3.1.

*Overview of path (triangle) layout parameters used in Experiment 1*

Internal angle $\alpha$	Distance $a$	Distance $b$	$\theta$
60°	300m	300m	120°
90°	300m	300m	135°
120°	300m	300m	150°

Distance  $a$ : Length of first straight segment (virtual metres)

Distance  $b$ : Length of second straight segment (virtual metres)

Internal angle  $\alpha$ : angle between approach road and exit-road

$\theta$ : correct response angle

In one version of both environment types, visual information was restricted to cues from optic flow only: translational flow was available on both the straight road segments and the roundabout, whilst rotational flow was also available from the surround texture on the roundabout. The presence of rotational optic flow in the environment was manipulated, by varying the amount of realistic texture surrounding participants at eye-level, as they moved along the gradually-curving segment of road around the roundabout. A high level of optic flow information was available in the urban environment, from increased texture provided by the repeated pattern of similar texture-mapped houses; whilst only minimal optic flow information was available in the rural environment, due to the sparse texture.

In the other version of both types of environment, additional visual information was provided by four large detailed structures surrounding the roundabout, one positioned at the end of each approach road. Structures appropriate to urban and rural environments were used; texture-maps, adapted from photographs of their real-world counterparts, were applied to polygons modelling the structures. To discourage use of the four structures as landmarks for piloting, their positions were alternated in the different environments, making it difficult for participants to learn the positions of individual structures during the large number of trials.

Table 3.2.

*Overview of the visual information available in Experiments 1, 2*

<b>OPTIC FLOW LEVEL</b>	<b>OPTIC FLOW ONLY</b>	<b>OPTIC FLOW + STRUCTURES</b>
<b>HIGH</b>	URBAN (Ur-N)	URBAN+ (Ur-S)
↕		
<b>LOW</b>	RURAL (Rur-N)	RURAL+ (Rur-S)



Figure 3.5. Urban environment with (above) and without (below) added structures

Table 3.3.

*Overview of the four environments (display conditions)*

URBAN		RURAL	
Complex textured environment: <ul style="list-style-type: none"> <li>• increased optic flow</li> <li>• textures derived from homogeneous blocks of houses</li> </ul>		Simple (basic) textured environment: <ul style="list-style-type: none"> <li>• reduced optic flow</li> <li>• textures derived from homogeneous fields of grass</li> </ul>	
Ur-N	Ur-S	Rur-N	Rur-S
Rotational flow only	Rotational flow plus depth (parallax) information	Rotational flow only	Rotational flow plus depth (parallax) information
No added structures	Added structures: depth cues from self-motion Maximum (rich) visual information	No added structures Minimal (sparse) visual information	Added structures: depth cues from self-motion

These structures incorporated many separate elements, thereby providing potential depth cues arising from self-motion of the participants through the environments, such as from motion parallax (the relative motion of images of the individual elements). The structures included a supermarket, with a surrounding car park and some parked cars; a church surrounded by a cemetery with gravestones; a row of various small shops with a cinema; a petrol station with several pumps, parked cars and a shop on the forecourt, and a drive-through carwash; a large farm barn, and a small wood with several trees.

Thus, in these environments, information for rotation was available from optic flow, from the textures; and depth information was also available, from the structures. Experimental conditions, therefore, included high (urban) and low (rural) optic flow, both with and without additional depth cues, from the added structures around the roundabouts. The urban environments contained both rotational and translational flow as participants moved around the roundabout. The rural scenes had fewer nearby objects and less translational flow.

***Authentic Environments***

The use of 3D Studio Max™ allowed a moderately realistic 3D model of four different environments to be created, which were typical of New Zealand rural and urban areas. The development of environments with an authentic appearance (but which were not recognisable as actual places) was intended to enhance ecological validity.

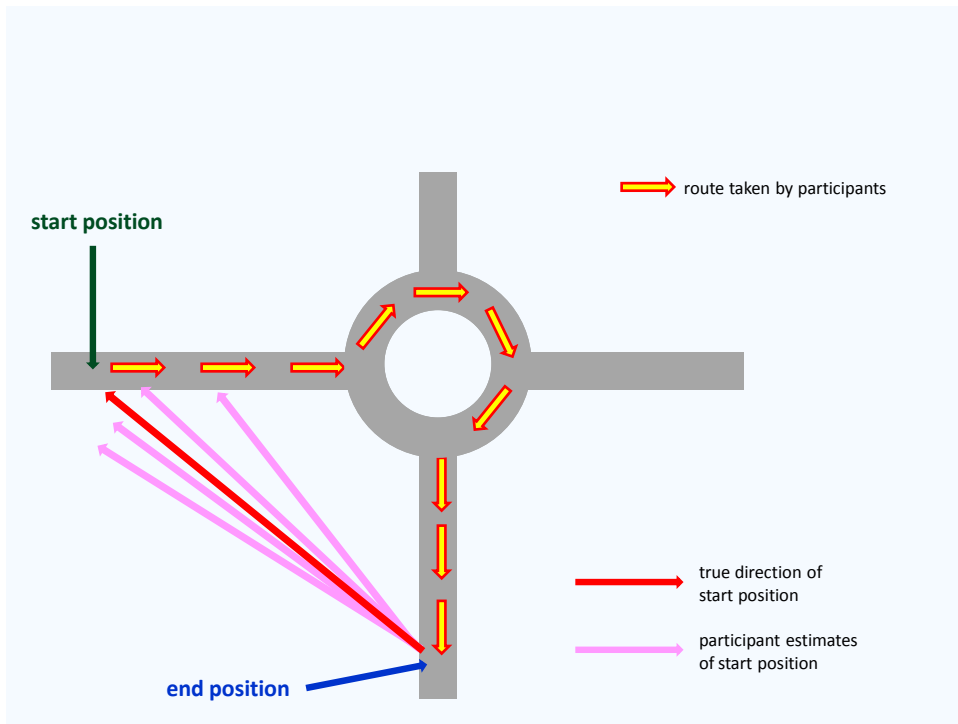


Figure 3.6. Plan of the route, showing the task (with  $90^\circ$  internal angle, or  $\alpha = 90^\circ$ )



Figure 3.7. Aerial view of the virtual roundabout (showing urban environment with structures)

The design of the experimental task was also intended to mirror real-life navigation. It was expected that these features would contribute to an increased level of immersion in the environments, and evoke a sense of presence for participants.

The unique New Zealand environments were modelled on real locations, and included local features in their design. The appearance of the virtual buildings, for example, was based on photographs of local buildings. Texture-maps were applied to objects in the virtual world, to create scenes resembling their real-world counterparts. An array of life-like textures in the virtual environments replicated the appearance of the corresponding real-world textures. However, the environments were modified, in order to prevent recognition; and they were also simplified, due to the memory constraints of the software system.

Thus, an approximation of real-life experience was enabled, which was intended, in turn, to evoke a sense of presence for participants, and thereby compensate for various visual shortcomings, especially of the desktop monitors. Increased presence was also expected to make participants feel more comfortable, and relaxed: this is an important consideration in using technological methods. The environments were trialled in a pilot study with five participants, who confirmed that the virtual environments evoked a sense of being in New Zealand.

The attempt to create authentic street scenes led to various challenges. In balancing fidelity of the environments with computer memory, it was important to ensure that compromises did not result in the streets having an artificial appearance; and to avoid houses unintentionally becoming landmarks, due to an incongruous or noticeable appearance, rather than blending into the background and becoming part of the general optic flow.

### ***The Task***

Participants performed a large-scale path-completion task, in which they were transported (“driven”) along a straight road, then along a curved section of road around a large roundabout, and finally along an exit-road from the roundabout. From their final position, participants indicated the estimated direction to the starting position of the route, which was not visible from the final location. They did this by pointing to it with a virtual dial, which appeared on the screen after the vehicle had stopped at the end of the route. The task is illustrated in figure 3.6, which shows a plan of the route (path layout) with the 90° internal angle ( $\alpha = 90^\circ$ ); whilst figures 3.8 and 3.9 provide an overview of the routes with the 60° and 120° internal angles, respectively ( $\alpha = 60^\circ$ , and  $\alpha = 120^\circ$ ). Figure 3.7 shows an aerial view of the virtual roundabout, located in an urban environment with structures.

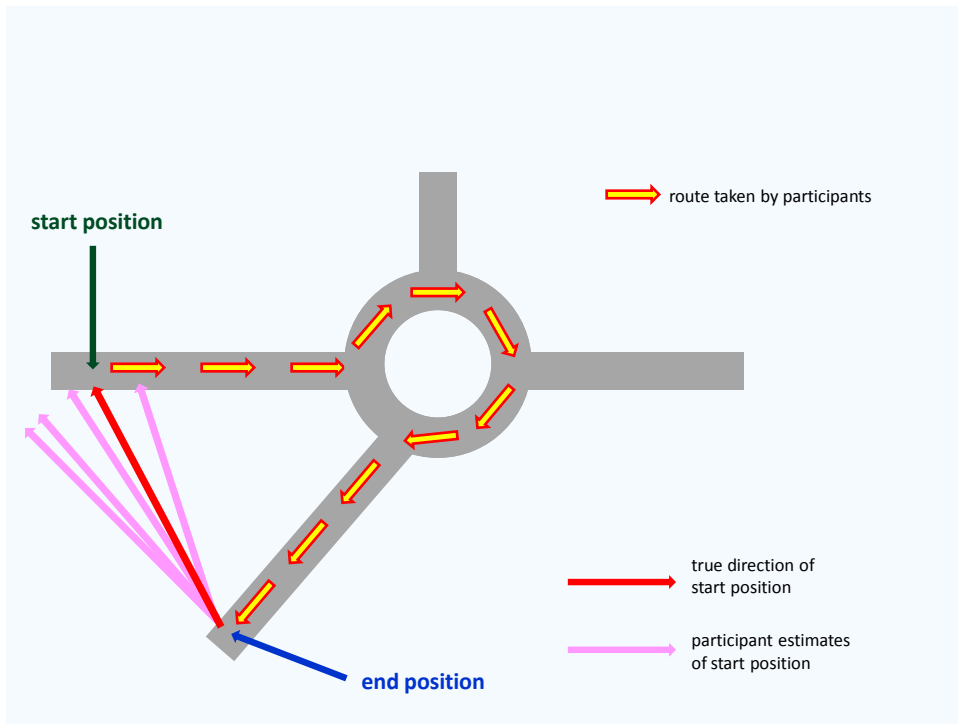


Figure 3.8. Path layout with the 60° internal angle ( $\alpha = 60^\circ$ )

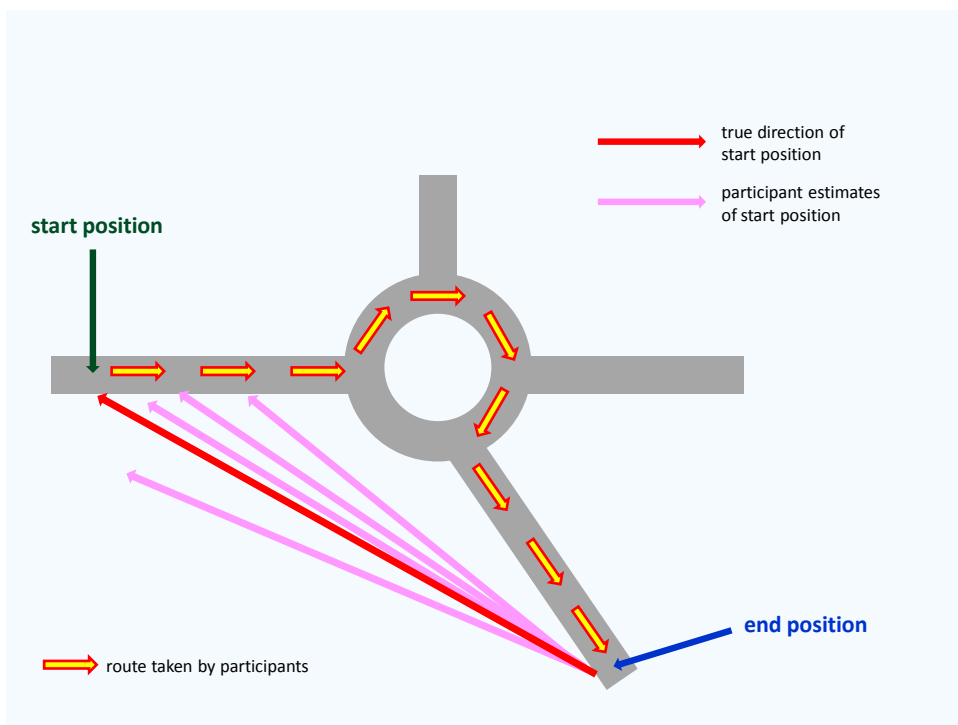


Figure 3.9. Path layout with the 120° internal angle ( $\alpha = 120^\circ$ )

The task could be regarded as either a path-completion task, with a complex path consisting of three segments in the outbound route, the second of which is a gradually curved stretch of road; or as a triangle-completion task, with a large degree of gradual rotation at the end of the second segment. It could also be considered as a combination of the two task types. The path is typical of many real-world routes found in New Zealand, where navigation of roundabouts is commonly required.

For return-to-origin tasks, error increases as a result of the number of *linear* segments and turns, especially when the segments cross over each other (Klatzky et al., 1990; Loomis et al., 1993). However, in this experiment, the effect of adding a *curved* segment is of interest. It is not clear how the addition of a curved segment, in this way, will affect task performance.

A mixed-measures design was used, with two within-participant factors (angle and environment), and one between-participant factor (gender). Each participant completed a total of thirty-six trials. Thirty-six triangles were presented in random order, corresponding to a factorial combination of three trials for each of three angles of the first (internal) turn  $\alpha$  ( $60^\circ$ ,  $90^\circ$ , and  $120^\circ$ ), distributed equally between four environments (urban, with and without the additional structures; rural, with and without structures).

There was no time limit for the response, and participants received no feedback about their performance accuracy during the experiment. The experimental session (including practice trials) lasted about 50 minutes to one hour.

The “driver” appeared to drive the car, by feigning the steering movements, whilst pre-recorded simulated motion along the route was projected onto the display screens. This ensured that all participants saw the same driving sequence for each route, thereby preventing inter-participant differences in the experimental experience, but with some naturalness in the situation.

### ***Procedure***

Prior to the experiment, participants were given printed background information, which provided a brief outline of the aims of the experiment, and an overview of the task; it also alerted them to the possibility of simulator sickness from the simulated motion, and what to do should this occur. Participants then signed an informed consent form and filled out a questionnaire, enquiring about their previous simulator experience and their general health. Finally participants read printed instructions for the task, which were also available for their reference throughout the experiment; and the experimenter also verbally explained the task, clarifying with real-life examples.

In order to ensure that participants could point from their current position to a recently visited location in the real world, they were asked to point to the carpark where they had left their car, or to the bus stop, if they had arrived by car or bus; or to their last location just prior to the experiment, if they had walked from elsewhere in the university.

The participants then seated themselves in the passenger seat of the car. Before starting the experiment, participants performed two or three randomly-generated practice trials, in order to familiarise themselves with the virtual environments, path-completion task and virtual dial; and with using the trackball to move the pointer on the dial. The paths used were different from those used in the actual experiments, to prevent learning effects. Test trials followed immediately after the practice trials, when participants indicated that they were ready to proceed.

### ***Example of a Trial***

Each trial began with a message displayed on an otherwise blank screen on the central monitor, informing participants of the number of the imminent trial. The “driver” (the experimenter or an assistant) initiated the trial, by pushing the indicator on the steering wheel downwards. A street scene replaced the previous message screen. The car was initially stationary at a location on one of the four roads in the virtual environment, facing in the direction of the roundabout. After a two-second pause, simulated self-motion automatically began on the screen, at which time the driver also stepped on the accelerator pedal and began steering movements with the steering wheel, in order to create the impression of driving.

Participants (passengers) observed the route as they were passively transported (“driven”) along it, watching pre-recorded self-motion. The simulated motion was slow at first, and gradually built up to a maximum of 50 km/h, consistent with the driver accelerating and then maintaining a constant speed. The low maximum speed was selected to minimise the possibility of simulator sickness, especially since symptoms could be exacerbated by motion around the roundabout.

The driver pretended to “drive” the car (that is, to control the simulated forward motion) along the first straight segment of the route, towards the roundabout, using the steering wheel and accelerator pedal. On approaching the roundabout, the speed of the motion was reduced slightly, as the driver appeared to gently apply the brakes. The driver then appeared to turn (left) onto the roundabout, proceeding along the gently curving segment of the route around the roundabout at 30 km/h, and past two exit roads. The driver appeared to drive the car into the third exit road from the roundabout, which formed the second straight segment of the route, and travelled

along this road at 50 km/h until reaching a line of orange traffic cones, flanked by two red stop signs on either side of the road. The cones blocked the road, preventing further forward motion. The driver pressed the brake pedal, and motion slowed and ceased, consistent with the vehicle decelerating and stopping at this barrier.

It may be noted that it was only possible to exit from the roundabout via the second right exit: thus, the direction of turning was always to the right. Several previous studies have found that turning direction (left or right) has no significant effect on path integration performance, and, thus, the data for left and right turns were combined for the analysis in these studies (Bakker, Werkhoven, & Passenier, 2001, 1999; Riecke, van Veen, & Bühlhoff, 2000, 2002). It was, therefore, decided that this was not a methodological issue in the current study, as it would be unlikely to bias the results.

After the simulated self-motion had stopped, a virtual dial automatically appeared on the central screen, on the road in front of the participant. This dial had a pointer (arrow), which could be moved a full 360° around the dial, by using the trackball. The position of the pointer on the dial, when it first appeared, was randomised on each trial; but it never pointed in the correct direction (participants were informed of this). Participants used the dial to indicate the location of the starting position of the route they had just travelled, which could no longer be seen from the end of the route, as accurately as possible.

Using the trackball, participants moved the pointer on the dial, until it pointed towards the starting position of the route, and then pressed a button. Participants were instructed to make their decision as accurately as possible. The participant's directional estimate was recorded. The dial and the street scene were replaced with a screen informing participants of the number of the next trial (inter-trial interval). The "driver" pushed the blinker, and a new street scene appeared. The next trial began when simulated self-motion resumed, after a two-second pause: that is, the "driver" appeared to resume driving the car.

In the interests of comfort and safety, participants were encouraged to take occasional breaks from the task between trials, and to leave the car and walk around or stretch for a few minutes, especially if they experienced any symptoms of simulator sickness (such as drowsiness or excessive yawning, eyestrain, headache, feeling overheated, or nausea). Sweet and savoury snacks, and water, were also available during breaks, and before and after the experiment. The experimenter was alert at all times for any signs of simulator sickness on the part of participants, and enquired about the participants' well-being in general terms (to avoid influencing participants) throughout the experiment and afterwards. Participants were requested to inform the experimenter if they felt unable to continue the experiment for any

reason, or to just stop, and the simulation would be immediately terminated. They were reminded that they were free to withdraw their participation at any time.

Most participants reported experiencing some sickness symptoms during the experiment, of varying degrees of severity. For five participants, the symptoms were severe enough to prompt them to withdraw from the experiment: their data were excluded from the analysis. The majority of participants reported a cessation of these symptoms by the time they had finished the post-experiment questionnaires, and very few participants had any longer-lasting symptoms.

After the simulation, participants completed two questionnaires about their experience in the virtual world: the ITC-Sense of Presence Inventory (Lessiter, Freeman, Keogh, & Davidoff, 2001), and a feedback questionnaire about the design of the virtual environments, which had been developed by the experimenter.

### **3.3 Results**

#### **3.3.1 Directional Estimates: Analysis**

Using functions from the MATLAB Circular Statistics (CircStats) Toolbox (Berens, 2009; Berens & Velasco, 2009) the mean directions and mean angular deviations of the directional estimates (Batschelet, 1981) were calculated, for each condition, for the sample of 21 participants. Arithmetic means and standard deviations were also calculated for the signed error, since this data is linear in nature. Based on the mean directions and mean angular deviations, outliers were identified, and their data were removed from the dataset prior to the analysis. ANOVAs, or their circular equivalents where appropriate, were performed on the absolute and signed error of the directional estimates.

#### **3.3.2 Elimination of Outliers**

Three participants (one female and two male) were identified as outliers, as their directional estimates were found to be more than three angular deviations away from the sample mean direction for the condition, on more than six trials overall. Their data were therefore excluded from the analysis. This altered the overall age composition of the group slightly: whilst the minimum and maximum ages remained unchanged (at 16 and 43 respectively), the mean age fell slightly from 28.7 to 28.2 years (with a standard deviation of 10). Thus, the analysis was conducted on data from 21 participants, of whom 11 were female, and 10 were male.

### 3.3.3 Overview of the Data: Mean Vector Length and Angular Variance

The magnitude of the mean vector length indicates the distribution of the directional data in each experimental condition. As can be seen from table 3.4, the mean vector length ( $R$ ) was close to 1.0 for all three internal angles  $\alpha$  (i.e., 60°, 90°, and 120°), across the four environments, averaged across the three trials. This indicates that the data were clustered fairly closely around the mean direction, with a correspondingly small angular variance. Mean vector lengths were of a similar magnitude for the 60° and 120° angles, whilst for the 90° angle the length was slightly closer to 1.0, indicating that the 90° angle data were a little more concentrated around the mean direction. The length of the mean vector differed only slightly between the genders.

Table 3.4.

*Mean vector length ( $R$ ) for three angles by environment (averaged data)*

Environment	$\alpha = 60^\circ$	$\alpha = 90^\circ$	$\alpha = 120^\circ$
Ur-S	0.89	0.92	0.87
Ur-N	0.85	0.91	0.88
Rur-S	0.88	0.91	0.88
Rur-N	0.79	0.89	0.91

### 3.3.4 Mean Directions and Mean Angular Deviations

The means of the directional estimates for each condition are shown in figures 3.10 and 3.11, with the error bars representing the standard error of the means. Table 3.5 displays the mean directions and mean angular deviations of the directional estimates by angle and environment, averaged across the three trials (as the inferential tests indicated that error was not significantly affected by the trial order). Table 3.6 shows the same data separately by gender.

It is clear from the graphs that there was a consistent general tendency to underestimate the degree of rotation required. Examination of the values of the measured angle  $\theta_m$  shows that, in every condition (that is, for all three internal angles  $\alpha$  in all four environments), participants did not turn the pointer far enough, indicating underestimation of the correct heading direction and corresponding correct angle  $\theta$ . This is shown by the line indicating the directional estimates, which appears below the line for the correct values, in the graph for each condition. The general pattern of error is similar to that found in studies of human visual path integration by Péruch, May, and Wartenberg (1997); Wartenberg, May, and Péruch (1998); and

Table 3.5.

*Mean directions and mean angular deviations (in brackets) of directional estimates by angle and environment*

$\alpha$	$\theta$	Environment	Means
60°	120°	Ur-S	102.09° (26.94°)
		Ur-N	104.23° (31.20°)
		Rur-S	108.93° (27.78°)
		Rur-N	93.97° (37.39°)
90°	135°	Ur-S	113.10° (23.61°)
		Ur-N	113.08° (23.94°)
		Rur-S	115.86° (24.31°)
		Rur-N	110.15° (27.18°)
120°	150°	Ur-S	121.37° (29.13°)
		Ur-N	120.32° (28.42°)
		Rur-S	114.29° (28.49°)
		Rur-N	120.11° (24.49°)

Kearns, Warren, Duchon, and Tarr (2002). The level of error is similar to that observed in the first two studies, but higher than that found by Kearns et al. (2002).

Error increased across the three angles from 60° to 90°. There is generally no great difference between the four environments. Similar patterns across all four environments can be observed in the graphs, except that, in the Rur-S condition, the 60° total data were slightly more accurate, and the 120° slightly less accurate.

It is also apparent from the graphs that, while both genders consistently underestimated the correct heading direction, and, thus, the angle  $\theta$ , the degree of underestimation was greater for female participants than for male participants, across all of the environments: this was especially so in the environments without structures, and for the 60° and 90° angle trials. There is greater convergence between the lines representing the male and female data for the environments with structures, and for the 120° angle trials. Furthermore, the error bars indicate that there is generally little overlap between the male and female estimates for the 60° and 90° angles across the four environments, whilst there is considerable overlap for the 120°. Male and female data also show more convergence in the Ur-S environment than in the other three; and both genders were least accurate in the Rur-N environment. The female error largely accounts for the lowered accuracy of the mean direction overall, as the male estimates are often closer to the correct values.

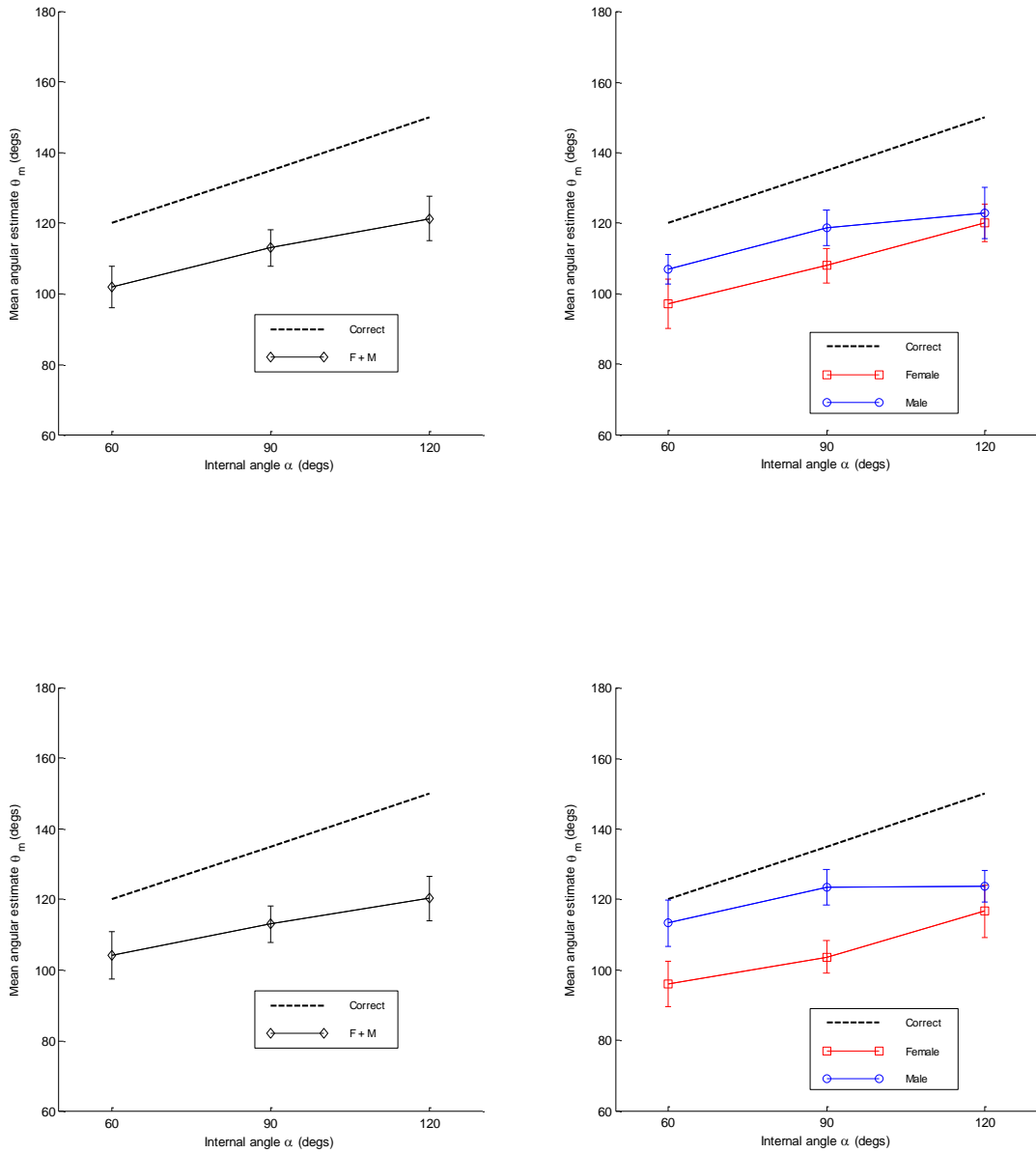


Figure 3.10. Mean directions for the three internal angles in the urban environments (*Ur-S* above and *Ur-N* below): combined (left) and separate (right) data for males / females

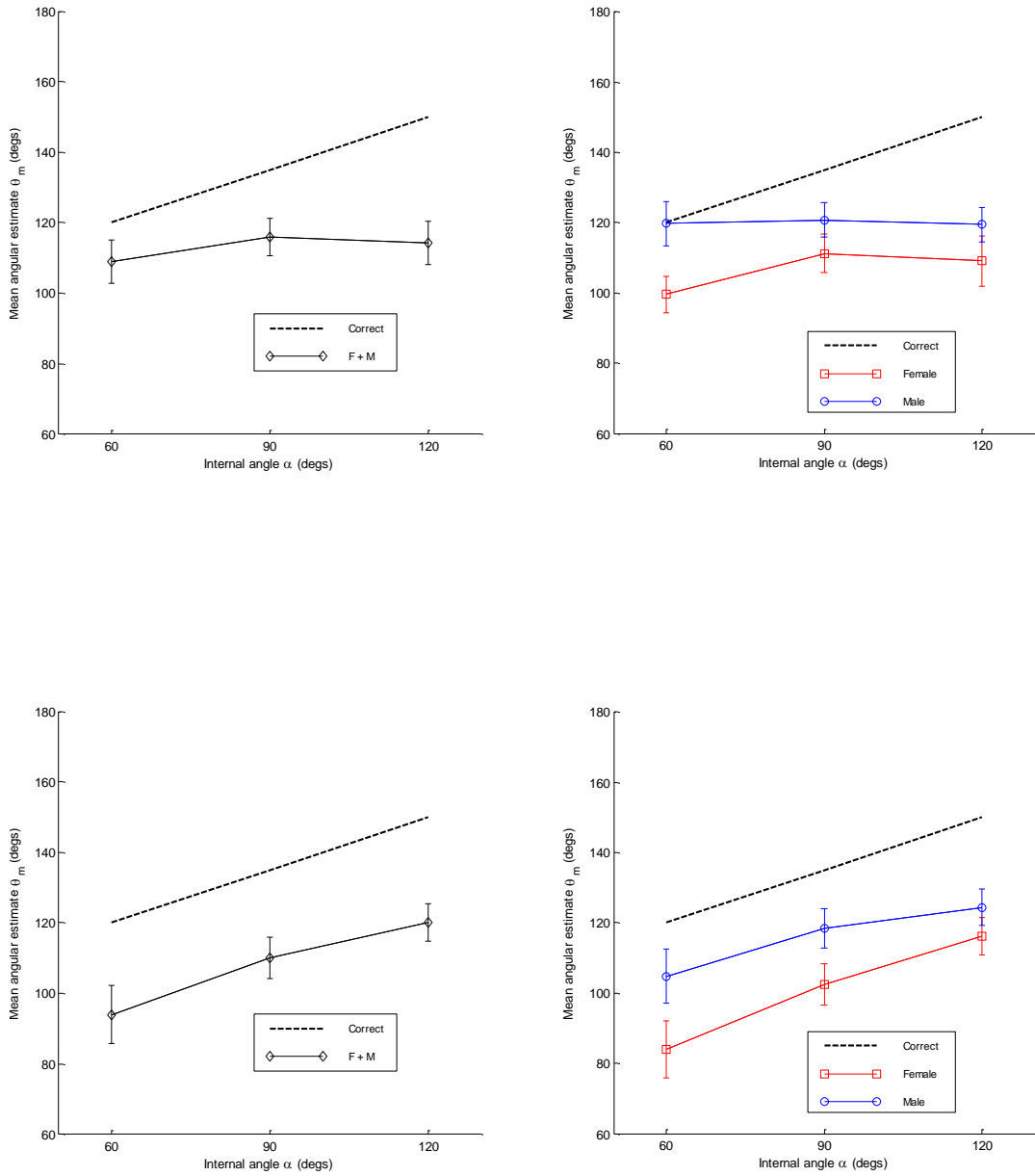


Figure 3.11. Mean directions for the three internal angles in the rural environments (*Rur-S* above and *Rur-N* below): combined (left) and separate (right) data for males / females

Table 3.6.

*Mean directions and mean angular deviations (in brackets) of directional estimates by angle and gender*

$\alpha$	$\theta$	Environment	Gender	Means
60°	120°	Ur-S	F	97.09° (31.86°)
			M	107.01° (19.01°)
		Ur-N	F	96.02° (29.91°)
			M	113.31° (30.42°)
		Rur-S	F	99.57° (23.46°)
			M	119.74° (28.72°)
		Rur-N	F	83.90° (36.98°)
			M	104.80° (35.32°)
90°	135°	Ur-S	F	108.01° (22.67°)
			M	118.72° (23.46°)
		Ur-N	F	103.70° (21.38°)
			M	123.50° (22.61°)
		Rur-S	F	111.27° (25.23°)
			M	120.79° (22.31°)
		Rur-N	F	102.47° (26.68°)
			M	118.52° (25.44°)
120°	150°	Ur-S	F	120.06° (24.45°)
			M	122.96° (33.48°)
		Ur-N	F	116.71° (33.81°)
			M	123.81° (20.39°)
		Rur-S	F	109.09° (32.29°)
			M	119.51° (22.52°)
		Rur-N	F	116.14° (24.12°)
			M	124.46° (24.14°)

The mean directions do not show a great deal of variation across the four environments. The most consistent data across environments are for the 120° angle. The underestimation was slightly lower, overall, in the Rur-S environment, especially for males, and slightly greater in the Rur-N environment, especially for females; but it is not a large difference. Performance across the three trials for each condition also did not differ greatly from the overall pattern for the averaged data for that condition: the lines on the graphs showed very similar patterns.

### **3.3.5 Analysis of the Absolute Error Data: Effects of Internal Angle $\alpha$ and Environment**

Watson-Williams tests for circular data (Watson & Williams, 1956; Batschelet, 1981) were conducted on the absolute error means of the directional estimates, using functions available in the MATLAB CircStats Toolbox (Berens, 2009; Berens & Velasco, 2009). The tests assessed the effect of the factors *internal angle* (three levels: 60°, 90°, and 120°), and *environment* (four levels: Ur-S, Ur-N, Rur-S, and Rur-N) on path integration performance. This test is analogous to a one-way ANOVA.

#### **3.3.5.1 Effects of Internal Angle $\alpha$**

There was a significant effect of *internal angle* ( $F_{(2,249)} = 6.82, p < 0.001$ ), indicating that the mean angles (or mean directions) of two or more of the samples differed significantly from each other (Batschelet, 1981).

The mean directions and mean angular deviations are shown in table 3.7, and the signed error means and standard deviations in table 3.8. It can be seen that the mean direction underestimates the correct value across all three angles; and the degree of underestimation increases with increasing angle, ranging from 14.92°, through 21.94°, to 30.71° for the 60°, 90°, and 120° angles respectively. There is, thus, a consistent tendency to underestimate the correct angle.

The mean direction for the 120° angle is close to the correct direction for the 60° angle (119.03° vs. 120.00°), suggesting a perception by participants that they had turned a smaller (60°) angle  $\alpha$ . The 90° and 120° angle estimates are very close in value, and there is only a 16.51° difference between all three angles, suggesting that the participants did not perceive the angles to be very different from each other. These findings indicate a compressed range of responses across the set of angles.

Variability is rather high overall, and similar across all three angles, within a difference of 7° between the highest and lowest. The responses for the 90° angles

Table 3.7.

*Mean directions and mean angular deviations (in brackets) of directional estimates by angle*

$\alpha$	$\theta$	$\theta_m$
60°	120°	102.52° (31.48°)
90°	135°	113.06° (24.88°)
120°	150°	119.03° (27.82°)

Table 3.8.

*Means and standard deviations (in brackets) of signed angular error by angle*

$\alpha$	Signed error
60°	14.92° (31.48°)
90°	21.94° (24.88°)
120°	30.71° (27.82°)

show the least variability, and responses for the 60° responses show the most variability. The greater consistency for the 90° angle suggests that the participants tended to find this angle easier to estimate overall.

### **3.3.5.2 Effects of Environment**

The effect of *environment* was not significant ( $F_{(3,248)} = 0.27, p = 0.848$ ). It can be seen from table 3.9 that the mean directions for all four of the environments are very similar (within 4.3° of each other), and that the angular deviations are also similar.

The signed error means and standard deviations are displayed in table 3.10. In every environment, there is an underestimation of the angle. The mean error is identical between the two urban conditions, and almost identical to the rural structured condition (within one degree of each other); whilst the rural unstructured environment showed only a slightly higher mean error.

Variability within each environment is quite high. There is also little difference in the level of variability across the environments: mean angular deviations are within 4.7° of each other. Thus, both the mean direction and variability are similar across the four environments.

Table 3.9.

*Mean directions and mean angular deviations (in brackets) of directional estimates by environment*

Environment	$\theta_m$	
Ur-S	112.13°	(27.67°)
Ur-N	112.63°	(28.67°)
Rur-S	113.05°	(27.07°)
Rur-N	108.75°	(31.76°)

Table 3.10.

*Means and standard deviations (in brackets) of signed directional error by environment*

Environment	Signed error	
Ur-S	21.83°	(27.67°)
Ur-N	21.61°	(28.67°)
Rur-S	20.96°	(27.07°)
Rur-N	26.11°	(31.76°)

### 3.3.6 Analysis of the Absolute Error Data: Combined Effects of Internal Angle and Gender

Harrison-Kanji tests for circular data (Harrison, Kanji, & Gadsden, 1986; Harrison & Kanji, 1988) were performed on the absolute error means of the directional estimates, to test for the simultaneous effects of the factors *internal angle* (three levels: 60°, 90°, and 120°) x *gender*, using the MATLAB CircStats Toolbox (Berens, 2009; Berens & Velasco, 2009). The test is a circular equivalent of the two-way ANOVA. The mean directions and angular estimates are summarised in table 3.11.

There was a significant effect of *internal angle* ( $F_{(2,246)} = 6.75, p < 0.001$ ) and *gender* ( $F_{(1,246)} = 11.37, p < 0.001$ ), but no significant interaction effect between the two factors ( $F_{(2,246)} = 0.56, p = 0.571$ ). This indicates that gender affected the level of accuracy for each angle separately.

It can be seen from table 3.12, which displays the signed error means and standard deviations, that both genders underestimated the value of all three angles, and that the underestimation increased with increasing size of angle. However, the range of mean absolute error values was larger for males than for females, with a quite small mean error (6.21°) for the 60° angle, increasing to 14.60° for the 90° angle (roughly double), and a larger mean error (27.32°) for the 120° angle (a range of 21.11°). Thus, the mean error shown by males on the 120° angle trials is over four times as high as the error shown on the 60° angle trials. Males were quite accurate on 60° angle trials, but rather inaccurate on 120° angle trials. Males, therefore, exhibited more variability in their responses across the set of angles, compared with females.

The range of mean absolute error values was more compressed for females, with a higher mean error for the 60° angle (23.00°) than the male mean for this angle, but the mean error for the 120° angle (34.14°) was only half as much (a range of 11.14°). Thus, while the mean error increased with increasing angle for each gender, the increase was more dramatic for males than for females.

Females underestimated the correct value by a greater amount than males, especially for the 60° and 90° angles, which showed differences of almost 17° and 14° respectively, the female mean error being almost four times higher for the 60° angle and almost twice as high for the 90° angle. For the 120° angle, the degree of error for the two genders was closer, showing a difference of only 7°.

The mean angle for the males for the 90° and 120° angles (120.40° and 122.68°, respectively) was close to the true value of the 60° angle (120°), for which the male mean absolute error was small. Males, thus, seemed to perceive the smallest internal angle fairly accurately, but behaved as though they had turned a 60° internal angle  $\alpha$  for all three of the angles, seeming to perceive the larger angles as close in size to the smallest one, as if all the angles were 60° angles.

Table 3.11.

*Mean directions and mean angular deviations (in brackets) of directional estimates for angle by gender*

$\alpha$	$\theta$	Female		Male	
60°	120°	94.44°	(31.41°)	111.24°	(29.48°)
90°	135°	106.36°	(24.31°)	120.40°	(23.57°)
120°	150°	115.60°	(29.26°)	122.68°	(25.69°)

Table 3.12.

*Means and standard deviations (in brackets) of signed error of directional estimates for angle by gender*

$\alpha$	Female		Male	
60°	23.00°	(31.41°)	6.21°	(29.48°)
90°	28.64°	(24.31°)	14.60°	(23.57°)
120°	34.14°	(29.26°)	27.32°	(25.69°)

For females, the mean error value for the 120° angle is close to the correct value for the 60° angle, suggesting that the 120° angle was perceived as a much smaller angle, that is, of 60°.

The standard deviations show that there were similar levels of variability between the genders, although there was slightly more variability among females (a slightly higher standard deviation) for each angle. The standard deviations also indicate a similar degree of variability across the three angles; however, there was slightly less variability among both males and females for the 90° angle. Overall, the level of variability is rather high.

### 3.3.7 Analysis of the Signed Error Data: Combined Effects of Environment, Internal Angle, Trial, and Gender

A mixed-design 4-way ANOVA (4 *environments* x 3 *angles* x 3 *trials* x *gender*) was performed on the means of the signed error of the directional estimates, in order to test for any higher-level effects. There were three within-participants factors: *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), *internal angle* (60°, 90°, and 120°), and *trial*; and one between-participants factor, that is, *gender*. Means and standard deviations (in brackets) of the signed error by environment, averaged across the three trials (as the ANOVA indicated that the trial order did not significantly affect the error) are given in table 3.13. Means and standard deviations for the signed error by gender, again averaged across the three trials, are shown in table 3.14.

There was a main effect of *angle* ( $F_{(2,38)} = 7.64$ ,  $p < 0.01$ , partial  $\eta^2 = 0.30$ ). Pairwise comparisons, with a Bonferroni adjustment for multiple comparisons, showed that all three angles differed significantly from each other, all at  $p < 0.001$ .

A polynomial contrast on angle also revealed a linear trend ( $F_{(1,19)} = 7.97$ ,  $p < 0.01$ ), indicating that the error increased as the value of angle  $\alpha$  increased.

The effects of *environment* ( $F_{(3,57)} = 1.76, p = 0.165$ ), *trial* ( $F_{(2,38)} = 1.90, p = 0.163$ ), and *gender* ( $F_{(1,19)} = 1.02, p = 0.325$ ) were not significant.

The means of the data averaged across the environments (as the ANOVA showed no significant effect for environment) are shown in Table 3.8. The difference between the responses for the three angles, and the tendency towards increasing error with increasing angle, is very clear from the averaged data. The means also confirm that, across all four environments, responses for the 60° angle were the most accurate, and responses for the 120° angle the least accurate, with the 90° responses intermediate: thus, there was a clear tendency for error to increase with increasing angle.

The effect of gender was not significant, when considered in conjunction with environment, angle, and trial. This is not surprising, given that neither environment nor trial had a significant effect on the error. It is clear from both the graphs and table 3.12, however, that when the data was averaged across trials, the mean error tended to be higher for females than for males, across all environments, especially on the 60° and 90° angle trials. Mean error on the 120° angle trials showed less divergence between males and females.

Table 3.13.

*Means and standard deviations (in brackets) of signed error of directional estimates by environment averaged across trials*

$\alpha$	$\theta$	Environment	Error
60°	120°	Ur-S	14.81° (27.79°)
		Ur-N	10.78° (33.32°)
		Rur-S	6.31° (31.25°)
		Rur-N	23.14° (40.07°)
90°	135°	Ur-S	18.37° (29.90°)
		Ur-N	22.38° (25.48°)
		Rur-S	17.91° (27.30°)
		Rur-N	25.86° (29.71°)
120°	150°	Ur-S	28.12° (30.85°)
		Ur-N	27.68° (29.90°)
		Rur-S	30.04° (28.52°)
		Rur-N	27.62° (29.87°)

Table 3.14.

*Means and standard deviations (in brackets) of signed error of directional estimates by gender, averaged across trials*

$\alpha$	$\theta$	Environment	Females	Males
60°	120°	Ur-S	18.65° (33.58°)	14.02° (38.19°)
		Ur-N	18.41° (32.00°)	2.39° (34.35°)
		Rur-S	15.15° (28.69°)	-3.41° (32.49°)
		Rur-N	31.44° (41.71°)	10.58° (20.61°)
90°	135°	Ur-S	20.55° (34.77°)	15.97° (25.12°)
		Ur-N	32.58° (23.05°)	11.15° (24.20°)
		Rur-S	21.97° (30.36°)	13.45° (24.29°)
		Rur-N	34.06° (29.17°)	16.83° (29.03°)
120°	150°	Ur-S	28.98° (25.73°)	25.26° (25.83°)
		Ur-N	29.59° (36.79°)	25.59° (21.74°)
		Rur-S	29.88° (33.19°)	30.22° (24.16°)
		Rur-N	29.77° (34.26°)	27.18° (37.11°)

### 3.3.8 The Virtual Experience: Presence and Authenticity

The virtual environments were considered in terms of their effectiveness in evoking presence and immersion, any negative effects, and authenticity, through participants' scores on the four factors of the ITC-SOPI (Lessiter, Freeman, Keogh, & Davidoff, 2001), and their responses to a questionnaire developed by the researcher. Both of these were given to participants following the simulation in the virtual environments.

#### 3.3.8.1 Presence and Immersion in the Virtual Environments

Four factor scores were generated for each participant, by calculating the mean of all the completed items contributing to each factor; and the group mean was calculated for each factor. The mean factor scores and standard deviations are shown in table 3.15. Results for each factor were analysed individually, as they cannot currently be combined into one "media experience" score. Additional comments (included in Appendix E) were grouped according to each of the factor's main themes.

The scores are around the mid-range of the scale on all factors. The participants felt a moderate sense of being present in the virtual environment as a real place. This score suggests that other aspects of the environments may have compensated for participants' limited interaction with, and control over, the virtual

Table 3.15.

*ITC-SOPI: Mean factor scores and standard deviations*

Factor	Score
Spatial Presence	3.07 (0.81)
Engagement	3.06 (0.51)
Ecological Validity / Naturalness	3.03 (0.99)
Negative effects	3.14 (0.81)

environments. The participants also found the virtual experience fairly engaging; and the virtual environments reasonably natural. However, the mean score for negative aspects was similar to the scores for the positive aspects (in fact, it was slightly higher, and the overall highest score), indicating that adverse physiological reactions and disorientation were commonly experienced. This issue is of some concern.

The standard deviations indicate a high level of variability on all factors, except for engagement. The standard deviation is, in fact, 0.99 for ecological validity, indicating that opinions were very divided. Very high standard deviations for spatial presence and negative effects also indicate a high level of polarisation.

There were few additional comments. They are indicative of varying reactions to the virtual environments: some participants found them very realistic, whilst others found them the opposite. They also draw attention to the disorientation and simulator sickness symptoms that many participants experienced.

### ***3.3.8.2 Analysis of the Signed Data: Combined Effects of Presence, Environment, and Angle***

Participants were divided into two groups, on the basis of their scores, on each of the four factors which make up sense of presence on the ITC-SOPI (Lessiter et al., 2001): that is, spatial presence, engagement, ecological validity / naturalness, and negative effects. These were a *high* and a *low* presence group (based on scores of between 1.00 - 2.99, and 3.00 - 5.00, respectively). Appendix G shows the sample sizes of the *high* and *low* presence groups on each factor.

The means of the signed error of the directional estimates were analysed with a mixed-design 3-way ANOVA (2 *presence levels* x 4 *environments* x 3 *angles*), in order to examine any effects of sense of presence. There was one between-participants factor, that is, *sense of presence* (High, Low), and two within-participants factors, which were *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), and *angle* (60°, 90°, and 120°). The ANOVA was conducted separately for each of the four presence

factors. A linear ANOVA was appropriate for this analysis, as the signed error was constrained within 180° on either side of the correct value. The means and standard deviations of the signed error by presence group and angle, averaged across the three trials, four environments, and gender, are displayed in Appendix F.

There was a main effect of *engagement* ( $F_{(1,19)} = 8.10$ ,  $p < 0.05$ , partial  $\eta^2 = 0.30$ ). There were no other significant effects: *spatial presence* ( $F_{(1,19)} = 3.36$ ,  $p = 0.083$ ), *ecological validity / naturalness* ( $F_{(1,19)} = 1.11$ ,  $p = 0.305$ ), and *negative effects* ( $F_{(1,19)} = 0.39$ ,  $p = 0.539$ ).

Thus, there was an effect of engagement on path integration performance, but no effect of presence from any of the other factors. Accuracy of task performance in this experiment was influenced by participants' level of psychological involvement and interest in the virtual world, and by their enjoyment of the virtual experience, but not by how present they felt in the environments, how believable and natural they found the virtual world, or by any adverse physiological effects they experienced.

### **3.3.8.3 Authenticity of the Virtual World**

The qualitative data were analysed using a series of structural frames (Kitchin, 1997). These were devised by the researcher, in accordance with themes that emerged from the respondents' written responses, and used to group the data into categories. The frequency of occurrence of items related to each theme was tallied, and the corresponding percentages were calculated. Comments from the original 24 participants were analysed, that is, including from the participants identified as outliers for the simulation, since it was judged that their overall impressions of their experience in the virtual environments were also of interest.

The main design features which participants considered contributed to the authenticity of the environments were the mountains and hills (19.67%), and the houses (18.03%). The structures (14.75%) and countryside / rural areas (13.11%) were also deemed authentic. These results are summarised in Appendix H.

Additional features which participants considered would lend greater authenticity to the environments are summarised in Appendix I. The two categories with the largest percentages of responses concerned animals / livestock, especially cattle and sheep (15.85%), and trees / forest, especially native trees (14.63%). Farm animals and forest are typical of local environments, and their absence makes an impression. On the other hand, the absence of other common real-life details, such as mail-boxes, was not commonly commented upon. Similarly, the lack of any sound (of the vehicle being driven, or in the background of the virtual environment) did not make a great impression: only two people mentioned it in the feedback.

## 3.4 Discussion

### 3.4.1 Path Integration Performance

*Hypothesis 1:* Higher accuracy of path integration performance would result from the use of a large display, compared with previous studies

*This hypothesis was not met.* The overall accuracy of participants' path integration performance was not increased by the use of a large display in this experiment, in comparison with previous studies. Thus, there was no direct effect of the large 3-screen display and the wide field of view it provided. Participants' responses exhibited a pattern and magnitude of error which are comparable to those observed in previous triangle-completion studies conducted in virtual environments, in which the standard path completion task was used in smaller-scale, and less realistic, virtual environments (Kearns, Warren, Duchon, & Tarr, 2002; Péruch, May, & Wartenberg, 1997; Wartenberg, May, & Péruch, 1998). Thus, responses tended to be rather inaccurate, but well above chance, and stereotyped. Participants responded in different ways, and with different levels of accuracy, on layouts with different angles. Accuracy on the 60° and 90° angle trials was similar to that found in previous studies of human path integration under visual conditions: that is, underestimation by between approximately 7° and 24° of the correct angle; and accuracy was a little lower than this on the 120° angle trials. The error is higher than that found in the study of non-visual path integration by Loomis et al. (1993).

*Hypothesis 2:* Accuracy would differ as a function of the internal angle  $\alpha$

*This hypothesis was met.* There was a very clear effect of the internal angle in the current experiment: a consistent tendency for participants to underestimate the final response angle, for triangle layouts with all three internal angles  $\alpha$ ; and the degree of underestimation tended to increase with increasing size of angle  $\alpha$ . Across the four environments, responses on layouts with the 60° angle were the most accurate, and responses on layouts with the 120° angle were the least accurate, with the 90° angle responses intermediate. Thus, accuracy decreased with increasing size of angle  $\alpha$ .

Thus, the internal angle  $\alpha$  exerted a strong influence over performance. A strong effect of the internal angle was also found in previous studies (Kearns et al., 2002; Péruch et al., 1997; Wartenberg et al., 1998; Loomis et al., 1993).

Péruch et al. (1997) and Wartenberg et al. (1998) also found a tendency for consistent underestimation of the final angle in visual path integration, for all values

of the internal angle  $\alpha$ , with increasingly larger underestimation for larger values of the internal angle. Similarly, Kearns et al. (2002) found a general trend towards underturning when only optic flow was available. The same effect, but not as strong, was found in real-world studies of path integration without vision, by Loomis et al. (1993), and by Klatzky et al. (1990).

There was a further observed tendency, in the current study, for participants to respond on the 120° angle trials as though they perceived that they had turned by a smaller (60°) angle  $\alpha$ ; whilst the mean error values for the estimates on the 90° and 120° angle trials were similar to each other. Thus, a compressed range of responses across the set of internal angles was seen, with a very small difference between the values for all three angles, suggesting that participants did not perceive the angles to be very different. Variability was rather high overall, and similar for all three angles. The responses on the 90° angle trials showed the least variability, and responses on the 60° angle trials showed the most variability.

Studies of human path completion tasks typically find stereotyped responses, of the kind obtained in the present study. There is often compression of the range of responses relative to the correct values, regression towards a mean response, and insensitivity to path layout parameters, such as differences in internal turn angles and outbound leg lengths. This leads to a general tendency to underestimate or underturn large angles ( $> 90^\circ$ ), and to overestimate or overturn small angles ( $< 90^\circ$ ), in the final response. A high level of variability among responses is also common (Kearns et al., 2002; Wartenberg et al., 1998; Péruch et al., 1997; Loomis et al., 1993; Klatzky et al., 1990).

*Hypothesis 3: Accuracy of path integration performance would depend on the levels of realistically-presented optic flow and depth cues in the environments*

*This hypothesis was not met.* Variation in the amount and type of visual information available in each environment had no effect: the angle was underestimated, and the mean absolute error was almost identical, in all four environments. Underestimation was slightly lower, overall, in the rural environment with structures, especially by males, and slightly greater in the rural environment with no structures, especially by females, but the difference was small. Variability within each environment was high, and of a similar level in every environment. Thus, the environmental manipulations were not reflected in differences in performance in this experiment. Overall accuracy was not increased by contextualising the optic flow in natural textures within authentic environments. Compared with previous studies, conducted in less realistic virtual environments, participants' path integration performance was not enhanced.

These findings differ from those of Kearns et al. (2002), who demonstrated a differential effect of the amount of information available from simulated optic flow in textured virtual environments. Performance was most accurate in a richly-textured environment, in which both rotational and translational optic flow were available to participants from wall and floor texture. Reduced rotational flow reduced turning accuracy in the final response.

*Hypothesis 4:* The 3-screen semi-surrounding display, realistic visual information, and authentic environments, together, would increase participants' sense of presence and engagement, by making the experience more immersive, in the absence of other immersive features

*This hypothesis was met.* The experimental apparatus, including the novel virtual environments, successfully evoked a sense of presence, especially of engagement, for participants. The virtual environments were also found to be reasonably believable and natural. The novelty factor of the simulator may have helped to increase the sense of presence for some participants. However, negative aspects, such as simulator sickness symptoms and disorientation, were also experienced by many participants, and these may have contributed to a decreased sense of presence for those participants. The limited opportunities to interact with the virtual environments may also have impacted on participants' sense of presence; however, other aspects of the environments compensated for this. A very high level of variability overall was observed, especially on the ecological validity factor, reflecting varied experiences and attitudes among the participants.

Overall, participants found the virtual environments reasonably authentic, mostly due to the inclusion of features such as mountains and hills, and houses. Additional features, such as farm animals and forest, would have made the environments more authentic: many participants noted the absence of these details. On the other hand, participants were generally tolerant of the absence of common real-life details such as sound or mailboxes. This suggests that virtual environments do not need to be greatly realistic or detailed, in order to seem reasonably lifelike for this type of task and testing method.

*Hypothesis 5:* A heightened sense of presence and engagement would result in more accurate path integration performance

*This hypothesis was not met.* Presence had no effect on task performance in this experiment, apart from the factor of engagement. Increased accuracy of task

performance resulted from increased participant levels of psychological involvement and interest in the virtual environments, and greater enjoyment of the virtual experience. However, performance was not affected by how present participants felt in the environment, by how realistic they found the virtual world, or by adverse effects of the experience, such as simulator sickness symptoms and disorientation. Limited interaction with the virtual world did not disturb participants. Overall, these findings suggest that the effects of the large-screen display were not due to presence.

This result may reflect some issues with the sample size and composition of the *high* and *low* presence groups. Most of the presence scores on all four factors were around the mid-point of the scale, which made it difficult to form sufficiently differentiated *high* and *low* groups on each factor. Scores which were more polarised would have resulted in a greater difference between the groups; however, there were only a few scores at the extreme ends of the scale. The dividing point between the two groups was rather arbitrary: participants with scores of up to 2.99 were included in the *low* group, and those with scores above 3.00 in the *high* group. It can be seen from Appendix G that there were also rather unequal sample sizes for the *high* and *low* groups on all the factors, except for engagement.

*Hypothesis 6:* Female performance would be particularly enhanced by the effects of the large screens, authentic environments, realistic visual information, and increased presence, leading to reduced or minimal gender differences, compared with previous studies

*This hypothesis was not met.* There were clear gender effects. Mean error for females was consistently larger than it was for males, across all environments, especially on trials on the layouts with 60° and 90° internal angles. The mean error for males and females was more convergent (within a few degrees of each other) on the layouts with the 120° angle. Males were quite accurate on the 60° angle, but rather inaccurate on the 120° angle; they exhibited more variability than females in their responses across the set of angles. Females performed less accurately than males on all layouts, that is, with all three internal angles.

Gender did not influence the direction of the error: the data for both genders followed the overall trend for underestimation of the final angle, on layouts with all three values of the internal angle; and for increasing underestimation with increasing size of the internal angle. However, this increase was more dramatic for males than for females, who showed greater compression of the range of mean absolute error values. Whilst both genders consistently underestimated the required heading direction, male estimates showed considerably less error and less variability.

Both genders responded to the larger internal angles (90° and 120°) as though they were smaller (closer to 60°). Males perceived the smallest internal angle fairly accurately, but still behaved as though they had turned a 60° internal angle for all three of the angles. They seemed to perceive the larger angles as close in size to the smallest one, as if all the angles were 60° angles. Similar levels of variability were observed between the genders, although there was slightly more variability among females for each angle. A similar degree of variability was also found across the three angles; however, there was slightly less variability among both males and females on the 90° angle trials.

Overall, therefore, gender differences were not reduced in comparison with previous research. There was no effect of the inclusion of authentic environments, optic flow stimulated through naturalistic presentation of textures, and a wide field of view provided by a display with three large screens. Female performance may have been less accurate than male performance, overall, due to the lack of landmarks, or because of effects of the equipment. Fewer effects on male performance are expected from the limited availability of landmarks, and from the apparatus. The results are, thus, consistent with previous studies which have found less accurate navigational performance by females, compared with males, in virtual environments (Fortenbaugh, Chaudhury, Hicks, Hao, & Turano, 2007; Tlauka, Brolese, Pomeroy, & Hobbs, 2005; Foreman, Sandamas, & Newson, 2004; Lawton & Morrin, 1999; Sandstrom, Kaufman, & Huettel, 1998; Moffatt, Hampson, & Hatzipantelis, 1998).

### **3.4.2 Explanatory Models and Predictions**

According to the basic models that were outlined in Chapter 2, the error obtained is predictable. Underestimation of the final angle, resulting in *positive* errors (when participants did not turn the pointer on the dial far enough), could arise from misperception of two different kinds: underestimation of the degree of rotation at the end of the first leg (combined with correct perception of distance), as shown in figure 3.12; or underestimation of the distance on the outbound path (together with correct perception of rotation), as shown in figure 3.13. The data indicate a particular class of error in the figures, through the position of the red line (representing an erroneous response) relative to the solid blue line (representing the correct directional response from the perceived position at the end of the second leg): when the red line is below the blue line, underestimation of either the angle or the distance is indicated. Thus, the error is predictable, depending on where participants perceive their location to be.

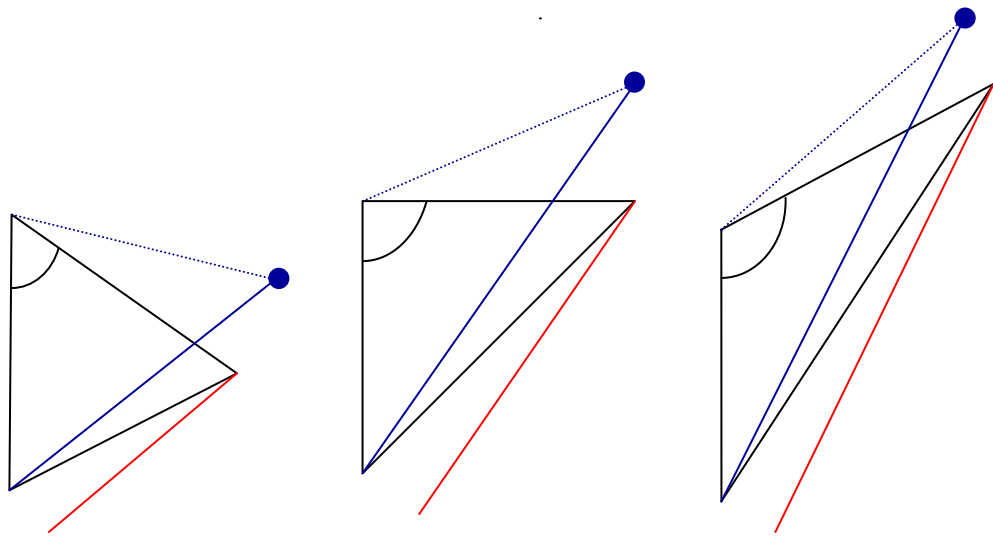


Figure 3.12. Model 1: Rotation underestimated by some percentage. Distance perceived correctly. (Hypothetical example)

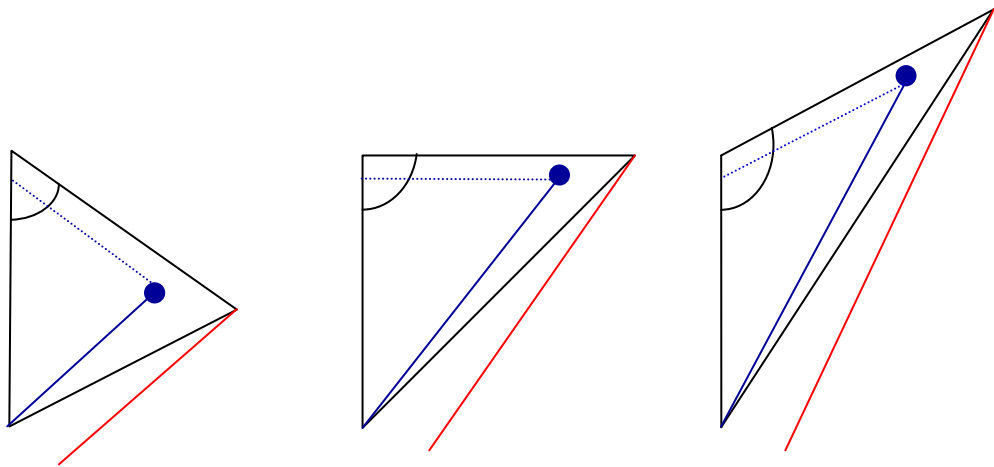


Figure 3.13. Model 2: Distance underestimated by some percentage. Rotation perceived correctly. (Hypothetical example)

- perceived (erroneous) location
- correct response from erroneous position
- error (parallel response from correct position)

The red and blue lines in figures 3.12 and 3.13 are analogous to the lines representing mean response and correct response values in figures 3.10 and 3.11 for Experiment 1. The line showing the mean response is consistently below the line for the correct response in figures 3.10 and 3.11. This is equivalent to the position of the red (error) line below the correct (blue) line, indicating positive error, in figures 3.12 and 3.13. All of the errors in Experiment 1 were positive: in all conditions, the participants underestimated the degree of rotation required in the final response.

The patterns of results shown in figures 3.10 and 3.11, therefore, fit the predictions based on underestimation of either internal angle or leg-length: they indicate that the error resulted from participants misperceiving either the degree of rotation, or the distance, that they had experienced on the outbound path, leading them to underestimate the degree of rotation required in the final response. Thus, the error observed in this experiment can be attributed to underestimation of either rotation or distance. Participants perceived *either* that they had rotated through fewer degrees than the actual value, along the curved segment of the route; *or* that they had translated a shorter distance than the actual distance, along the straight segments of the route.

It is assumed in these models that participants correctly execute the directional response towards the final position; and that, in the case of correct perception of rotation, participants perceive the length of the first and second legs (correctly, in this experiment) to be equal.

A further assumption is that the consistent underestimation of the final angle is likely to have resulted from participants' misperception (underestimation) of the distance they had travelled along the outbound path, rather than of the degree of rotation. Underestimation of distance in virtual environments is a very well-documented phenomenon, which has been found in many previous studies, conducted in different conditions and using a variety of tasks (Frenz & Lappe, 2005; Frenz, Lappe, Kolesnik, & Bührmann, 2007; Lappe, Jenkin, & Harris, 2007; Bakker, Werkhoven, & Passenier, 1999; Witmer & Kline, 1998; Loomis & Knapp, 2003; Thompson et al., 2004; Willemsen, Colton, Creem-Regehr, & Thompson, 2009). Compression of space is typically found in virtual environments. Furthermore, human estimates of egocentric distance in direct view tend to be underestimated for long distances (greater than about 2-3m), whilst overestimation occurs for short distances. Large variability between individuals is also commonly reported (Roumes, Meehan, Plantier, & Menu, 2001).

In real-world studies of non-visual path integration, Cornell and Bourassa (2007), and Cornell and Greidanus (2006) found that including a large gradual curve

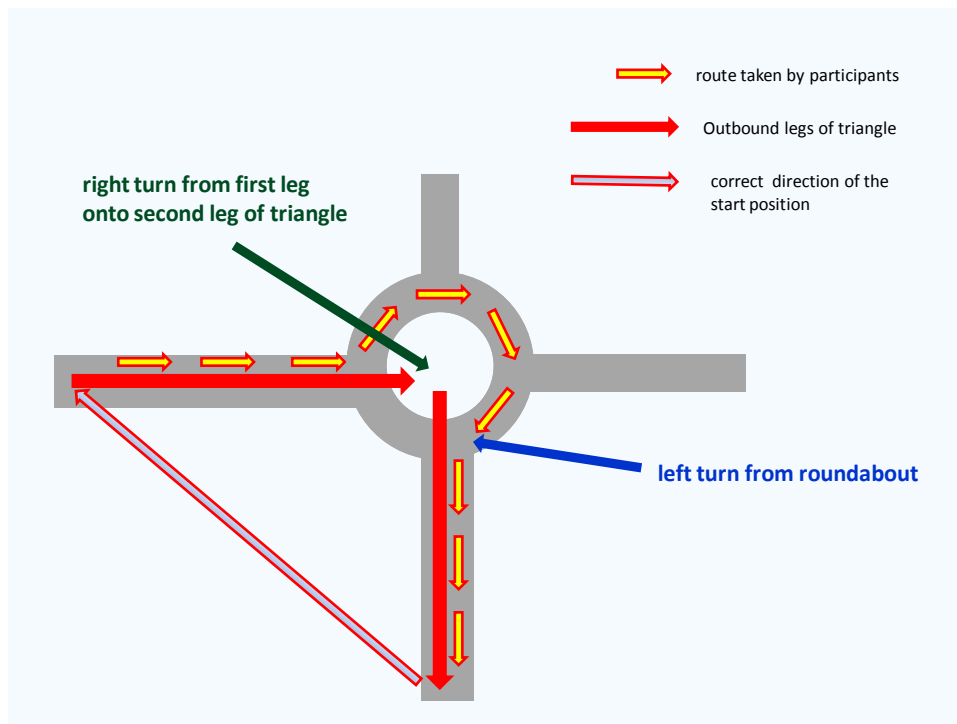


Figure 3.14. Simultaneous left and right turn on the roundabout

on the route led to greater error than on smaller-scale routes, such as those used by Loomis et al. (1993) and Klatzky et al. (1990). However, the same effect was not found on visual path integration in virtual environments in the current experiment: inclusion of a large curved section on the route did not lead to greater error, when compared with similar studies conducted on more linear routes (Kearns et al., 2002; Wartenberg et al., 1998; Péruch et al., 1997).

It is possible that the lack of an effect of the curve was due to motion signals cancelling each other out during integration of the rotation, which was quite complex. Participants needed to turn *left* in order to exit the roundabout, but this also constituted a turn to the *right* to complete the triangle, in terms of the relationship of the second leg of the path to the first. This situation is illustrated in figure 3.14. Thus, as negotiating the roundabout involved a simultaneous turn to the *left* and a turn to the *right*, integration of the sensory cues may have cancelled each other out.

It is, therefore, assumed that participants perceived that they had travelled less far along the outbound path than they actually had. This underestimation of the distance may have been due to a misperception by participants of the velocity of their self-motion, whereby they perceived the speed of their self-motion to be slower than the actual speed. There are several possible factors which may have contributed to participants' perception of travelling more slowly than they really were: these will be

discussed in chapter 6. The factors include framing effects, limited depth cues, perceptual distortions of size and distance, and contrast effects. A combination of these may have led participants to misperceive the scale of the space, and therefore the speed, and ultimately the distance, of their self-motion.

### 3.5 Unresolved Issues from Experiment 1

A number of questions were raised by the results of Experiment 1, which require closer examination. These unresolved issues will be addressed in Experiment 2.

The participants were passive in this experiment, as they could not control the steering of the simulated vehicle motion. In the second experiment, the effect of participants having some degree of active control over the simulated motion will be examined: one group of participants will control their own self-motion through the environments, by using a steering wheel and pedals. It is possible that either the additional proprioceptive information provided by steering wheel and pedal motions, or the perceived control over the self-motion, will increase the accuracy of participants' directional estimates.

The experimental task involved a more complex rotational element than in many previous studies, since it included a greater degree of gradual curvature around the roundabout. Participant error may have been increased by the inclusion of the roundabout, even in more authentic environments than those commonly used, because of the complex rotations required. Rotating around the roundabout is rather complex, partly because it requires participants to turn *right* along the triangular route, by simultaneously turning *left* to exit from the roundabout. This could be expected to adversely affect directional estimates. The inclusion of a longer curved section of route increased error in real-world non-visual studies (Cornell & Greidanus, 2006; Cornell & Bourassa, 2007). Therefore, in Experiment 2, a further condition will be included, in which the roundabout will be replaced with a crossroads-type intersection, thereby allowing comparison of estimation with and without gradual rotation. These trials will enable the effect of the gradual curve to be examined in more detail.

Only isosceles or equilateral triangles were used in the first experiment. The simplicity of the triangle geometry, and the regularity of the distances involved (as the length of the approach and exit road were always equivalent) may have influenced participants' responses, by seeming to make the task too predictable; thus, the participants may have responded to all the triangles in a similar way. In the second experiment, a wider range of triangle layouts will be included, by incorporating triangles with different lengths of the first and second legs, as well as a replication of

the equilateral and isosceles triangle layouts which were used in the first experiment. This will provide a test of whether participants are responding to all the triangles in a similar way, that is, as if they are all equilateral or isosceles triangles, regardless of the actual geometry. Such a strategy would be expected to lead to increased error.

The wider range of layouts will also enable the role of self-motion to be examined more closely, by providing evidence of perceived travel distance. With a more complex set of triangle layouts, participants will need to be able to perceive the distance they have travelled on the outbound route correctly, in order to perform the task accurately; and they will not be able to use a "special triangle" heuristic. The kinds of errors made by participants will, thus, shed light on the distance which participants perceive that they have travelled on the outbound route.

The high level of simulator sickness found in the first experiment may have reduced the accuracy of participants' task performance, either directly or through a decreased sense of presence. Additionally, some females found the experimental set-up quite intrusive, and this may also have affected their performance, leading to lowered accuracy. In the second experiment, small-screen conventional computer monitors will be used to display the virtual world. The effects of the smaller and larger screens on task performance will be compared, in order to ascertain whether there are any disadvantages of using the small-screen apparatus.

Finally, it is possible that participants' responses were influenced by the way the virtual dial was represented on the screen. Care had been taken to ensure that the pointer was randomly placed on the dial, when it first appeared on each trial, in order to avoid influencing participants into thinking that it provided directional information. However, the circular form of the dial, and the movable pointer, may have made it seem like a compass within a navigational context. Thus, some participants may have believed that placing the pointer at particular points on the dial corresponded to pointing in certain directions. For this reason, in the second experiment, participants will be told explicitly that this is not the case, and the random positioning of the pointer will be stressed.

## Chapter 4. Experiment 2

### 4.1 Aims

The aims of this experiment were to test the effects of several variables on path integration performance, within a large-scale virtual environment. The variables were: three desktop flat-screen monitors, arranged so that they partially enclosed the participant; visual information presented in natural contexts within authentic virtual environments; a variety of route layouts, in which the lengths of the two outbound roads, and the internal angle between them, were varied; the large gradual complex curve on the roundabout; the participant's mode of navigation, that is, active versus passive; and gender. Experiment 2 partially replicated Experiment 1, through the inclusion of three triangle layouts in which the 60°, 90°, and 120° angles were combined with equal-length outbound legs: this enabled performance to be compared between the two experiments.

It was found in the first experiment that the use of three large tilted screens did not improve overall accuracy of path integration performance, or reduce gender differences. Although participants were able to perform path integration, they did so with a level and pattern of error which was comparable to those found in previous studies: responses generally underestimated the required degree of rotation, and were compressed into a narrow range. Gender effects were also evident, with females tending to perform less accurately than males.

There were some other issues which arose from the use of the large screens and the simulator. There was a very high incidence of simulator sickness. Almost all of the participants reported experiencing at least some symptoms, and, for some people, these were quite severe. The experimenter and assistant were able to experience this first hand, in the role of "driver": although neither was badly affected, both noticed that symptoms such as increased swallowing, a feeling of overheating, and sore eyes, tended to set in after a short time in the simulator. The symptoms most commonly reported by the participants were eyestrain, headache, sweating, disorientation, and feeling overheated; and some people also experienced nausea.

Although most participants experienced only mild symptoms, and quickly recovered from these after the simulation ended, it made the virtual experience somewhat unpleasant for the affected individuals. Performance may also have been affected, as, at the very least, the symptoms may have distracted participants from the task. More seriously, participants' perception of rotation and distance may have been adversely affected. The symptoms could also have been detrimental for

participants' sense of presence in the virtual environments, and for their judgments of the authenticity of the environments.

A further issue is that the simulator was experienced as being quite intrusive, and a little intimidating, by some participants, especially females: it was their first experience of a motion simulator for most participants, and, although they mostly found it interesting, some female participants were also a little apprehensive about it.

The experimenter and assistant noticed, incidentally, that females tended to display a lack of confidence during the experiment: they often eyed the car nervously when they entered the room, were apologetic about their performance in advance, and tended to ask for confirmation that they were performing the task correctly. Males generally did not do this. This apparent "technophobia" may also have affected females' performance, experience of presence, and judgments of authenticity.

Waller (2000) showed that women's navigational performance in a desktop virtual environment may be affected by the type and sophistication level of the technology used for the interface, and that when this is factored out, there is more equivalent performance between males and females.

In the second experiment, the effect of using a small-screen display was examined: a wide field of view was again achieved through the use of three screens, but, this time, three conventional flat-screen desktop computer monitors were used. This arrangement enabled peripheral information to be presented, the intention being to compensate for the absence of information from head movements (and other physical cues) during the simulated motion.

It was expected that the simple desktop arrangement would be found less intrusive and off-putting by participants than the driving simulator, especially by females, since they would already be familiar with desktop computers and feel comfortable with using them. The use of less technologically sophisticated equipment was, therefore, expected to lead to more accurate path integration performance.

A further aspect of the first experiment, which potentially affected participant performance, was the simplicity and regularity of the triangle (route) layouts used: these may have been too similar to each other, which, in turn, may have led to the compressed range of responses. Use of only equilateral or isosceles triangle layouts, thus, possibly influenced participants to produce stereotyped responses. Additionally, all the route layouts included a roundabout, which made it difficult to separate the effect of the large gradual degree of curvature from the effects of overall triangle geometry.

The triangle layout was varied in this experiment, to include triangles with non-equivalent lengths of the first and second leg on the outbound route: this produced a wider range of internal angles  $\alpha$ , and associated values of the required

angle of rotation in the response. This afforded insights into whether participants are sensitive to differences in triangle geometry, or whether they tend to respond to all triangles in a similar way, as if all are equilateral or isosceles triangles: that is, whether participants use a regular triangle heuristic in completing the task, leading to stereotyped responses. This manipulation enabled a more detailed examination of the role of self-motion, since the kinds of errors resulting from the less regular triangles indicate how participants perceive the distances, and degrees of rotation, that they have travelled along the outbound path (roads).

Experiment 2 also partially replicated Experiment 1, through the inclusion of a sub-set of three triangle layouts, in which the 60°, 90°, and 120° internal angles were combined with equal-length legs. This facilitated a comparison of performance across experiments.

Route layout was further manipulated, through the inclusion of a set of trials in which the roundabout was replaced with a crossroads intersection (with a smaller turn) on layouts with the 90° angle. This allowed the effect of the large gradual curve to be investigated. This curve introduces a complex rotation, involving considerable exposure to optic flow and depth cues: there is a simultaneous right turn (onto the third leg of the triangle) and left turn (onto the exit road from the roundabout). The role of the curve in the perceptual process was of interest, therefore; it was examined by comparing the participant error observed on route layouts with the two turn types.

This experiment also considered the importance of navigator autonomy in the virtual world, by manipulating the navigator's mode of exploration. In the Active condition, participants could control their own simulated self-motion along the route, using a steering wheel and foot pedals; whilst participants in the Passive condition watched pre-recorded simulated self-motion along the route, and had no control over it, in a similar way to the participants in the first experiment. Wilson (1997) distinguishes between physical and psychological activity in virtual environments (that is, between interaction with the computer, and control of the exploration, respectively), noting that both may have effects on knowledge acquisition.

Studies of the effects of active versus passive navigation on human path integration performance have produced inconsistent findings. Gaunet, Vidal, Kemeny, and Berthoz (2001) found that the accuracy of directional estimates, based on visual path integration in a large-scale complex environment, was not affected by navigation mode (that is, by actively using a joystick, versus passively watching a video). Similarly, Wilson, Foreman, Gillett, and Stanton (1997) observed that target location performance, in a small-scale simple desktop virtual environment, was not affected by whether participants had actively explored the environment or passively

observed it; however, in a similar study, path integration was facilitated by active navigation (Péruch, Vercher, & Gauthier, 1995).

Bremmer and Lappe (1999) found that participants were able to reproduce the distance of a visually-simulated motion sequence with active motion simulation, by controlling the speed and duration with a joystick. Excellent performance was observed, indicating that participants were able to indicate estimated travel distance equally well through passive judgments, or with active control behaviour.

User control over the virtual experience, in terms of both autonomy and interaction with the virtual world, is also important for presence (Witmer & Singer, 1998; Slater, 1999; Slater & Wilbur, 1997; Slater & Usoh, 1993; Bystrom, Barfield, & Hendrix 1999; Steuer, 1992; Welch, Blackmon, Liu, Mellers, & Stark, 1996). Lessiter, Freeman, Keogh, and Davidoff (2001) observed that participants gave relatively high presence ratings, after playing computer games in which they had some control over the virtual world, even when the field of view was relatively small and photorealism was limited. This suggests that the ability to physically control and manipulate aspects of the virtual environment, even using unsophisticated control devices, can enhance a sense of presence within that environment. There may, therefore, be compensatory interaction between different physical properties of a display. Chance, Gaunet, Beall, and Loomis (1998) found that increased physical control in a virtual environment also led to a reduced likelihood of experiencing symptoms of discomfort.

The same four environments were used in this experiment as in the first experiment, since the ITC-SOPI scores and qualitative data from that experiment had indicated that they evoked a sense of presence for participants and were generally judged to be authentic.

#### *Hypotheses:*

1. Higher accuracy of path integration performance would result from the use of a small desktop flat-screen display, compared with previous studies and Experiment 1
2. Accuracy would differ as a function of route layout (internal angle and leg-length combination)
3. Path integration performance would be more accurate on 90° angle routes with a small turn (intersection) than on 90° angle routes with a large turn (roundabout)
4. More accurate path integration performance would result from participant control over the simulated self-motion in the Active condition, compared with passive participant observation of the self-motion (in the Passive condition in this experiment, and in Experiment 1)

5. Accuracy of path integration performance would depend on the levels of realistically-presented optic flow and depth cues in the environments
6. The 3-screen semi-surrounding display, realistic visual information, and authentic environments, together, would increase participants' sense of presence and engagement, by making the experience more immersive, in the absence of other immersive features
7. Sense of presence would be greater in the Active than in the Passive condition, due to the inclusion of some interactivity and participant control
8. A heightened sense of presence and engagement would result in more accurate path integration performance
9. Female performance would be particularly enhanced by the effects of the small screens and authentic environments, realistic visual information, and increased presence: as females would benefit from the use of less intrusive apparatus leading to increased confidence, and hence reduced or minimal gender differences compared with previous studies and Experiment 1

## **4.2 Method**

### ***Participants***

A total of 86 participants took part in this experiment, half of whom were randomly assigned to the Active condition, and the other half to the Passive condition. There were 22 males and 21 females in each condition. The age of participants in the Active condition ranged between 16 and 63, with a mean age of 26.4; while those in the Passive condition were aged between 16 and 56, with a mean age of 27.9.

30 participants in the Active condition, and 31 participants in the Passive condition, were undergraduate students at the University of Waikato, the vast majority of whom were enrolled in first year psychology courses and had been recruited through advertisements placed on course websites. The remainder were PhD students and university staff members, or employees from outside the university, and three were high school students. These participants had been recruited through either word of mouth or referral by other participants. First year psychology undergraduates participated in return for course credit, whilst all other participants received their choice of either a petrol voucher or book token worth \$20 in return for taking part. All the participants had normal or corrected to normal vision.

Forty-eight participants had had no previous experience in a motion

simulator. Of the 39 participants who had had previous experience, 32 reported that their participation was below five hours in total, and six had spent between 5 and 50 hours in a motion simulator. For 29 participants, the experience had been for entertainment, and five had taken part in previous psychology experiments in the University of Waikato driving simulator. One participant had work-related experience.

### ***Apparatus***

The experiments were performed on a Dell Optiplex 760 computer, using an Intel Core Duo 3-D graphic card to generate four virtual environments. The environments were displayed on three Sony Trinitron Multiscan G400 CRT flat-screen desktop computer monitors, arranged so that participants were seated facing a central screen, with two peripheral monitors positioned on either side of the centre monitor, and inclined slightly towards the participant's position. Participants sat at a distance of about 70cm from the centre monitor. Figure 4.1 shows a participant using the apparatus.

The image displayed on the central screen measured 18in wide by 18in high, at a resolution of 1600 x 1200 pixels; and the image displayed on each of the two side screens also measured 18in wide by 18in high, with an extended graphics array (XGA) resolution of 1024 by 768 pixels. Together, the three screens provided a field of view of 107.2° (horizontal) by 39.3° (vertical). The update rate of the projected images was a minimum of 100 Hz.

Participants in the Active condition controlled their own smooth self-motion through the virtual environments, by using a Thrustmaster Formula T2 steering interface as an input device: this incorporated a real full-size Mitsubishi Turbo steering wheel ( $\frac{3}{4}$  turn lock-to-lock), and accelerator and brake pedals. A knob and two buttons mounted on the Thrustmaster console were used by participants in both conditions to interact with the equipment, as they initiated each trial by pushing the knob, and ended each trial by pushing one of the buttons. The original steering wheel attached to the console was replaced with the full-size steering wheel, because this was deemed to make steering more realistic. Normal acceleration was enabled.

The simulated motion was constrained to within 0.5 virtual metres beyond the edge and the centre of the road, in order to prevent Active participants from driving on the wrong side of the road; or from driving off the road altogether and into the surrounding scenery, through buildings, or across the roundabout.

The experimental equipment was located in an office in the Department of Psychology at the University of Waikato. The room was light and airy, as natural light



*Figure 4.1.* Participant using the experimental apparatus

was available from one of two large windows, which participants could also open if they wished. The blinds on the other window were kept closed, to prevent glare on the monitors, as the window was near to the experimental apparatus. The aim was to encourage participants to feel relaxed, by providing comfortable and non-threatening surroundings, and a non-intrusive set-up.

The steering wheel was selected as a relatively intuitive interface, even for participants in the Passive condition, who were not actually “driving”. A consistent driving metaphor was maintained, as the vast majority of New Zealanders drive most days, and so this would be a very familiar activity and add to the naturalness of the situation for most of the participants. This is one way to mitigate the problem of individual differences in the ability to master interfaces in virtual environments, whereby some users are able to easily grasp even quite complex techniques, whilst others struggle to do so (Bowman, 2002).

### ***Path Layouts***

Thirty six of the path layouts were made up of a factorial combination of two lengths of the straight segments (distances of 150m or 300m), and three internal angles of the exit-road from the roundabout (60°, 90°, and 120°). The length of the curved segment depended on the internal angle. The paths were navigated in the same four environments, under the same four different visual information conditions, that were

used in Experiment 1. These nine path layouts were broadly based on a subset of the triangles used by Loomis et al. (1993), in their study of non-visual path integration, and in various visual path integration studies (Péruch, May, & Wartenberg, 1997; Kearns, Warren, Duchon, & Tarr, 2002; Riecke, van Veen, & Bühlhoff, 2000, 2002); they included the same angles, and pathways with long-short, short-long, and equal-length configurations of the straight segments. This manipulation provided a wider range of angles compared with Experiment 1 (see table 4.1), and tapped into perceived travel distance: the types of errors produced on different triangle layouts indicated whether participants were providing stereotyped answers, based on an equilateral triangle heuristic, as well as the distance that participants perceived that they had travelled along the first and second legs.

However, the layouts also differed from these previous studies, because of the addition of the curved section of road on the roundabout: thus, the pathways were not strictly triangular. The curved segment of the route was included, in order to provide a realistic rotation component, similar to that which is found in the real world. Driving around roundabouts is a common feature of modern road environments, and can, indeed, be a real-world example of a triangle-completion task, on occasion. Thus, the task was embedded within a real-life context.

A further twelve pathways were included, which were the same as the subset of 90° angle layouts, but with the roundabout removed: participants were presented, instead, with a crossroads-style intersection, and a turn was made directly to the right, instead of to the left, after moving around the curved section of the roundabout. The purpose of including this subset of route layouts was to examine the effect of the large degree of curvature on the roundabout, and the complex set of rotations it introduced: a simultaneous left turn from the roundabout, and right turn onto the third leg of the triangle. Thus, it enabled path integration performance on the intersection routes to be compared with performance on the equivalent roundabout versions.

### ***The Task***

Participants performed a large-scale path-completion task, in which they either controlled their own self-motion (Active condition), or were transported (Passive condition), along a route: firstly, along a straight road, then along a curved section of road around a large roundabout, and finally along a straight exit-road from the roundabout; or, alternatively, along a straight road, and then into another straight road to the right (intersection version). From their final position, participants indicated the estimated starting point of their route, which was not visible from their final location, by using a virtual dial to point to it.

Table 4.1.

*Values of  $\theta$  by triangle layout (angle and leg-length configuration)*

Internal angle ( $\alpha$ )	Combination of leg-lengths (first and second roads)	Correct response ( $\theta$ )
60°	L-L (both long)	120°
	L-S (first long, second short)	90°
	S-L (first short, second long)	150°
90°	L-L (both long)	135°
	L-S (first long, second short)	115°
	S-L (first short, second long)	155°
120°	L-L (both long)	150°
	L-S (first long, second short)	140°
	S-L (first short, second long)	160°

The roundabout task could be considered a complex path-completion task, with a path consisting of three outbound segments, the second of which is a gradually curving section of the route. Alternatively, it can be seen as a triangle-completion task, with a large degree of gradual rotation at the end of the second segment; or as a task that lies somewhere between the other two types. The intersection task is a more conventional version of the triangle-completion task, since the route is more clearly triangular.

A mixed-measures design was used, with three within-participants factors (internal angle  $\alpha$ , environment, and distance-combinations of legs  $a$  and  $b$ ); and two between-participants factors (navigation mode and gender). This design was used, as the number of trials required would, otherwise, have been impractical.

Participants were randomly assigned to either the Active or Passive condition and performed a total of forty-eight trials, which were presented in random order. Participants navigated through four large-scale virtual environments, developed with 3D Studio Max™ and presented on desktop computer monitors, in conditions which either provided or restricted particular kinds of visual information. A summary of the conditions is shown in Table 4.2. Participants' directional estimates to the origin were recorded, and the angle measured. Tables 4.1 and 4.2 show the correct values of  $\theta$ .

Thirty-six of the trials corresponded to a factorial combination of three angles of the first turn  $\alpha$  (60°, 90°, and 120°), three combinations of the distance of the first and second straight segments of road (300m or 150m), and four environments (urban and rural, with and without additional structures). The other twelve trials had a first turn angle of 90°, but the path layout did not include the roundabout: it was replaced with a crossroads intersection. These trials were included for the purpose of comparison with the 90° roundabout trials, in order to examine the effect of the gradual curve, and the associated complex rotation. Thus, there were twelve triangle

layouts in total, in four environments. There was no time limit for completing the task, and no feedback about performance accuracy during the experiment. Typically, the experiment lasted about 50 minutes to one hour.

### **Procedure**

Prior to beginning the experiment, participants were provided with written background information, which briefly outlined the aims of the experiment, and provided an overview of the task. It also informed them of the slight possibility of experiencing some discomfort from simulated motion, or from prolonged observation of a computer monitor; and of their right to terminate the experiment, should this occur. Participants then signed an informed consent form, and filled out a questionnaire about their experience with simulators and video games, and about their general health.

As a check of their ability to point to a recently visited real-world location in relation to their current position, participants were asked to point to the carpark or bus stop, or to some other part of the university from where they had come. Participants first read printed instructions for the task, which were available for reference throughout the experiment. The experimenter also verbally explained the task, illustrating with real-world examples for clarity. Participants then seated

Table 4.2.

*Overview of path (triangle) layout parameters used in Experiments 2 and 3*

Triangle layout	Angle $\alpha$	Distance $a$	Distance $b$	Distance combination	Angle $\theta$
60° L-L	60°	300m	300m	long-long	120°
60° L-S	60°	300m	150m	long-short	90°
60° S-L	60°	150	300m	short-long	150°
90° L-L	90°	300m	300m	long-long	135°
90° L-S	90°	300m	150m	long-short	115°
90° S-L	90°	150	300m	short-long	155°
120 L-L	120°	300m	300m	long-long	150°
120 L-S	120°	300m	150m	long-short	140°
120 S-L	120°	150	300m	short-long	160°

Distance  $a$ : Length of first straight segment

Distance  $b$ : Length of second straight segment

Internal angle  $\alpha$ : angle between approach road and exit-road

Distance combination: the lengths of legs  $a$  and  $b$  used together in one layout

Angle  $\theta$ : correct response angle

*The intersection routes were identical to the 90° triangle layouts, but with a crossroads intersection replacing the roundabout.*

themselves at the computer, and adjusted the seat height as necessary, to set their eye height as close as possible to the centre of the screen.

Before starting the experiment, participants performed two or three practice trials, in order to familiarise themselves with the virtual environments, the path-completion task, and the virtual dial; and with the use of the equipment, that is, the steering wheel, brake and accelerator pedals for the Active condition; and the use of the indicator knob and red button in both conditions. The practice trials were similar to those used in the actual experiment, but with different path layouts, which were generated randomly.

Test trials followed immediately after the practice trials, upon participants indicating that they were ready to proceed (Passive condition); or demonstrating that they could control the simulated self-motion along the roads (Active condition).

It was explicitly drawn to the participants' attention that the pointer on the dial was randomly placed when it first appeared on each trial, and, therefore, that no directional information could be inferred from its placement. Participants were told explicitly that placing the pointer at a particular point on the dial did not correspond to pointing in any particular compass direction, for example.

### ***Example of a Trial***

Participants faced the central computer screen. As in the first experiment, each trial began with the trial number displayed on the screen; and this was replaced by a virtual street scene, when participants pushed the knob on the console forwards. Participants were initially motionless in a position on one of the four roads, facing towards the roundabout. Simulated self-motion along the route on the screen was initiated by participants stepping on the accelerator pedal in the Active condition; and it began automatically after a two-second pause in the Passive condition. As in the first experiment, the routes consisted of a straight approach road, a gently curving section of road which formed part of the roundabout, and a straight exit-road.

Participants in the Active condition controlled their own simulated forward self-motion through the virtual environments, using the steering wheel and the accelerator pedal, but they followed predetermined routes. They "drove" along the first route segment, towards the roundabout. As they approached the roundabout, they slowed down or stopped, then turned (left) onto it, and drove along the curved segment of road around the roundabout. They drove past two exit roads, and turned off at the third exit road from the roundabout, and travelled along this road, until they reached a row of traffic cones blocking the road between two stop signs. Participants used the brake pedal to bring the car to a stop, just in front of this barrier. They were

instructed to maintain a constant speed of 50 km/h on the straight sections of the route, according to a speedometer shown at the bottom of one side screen.

Active participants were directed towards the correct exit road by a road sign positioned a short distance before it (with the words “turn next left”), and a chevron sign indicating the start of the correct road. On the non-roundabout trials, a road-sign with the words “turn next right” was positioned on the left-hand side of the road, a short distance from the intersection. When participants reached the intersection, they turned (right) into the road, shown by a chevron sign. As these signs could not be seen from the end of the route, it is unlikely that they were used as landmarks.

Passive participants watched a pre-recorded simulated self-motion (‘driving’) sequence along each route, as they were passively transported (“driven”) along it. The routes were the same as the routes followed by the Active participants, and included the chevron signs, as in the Active condition, in order to maintain equivalence of the visual surroundings. Thus, the Passive participants also saw the chevron signs, although they did not actually need them, as they were not controlling the self-motion (“steering” the vehicle). Simulated motion began slowly, and gradually accelerated, to reach a maximum of 50 km/h; it decelerated, and ceased at the traffic cones and stop signs, at the end of the route. The low maximum speed was intended to minimise the possibility of cybersickness symptoms, especially during motion around the roundabout. As in the first experiment, participants could only exit the roundabout by taking the second right exit; thus, the direction of turning was always to the right.

Once the simulated self-motion had stopped, a virtual dial automatically appeared on the central screen, as in the first experiment. Participants moved the pointer around the dial by turning the steering wheel, so that it pointed directly towards the starting position of the route; and then pressed a button on the console. Their directional estimate was recorded. Participants were instructed to make their decision as accurately as possible. It had been carefully explained to the participants that the placement of the pointer on the dial was random on each trial, and provided no directional information: this fact was emphasised on the first few trials.

The number of the next trial appeared on the screen; and this was replaced with a new street scene, when participants initiated the trial by pushing the black knob on the console forward. The trial began when the motion resumed after a two-second delay (the “car” started “moving”) for the Passive participants; or when the Active participants initiated self-motion with the wheel and pedals (started to “drive” the car).

Participants were encouraged to take breaks between trials, and to stretch or stand up. The experimenter carefully monitored participants for any symptoms of

cybersickness (for example, eyestrain, headache, excessive yawning or drowsiness, over-heating, nausea), and made general enquiries about their well-being, both throughout the experiment, and afterwards. Participants were informed that the simulation would be terminated immediately if they felt unable to continue, and reminded of their right to withdraw their participation at any time.

Although most participants experienced some minor symptoms during the experiment, particularly in the Active condition, most opted to continue the simulation; and, for the majority of participants, their symptoms had ceased by the time they had finished the post-experiment questionnaires. Three participants in the Active condition experienced adverse symptoms of sufficient severity for them to withdraw from the experiment. Their data were excluded from the analysis.

After the simulations, participants completed two questionnaires about their experience in the virtual world: the ITC-Sense of Presence Inventory (Lessiter, Freeman, Keogh, & Davidoff, 2001); and a feedback questionnaire about the design of the virtual environments, developed by the experimenter.

## **4.3 Results**

### **4.3.1 Directional Estimates: Analysis**

The mean directions and mean angular deviations (Batschelet, 1981) of the directional estimates were calculated, for each condition, for the sample of 80 participants, using the CircStats Toolbox (Berens, 2009; Berens & Velasco, 2009). Outliers were identified, and their data removed from the sample prior to analysis. Arithmetic means and standard deviations were calculated for the linear signed error data. ANOVAs, or their circular equivalents where appropriate, were performed on the absolute and signed error of the directional estimates.

### **4.3.2 Elimination of Outliers**

Six participants were identified as outliers, as their directional estimates fell beyond three angular deviations from the sample mean direction for the particular condition, on more than six trials overall; their data were consequently eliminated from the analysis. The data from two males and one female were excluded from the Active condition; whilst data from two females and one male were removed from the Passive condition. There were 40 participants in each condition (navigation mode).

Thus, the analysis was conducted on data from 80 participants, of whom 39 were female, and 41 were male.

The elimination of outliers resulted in a slight change to the age composition of the groups. The mean age of participants fell, in the Active condition from 26.4 to 25.48 (with a standard deviation of 9); and in the Passive condition from 27.9 to 27.1 (with a standard deviation of 11). The minimum age in both groups remained 16; however, the maximum age fell to 50 (from 63), and to 54 (from 56), in the Active and Passive conditions, respectively.

### **4.3.3 Overview of the Data: Mean Vector Length and Angular Variance**

The distribution of the directional estimates for each condition was first examined. Mean vector length ( $R$ ) values are shown in table 4.3. (Mean vector lengths by navigation mode and gender are shown in Appendix A; and by turn type and environment in Appendix B). Mean vector lengths were generally close to 1.0 (at least 0.7 or 0.8), in both the Active and Passive conditions, for all three angles, across all environments and distances, and in both intersection and roundabout conditions: thus, the data were located close to the mean direction, and the corresponding angular variance was small. Mean vector lengths tended to be slightly closer to 1.0 for the Active group than the Passive group, across all of the angle-distance configurations, and all environments; thus, indicating slightly more consistent responses for the Active participants, in general.

There was a consistent tendency, in both the Active and Passive groups, and across all angles and distances, for males to exhibit a higher mean vector length (at least 0.8), and smaller angular variance, than females (average of 0.7), especially in the Passive group. Thus, the data were more tightly concentrated around the mean direction for males than for females in every condition, indicating greater consistency across participants among male responses than female responses.

The difference between the mean vector length for males and females was particularly pronounced on the 60° and 90° angle trials, especially in the Passive condition. Mean vector lengths showed less overall divergence between the genders in the Active condition; in responses for the 120° angle, across all environments and distance combinations (both genders tending to exhibit a mean vector length above 0.8); and also with the L-L (equal-length) triangle layouts. Thus, both genders were more consistent with equilateral triangles, with 120° angles, and when they actively controlled their navigation through the environment.

The greater variability in the Passive data than the Active data, overall, was mainly due to the greater variability in the female data: the lower mean vector lengths

Table 4.3.

*Mean vector lengths (R) for three angles by environment, navigation mode and leg-length (combined male and female data)*

Leg-length	Environment	ACTIVE			PASSIVE		
		60°	90°	120°	60°	90°	120°
L-L	Ur-S	0.86	0.86	0.84	0.75	0.84	0.79
	Ur-N	0.78	0.86	0.86	0.80	0.73	0.79
	Rur-S	0.82	0.83	0.85	0.62	0.74	0.81
	Rur-N	0.80	0.79	0.81	0.78	0.82	0.86
L-S	Ur-S	0.79	0.84	0.80	0.74	0.75	0.83
	Ur-N	0.77	0.86	0.85	0.74	0.71	0.78
	Rur-S	0.82	0.77	0.89	0.67	0.78	0.80
	Rur-N	0.77	0.77	0.79	0.79	0.76	0.76
S-L	Ur-S	0.76	0.83	0.79	0.78	0.81	0.78
	Ur-N	0.82	0.85	0.80	0.78	0.80	0.82
	Rur-S	0.81	0.87	0.85	0.78	0.78	0.84
	Rur-N	0.78	0.76	0.81	0.76	0.75	0.76

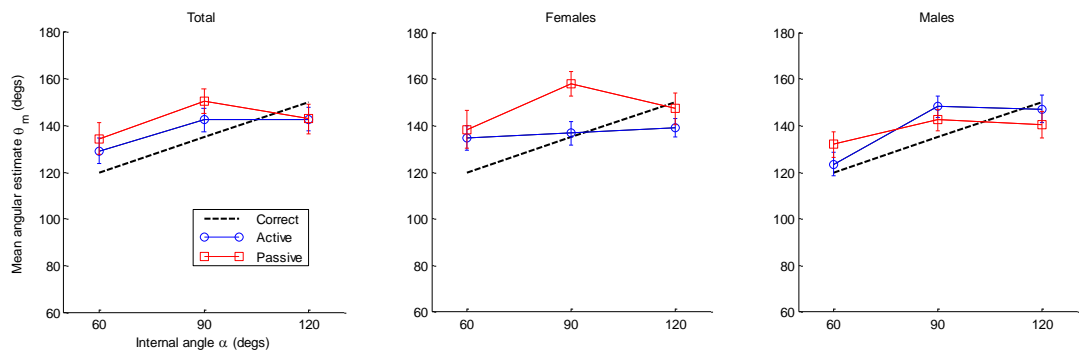
for females resulted in lower mean vector lengths in the Passive group data overall, compared with the Active group data.

Environment did not have a great influence: similar data patterns, indicating similar levels of consistency, were found across all the environments.

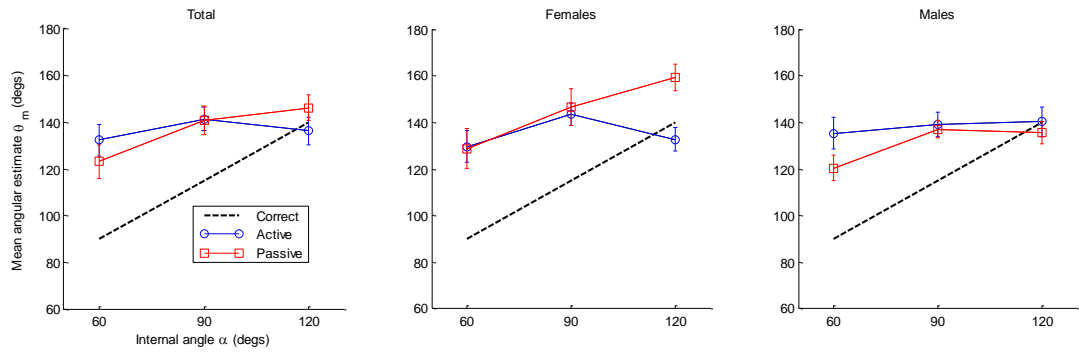
#### 4.3.4 Mean Directions and Mean Angular Deviations

The means of the directional estimates for the three internal angles and leg-length combinations are shown, for each environment, in figures 4.2, 4.3, 4.4, and 4.5 (combined and separately by gender). Mean directions for turn type (intersection and roundabout conditions) are shown in Figure 4.6, and separately by gender in figure 4.7. The error bars show the standard error of the means. Mean directions and mean angular deviations of the directional estimates are also displayed in tables 4.4 and 4.5. (Tables showing mean directions separately by gender are included in Appendix C). Several general tendencies are apparent from the graphs.

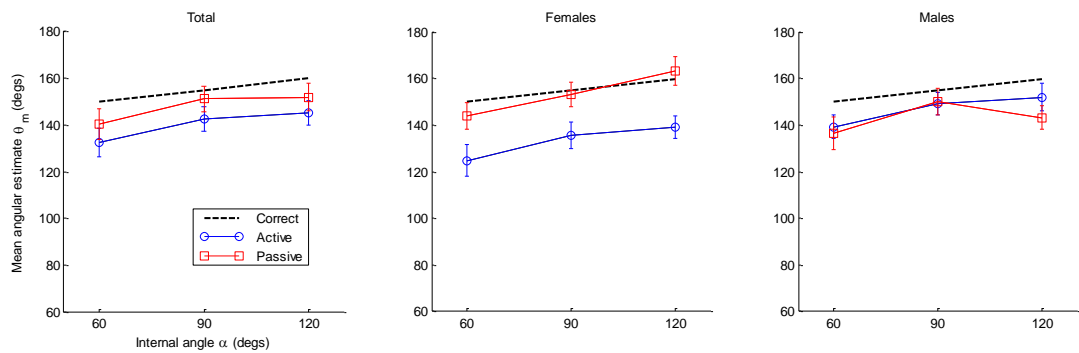
*Triangle Layout:* A different pattern of results was observed between the 60° and 90° angle trials, on the one hand, and the 120° angle trials, on the other: a tendency for overestimation versus underestimation, respectively. Similarly, the response pattern



Distance: L-L

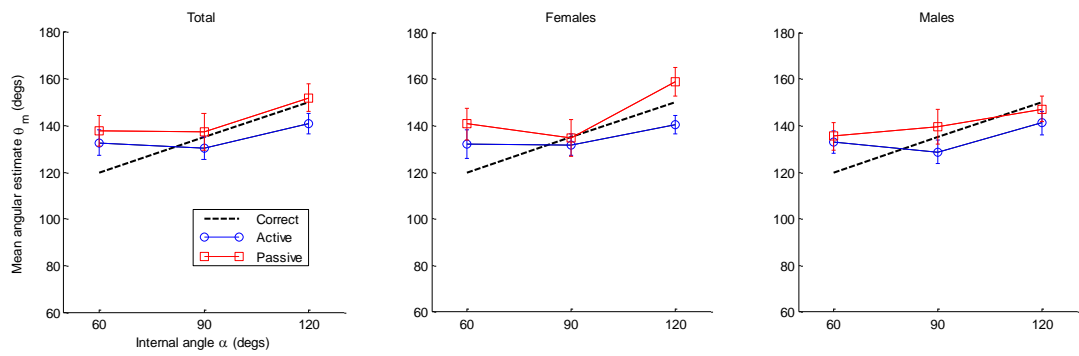


Distance: L-S

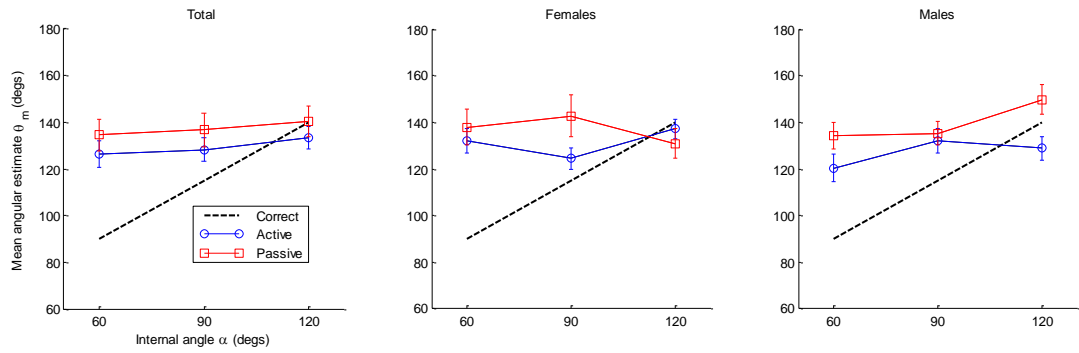


Distance: S-L

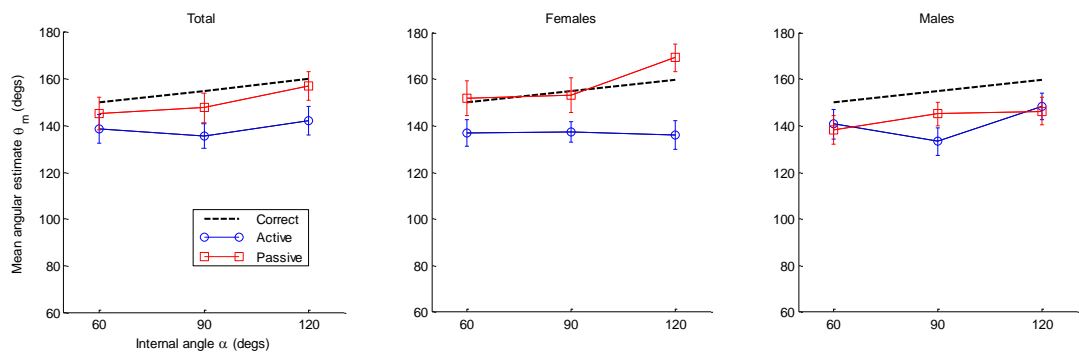
Figure 4.2. Mean directional estimates for the three internal angles and three distances in the Ur-S environment, combined (left) and separately by gender



Distance: L-L

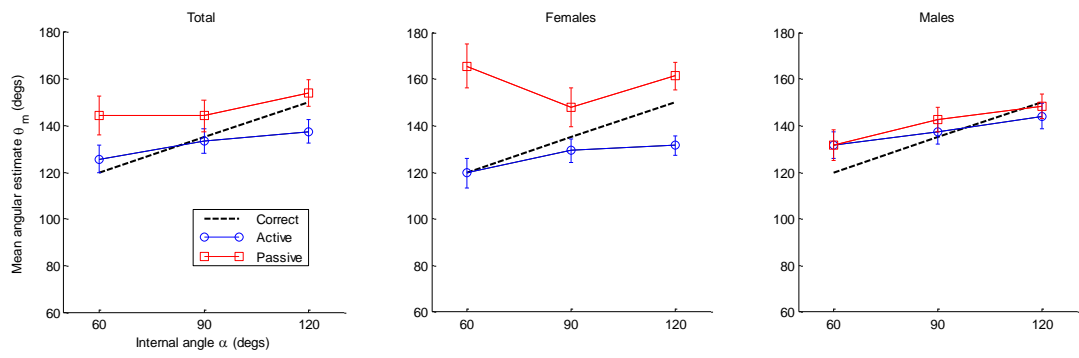


Distance: L-S

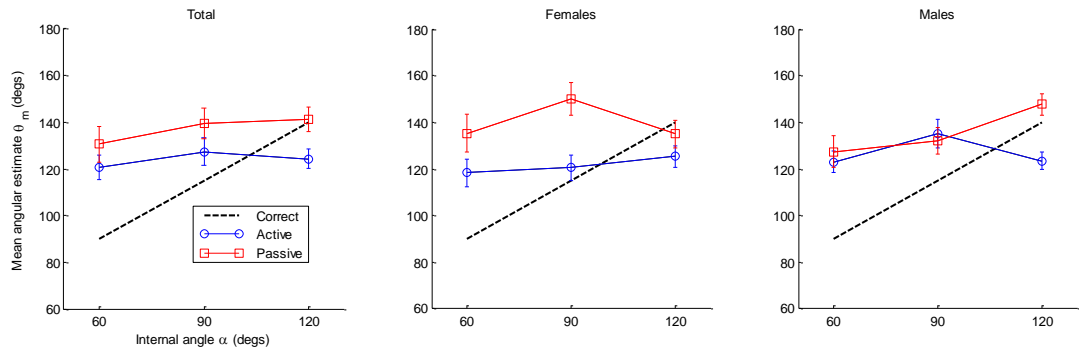


Distance: S-L

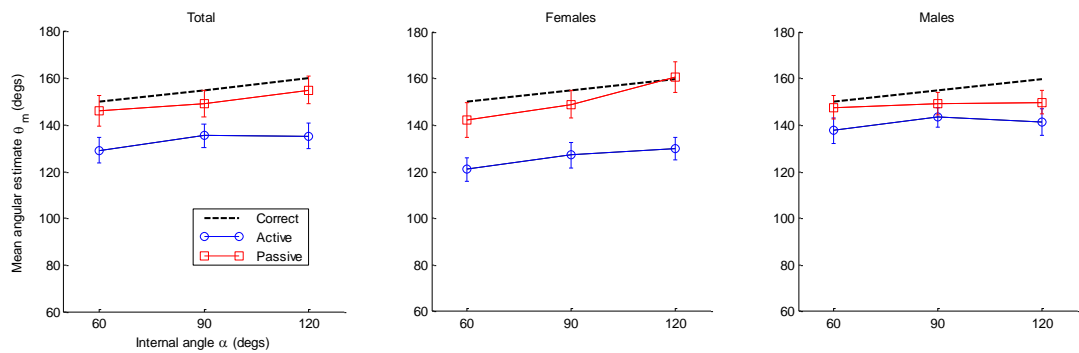
Figure 4.3. Mean directional estimates for the three internal angles and three distances in the Ur-N environment, combined (left) and separately by gender



**Distance: L-L**

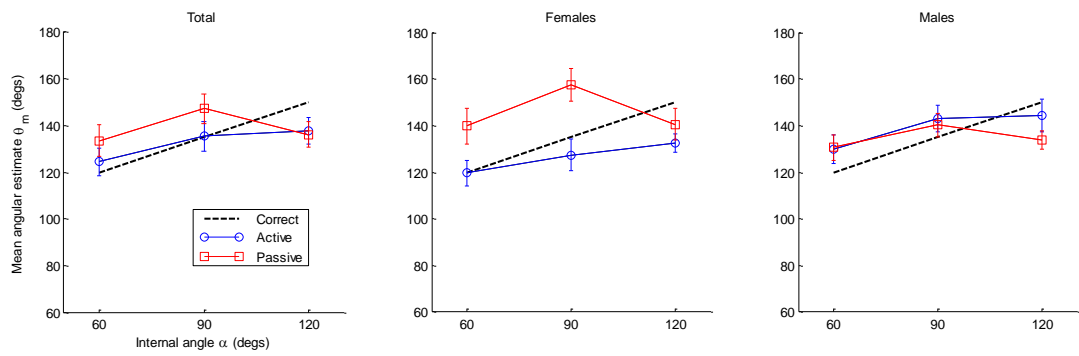


**Distance: L-S**

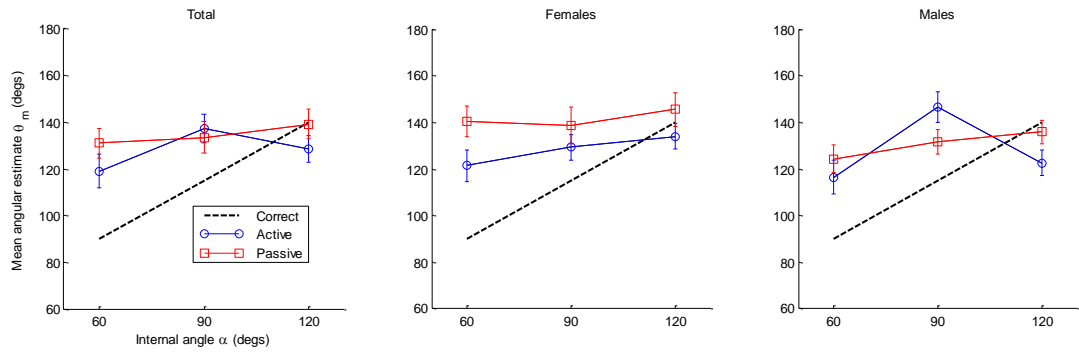


**Distance: S-L**

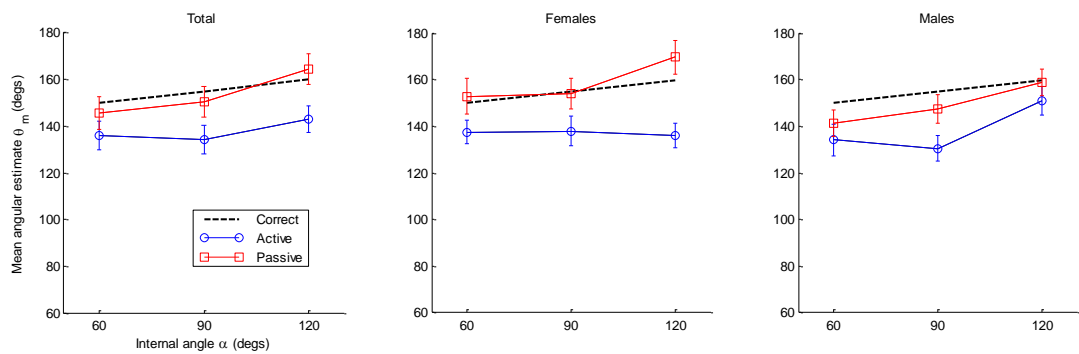
**Figure 4.4.** Mean directional estimates for the three internal angles and three distances in the Rur-S environment, combined (left) and separately by gender



Distance: L-L



Distance: L-S



Distance: S-L

Figure 4.5. Mean directional estimates for the three internal angles and three distances in the Rur-N environment, combined (left) and separately by gender

differed between the L-L (equal-length) and L-S (long-short) layouts, on the one hand, and the S-L (short-long) layout, on the other: again, a pattern of overestimation versus underestimation, respectively.

There was a general tendency for overestimation of the final angle on the 60° and 90° angle trials on the L-L and L-S triangle layouts, across all four environments. This effect was found for both genders, in both the Active and Passive conditions. In the 60° angle trials, the final angle was, in fact, overestimated on every triangle layout in every environment by males, in both the Active and Passive conditions; as well as by females in the Passive condition. It was also generally overestimated by females in the Active condition. In the 90° angle trials, the final angle was overestimated in almost every environment, in both the Active and Passive conditions, by both males and females. In the figures, the blue and red lines which represent the Active and Passive data, respectively, tend to be above the dotted line, representing the correct response, where they connect the data points for the 60° and 90° angle trials.

In contrast, the final angle was consistently underestimated for the 60° and 90° angles on the S-L layout, in all four environments. This response pattern was again found for both genders, in both the Active and Passive conditions. Both the blue and red lines connecting the relevant data points tend to be below the dotted line in the figures. Females in the Active condition tended to greatly underestimate the angle, considerably more so than in the Passive condition, so that the data for the two conditions diverged greatly. Data for the males generally showed more convergence between the Active and Passive modes. This can be seen from the relative distance of the blue and red lines from the dotted line for each gender.

In the 120° angle trials, there was a consistent tendency in the Active condition for the final angle to be underestimated, in all four environments, and for all three layouts. On the figures, this is clear from the fall of the blue line below the dotted line for the 120° angle data. Passive responses were more mixed: male participants mostly underestimated the angle, whilst female participants mostly overestimated it. The red line appears below and above the dotted line, accordingly, in the figures for each gender.

The magnitude of the error also differed according to triangle layout. In both the Active and Passive conditions, across all environments, and for both males and females, mean error was large for the 60° and 90° angle trials on the L-S layout, and greater than on either the L-L or S-L layouts. Mean error for the 120° angle, on the other hand, was small with the L-S layout, and much smaller than with either the L-L or S-L layouts. This is clear from the relative distance of the data points from the dotted (correct) line in the figures.

Table 4.4.

*Mean directions and mean angular deviations (in brackets) of the directional estimates*

$\alpha$	Dist. comb.	$\theta$	Environment	Active	Passive
60°	L-L	120°	Ur-S	129.19° (33.10°)	134.43° (43.26°)
			Ur-N	132.56° (34.39°)	137.82° (41.26°)
			Rur-S	125.65° (37.77°)	144.28° (53.37)
			Rur-N	124.42° (36.81°)	133.47° (42.64°)
	L-S	90°	Ur-S	132.42° (42.39°)	123.21° (45.65°)
			Ur-N	126.53° (35.80°)	134.50° (42.99°)
			Rur-S	120.70° (33.02°)	130.61° (48.08°)
			Rur-N	119.12° (44.26°)	131.10° (40.57°)
	S-L	150°	Ur-S	132.32° (37.99°)	140.24° (41.15°)
			Ur-N	138.66° (37.87°)	145.24° (43.87°)
			Rur-S	129.03° (34.22°)	145.94° (41.22°)
			Rur-N	136.01° (38.25)	145.73° (43.70°)
90°	L-L	135°	Ur-S	142.41° (30.86°)	150.49° (32.76°)
			Ur-N	130.24° (30.36°)	137.19° (49.52°)
			Rur-S	133.30° (32.42)	144.09° (43.88°)
			Rur-N	135.35° (40.41°)	147.21° (39.69°)
	L-S	115°	Ur-S	141.39° (32.29°)	140.80° (40.08°)
			Ur-N	128.14° (31.40°)	136.71° (46.07°)
			Rur-S	127.42° (37.61°)	139.38° (41.29°)
			Rur-N	137.22° (38.99°)	133.51° (42.90°)
	S-L	155°	Ur-S	142.56° (34.00°)	151.22° (35.13°)
			Ur-N	135.58° (32.44°)	147.70° (40.09°)
			Rur-S	135.33° (31.11°)	149.11° (34.95°)
			Rur-N	134.21° (37.37°)	150.43° (40.51°)
120°	L-L	150°	Ur-S	142.72° (31.47°)	142.89° (40.56°)
			Ur-N	140.78° (28.24°)	151.83° (37.05°)
			Rur-S	137.37° (31.33°)	153.83° (36.08°)
			Rur-N	137.57° (35.5 7)	136.04° (34.72°)
	L-S	140°	Ur-S	136.28° (36.42°)	146.23° (35.55°)
			Ur-N	133.24° (29.74°)	140.34° (41.80°)
			Rur-S	124.36° (26.30°)	141.23° (34.31°)
			Rur-N	128.47° (34.74°)	139.20° (40.26°)
	S-L	160°	Ur-S	145.16° (33.70°)	151.83° (36.97°)
			Ur-N	142.24° (38.18°)	157.15° (39.08°)
			Rur-S	135.23° (33.72°)	155.03° (37.31°)
			Rur-N	143.06° (36.24°)	164.28° (41.77°)

*Turn Type (Degree of Rotation):* In the Active condition, turn type did not greatly influence the responses: the data for roundabout and intersection trials converge quite closely on the graph for each layout, indicating similar levels of accuracy. There was a larger effect in the Passive condition: the data are more divergent, and the intersection data are more accurate. In both the Active and Passive conditions, however, there is generally quite high accuracy for both turn types, and differences in accuracy between the turn types are small. Similar patterns of data are displayed for both turn types on the three route layouts, in all four environments, and in both Active and Passive conditions, as shown by the red and blue lines in the figures. Responses were more accurate, overall, on the L-L layout, across all environments, than on the L-S and S-L layouts. In general, estimates were more accurate on intersection trials on the L-L and L-S layouts, and on roundabout trials on S-L layouts.

Turn type did not have a great effect on male responses, in either the Active or Passive condition, or on female responses in the Active condition: the intersection and roundabout data show broadly convergent patterns across environments, indicating similar levels of accuracy. There was a larger effect on female estimates in the Passive condition: the roundabout and intersection data are more divergent, with some differences in accuracy. Performance by both genders generally followed the overall trends in the data for both turn types.

*Navigation Mode:* Overall, responses were more accurate in the Active condition than in the Passive condition, as can be seen from the graphs showing the combined male and female data: the blue (active) line tends to be closer to the black dotted (correct) line than the red (passive) line. However, there are gender differences. Female responses show considerable divergence between the Active and Passive data; and their responses on L-L and L-S layout trials were generally more accurate in the Active than the Passive condition, on trials of all three internal angles, across all four environments. Male performance on the L-L and L-S layout trials was less consistent: responses in the Passive condition tended to be more accurate than in the Active condition, especially on the 90° and 120° angle trials. There was often quite close convergence between the Active and Passive data, however. On the S-L layout, Passive responses tended to be more accurate than Active responses overall, especially for females. Thus, the L-L and L-S layout trials present a more mixed picture than the S-L layout trials. The graphs show considerable overlapping of the error bars between the Active and Passive groups for males, but much less for females; indicating more variability among females across the two conditions than among males. The effects of navigation mode are, therefore, quite complex, and difficult to separate from the effects of gender.

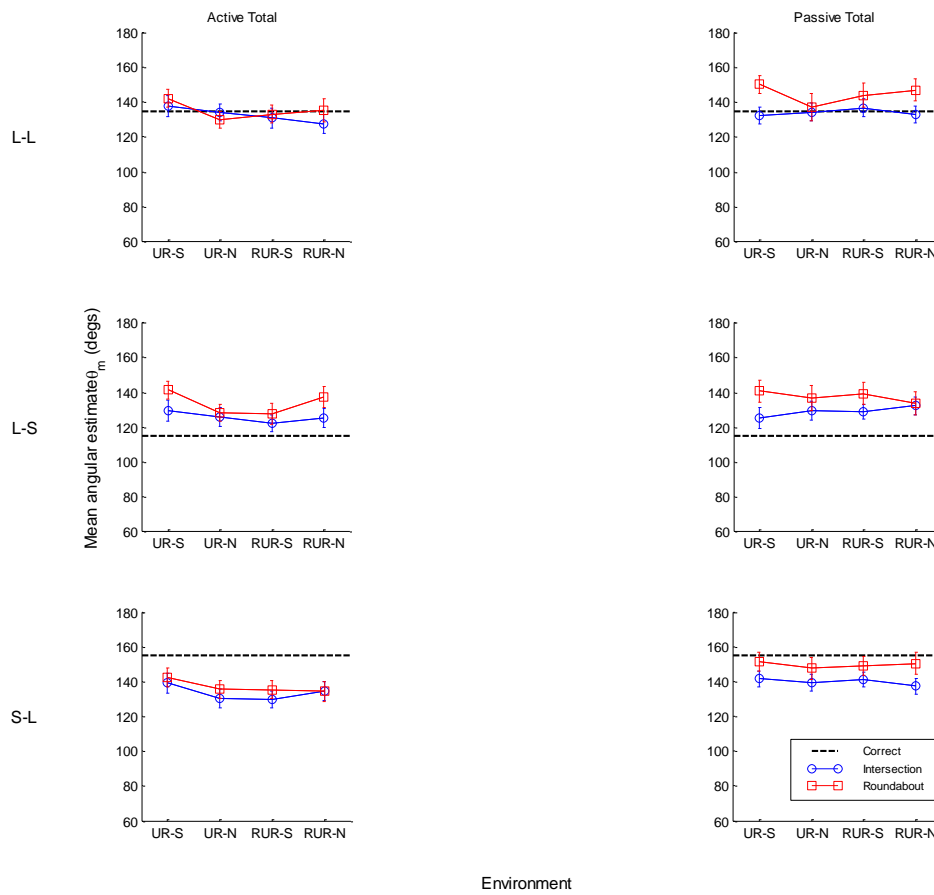


Figure 4.6. Mean directions by environment and distance-combination, for intersection and roundabout data in active and passive conditions, male and female data combined

*Gender:* The magnitude of the error showed some gender differences. However, no clear picture emerged in terms of accuracy: sometimes females were more accurate than males, and sometimes vice versa. In the Active condition, for example, on the L-L layout, in the Rur-S and Rur-N environments, females were more accurate on the 60° angle trials; whilst males were more accurate on the 120° angle trials. Accuracy did not always differ greatly between the genders. Performance on 90° angles by both genders was very inaccurate on L-S layouts in the Ur-L environment, for example, but quite accurate on the L-L layouts in the Rur-N environment.

Females were consistently more accurate than males on the S-L layout trials in the Passive condition. Males were most accurate on the L-L layout trials, across all environments, equally in the Active and Passive conditions; whereas female data for the L-L trials showed quite a high level of divergence between the Active and Passive conditions, and the Passive data was often very inaccurate.

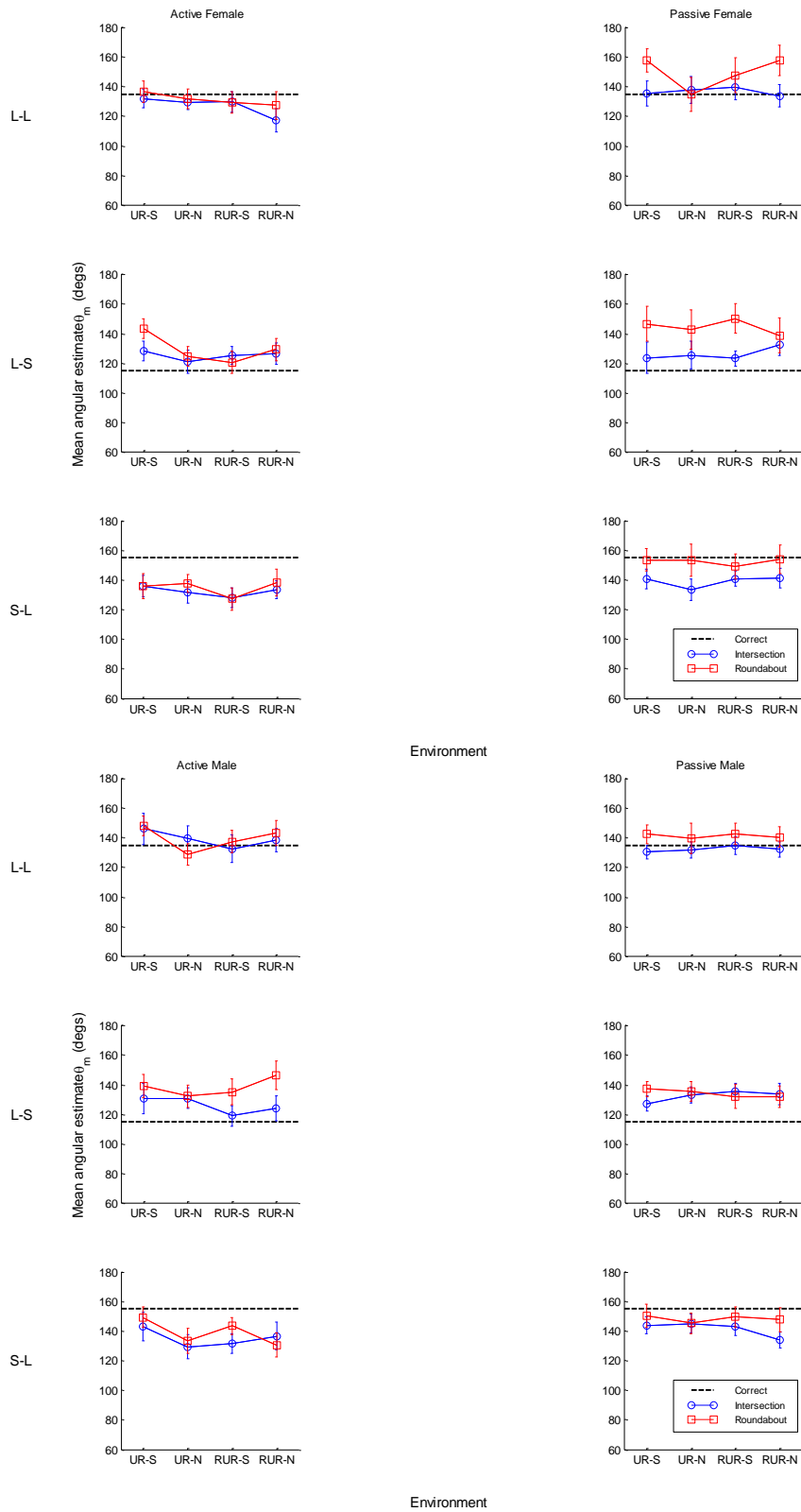


Figure 4.7. Mean directions by environment and distance-combination, for intersection and roundabout data in the active and passive conditions, shown separately by gender

Table 4.5.

*Mean directions and mean angular deviations (in brackets) of the directional estimates by turn type*

Dist. com. $\theta^\circ$	Env.	Roundabout		Intersection	
		Active	Passive	Active	Passive
L-L 135°	U-S	142.41° (30.86°)	150.49° (32.76°)	138.00° (38.40°)	132.22° (30.19°)
	Ur-N	130.24° (30.36°)	137.19° (49.52°)	134.19° (31.31°)	134.36° (33.08°)
	Rur-S	133.30° (32.42°)	144.09° (43.88°)	131.02° (35.79°)	136.84° (31.81°)
	Rur-N	135.35° (40.41°)	147.21° (39.69°)	127.64° (35.33°)	132.92° (29.56°)
L-S 115°	U-S	141.39° (32.29°)	140.80° (40.08°)	129.31° (38.00°)	125.03° (37.30°)
	Ur-N	128.14° (31.40°)	136.71° (46.07°)	125.83° (33.82°)	129.34° (33.75°)
	Rur-S	127.42° (37.61°)	139.38° (41.29°)	122.12° (29.12°)	128.76° (25.73°)
	Rur-N	137.22° (38.99°)	133.51° (42.90°)	125.19° (35.32°)	132.36° (32.37°)
S-L 155°	U-S	142.56° (34.00°)	151.22° (35.13°)	139.02° (37.51°)	141.53° (27.66°)
	Ur-N	135.58° (32.44°)	147.70° (40.09°)	130.44° (33.70°)	139.32° (30.50°)
	Rur-S	135.33° (31.11°)	149.11° (34.95°)	129.50° (29.73°)	141.07° (26.25°)
	Rur-N	134.21° (37.37°)	150.43° (40.51°)	134.73° (33.67°)	137.23° (28.09°)

*Environments:* The data were very consistent across the four different environments, showing very similar trends: it was difficult to discern any large differences in the pattern of data for the different environments. The triangle layout parameters (angle and leg-length) were more influential.

*Overall:* Thus, in terms of the effect upon path integration accuracy, no clear advantage was apparent from the graphs for either gender, for either navigation mode, or for any one environment. No consistent pattern emerges from the results. Triangle layout (the internal angle and different leg-length combinations) had a greater impact on performance than turn type, in general.

#### **4.3.5 Analysis of the Absolute Error Data: Effects of Internal Angle $\alpha$ and Environment**

Watson-Williams tests for circular data (Watson & Williams, 1956; Batschelet, 1981) were performed on the absolute error means of the directional estimates, to test for the effect of the independent variables *internal angle* (three levels: 60°, 90°, 120°), and *environment* (four levels: Ur-S, Ur-N, Rur-S, Rur-N). Separate tests were conducted for the Active and Passive conditions. Functions in the CircStats Toolbox

(Berens, 2009; Berens & Velasco, 2009) were used to conduct the tests, which are equivalent to one-factor ANOVAs.

#### 4.3.5.1 Effects of Internal Angle $\alpha$

There was a significant effect of *internal angle* in both the Active condition ( $F_{(2,1401)} = 6.26, p < 0.01$ ), and the Passive condition ( $F_{(2,1437)} = 7.40, p < 0.001$ ), indicating that the mean angles (or mean directions) of two or more of the samples differed significantly from each other (Batschelet, 1981). Mean directions and mean angular deviations are shown in table 4.6. Means and standard deviations are shown for the signed error in table 4.7.

In both the Active and Passive conditions, the final angle tended to be overestimated on the 60° and 90° angle trials, whilst it was generally underestimated on the 120° angle trials.

As can be seen from table 4.6, in the Active condition, the mean directional estimate was very accurate on 90° angle trials: the final angle was only very slightly overestimated, with a signed error of -1.35°. On 60° trials, it was overestimated, with a signed error of -9.20°; and on 120° trials, the angle was underestimated by 12.19°.

Thus, the magnitude of the error was smallest for the 90° angle, and largest for the 120° angle; and responses showed a tendency for overestimation of the small angle, and underestimation of the large angle (as has frequently been found in previous research). Moreover, the mean directional estimates for the 120° and 60° angle trials were very close to the correct value for the 90° angle (a difference of only 1.84° and 6.38°, respectively). This indicates that the Active participants tended to treat the 120° and 60° internal angles as 90° angles as well.

This is, again, a commonly found phenomenon. It may occur as a result of a distorted mental representation, leading to a tendency for directional estimates to be

Table 4.6.

*Mean directions and mean angular deviations (in brackets) of directional estimates by angle and by navigation mode*

$\alpha$	$\theta$	Active	Passive
60°	120°	128.90° (37.63°)	137.20° (44.49°)
90°	135°	135.28° (34.56°)	144.34° (41.15°)
120°	150°	137.12° (33.60°)	148.25° (38.72°)

Table 4.7.

*Means and standard deviations (in brackets) of signed error by angle and by navigation mode*

$\alpha$	Active	Passive
60°	-9.20° (40.17°)	-17.78° (46.12°)
90°	-1.35° (36.44°)	-7.90° (41.64°)
120°	12.19° (34.15°)	1.98° (38.25°)

biased towards right angles (Waller, Beall, & Loomis, 2004; Sadalla & Montello, 1989; Moar & Bower, 1983). Alternatively, it may occur because the use of a dial as the response method encourages participants to use an orthogonal reference system (that is, ahead, behind, left and right) in estimating egocentric directions; or to rely on heuristics to cope with the high demands that indirect pointing places on working memory, as the environment and heading have to be imagined (Waller et al., 2004; Montello, Richardson, Hegarty, & Provenza, 1999).

In the Passive condition, the final angle was again overestimated on the 60° and 90° angle trials, and by a greater amount for the 60° angle than the 90° angle; but the 90° angle trials were not the most accurate in the Passive data. In fact, the most accurate mean response was for the 120° angle trials, with a signed error of 1.98°, which is very accurate. In the Passive condition, there is greater error than in the Active condition for the 60° and 90° angle trials (almost twice as large for the 60° angle; and almost six times as large for the 90° angle). On the other hand, the 120° angle trials show considerably less error in the Passive data, with error of only 1.98°, as opposed to 12.19° in the Active data (thus, the Active error is roughly six times the Passive error).

The 120° angle trials may have shown the greatest accuracy because it was easier for Passive participants to take advantage of information about the closeness of the exit road to the approach road: as their attention was not focused on actively controlling the simulated self-motion along the route. As the exit road was closer to the approach road on 120° angle trials, than on 60° and 90° angle trials, participants travelled a shorter distance around the roundabout, thereby experiencing less rotation. Passive participants may, therefore, have been able to perceive the distance they had travelled, or the degree of rotation they had gone through, more accurately.

Thus, the final angle was overestimated on both 60° and 90° angle trials (by a considerably greater amount for the 60° than the 90° angle) in both the Active and Passive conditions, and the final angle was underestimated on 120° angle trials in both the Active and Passive conditions. There is, thus, a very similar *pattern* of error.

The *magnitude* of the error is very different for the two navigation modes, however. The Active participants performed most accurately on the 90° angle trials, and least accurately on the 120° angle trials; whereas Passive participants showed the greatest accuracy on the 120° angle trials, and the lowest accuracy on the 60° angle trials. However, in both conditions, low overall error is evident for all three angles.

There is a high level of variability overall in both conditions: similar levels for all three angles within one condition; and showing a progression from least variability for the 120° angle, and most for the 60° angle, with the 90° angle intermediate. On each angle, variability is higher for the Passive responses than for the Active responses.

The overall pattern of results differs from the pattern of consistent underestimation of the final angle obtained in Experiment 1 of this study; and which was also found in previous studies of purely visual path integration by Péruch, May, and Wartenberg (1997), Wartenberg, May, and Péruch (1998), and Kearns, Warren, Duchon, and Tarr (2002).

#### **4.3.5.2 Effects of Environment**

There was a significant effect of *environment* in both the Active condition ( $F_{(3,1868)} = 2.68, p < 0.05$ ) and in the Passive condition ( $F_{(3,1916)} = 6.34, p < 0.001$ ). Mean directions and angular deviations are shown in table 4.8, and the means and standard deviations for the signed error are also shown, in table 4.9. As can be seen, accuracy is higher for the Active condition across all environments, and there are different patterns in the Active and Passive data. For Active participants, mean estimates tended to be similar across the two rural environments and urban no-structure environment, but slightly *higher* for the urban structured environment;

Table 4.8.

*Mean directions and mean angular deviations (in brackets) of directional estimates by environment and by navigation mode*

Environment	Active	Passive
Ur-S	136.97° (35.56°)	142.00° (40.70°)
Ur-N	131.85° (33.63°)	144.11° (43.74°)
Rur-S	132.76° (36.90°)	144.28° (40.56°)
Rur-N	130.49° (34.72°)	134.35° (31.03°)

Table 4.9.

*Means and standard deviations (in brackets) of signed error of directional estimates by environment and by navigation mode*

Environment	Active	Passive
Ur-S	5.24° (38.94°)	10.12° (42.04°)
Ur-N	-1.77° (35.51°)	7.29° (44.66°)
Rur-S	-5.88° (38.30°)	4.96° (41.14°)
Rur-N	-4.36° (34.46°)	-0.78° (32.24°)

whereas for Passive participants, similar mean estimates can be seen across both the urban environments and the rural environment with structures, whilst there is a *lower* mean estimate for the rural non-structured environments.

In the Active condition, performance was more accurate in the urban and rural environment without additional structures than in the equivalent environments with structures; error was lowest in the Ur-N environment. In the Passive condition, performance was more accurate in both rural environments than in both urban environments; error was lowest in the Rur-N environment.

Participants may have tried to use piloting to navigate, possibly together with path integration, by using the structures as landmarks. However, the structures were not a stable source of information, as their positions were not fixed, but changed in each environment: using them as environmental references would have been misleading and reduced performance accuracy. This strategy would have resulted in less accurate performance in the conditions with structures. Active participants would have performed more accurately in the environments without structures, however, as only the optic flow cues, together with some basic proprioception information (from steering) would have been available, enabling more accurate speed estimation. Passive participants lacked the extra physical feedback, so could not judge the velocity of their self-motion as accurately from the optic flow in the more detailed urban environments. However, they may have been able to use information from the simpler overall visual structure in the rural environments; thus, they showed higher accuracy in those environments.

A high level of variability was again apparent in both the Active and Passive conditions: whilst the level was similar across environments for each condition, there was a tendency for higher variability among the Passive responses than the Active responses (except in the Rur-N environment, where variability was slightly lower).

### 4.3.6 Analysis of the Absolute Error Data: Combined Effects of Internal Angle $\alpha$ , Layout and Gender

Harrison-Kanji tests for circular data (Harrison, Kanji, & Gadsden, 1986; Harrison & Kanji, 1988) were conducted on the absolute error means of the directional estimates, to test for the effects of the factors *internal angle* (three levels: 60°, 90°, and 120°) x *gender*, and the factors *layout* (nine levels) x *gender*. Tests were performed separately for the Active and Passive conditions, using functions from the MATLAB Circular Statistics Toolbox (Berens, 2009; Berens & Velasco, 2009). The test is analogous to the two-factor ANOVA.

#### 4.3.6.1 Angle by Gender

In the Active condition, there was a significant effect of *internal angle* ( $F_{(2,1398)} = 6.20$ ,  $p < 0.01$ ) and *gender* ( $F_{(1,1398)} = 6.76$ ,  $p < 0.01$ ), but no significant interaction effect between them ( $F_{(2,1398)} = 0.84$ ,  $p = 0.43$ ). Similarly, in the Passive condition, there was a significant effect of *angle* ( $F_{(2,1434)} = 7.77$ ,  $p < 0.001$ ) and *gender* ( $F_{(1,1434)} = 28.15$ ,  $p < 0.001$ ) but, again, no significant interaction effect ( $F_{(2,1434)} = 0.24$ ,  $p = 0.79$ ). Mean directions and angular deviations are shown in table 4.10, and means and standard deviations for the signed error are also shown in table 4.11.

In the Active condition, the final angle was overestimated on 60° angle trials by both females and males, to a similar degree (by -7.80° and -10.69° respectively), and the final angle was underestimated on 120° trials by both females and males (by

Table 4.10.

*Mean directions and mean angular deviations (in brackets) of directional estimates for angle by gender, and by navigation mode*

$\alpha$	$\theta$	Active		Passive	
		Female	Male	Female	Male
60°	120°	127.39° (37.50°)	130.50 (37.72°)	142.04° (49.46°)	133.36° (38.24°)
90°	135°	131.80° (34.15°)	138.96° (34.68°)	148.29° (47.18°)	141.09° (34.50°)
120°	150°	134.54° (30.12°)	140.06° (36.74°)	151.78° (43.00°)	144.59° (34.14°)

Table 4.11.

*Means and standard deviations of signed error (in brackets) of directional estimates for angle by gender, and by navigation mode*

$\alpha$	$\theta$	Active		Passive	
		Female	Male	Female	Male
60°	120°	-7.80° (39.68°)	-10.69° (40.64°)	-21.10° (50.95°)	-13.97° (40.43°)
90°	135°	0.94° (34.69°)	-3.87° (38.06°)	10.39° (47.92°)	-5.25° (34.89°)
120°	150°	15.01° (30.61°)	8.95° (37.32°)	-1.08° (42.35°)	5.60° (34.17°)

15.01° and 8.95°, respectively). Thus, females were slightly more accurate on the 60° angle, and males were more accurate on the 120° angle, than their counterparts of the other gender. Both genders were most accurate on 90° angle trials: females were very accurate on this angle, with mean error of 0.94°, more so than males, with mean error of -3.87°. However, errors are quite small, overall, for both genders. Thus, similar error was found for both genders, showing high accuracy on the 90° angle.

However, different patterns of error are apparent between the genders for the 90° angle trials: females underestimated the final angle, whilst males overestimated it. On the other hand, both males and females overestimated the final angle on 60° trials, and underestimated it on 120° trials: thus, there was a tendency for the small angle to be overestimated, and for the large angle to be underestimated, consistent with a trend which is commonly found in path integration studies (Kearns et al., 2002; Loomis et al., 1993; Loomis, Klatzky, Golledge, & Philbeck, 1999; Klatzky et al., 1990). Estimates on the 90° angle trials were intermediate between the two.

Thus, the errors for both genders are quite small in the Active condition, and neither gender shows consistently superior performance: for example, male mean error is greater than female mean error on the 60° angle trials, but smaller on the 120° angle trials.

Similarly, in the Passive condition, the final angle was overestimated by both males and females on the 60° angle trials; and underestimated by both genders on the 120° angle trials. Both genders, thus, again showed the typically-found tendency to overestimate the small angle and underestimate the large angle, with the 90° angle intermediate between the two. Males had lower mean error on the 60° angle and 90° angle trials, whilst females had lower mean error on the 120° angle trials.

Thus, again, no clear pattern emerges from the data, in terms of accuracy between the genders. On the 60° and 90° angle trials, females were more accurate in the Active condition, whilst males were more accurate in the Passive condition. Conversely, on the 120° angle trials, males were more accurate in the Active condition, and females were more accurate in the Passive condition.

In addition, there was again considerable variability among responses by both genders, in both the Active and Passive conditions; as well as a progression in the level of variability, from lowest for the 120° angle, through the 90° angle, to highest for the 60° angle. Males showed similar levels of variability in both the Active and Passive conditions; females showed more variability in the Passive condition.

#### **4.3.6.2 Layout by Gender**

In the Active condition, there was a significant effect of *layout* ( $F_{(8,1386)} = 2.51$ ,  $p < 0.01$ ) and *gender* ( $F_{(1,1386)} = 6.76$ ,  $p < 0.01$ ), but no significant interaction effect ( $F_{(8,1386)} = 0.90$ ,  $p = 0.52$ ). Likewise, in the Passive condition, there was a significant effect of *angle* ( $F_{(8,1422)} = 3.29$ ,  $p < 0.01$ ) and *gender* ( $F_{(1,1422)} = 28.13$ ,  $p < 0.001$ ), but no significant interaction effect ( $F_{(8,1422)} = 0.20$ ,  $p = 0.990$ ). Mean directions and angular deviations are summarised in table 4.12, and the means and standard deviation of the signed error are shown in table 4.13.

The means for both the Active and Passive conditions show consistent overestimation of the final angle on the 60° and 90° angle trials with both the L-L and L-S distance combinations, but consistent underestimation with the S-L distance combination, by both genders. Interaction between leg-length and angle is evident.

The 120° angle trials showed consistent underestimation of the final angle on all three distance layouts, in both the Active and Passive conditions, by males; whilst females underestimated it in the Active condition, but consistently overestimated it in the Passive condition, again across all three distance layouts. Thus, a gender difference is apparent here.

Absolute error tended to be lower for females than males in the Active condition, especially for the 60° and 90° internal angles; whilst males tended to have lower absolute error than females in the Passive condition, especially for the 60° and 90° internal angles. For the 120° internal angle, males were more accurate in the Active condition, whilst females displayed greater accuracy in the Passive condition.

Again, thus, the picture concerning gender is quite complex: one gender was not consistently more or less accurate than the other. The situation concerning the Active and Passive conditions is also complex: responses in the Active condition

Table 4.12.

*Mean directions and mean angular deviations (in brackets) of directional estimates for layout by gender, and by navigation mode*

Layout	$\alpha$ + leg-lengths	$\theta$	Active		Passive	
			Female	Male	Female	Male
1	60° + L-L	120°	126.87° (37.32°)	131.34° (35.91°)	140.17° (50.48°)	133.44° (38.31°)
2	60°+ L-S	90°	121.45° (42.17°)	116.47° (46.25°)	140.39° (41.09°)	124.37° (38.35°)
3	60°+ S-L	150°	137.53° (32.44°)	134.13° (43.49°)	152.94° (49.37°)	141.29° (35.80°)
4	90°+ L-L	135°	131.48° (33.50°)	139.12° (33.71°)	148.00° (46.91°)	141.43° (34.11°)
5	90°+ L-S	115°	129.31° (34.07°)	146.64° (42.19°)	138.76° (50.51°)	131.62° (33.28°)
6	90°+ S-L	155°	138.01° (39.63°)	130.50° (34.49°)	153.95° (42.03°)	147.49° (37.80°)
7	120°+ L-L	150°	134.43° (29.40°)	140.78° (36.31°)	150.94° (41.31°)	144.09° (33.74°)
8	120°+ L-S	140°	134.03° (34.23°)	122.60° (34.48°)	145.52° (46.18°)	135.87° (32.50°)
9	120°+ S-L	160°	136.17° (32.72°)	150.90° (38.46°)	169.76° (45.49°)	159.02° (36.32°)

showed greater overall accuracy, but it was not a consistent tendency; and the difference in the error magnitude between the two conditions was often quite small.

High variability was again evident across all the conditions. Variability was higher for males and lower for females in the Active condition; whilst variability was higher for females and lower for males in the Passive condition. Variability tended to be higher overall for the Passive condition than for the Active condition.

Table 4.13.

*Means and standard deviations (in brackets) of signed error of directional estimates for layout by gender, and by navigation mode*

Layout	$\alpha$ + leg-lengths	$\theta$	Active		Passive	
			Female	Male	Female	Male
1	60°+ L-L	120°	-7.44° (40.80°)	-11.32° (39.13°)	-20.28° (51.27°)	-14.15° (40.30°)
2	60°+ L-S	90	-23.83° (34.31°)	-24.54° (45.36°)	-46.89° (41.09°)	-29.58° (39.36°)
3	60°+ S-L	150°	3.89° (27.20°)	10.36° (44.83°)	-8.00° (49.34°)	2.96° (37.63°)
4	90°+ L-L	135°	0.69° (34.09°)	-3.91° (36.73°)	-10.64° (47.71°)	-5.69° (34.43°)
5	90°+ L-S	115°	-7.00° (33.76°)	-26.12° (42.47°)	-21.62° (49.86°)	-10.39° (34.23°)
6	90°+ S-L	155°	12.32° (39.15°)	16.92° (37.41°)	1.91° (42.03°)	4.82° (38.49°)
7	120°+ L-L	150°	15.21° (30.43°)	8.19° (37.10°)	-0.84° (40.47°)	6.17° (34.13°)
8	120°+ L-S	140°	6.17° (27.62°)	17.81° (34.11°)	-2.98° (45.91°)	5.14° (31.84°)
9	120°+ S-L	160°	22.34° (33.28°)	7.28° (41.41°)	-10.62° (45.47°)	0.20° (36.32°)

#### 4.3.7 Analysis of the Signed Error Data: Combined Effects of Environment, Internal Angle, Distance, Navigation Mode and Gender

To test for any higher-level effects, a mixed-design 5-way ANOVA (4 *environments* x 3 *angles* x 3 *distance combinations* x 2 *navigation modes* x *gender*) was conducted on the signed error means of the directional estimates. This included three within-participants factors, which were *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), *internal angle* (60°, 90°, and 120°) and *distance-combination* (L-L: long-long, L-S: long-short, S-L: short-long); and two between-participants factors, which were *navigation mode* (that is, Active, Passive) and *gender*. The means and standard deviations (in

brackets) of the signed error of the directional estimates, by triangle layout and navigation mode for each condition, averaged across environments, are displayed in table 4.14. (Appendix D shows means and standard deviations by triangle layout and navigation mode, separately by environment).

There was a main effect of *internal angle* ( $F_{(2,152)} = 73.96, p < 0.001$ , partial  $\eta^2 = 0.49$ ), a main effect of *distance-combination* ( $F_{(2,152)} = 126.43, p < 0.001$ , partial  $\eta^2 = 0.63$ ), and also an interaction effect of *internal angle x distance combination* ( $F_{(4,304)} = 26.54, p < 0.001$ , partial  $\eta^2 = 0.26$ ).

Pairwise comparisons, with a Bonferroni adjustment for multiple comparisons, were conducted on the means of both *angle* and *distance-combination*. These showed that all three angles differed significantly from each other, all at  $p < 0.001$ . Similarly, all three distance-combinations differed significantly from each other, again all at  $p < 0.001$ . A polynomial contrast showed that angle also displayed a linear tendency ( $F_{(1,76)} = 108.07, p < 0.001$ , partial  $\eta^2 = 0.59$ ), indicating that the error increased as the value of angle  $\alpha$  increased.

There was no significant effect of *environment* ( $F_{(3,228)} = 1.02, p = 0.385$ ), or *gender* ( $F_{(1,76)} = 0.08, p = 0.775$ ), and no other interaction effects. Navigation mode almost reached significance ( $F_{(1,76)} = 3.70, p = 0.058$ , partial  $\eta^2 = 0.46$ ). This is clear from figures 4.2, 4.3, 4.4, and 4.5, where the difference between the Active and Passive data, shown by the blue and red lines, respectively, is often striking. The effect size for navigation mode was also quite large. Passive responses were consistently more accurate than Active responses on S-L layout trials.

Table 4.14.

*Means and standard deviations (in brackets) of the signed error of the directional estimates (averaged across environments)*

$\alpha$	Distance combination	$\theta$	Active	Passive
60°	L-L	120°	-9.87°	-25.23°
	L-S	90°	-31.45°	-41.52°
	S-L	150°	9.38°	7.46°
90°	L-L	135°	-0.18°	-15.16°
	L-S	115°	-19.92°	-22.96°
	S-L	155°	10.97°	0.32°
120°	L-L	150°	8.10°	1.74°
	L-S	140°	7.13°	2.48°
	S-L	160°	14.44°	3.01°

#### 4.3.8 Analysis of the Signed Error Data: Combined Effects of Turn-type, Environment, Distance, Navigation Mode and Gender

The means of the signed error of the directional estimates on the 90° angle trials, on the roundabout and intersection routes, were analysed with a mixed-design 4-way ANOVA (2 *turn types* x 4 *environments* x 3 *distance-combinations* x *gender*), in order to test for effects of turn type. There were three within-participants factors, *turn type* (roundabout, intersection) *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), and *distance combination* (L-L: long-long, L-S: long-short, and S-L: short-long); and two between-participants factors, which were *navigation mode* (that is, Active, Passive) and *gender*. A linear ANOVA was appropriate for this analysis, as the signed error is constrained within 180° on either side of the correct value. Means and standard deviations are summarised, averaged across environments, in table 4.15; and separately by environment, in table 4.16.

There was a significant effect of *turn type* ( $F_{(1,76)} = 9.25, p < 0.01$ , partial  $\eta^2 = 0.11$ ) and *distance-combination* ( $F_{(2,152)} = 147.31, p < 0.001$ , partial  $\eta^2 = 0.66$ ), but there was no significant interaction effect between turn type and distance ( $F_{(2,152)} = 0.58, p = 0.563$ ). Pairwise comparisons showed that all three distance-combinations differed, all at  $p < 0.001$ .

There was no significant effect of *environment*, *navigation mode* ( $F_{(2,152)} = 1.85, p = 0.18$ ), or *gender* ( $F_{(2,152)} = 0.02, p = 0.897$ ). The means and standard deviations, for the signed error for the angles and distance-combinations (layout), show that there was a tendency for the Passive data to show higher mean error than the Active data on the L-L and L-S distance layouts, on both the intersection and roundabout trials; with the Passive intersection data having higher error than the Passive roundabout data. Conversely, however, the S-L data show a tendency for higher mean error in the responses in the Active condition than the Passive condition, on both intersection and roundabout trials; and for higher mean error in the

Table 4.15.

*Means of the directional estimates (signed error) by turn type, averaged across environments*

Leg-lengths	$\theta$	Roundabout		Intersection	
		Active	Passive	Active	Passive
L-L	135°	-0.18°	-15.16°	1.00°	0.92°
L-S	115°	-19.92°	-22.96°	-10.98°	-14.54°
S-L	155°	10.97°	-0.32°	19.01°	12.94°

Table 4.16.

*Means and standard deviations (in brackets) of the signed error of the directional estimates by turn type and environment*

Env.	Roundabout		Intersection	
	Active	Passive	Active	Passive
U-S	-4.66° (36.06°)	-15.65° (35.25°)	-7.03° (40.52°)	0.20° (33.17°)
Ur-N	6.37° (38.38°)	-14.60° (58.20°)	1.22° (31.72°)	4.23° (38.02°)
Rur-S	2.76° (36.52°)	-15.82° (51.95°)	0.61° (37.80°)	-5.25° (35.23°)
Rur-N	-5.18° (46.97°)	-14.58° (44.41°)	9.20° (40.29°)	0.33° (31.66°)
U-S	-25.53° (34.95°)	-25.44° (45.72°)	-13.63° (38.72°)	-16.55° (41.49°)
Ur-N	-12.65° (35.55°)	-23.96° (52.84°)	-12.69° (34.41°)	-10.46° (37.15°)
Rur-S	-13.75° (38.57°)	-20.91° (46.14°)	-3.48° (32.92°)	-12.90° (26.84°)
Rur-N	-17.75 (41.92°)	-21.53° (49.86°)	-14.13° (32.28°)	-18.25° (36.19°)
U-S	6.40° (33.70°)	1.37° (39.59°)	17.68° (32.82°)	11.62° (28.96°)
Ur-N	13.55° (36.51°)	1.16° (44.77°)	19.03° (33.71°)	13.50° (32.10°)
Rur-S	11.55° (29.24°)	0.35 ° (37.95°)	22.02° (31.15°)	10.69° (29.09°)
Rur-N	12.36° (41.29°)	0.22° (45.59°)	17.30° (39.79°)	15.93° (29.34°)

Active intersection data than in the Active roundabout data. The S-L data show consistent overestimation, and the L-S data show consistent underestimation, across all environments and conditions; whilst for the L-L data, Passive responses show consistent underestimation, and Active responses mostly show overestimation on both intersection and roundabout trials.

### 4.3.9 The Virtual Experience

The virtual environments were considered in terms of their effectiveness in evoking presence and immersion, any negative effects, and their authenticity, through participants' scores on the four factors of the ITC-SOPI (Lessiter, Freeman, Keogh, & Davidoff, 2001), and responses to a questionnaire developed by the researcher. Participants completed both of these following the simulation in the virtual environments.

#### 4.3.9.1 Presence and Immersion in the Virtual Environments

For each participant, the mean of all the completed responses to the items contributing to each factor were calculated, to produce four factor scores, and the

group mean was calculated for each factor. Means and standard deviations for the factor scores are summarised in table 4.17. The scores for each factor were analysed individually, as they cannot be combined into a single score. Additional comments from the single open-ended question, grouped according to the four factor themes, are shown in Appendix E.

The spatial presence scores indicate a moderate sense of being present in the virtual world, for participants in both conditions. The mean score is higher for the Active condition (3.10) than the Passive condition (2.81), possibly because Active participants had some control over their experience in the virtual environments, as they were able to steer the car. Engagement ratings are similar for both conditions (2.99 for Active versus 2.90 for Passive), indicating a moderate level of psychological involvement and interest in the virtual environments, and general enjoyment of the virtual experience. The naturalness of the environment was judged to be higher by the Passive participants (3.14) than the Active participants (2.86). Negative effects were higher in the Active group (2.72) than the Passive group (2.31), possibly reflecting the fact that controlling the car was more nauseogenic.

Variability among participants was again high, especially for ecological validity and negative effects for the Active condition; and for spatial presence and ecological validity for the Passive condition. This difference in variability reflects the different experiences in the two conditions. This is reinforced by the participants' comments: some Active participants found the virtual experience very nauseogenic.

Scores for spatial presence, engagement, and ecological validity are generally slightly lower than in the first experiment (except for spatial presence, which was slightly higher in the Active condition, and ecological validity / naturalness, which was higher in the Passive condition). This indicates that the large screen was more successful at evoking presence, in general. However, the scores for negative effects are also lower in this experiment, indicating that there were fewer adverse physiological effects experienced in both conditions, compared with Experiment 1.

Table 4.17.

*ITC-SOPI: Mean factor scores and standard deviations by condition (Active and Passive)*

Factor	Score	
	Active	Passive
Spatial Presence	3.10 (0.71)	2.81 (0.71)
Engagement	2.99 (0.53)	2.90 (0.51)
Ecological Validity / Naturalness	2.86 (0.83)	3.14 (0.70)
Negative effects	2.72 (0.99)	2.31 (0.64)

Variability was comparable to Experiment 1 on engagement, but lower on spatial presence and ecological validity / naturalness; while variability for negative effects was higher in the Active condition, but lower in the Passive condition.

The few additional comments indicate particular interest, by participants in both conditions, in the ecological validity and naturalness of the virtual environments: some participants found them very realistic, whilst others found them less so. Some issues with the design of the virtual environments are highlighted, such as artificiality and glitches (for example, a flashing stop sign and blurry graphics). Comments also tend to reflect the rather different virtual experience of the participants in each condition: judging speed and using the controls of the car are mentioned in some Active responses, whilst the richer context and detail provided by the additional structures are mentioned in some Passive responses. A few participants in each condition refer to experiencing adverse effects, such as disorientation and simulator sickness symptoms (nausea, eyestrain, and dizziness).

#### **4.3.9.2 Analysis of the Signed Error Data: Combined Effects of Presence, Environment, Internal Angle, and Distance**

Based on their score, participants were assigned to either a *high* presence group (scores from 3.00 to 5.00) or *low* presence group (scores from 1.00 to 2.99), on each of the four factors which make up sense of presence on the ITC-SOPI (Lessiter et al., 2001): spatial presence, engagement, ecological validity, and negative effects.

In order to assess any effects of sense of presence, the means of the signed error of the directional estimates were analysed with a mixed-design 4-way ANOVA (*2 presence levels x 4 environments x 3 angles x 3 distance-combinations*). There was one between-participants factor, that is, *sense of presence* (High, Low); and three within-participants factors which were: *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), *angle* (60°, 90°, and 120°) and *distance-combination* (L-L: long-long, L-S: long-short, and S-L: short-long). The ANOVA was performed separately on each of the four factors. Since the signed error was constrained within 180° on either side of the correct value, a linear ANOVA was appropriate for the analysis. Means and standard deviations of the signed error, by presence group, angle and distance-combination, averaged across environments, navigation mode and gender, are summarised in Appendix F. Appendix G shows the sample size of the high and low presence groups on each factor.

There were no significant effects of any of the four factors: *spatial presence* ( $F_{(1,78)} = 1.49$ ,  $p = 0.227$ ), *engagement* ( $F_{(1,78)} = 0.24$ ,  $p = 0.622$ ), *ecological validity / naturalness* ( $F_{(1,78)} = 2.43$ ,  $p = 0.123$ ), or *negative effects* ( $F_{(1,78)} = 1.11$ ,

$p = 0.296$ ). Thus, presence had no effect on task performance. There was no effect of any of the four factors on the directional estimates. The accuracy of participants' task performance in this experiment was not influenced by their sense of being present in the virtual world, nor by their level of psychological involvement in the virtual environments or general enjoyment of the virtual experience; it was also not affected by how believable or natural they found the world, or by negative effects.

#### **4.3.9.3 Authenticity of the Virtual World**

The qualitative data were analysed and grouped into categories, using the same set of structural frames (Kitchin, 1997) that were used in Experiment 1. The frequency of occurrence of items related to each theme was tallied, and the corresponding percentages were calculated. Comments from the original 86 participants were analysed, that is, including those from the participants identified as outliers for the simulation, on the grounds that their overall impressions of their experience in the virtual world were also of interest.

The features most commonly referred to as authentic, in both the Active and Passive conditions, were aspects of the roads, the countryside / rural areas, the mountains / hills, and the houses, albeit in a slightly different order of importance: clearly, these are salient aspects of the environment for participants. Tables showing these data are included in Appendix H.

In the Active condition, features which contributed the most to participants' perceptions of the virtual environments as authentic were aspects of the road itself, such as markings, street lights, signs, and roundabout design / appearance (18.68%); the mountains / hills (17.58%); the appearance of the houses (15.38%); and the countryside and rural areas (13.19%). The structures were less important (8.80%). This was similar in the Passive condition, but with a different emphasis, and the structures were more important: the countryside and rural areas, and the structures, share top position (with 15.75% of the responses each), followed by road aspects (14.96), appearance of the houses (13.39%) and the mountains / hills (12.60%). Active participants (drivers) also mention road- and driving-related aspects more frequently, commenting, for example, on the driving being on the left hand side of the road (4.40%), which was not mentioned at all by Passive participants.

There were also some differences between the two conditions, in terms of the features which participants indicated should be changed, in order to make the virtual environments more authentic: these differences reflect the different conditions under which participants experienced the virtual world. Tables showing these data are included in Appendix I. Participants in both conditions overwhelmingly referred to

farm animals as the most conspicuously absent feature: it accounted for 20.45% and 21.51% of responses in the Active and Passive conditions, respectively. However, the other major categories of features noted by Active participants tended to be those which could be useful in driving, such as names on buildings (which could potentially serve as landmarks), and road signs and markings, with 11.36% and 9.09% of responses, respectively. For Passive participants, on the other hand, trees and other vehicles were more important, with 11.83% of responses for both categories.

## 4.4 Discussion

### 4.4.1 Path Integration Performance

*Hypothesis 1:* Higher accuracy of path integration performance would result from the use of a small desktop flat-screen display, compared with previous studies and Experiment 1

*This hypothesis was met.* The directional estimates in this experiment were more accurate, overall, than in previous studies and in Experiment 1. Path integration performance was at an above-chance level, as in the first experiment. Systematic error was observed, which depended on route layout, navigation mode and gender. The overall pattern of error obtained in Experiment 2 was strikingly different from that found in Experiment 1, as a comparison of the figures for the two experiments reveals. The consistent underestimation of the final angle, which was observed in Experiment 1, was not found in Experiment 2. Instead, there was a general tendency for overestimation of the final angle on the 60° and 90° internal angle trials on L-L and L-S route layouts; and consistent underestimation of the final angle on 120° internal angle trials on all route layouts, and on the S-L route layout with all three internal angles. The trends were similar in the Active and Passive conditions. This pattern is shown in figures 4.2, 4.3, 4.4, and 4.5 for Experiment 2.

The L-L layouts used in Experiment 2, that is, those with equal-length legs, are directly comparable to the triangle layouts which were used in Experiment 1, which all had equal-length legs. Comparison with the Passive condition is especially appropriate, as participants were also passive in Experiment 1. Differences in the overall pattern of results on these equivalent trials are clear from a comparison of the figures for the two experiments.

In Experiment 1, participants' responses showed consistent underestimation of the final angle, on trials with all three internal angles. This is shown in figures 3.10 and 3.11. In contrast, in Experiment 2, while consistent underestimation of the final

angle was observed on 120° angle trials, consistent overestimation was seen on 60° and 90° angle trials. This is clear from figures 4.2, 4.3, 4.4 and 4.5. Therefore, the final angle was underestimated on 60° and 90° angle trials in Experiment 1, but overestimated in Experiment 2. However, the final angle was underestimated on 120° angle trials in both experiments.

Differences in accuracy are also apparent from the figures. Overall accuracy was higher in Experiment 2 than in Experiment 1. Active participants performed with greater general accuracy on L-L trials on every angle (considerably so with the 90° and 120° angles) than on the equivalent trials in Experiment 1. Accuracy was especially high for the 90° angle (for which mean error was only -0.18°). Passive participants also displayed greater general accuracy on L-L 90° and (especially) 120° angle trials than in Experiment 1. Overall, accuracy was lower only on the 60° angle trials in the Passive condition.

The enhanced accuracy obtained in both the Active and Passive conditions, on S-L and 120° angle trials, and generally also on L-L layout trials, indicates that the leg-length combination on the outbound route exerts an effect on the estimates of the final angle.

Performance overall in this experiment was more accurate than in several previous studies of visual path integration. In the Active condition, mean error ranged from -1.35° ( $\alpha = 90^\circ$ ), through -9.20° ( $\alpha = 60^\circ$ ), to 12.19° ( $\alpha = 120^\circ$ ); and in the Passive condition, from 1.98° ( $\alpha = 120^\circ$ ), through -7.90° ( $\alpha = 90^\circ$ ), to -17.78° ( $\alpha = 60^\circ$ ). By comparison, in studies conducted in conditions of sparse optic flow information, mean underturning by 24° and 19° was reported by Wartenberg, May, and Péruch (1998); and by 20.9° overall, and by 20.3° for isosceles triangles, by Péruch, May, and Wartenberg (1997). Accuracy was higher in a study in which both rotational and translational optic flow were available: Kearns, Warren, Duchon, and Tarr (2002) observed mean underturning by 7.1°. The level of accuracy observed in the current experiment is not as high as that seen in the studies by Riecke, van Veen, and Bühlhoff (2002, 2000), who reported minimal error for rotational estimates; however, the elevated accuracy in those studies may have resulted from provision of performance feedback to participants. Cornell and Bourassa (2007), and Cornell and Greidanus (2006), on the other hand, observed much less accurate performance on routes including large gradual curves in real-world studies.

*Hypothesis 2: Accuracy would differ as a function of route layout (internal angle  $\alpha$  and leg-length combination)*

*This hypothesis was met.* Effects of route (triangle) layout were clear. Triangle layout

exerted a strong influence on performance. Very pronounced effects were apparent, with participant responses exhibiting different patterns and accuracy levels for each layout. An effect of triangle layout on performance was also found in previous studies (Kearns, Warren, Duchon, & Tarr, 2002; Wartenberg, May, & Péruch, 1998; Péruch, May, & Wartenberg, 1997; Loomis et al., 1993).

There were very strong effects of angle: responses in both the Active and Passive conditions showed a tendency for overestimation of the final angle on trials with the 60° and 90° internal angles, and underestimation on trials with the 120° angle. Performance was also clearly influenced by the different combinations of leg-lengths on the routes. The final angle was consistently overestimated on the 60° and 90° angle trials on both the L-L and L-S layouts, in both the Active and Passive conditions, by both genders; and consistently underestimated on the S-L layouts.

The effects of the different distances on estimation of the final angle can be predicted, if it is assumed that changing the leg-lengths influences participants to misperceive how far they had travelled along the straight segments of the route, leading to either overestimation or underestimation of the final angle.

In both the Active and Passive conditions, the typically-observed tendency to underestimate larger angles, and to overestimate smaller ones, in the final response (Kearns et al., 2002; Péruch et al., 1997; Wartenberg et al., 1998; Loomis et al., 1993) was observed, to some extent, on L-L and L-S layouts. However, the final angle was always underestimated on S-L layout trials. Passive estimates were less accurate than Active estimates on 60° and 90° internal angle trials on L-L and L-S layouts; however, they were *more* accurate than Active estimates on 120° angle trials on L-L and L-S layouts, and on S-L layouts with all angles.

*Hypothesis 3:* Path integration performance would be more accurate on 90° angle routes with a small turn (intersection) than on 90° angle routes with a large turn (roundabout)

*This hypothesis was partly met.* In both the Active and Passive conditions, estimates on the intersection trials were more accurate than on the roundabout trials on L-S layouts, while estimates on the roundabout trials were generally more accurate than on the intersection trials on S-L layouts. On L-L layouts, differences in accuracy between responses for both turn types were small in the Active condition, showing that, in general, responses were not influenced greatly by turn type. However, there was a greater effect of turn type on responses in the Passive condition, which was largely due to differences in the accuracy of estimates between the two turn types by female participants.

Overall error patterns depended on route layout on both intersection and roundabout routes: on trials of both turn types, the final angle was consistently overestimated on L-S layouts, and underestimated on S-L layouts, across all environments, in both the Active and Passive conditions. Responses on L-L layouts are slightly less consistent: participants in the Passive condition mostly slightly underestimated the final angle on intersection trials, but overestimated it on roundabout trials; whilst participants in the Active condition very slightly underestimated it, on both intersection and roundabout trials. Responses were more accurate overall on the L-L layout, across all environments, than on the L-S and S-L layouts layouts, in both the Active and Passive conditions.

Turn type was not very influential on male responses in either the Active or Passive condition, or on female responses in the Active condition: estimates on the intersection and roundabout trials showed similar levels of accuracy across environments. However, turn type had some effect on estimates by female participants in the Passive condition: compared with estimates by females in the Active condition, and by males in both conditions, there was greater divergence between the intersection and roundabout trials in terms of accuracy, which also depended on route layout (length of the first outbound route). For Passive female participants, the pattern of error differed between routes with a longer outbound route and routes with a shorter outbound route: on intersection trials, estimates were much more accurate on L-L and L-S layouts; whilst on roundabout trials, they were much more accurate on S-L layouts.

The general trends in the data were the same for both genders: for both turn types, in both the Active and Passive conditions, and across all four environments, greater accuracy on the L-L layouts than on the other layouts (except for female responses on L-S layouts); and consistent overestimation of the final angle on the L-S layout, and underestimation on the S-L layout.

Female participants may have been particularly sensitive to the inability to rely on the rotational self-motion information in the Passive condition of Experiment 2. Active participants could rely on rotational optic flow information to estimate the velocity of their self-motion to a greater extent than their Passive counterparts, because of the additional basic proprioceptive information provided by the steering action (that is, sensory feedback from physical action): thus, they were better able to track their orientation and position. Passive participants were less able to judge their speed from the flow. Males may have been able to compensate for this to a greater extent than females, and, therefore, there was less divergence between their responses in the Active and Passive conditions. The lack of psychological control in the Passive condition may also have had a greater impact on females than males.

Thus, in this experiment, the inclusion of a larger curved section of the route did not lead to vastly greater error than in most previous studies of visual path integration, in contrast with real-world non-visual studies which have found such an effect (Cornell & Bourassa, 2007; Cornell & Greidanus, 2006). Triangle layout had a greater effect on performance than the large rotation, in general (except for performance by females in the Passive condition).

The lack of a strong effect of turn type in Experiment 2 may have been because the sensory signals for rotation cancelled each other out during integration, due to the complexity of the rotational stage in the roundabout design: the action of turning left, off the roundabout, simultaneously constituted turning right, onto the second leg of the triangular route. Females may have been more sensitive to the rotational information in the Passive condition, perhaps because in the Active condition they were able to use alternative information obtained from the active control of their self-motion.

*Hypothesis 4:* More accurate path integration performance would result from participant control over the simulated self-motion in the Active condition, compared with passive participant observation of the self-motion (in the Passive condition in this experiment and in Experiment 1)

*This hypothesis was partly met.* Overall, responses on 60° and 90° internal angle trials, on L-L and L-S layouts, tended to be more accurate in the Active condition than in the Passive condition. However, greater accuracy was shown in the Passive condition than in the Active condition on 120° internal angle trials on all layouts, and on S-L layout trials with all internal angles. This is shown in figures 4.2, 4.3, 4.4 and 4.5. There was a high level of variability overall in both conditions, especially in the Passive condition, which is clear from the error bars.

Participants in the Active condition tended to treat all the internal angles as 90° angles: a phenomenon which has been found in previous research (Loomis et al., 1993; Loomis, Klatzky, Golledge, & Philbeck, 1999). This is indicated by the mean directional estimate on 60° and 120° angle trials being close to the correct response value for 90° angle trials. In figures 4.2, 4.3, 4.4 and 4.5, the blue (Active) line is quite flat. Active participants showed the least mean error on 90° angle trials and the greatest mean error on 120° angle trials.

The tendency for directional estimates to be biased towards 90° angles is a common response bias, which may arise from a distorted mental representation (Waller, Beall, & Loomis, 2004; Sadalla & Montello, 1989; Moar & Bower, 1983). It may also result from the use of a circular dial: this can lead to the orthogonal axes

being used as a reference system when estimating egocentric directions; or to a reliance on heuristics, in order to cope with the high demands placed on working memory by the need to imagine the environment and heading direction (Waller et al., 2004). In studies in which a dial is used to point, directional estimates have been observed to be most accurate near the orthogonal directions of 0°, 90°, 180° and 270°; and error has been found to increase, the further the target direction from one of the orthogonal axes, that is, ahead, behind, left and right (Montello, Richardson, Hegarty, & Provenza, 1999; Sadalla & Montello, 1989). Error in the estimates may result from an adjustment process, whereby directions are first roughly judged as being closest to one of the four axes, then more finely aligned within one of the four quadrants of egocentric space (Montello et al., 1999).

Participants in the Passive condition, on the other hand, were most accurate on 120° angle trials, and least accurate on 60° angle trials. In comparison with participants in the Active condition, Passive participants showed greater error on 60° and 90° angle trials, but considerably less error on 120° angle trials.

Passive participants may have shown the greatest accuracy on the 120° angle trials because they were especially able to benefit from the proximity of the exit road to the approach road, as they did not need to focus their attention on controlling the simulated self-motion with the steering wheel and pedals. Participants travelled a shorter distance around the curved segment of the route on 120° angle trials, than on trials with the other angles, as the exit road was closer to the approach road; thus, participants experienced less rotation, as they arrived at the exit road more quickly. This may have assisted Passive participants to perceive the distance they had travelled, or the degree of rotation they had gone through, more accurately.

*Hypothesis 5:* Accuracy of path integration performance would depend on the levels of realistically-presented optic flow and depth cues in the environments

*This hypothesis was partly met.* Effects of environment were found in this experiment, but they were not the expected ones. Performance was expected to be more accurate in the more detailed urban environments than in the rural ones: the urban environments had richer texture, and, therefore, provided a high level of both translational and rotational optic flow. Performance was also expected to be more accurate in the environments with the additional structures than in those without structures, due to the depth cues which the structures provided.

In fact, Active participants showed more accurate overall performance in the urban and rural environment with no additional structures, in comparison with the corresponding two environments with structures; accuracy was greatest in the urban

environment with no structures (Ur-N). Thus, the effect was not completely in the expected direction. Passive participants performed more accurately, overall, in both rural environments than in the two urban environments; estimates were most accurate in the rural environment with no structures (Rur-N). Thus, the effect was in the opposite direction to the one expected. However, the differences in mean error between the four environments were very small, in both navigation modes: that is, a range of only  $4.11^\circ$  in the Active condition, and  $9.34^\circ$  in the Passive condition.

Overall, therefore, there was a tendency for more accurate performance in the environments without structures. Participants may have performed less accurately in the environments with structures because they tried to use the structures as visual references to help keep track of their heading and position; that is, they may have attempted to navigate by piloting, by using one or more of the structures as landmarks. Piloting is the preferred strategy in human visual navigation, when salient landmarks are available: thus, it is understandable that participants would attempt to use it to perform the task. However, this strategy was misleading in this experiment, as the structures were actually not a stable source of information.

The structures provided unreliable tracking and directional information, as their positions were not fixed: they were interchanged in the four environments. Thus, the information which participants perceived from the structures conflicted with the information which the structures actually provided. Attempting to use the structures as fixed reference points would have resulted in inaccurate performance, therefore.

Participants may have tried to navigate using piloting, either by itself, or together with path integration: for example, by using the structures as reference points, together with information from the optic flow (and also from the rudimentary proprioceptive feedback resulting from the steering action, in the Active condition). External references, such as landmark information and self-motion cues, normally interact continuously during navigation, and complement each other: the information they provide is integrated, and preference is given to one or the other, depending on its salience or reliability.

Active participants were able to estimate the speed of their self-motion more accurately in the environments (both urban and rural) without structures, than in those with structures. The self-motion information available to them from the active control was more reliable and informative in the environments without structures, as the optic flow cues were supplemented by the proprioception signals, and there was no confounding visual information from the additional structures. Thus, Active participants performed more accurately in the conditions with no structures, as they relied only on the optic flow, and were not influenced by the additional structures. Hence, their performance was most accurate in the Ur-N environment, which

provided the highest level of optic flow information (as it had the greatest amount of complex texture), together with some minimal physical feedback.

However, Passive participants could not take advantage of the rich optic flow information in the highly-textured urban environments, to judge the velocity of their self-motion as accurately as Active participants, as there was no additional proprioceptive information available in the Passive condition. However, Passive participants were able to perform reasonably accurately in the rural environments, which had a simpler overall visual structure: thus, they displayed greater accuracy in these environments than in the rural environments.

Péruch, Vercher, and Gauthier (1995) also found that active navigation (self-initiated movement, and the ability to change viewpoints with a joystick) facilitated human path integration performance, by comparison with passive navigation, in a small-scale simple virtual environment. Active participants were faster and more accurate in reaching targets, which were not visible from the starting point, by the shortest path; performing path integration was also found to be easier during active navigation than during passive navigation.

No effect of environment was found in Experiment 1, in which all of the participants experienced the simulated self-motion passively, and a more limited set of route layouts was used, together with the large-screen display. The effect of environment may interact with display parameters and / or with the route layout. The routes were more varied in the second experiment, and included layouts in which the lengths of the two outbound roads were not equivalent.

These findings contrast with those of Kearns et al. (2002): when the amount of information available from simulated optic flow was varied, a richly-textured environment containing both wall and floor texture increased the accuracy of performance, as participants had access to both rotational and translational optic flow. Reduced rotational flow reduced turning accuracy, in the final response.

*Hypothesis 6:* The 3-screen semi-surrounding display, realistic visual information, and authentic environments, together, would increase participants' sense of presence, by making the experience more immersive, in the absence of other immersive features

*This hypothesis was met.* The spatial presence and engagement scores in Experiment 2 are similar to those in Experiment 1. This suggests that the use of the small screens did not impact negatively on participants' sense of presence in the virtual environments, nor on their engagement with the virtual experience, in comparison with the use of the large simulator screens. Participants' impressions of

the believability of the environments were not negatively affected, either, since participants in both experiments found them reasonably ecologically valid. Compared with participants in Experiment 1, Passive participants found the environments slightly more natural, whilst Active participants judged them to be slightly less natural; but there is not a great difference.

There was no great effect of the change to small screens from the large screens on these three presence factors, therefore. This indicates successful compensation for possible reduced immersion. The change of equipment did impact positively on negative effects, however: scores in the second experiment were considerably lower than in the first experiment, for both the Active and Passive groups. This confirms that the small-screen display was less likely to cause disorientation and cybersickness symptoms for participants.

Thus, in general, the smaller-screen apparatus was able to elicit a sense of presence as well as the large simulator, and it was not detrimental to the perception of the virtual environments as believable and lifelike. The small-screen arrangement also had the considerable advantage that it was less likely to have adverse effects. Overall, these findings indicate that virtual environments do not require a high level of photorealism or detail in order to evoke a sense of presence; very sophisticated technical equipment is not needed, either. In fact, less sophisticated equipment can even be beneficial, because it leads to fewer adverse reactions.

The very similar findings from Experiments 1 and 2, in terms of participants' experience of presence, contrast greatly with the large difference between the two experiments in terms of the path integration measures. This suggests that the difference in path integration performance was not due to a sense of presence resulting from the display and other features. This confirms the importance of the effects of other factors, such as the geometric parameters of the route layouts (internal angle and outbound leg-lengths) on path integration performance.

*Hypothesis 7:* Sense of presence would be greater in the Active than in the Passive condition, due to the inclusion of some interactivity and participant control

*This hypothesis was met.* A sense of presence was experienced by participants in both conditions, but more so by Active participants than Passive participants. The participants in the Active condition possibly felt more present in the virtual world because they were engaged in an activity in it; whilst the experience of Passive participants was, by definition, less participatory. The similar ratings for engagement in both conditions suggest that either having control did not enhance engagement, or that not having control did not lessen it.

The environments were found to be more natural by the Passive participants than the Active participants, perhaps because they were less distracted by adverse effects. The higher scores for negative effects for the Active group than the Passive group reflect the nauseogenic nature of controlling the self-motion. Whilst this is contrary to much of the literature, it supports the experimenter's observations during the experiment, as well as participants' own self-reported experience of sickness symptoms, together with the fact that it was mostly Active participants who withdrew from the experiment due to cybersickness. Differences in overall variability between participants in the two navigation modes are also related to this issue, as Active participants showed more variability than Passive participants for negative effects. Passive participants may also have had a greater appreciation of the design of the virtual environments, as they did not have to focus on controlling the simulated self-motion, and so they had more opportunity to look at them.

Features which were found to be reasonably authentic by participants in both conditions were aspects of the roads, the countryside, the mountains / hills, and the houses. In the Active condition, the features which participants perceived as most authentic were road- and driving-related aspects, such as markings, street lights, signs, and roundabout design and appearance (which were not mentioned at all by Passive participants). Active participants, as "drivers", had to pay more attention to these features than the Passive participants, and needed to use the information obtained from the features to perform the task itself. Passive participants, however, could look at whatever they found interesting. Thus, the active navigation mode tended to focus drivers' attention on the road.

The features which participants indicated should be changed, in order to make the virtual environments more authentic, also reflected the different conditions under which participants experienced the virtual world. Participants in both conditions overwhelmingly referred to farm animals as the most important missing feature. However, the other major categories of features suggested by Active participants tended to be those useful in driving, such as names on buildings (which are salient for drivers, as they could potentially serve as landmarks), road signs and markings; whilst for Passive participants, trees and other vehicles were more important.

The level of variability among participants was again high, and also reflected the different experiences between participants in the two conditions. Higher variability among Active participants for negative aspects, for example, reflected the fact that cybersickness symptoms were especially high for some Active participants, whilst others had none at all; whereas fewer Passive participants experienced symptoms overall. Similarly, greater variability among Passive participants for spatial presence reflects their less participatory role than that of Active participants, which would have

diminished a sense of presence for some (perhaps especially those accustomed to taking active roles in computer game playing).

*Hypothesis 8:* A heightened sense of presence and engagement would result in more accurate path integration performance

*This hypothesis was not met.* There was no effect of any of the four factors on the sense of presence scale: thus, higher levels of presence did not lead to higher accuracy of path integration performance. Sense of presence had no effect on path integration performance, overall. Accuracy of performance was unaffected by participants' level of presence, engagement with the virtual experience, impressions of the naturalness of the virtual world, and negative effects.

The lack of an effect may have been because the environments were not immersive enough, in general. The mean scores on each presence factor were mostly only around the mid-point of the scale, reflecting a quite average level of presence. As a result, it was difficult to form sufficiently differentiated *high* and *low* groups on each factor, due to limited numbers of scores at the extreme ends of the scale. A greater difference between the groups would have been possible if scores had been more polarised. It is apparent from Appendix G that the sample sizes for the *high* and *low* groups were also quite unequal on some factors. The cut-off point between the groups was also rather arbitrary: participants with scores of up to 2.99 were included in the *low* group, and those with scores above 3.00 in the *high* group.

*Hypothesis 9:* Female performance would be particularly enhanced by the effects of the small screens and authentic environments, realistic visual information, and increased presence, as females would benefit from the use of less intrusive apparatus leading to increased confidence, and thus reduced or minimal gender differences compared with previous studies and Experiment 1

*This hypothesis was partly met.* Gender effects were evident. There were differences in accuracy for males and females. No clear pattern emerged in terms of accuracy between the genders, however. On 60° and 90° angle trials, females were more accurate in the Active condition, and males were more accurate in the Passive condition; whilst on 120° angle trials, males were more accurate in the Active condition, and females more accurate in the Passive condition. Both genders were most accurate on the 90° angle, showing quite small errors overall: females were especially accurate, more so than males. However, patterns of error for the 90° angle differed: females tended to underestimate it, and males to overestimate it. On the

other hand, both genders overestimated the 60° angle and underestimated the 120° angle, thereby showing the typical tendency to overestimate the small angle, and underestimate the large angle (Loomis et al., 1993, 1999b). Thus, the gender picture is quite complex: one gender was not consistently more accurate than the other. Both genders also showed high levels of variability.

The use of the small-screen apparatus contributed to reduced gender differences, compared with Experiment 1. The different route layouts may also have contributed to this effect, by widening the set of conditions on which participants performed. As females tended to perform more accurately than males on some layouts (for example, the S-L layout), it is possible that the more restricted set of equilateral triangles used in the first experiment masked gender differences, which would have favoured females and resulted in an increased overall level of accuracy for female performance. This would have reduced the apparent male performance advantage.

Reduced gender differences also resulted from the use of different navigation modes. There were clear differences in accuracy between males and females, which implicated mode of navigation: for example, absolute error on the 60° and 90° angles tended to be lower for females than males in the Active condition; but lower for males than females in the Passive condition. Since all participants were passive in the first Experiment, this may have contributed to an apparent male advantage in accuracy.

Some interaction between gender, navigation mode, angle, and leg-length combination is also apparent. Males consistently underestimated the final angle on 120° angle trials, with all three leg-length combinations, in both the Active and Passive conditions; whilst females underestimated the final angle on 120° angle trials with all three leg-length combinations in the Active condition, but consistently overestimated it in the Passive condition.

#### **4.4.2 Explanatory Models and Predictions**

Two models were proposed in Chapter 2, in order to account for the error in the directional estimates. *Negative* errors, that is, overestimation of the final angle (when participants turned the pointer on the dial too far), were proposed to result from misperception of two kinds: overestimation of *rotation* at the end of the first leg on the outbound path (together with correct distance perception), as shown in figure 4.8; or overestimation of *distance* on the outbound path (combined with correct perception of rotation), as shown in figure 4.9. The type of error is illustrated, in the figures, by the

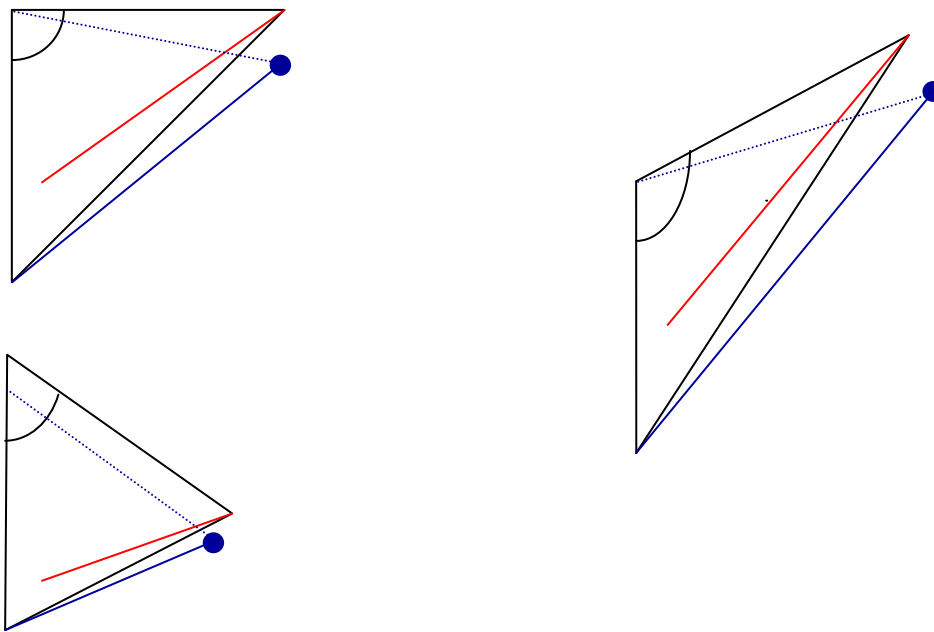


Figure 4.8. Model 1: Rotation overestimated by some percentage. Distance perceived correctly. (Hypothetical example)

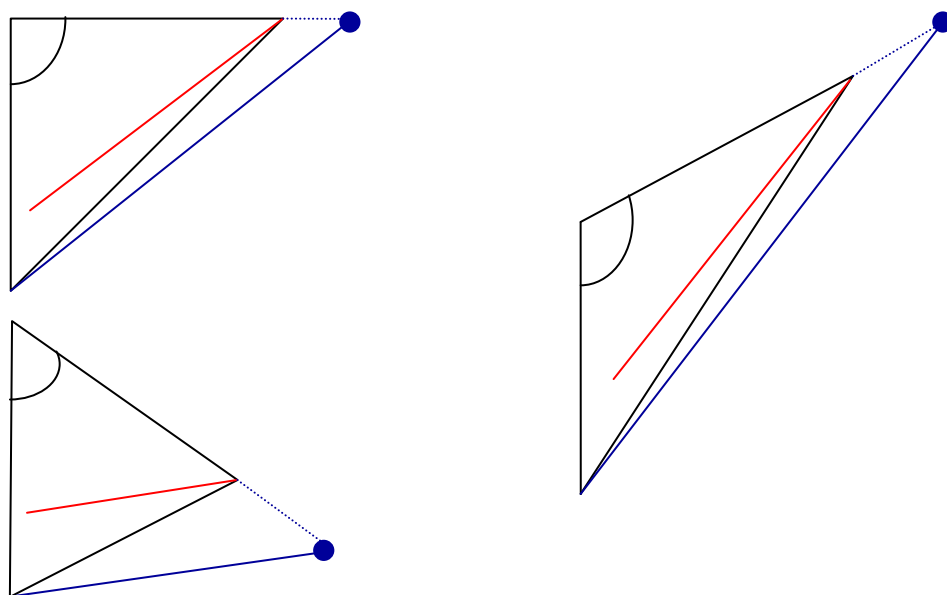


Figure 4.9. Model 2: Distance overestimated by some percentage. Rotation perceived correctly. (Hypothetical example)

- perceived (erroneous) location
- correct response from erroneous position
- error (parallel response from correct position)

position of the red line (representing an erroneous response) with respect to the solid blue line (which represents the correct response from the perceived final position).

In Experiment 2, consistent overestimation of the final angle was found on the 60° and 90° angle trials on the L-L (equal-length) and L-S (long-short) route layouts. From figures 4.2, 4.3, 4.4, and 4.5, it can be seen that both the blue and red lines, (which represent the Active and Passive condition, respectively) are consistently above the black dotted line (representing the correct response), where they connect to the data points for the 60° and 90° angles. This indicates negative error. It can be attributed to overestimation of either rotation or distance on the outbound path.

Conversely, *positive* errors, that is, underestimation of the final angle (when participants did not turn the pointer on the dial far enough), were proposed to result from underestimation of rotation (combined with correct perception of distance); or from underestimation of distance (together with correct perception of rotation) on the outbound path. Both types of error are illustrated by the position of the red (error) line below the blue (correct response) line, in figures 3.12 (underestimation of rotation) and 3.13 (underestimation of distance).

In Experiment 2, underestimation of the final angle was found on the 120° angle and S-L (short-long) layout trials. It is apparent from figures 4.2, 4.3, 4.4, and 4.5, for Experiment 2, that the blue (Active) and red (Passive) lines consistently fall below the dotted (correct) line, where they connect to the data points for the 120° angle. This indicates positive error, which is attributable to underestimation of either rotation or distance. Underestimation of the final angle was illustrated by the data for all three internal angles in Experiment 1: in figures 3.10 and 3.11, the lines which connect the data points, representing the mean directional estimates, are positioned below the dotted (correct) line.

Thus, the data indicate a particular class of error, through the position of the red line, relative to the correct directional response: overestimation of either the angle, or the distance, if the red line is above the blue line; and underestimation of either the angle, or the distance, if the red line is below the blue line.

It is assumed that participants are able to execute the correct response towards the final position at the end of the second leg; and that the error, thus, results, instead, from misperception either of distance on the outbound legs, or of the degree of rotation between them. It is further assumed that, in the case of correct perception of the rotation, participants perceive the length of the second leg to be equal to the length of the first leg; this perception is incorrect in some cases in Experiment 2, as the legs were actually of different lengths on some layouts. As was pointed out earlier, the nature of the data renders it inappropriate for discrimination between the rotation and distance error models; or to ascertain

whether the error can be explained by a mixture of the two models, that is, by simultaneous misperception of rotation and distance. However, classifying the types of errors that can occur in this way, as illustrated by the graphs, can be considered a first step in the analysis. The models could be further refined with more data.

As noted in chapters 2 and 3, overestimation and underestimation of the final angle are assumed to indicate misperception of the distance travelled on the outbound path; rather than of rotation between the two outbound legs of the route. Previous studies of human path integration based on optic flow cues, conducted in virtual environments, and using a range of tasks and conditions, have demonstrated both underestimation of distance (Frenz & Lappe, 2005; Frenz, Lappe, Kolesnik, & Bührmann, 2007; Lappe, Jenkin, & Harris, 2007; Bakker, Werkhoven, & Passenier, 1999); and overestimation of distance (Redlick, Jenkin, & Harris, 2001; Lappe et al., 2007; Kearns et al., 2002; Bakker, Werkhoven, & Passenier, 2001).

Thus, overestimation and underestimation of the final angle are assumed to indicate misperception by participants of how far along the outbound path they had travelled. Overestimation may have been due to participants perceiving that they were travelling more quickly than they actually were, and, hence, that they had covered a greater distance than the true distance, and progressed further. In the case of underestimation, on the other hand, participants may have perceived that they were travelling more slowly than they really were, and, hence, that they had covered a shorter distance than the true distance, and progressed less far.

There are several factors which potentially contributed to misperception of the final angle. Perceived velocity of self-motion, and, ultimately, perceived travelled distance, may have been influenced by the effects of oculomotor responses, limited depth cues, presence and immersion. These factors will be discussed in chapter 6. The results for the 60° and 90° angle trials with L-L (equal) leg lengths in the second experiment are different from those obtained for comparable (that is, 60° and 90° angle) trials in the first experiment, in which the final angle was consistently underestimated, and error increased with increasing size of the internal angle. A number of factors may have contributed to this difference in the pattern and accuracy of results. These include effects due to differences in accommodative distance, display screen size, and levels of presence and immersion. They will also be discussed in chapter 6.

The routes with the 120° angle and S-L layout differ from the other routes, in that the first part of the journey for both is shorter. The 120° angle routes have a shorter segment on the roundabout than the 60° and 90° angle routes, as the 120° angle exit-road is closer to the approach road; similarly, S-L layouts have a shorter

first leg than L-L and L-S layouts. As the distance on both these routes is shorter, travel duration on the routes is also shorter, compared with the other route layouts.

## 4.5 Unresolved Issues from Experiment 2

The second experiment has raised the issue of the effect of different triangle layouts on distance estimation in path integration. The distance which participants perceive they have travelled, along the two outbound path legs, clearly influences their perception of the required degree of rotation, in the final turn towards the origin: the results differed for layouts in which the combination of the first and second leg-lengths was varied, with effects on both the pattern of error and accuracy. It was found that routes with a long first road (that is, the L-L and L-S layouts) produced a pattern of overestimation on the 60° and 90° angle trials, whilst the route with a short first road (that is, the S-L layout), by contrast, produced a consistent pattern of underestimation for all angles. These errors can be predicted from the model of distance underestimation on the outbound route which has been proposed, if it is assumed that participants perceive the lengths of the first and second legs to be equal.

It is possible that the ability to use optic flow to estimate the final angle was influenced by the different leg-length combinations: it may have been more difficult to estimate distance on some layouts than others, because of the different availability of optic flow information. The use of optic flow to estimate velocity of self-motion, travel duration, and, ultimately, distance, on the different layouts may have been facilitated by some combinations. In the third and final experiment, therefore, the importance of optic flow information for path integration will be further considered, by examining the effects of removing the smooth optic flow on performance on the different triangle layouts (with different leg-length combinations).

Optic flow generated during self-motion through an environment is an essential source of information for visual navigation by path integration (Lappe, Bremmer, & van den Berg, 1999). Human observers can use optic flow to estimate the direction of their self-motion, or heading (Warren, Morris, & Kalish, 1988; Warren & Hannon, 1990; Gibson, 1950) and the distance they have travelled (Bremmer & Lappe, 1999; Frenz, Bremmer, & Lappe, 2003; Redlick, Jenkin, & Harris, 2001; Riecke, van Veen, & Bühlhoff, 2002; Sun, Campos, & Chan, 2004). Accurate heading and distance estimation are required for effective navigation. Heading information extracted from self-motion can be distinguished from potentially confounding information from eye movements (Warren & Hannon, 1990; Royden, Banks, & Crowell, 1992; Stone & Perrone, 1997).

Optic flow provides important cues about direction, speed and duration of self-motion through an environment, which can be integrated to estimate the distance that has been travelled, and the magnitude of turns along the route (Bremmer & Lappe, 1999; Péruch, May, & Wartenberg, 1997; Riecke et al., 2002). The distance and direction of self-motion are tracked during path integration, by integrating changes of position that occur over short sections of the path to yield the total path, including the direction and magnitude of any turns. Optic flow provides information about the direction and magnitude of both the linear and rotational components of the self-motion.

The distance travelled during self-motion can be estimated from optic flow (from which an estimate of self-motion velocity, relative to the environment, is derived), together with depth cues, which provide information about the structure of the environment. Navigators first need to estimate the speed and duration of their own self-motion from the optic flow speed, which requires knowledge of, or assumptions about, scale (depth) in the environment, that is the distance between individual objects in the environment and the observer. The estimated velocity of simulated self-motion is integrated over time, using a 3D percept of self-motion through the environment (Bremmer & Lappe, 1999; Frenz et al., 2003; Redlick et al., 2001; Riecke et al., 2002; Sun et al., 2004).

Optic flow does not specify travel distance, because the speed of optic flow experienced by moving observers is influenced by both the velocity of their own self-motion and the distance between themselves and visible objects (Lee, 1974). Thus, optic flow speeds covary with dimensions of the environment, and so depend on the scale of the particular environment. Optic flow is ambiguous with respect to scale, as covarying observer speed and the distances to objects in the scene can produce identical optical flow. Thus, to recover absolute speed or distance travelled from optic flow, information about the scale of the visual environment (such as objects of known size in the scene) is needed, to calibrate optic flow speed to the environment. Thus, the ability to update position in the environment following self-motion, using the estimated travel distance, requires explicit use of the scale of the environment (Frenz et al., 2003; Redlick et al., 2001).

The availability of optic flow can facilitate accurate performance on the triangle-completion task: it provides information about linear and angular velocity during self-motion, which human navigators need to determine both the distance they have travelled along the straight sections, and the degree of rotation they have turned through, on the outbound route. This, in turn, enables accurate updating of the vector representation that specifies the distance and direction of their current position

and heading, relative to the origin. Integrating velocity information enables continual successive estimates of translational and rotational displacements from the origin.

Monitoring the rate of optic flow from visual textures on the ground and in the surrounding environment is important for path integration, as these specify the speed and direction of translation and rotation, respectively. Integration of the rate of optic flow from the ground over time (assuming constant eye height) allows the distance travelled during translation to be determined; while integration of the rate of optic flow from the surrounding environment over time enables angles turned during rotation to be ascertained (Kearns, Warren, Duchon, & Tarr, 2002). Integration of turn rate over time enables navigators to determine the turn since last known heading. Flow increases from the ground to surfaces at eye-level.

Previous studies suggest that the accuracy of path integration performance in the triangle-completion task increases with greater availability of optic flow: especially complex optic flow which is embedded in a realistic context.

Previous triangle-completion studies have found a general underestimation of the final angle, and a bias towards stereotyped responses, in both visual and non-visual path integration; performance also tends to be influenced by triangle geometry, whereby larger angles are increasingly underestimated (Kearns et al., 2002; Péruch et al., 1997; Wartenberg, May, & Péruch, 1998; Loomis et al., 1993; Klatzky et al., 1990). These effects, especially the underestimation of the final angle, were particularly strong in the studies of visual path integration in virtual environments by Péruch et al. (1997) and Wartenberg et al. (1998), when compared with the studies in non-visual conditions by Loomis et al. (1993) and Klatzky et al. (1990). Accuracy was considerably lower than in non-visual studies. Very limited optic flow information was available in these studies of visual path integration.

More accurate visual path integration performance was found when rotational and translational flow were available simultaneously (Kearns et al., 2002). However, participants were not very sensitive to triangle layout, tending to produce very similar turning angles for different layouts: they seemed unable to use rotational optic flow to extract the turning angle. However, responses showed sensitivity to changes in segment length of the triangles, suggesting an ability to estimate the distance travelled, by integrating optic flow from translations. Optic flow information was available from an abstract texture pattern in this study.

Highly accurate performance was found when visual path integration was based on complex optic flow, which was contextualised in more realistic virtual environments: Riecke, van Veen, & Bühlhoff (2000, 2002) found very small systematic turning error, although larger angles were increasingly undershot and small angles overshot.

In the final experiment of the current study, participants will perform the triangle-completion task without access to information from smooth optic flow. It is predicted that less accurate performance in the triangle task, overall, will result from the disrupted optic flow cues.

It is further predicted that performance will be impaired to a greater extent on routes with longer outbound paths (that is, on those with L-L and L-S layouts, combined with 60° and 90° angles), than on routes with shorter outbound paths (that is, on those with the S-L layout and 120° angle). Error accumulates with distance during path integration. It will be more difficult for participants to perform path integration, with disrupted self-motion cues, on longer outbound paths. The disrupted optic flow will make estimation of velocity during self-motion more difficult, and, hence, less accurate, over longer distances. This, in turn, will make it more difficult for participants to estimate the distance they have travelled, by using the self-velocity information; resulting in less accurate distance estimates. This will lead to greater error in the final angle estimates: in this study, error in the directional estimates has been attributed to misperception of the distance travelled on the outbound path.

Performance on the shorter outbound routes is expected to show higher accuracy, as participants will be less susceptible to the effects of disrupted self-motion information over the shorter distance. The cumulative effect of error during path integration will be less, over the shorter distances.

A high level of accuracy in the directional estimates, overall, would indicate that the optic flow cues are not essential for performance of the task; and that participants are able to compensate for the lack of optic flow by using some other information, or, possibly, some other strategy altogether.

## Chapter 5. Experiment 3.

### 5.1 Aims

The main aim of this experiment was to investigate the importance of optic flow, produced by self-motion, for path integration. Visual information was presented intermittently, thereby disrupting smooth self-motion, and, hence, the optic flow: the effects on path integration performance within a large-scale virtual environment were examined. The effects of three other variables were also assessed: these were variations in route layout (that is, the lengths of the two outbound roads and the angle between them); the large curve on the roundabout; and gender.

The perception of both rotational and translational self-motion is important for navigation. Humans are able to estimate distance and angular displacement quite accurately from the combined translational and rotational components of optic flow, during both linear and curvilinear, or circular, self-motion. This information is essential for visual path integration. Under normal circumstances, information derived from visual motion, such as depth and 3D structure, is integrated with information from other visual cues; and with extra-retinal information about eye and head movements.

Information from optic flow is, thus, important for performing the triangle completion task: it enables the distance, which is travelled along the outbound legs of the route, and the value of the angle between them, to be estimated. This information is required to update the vector representation of position and orientation to the origin of travel, which supports accurate performance.

Restricting optic flow information was, therefore, expected to impair the ability of participants to perform path integration. It was anticipated that, without information from self-motion enabling integration of speed over time, participants would find it difficult to judge how far they had travelled along the straight segments of the route, and the degree of rotation they had experienced on the curved segment. This would hinder participants' ability to accurately keep track of the starting point of the route.

A further expectation was that variations in the triangle (route) layout, that is, in the leg-length combination and internal angle, would differentially impair participants' ability to perform path integration in the absence of optic flow. Accuracy of performance depended on route layout when reliable optic flow cues were available in Experiment 2: without such visual information, completing the task would be more difficult. The pattern of error, that is, underestimation versus overestimation of the final angle, also differed according to layout in Experiment 2: the length of the outbound path was especially important. The kinds of error produced, therefore, indicate the effects of angle and distance on path completion performance.

It was further expected that path integration would be found particularly difficult, leading to greater inaccuracy in performance, on routes with a small turn (sharp curve), compared with routes with a large turn (gradual curve): that is, performance would be less accurate on intersection trials than on roundabout trials. It was expected that the larger curve, and associated longer travel duration, would provide more opportunities for the use of other visual information and strategies to compensate for the difficulty using the optic flow information.

Several previous studies have examined the effects of intermittent versus dynamic presentation of visual information on human path integration performance, in virtual environments. However, the findings are inconsistent. Some studies have found that continuous presentation of visual information is not required. Gaunet, Vidal, Kemeny, and Berthoz (2001) observed that path integration performance was supported by intermittent views of a large-scale urban virtual environment: that is, a series of still snapshots of the route, presented sequentially from every 4m along it. Péruch, Vercher, and Gauthier (1995) also found that participants were able to reach specified targets in a virtual environment, after viewing a series of static scenes of a route, which were presented from successive points along it; although it was difficult for them. Finally, Mestre (1988) observed that participants were able to successfully steer a large virtual ship along a simulated channel, using visual information from a perspective view of the channel that was presented as a sequence of static frames, which were updated every 3s.

However, Kirschen, Kahana, Sekuler, and Burack (2000) found that smooth optic flow led to more accurate path integration than disjointed optic flow in a virtual city-block environment. The two optic flow conditions were very different in this study: the display was updated either twice or 50 times, respectively, during movement along equal-length segments of a route. Thus, intermittent optic flow had a detrimental effect on path integration performance, compared with smooth optic flow. This suggests that the quality of the optic flow presented in the stimulus is important.

Finally, gender effects were of interest in the current experiment. Two previous studies suggest that females depend less than males on optic flow to perform visual path integration in virtual environments, and that they rely, instead, on non-visual cues and static visual information; or on the use of other strategies, such as timing. Males pay more attention to visual cues, such as optic flow, than static visual information. Kearns et al. (2002) found that females were less affected than males by the amount and type of optic flow information available. Males tended to perform randomly in an environment with minimal texture. Fortenbaugh, Chaudhury, Hicks, Hao, and Turano (2007) found that males could switch between cues, depending on the level of information they provided, and use non-visual cues if visual

cues were less informative. Females found it difficult to do this, as they were less able to use visual cues. Males tended to use visual cues in environments with photorealistic textures, and auditory cues if texture was minimal. Males could also ignore misleading auditory cues when a salient visual cue was available.

Thus, there are gender differences in the types of sensory information which are preferred for spatial updating. Male performance, therefore, was expected to be particularly impaired by the disrupted optic flow information, resulting in lower overall accuracy. The restricted self-motion was expected to have less effect on female performance.

Participants observed a series of static scenes viewed from successive points of view along a route, similar to a slide show made up of sequential snapshots. Severely restricting smooth self-motion through the environments led to limited availability of optic flow information for performing the task. Otherwise, the visual information was presented in the same natural contexts, and authentic virtual environments, which had been used in the previous experiments.

The same experimental apparatus was used as in Experiment 2. It had been found that participants were able to perform path integration reasonably accurately with the small-screen display; and, certainly, within the range of performance ability which has typically been found in previous studies of visual path integration, conducted in virtual environments (Kearns, Warren, Duchon, & Tarr, 2002; Wartenberg, May, & Péruch, 1998; Péruch, May, & Wartenberg, 1997). Reduced gender differences and cybersickness symptoms had also been demonstrated in Experiment 2, compared with Experiment 1, in which large screens had been used. It was, therefore, deemed appropriate to conduct the third experiment using the small-screen apparatus.

Thus, a wide field of view was achieved, through the use of three standard desktop computer monitor flat screens, which partially enclosed the participant. This ensured that peripheral information was available: the intention being to compensate for the lack of information from head movements, which would be available with real motion.

#### *Hypotheses:*

1. Restricted optic flow information would result in lower overall accuracy of path integration performance, compared with Experiments 1 and 2, and with previous studies
2. Accuracy would differ as a function of route layout (internal angle and leg-length combination)

3. Path integration performance on 90° angle routes would be particularly inaccurate with a small turn (intersection), compared with a large turn (roundabout)
4. Female performance would be less impaired than male performance by the disrupted optic flow
5. Performance would be more accurate in environments with added structures, as these would compensate for the absence of reliable optic flow, by providing additional visual cues (depth)
6. Sense of presence would be lower than in Experiments 1 and 2, as the experience would be less immersive, due to the manner of presenting the visual information
7. A lowered sense of presence and engagement would result in less accurate path integration performance, compared with Experiments 1 and 2

## **5.2 Method**

### ***Participants***

There were 30 participants in this experiment, divided equally between males and females. Participants were aged between 17 and 56, with a mean age of 31.6 years. 17 of the participants were students (11 undergraduate and 6 postgraduate), and 9 were staff members, at the University of Waikato. Four participants were employed outside the university. All had either responded to advertisements placed on notice boards around the university campus, or had been recruited through word of mouth, or personal referral, by other participants. All the participants received their choice of either a petrol voucher or book token, to the value of \$20, for their participation. All had normal or corrected to normal vision.

17 of the participants had had no previous experience in a motion simulator; of the 13 who had had previous experience, 12 reported participation of 5 hours or less in total, and one reported total participation of between 5 and 50 hours. All 13 stated that their experience was either for entertainment (9) or as a participant in previous psychology experiments (4) in the University of Waikato driving simulator.

## ***Apparatus: Virtual Environments and Task***

The environments and the task were the same as those which had been used in the previous two experiments. The path layouts were identical to those which had been used in Experiment 2. Thus, this experiment included 48 trials: of which 36 trials were on routes with roundabouts, and 12 trials were on routes with intersections.

In order to compare performance across experiments, Experiment 3 partially replicated Experiments 1 and 2: through the inclusion of three route layouts in which the 60°, 90°, and 120° internal angle were paired with the L-L leg-length combination. This experiment also included a replication of the subset of 90° angle route layouts with an intersection, which had been used in Experiment 2.

## ***Procedure***

The procedure was the same as that used in the Passive condition of Experiment 2, but with one difference: the routes were not displayed as a dynamic image, with realistic simulated smooth self-motion. Instead, participants were presented with a series of still pictures of each route, which had been created by stopping the virtual camera at regular intervals along the route, rather than seeing it as a continuous smoothly-flowing series of images. The virtual camera was stopped every 20 virtual metres along the route. The purpose of presenting the routes in this way was to examine the importance of participant self-motion for path integration in the virtual environments. The presentation of the series of still pictures was paced so that the total time of the experiment was the same as in Experiment 2. The picture remained on screen for 3 seconds, before being replaced by the next picture; thus, a .33 Hz refresh rate was used.

## **5.3 Results**

### **5.3.1 Directional Estimates: Analysis**

Functions from the MATLAB CircStats Toolbox (Berens, 2009; Berens & Velasco, 2009) were used to calculate the mean directions and mean angular deviations (Batschelet, 1981) of the directional estimates, for each condition, for the sample of 30 participants. Outliers were identified, and their data removed prior to the analysis. Arithmetic means and standard deviations were also calculated for the signed error,

as this data is linear. ANOVAs, or their circular equivalents where appropriate, were performed on the absolute and signed error of the directional estimates.

### 5.3.2 Elimination of Outliers

No participants were identified as outliers: none had directional estimates that were more than three mean angular deviations from the sample mean direction for the relevant condition, on more than six trials overall. Thus, data from all 30 participants, of whom 15 were female and 15 were male, were included in the analysis.

### 5.3.3 Overview of the Data: Mean Vector Length and Angular Variance

The distribution of the directional data for each experimental condition was firstly determined, by examining the mean vector lengths ( $R$  values): these are displayed in table 5.1. (Mean vector lengths by gender are shown in Appendix A, and by turn type in Appendix B). Across the three angles, four environments, three leg-lengths, and both turn types, the data were clustered fairly closely around the mean direction: mean vector length was uniformly close to 1.0, with a correspondingly small angular variance. Mean vector length was generally above 0.8 for the 90° angle (for both turn

Table 5.1.

*Mean vector lengths ( $R$  values) for the three angles by environment and distance (combined male / female data)*

Leg-length	Environment	60°	90°	120°
L-L	Ur-S	0.77	0.79	0.84
	Ur-N	0.82	0.85	0.83
	Rur-S	0.86	0.85	0.82
	Rur-N	0.81	0.82	0.85
L-S	Ur-S	0.76	0.80	0.81
	Ur-N	0.81	0.80	0.77
	Rur-S	0.74	0.79	0.82
	Rur-N	0.79	0.84	0.86
S-L	Ur-S	0.83	0.85	0.83
	Ur-N	0.84	0.86	0.85
	Rur-S	0.86	0.87	0.83
	Rur-N	0.82	0.83	0.84

types), and for the 120° angle, and above 0.7 for the 60° angle, on average, across all four environments, and for both genders. There were differences of only a few degrees between environments. There was no clear gender difference: the data were concentrated uniformly around the mean direction for both males and females. Leg-length showed a little more dispersion: for the L-S data, the mean vector length tended to be slightly lower (average of at least 0.7) across three of the environments.

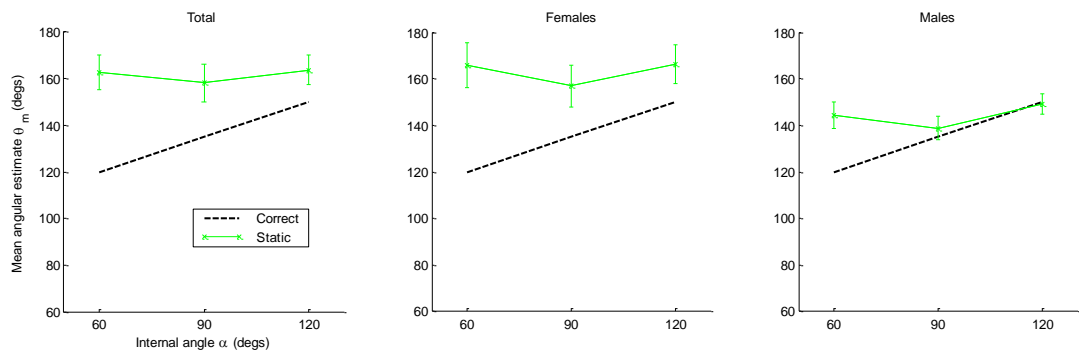
### **5.3.4 Mean Directions and Mean Angular Deviations**

The mean directional estimates for the three internal angles and leg-length combinations are shown, for each environment, in figures 5.1, 5.2, 5.3, and 5.4; and by turn type, in figure 5.5. The data are shown separately by gender, and combined. The error bars show the standard error of the means. The mean directions and mean angular deviations are also shown, by distance and by environment, in table 5.2; and by turn type in table 5.3. (Tables showing mean directions and mean angular deviations, separately by gender, are included in Appendix C).

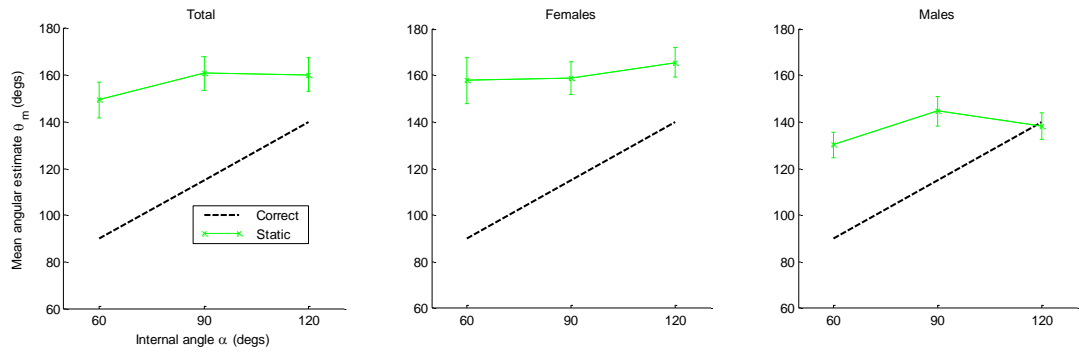
From the figures, it is apparent that there was a general tendency for the participants to overestimate the degree of rotation required on the L-L and L-S layouts, particularly on the 60° angle trials, and to a lesser extent on the 90° angle trials. The error was considerable, especially on the 60° angle trials. The mean error for each condition tended to be much larger than was found in both Experiment 1 and Experiment 2. This is clear, in the graphs for the L-L and L-S layouts, from the position of the green line connecting the data points for the 60° and 90° angle trials (which indicate the mean directional estimates): it is some distance above the black dotted line showing the correct responses. Female estimates showed especially high mean error. Male estimates, although also very inaccurate, tended to be more accurate than female estimates, on average (especially for the 90° angle trials).

Responses on the 120° angle trials, whilst showing an overall pattern of overestimation, tended to be more accurate than on trials with the other two angles: this is shown, in the figures, by a tendency for the green line to fall at the data point for the 120° angle, so that it is closer to the black dotted line. Male estimates, again, tended to be more accurate than female estimates, in general.

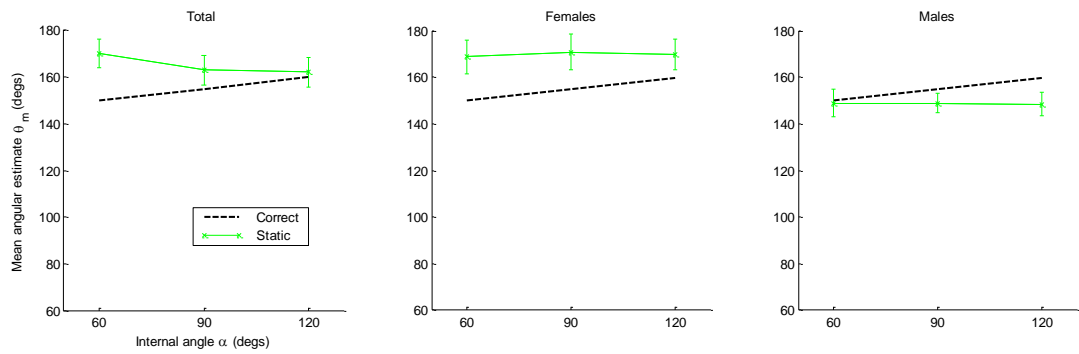
Responses tended to be more accurate, overall, on the S-L layouts. The green line is much closer to the black dotted line in the figures for the S-L layouts than in those for the other two layouts, for all three angles. A different pattern of error is also apparent, compared with those for the L-L and L-S layouts, which is manifested as a gender difference. On trials with all three internal angles, the final angle was mostly overestimated by females; but it was consistently underestimated



Distance: L-L

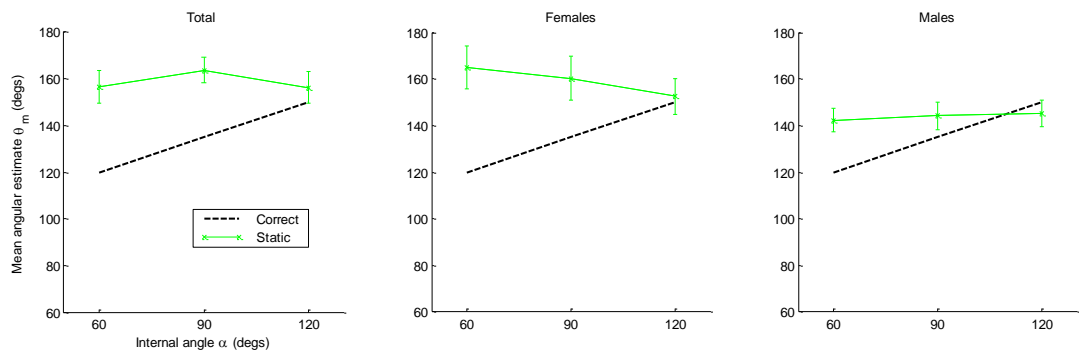


Distance: L-S

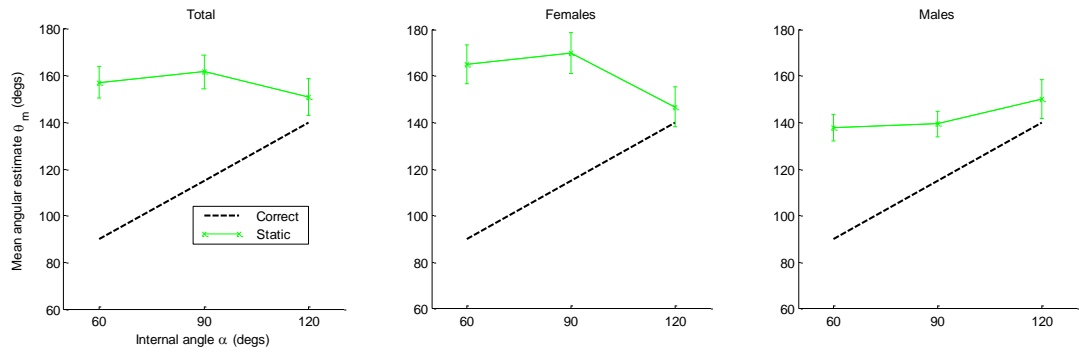


Distance: S-L

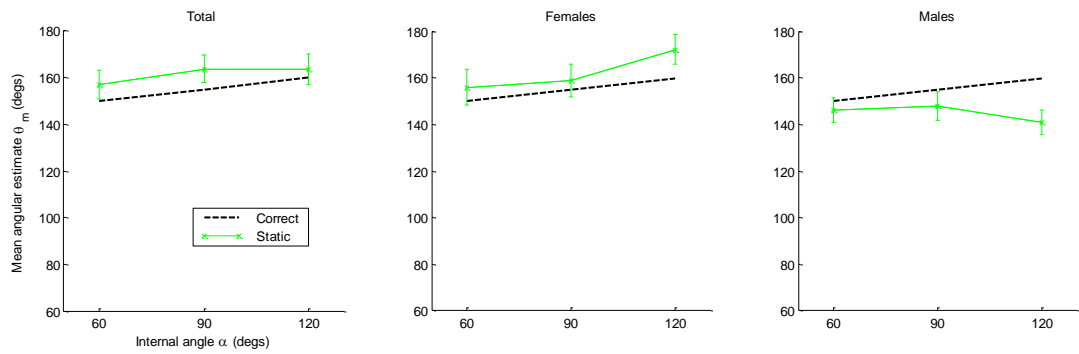
Figure 5.1. Mean directional estimates for the three internal angles and three distances in the Ur-S environment, combined (left) and separately by gender



Distance: L-L

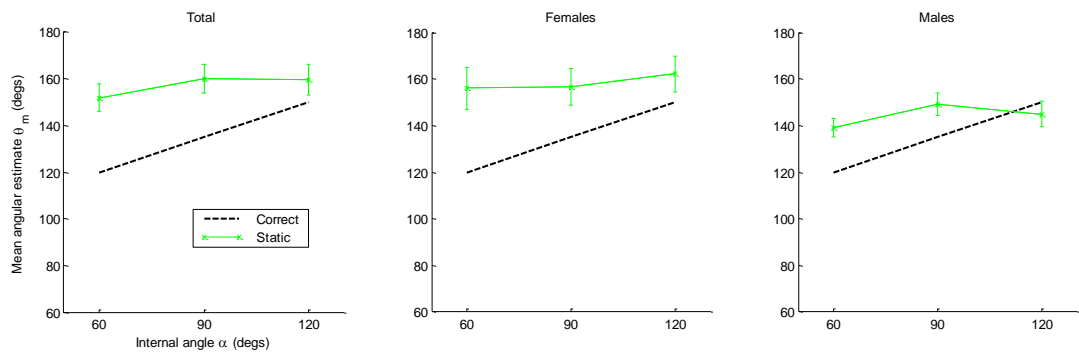


Distance: L-S

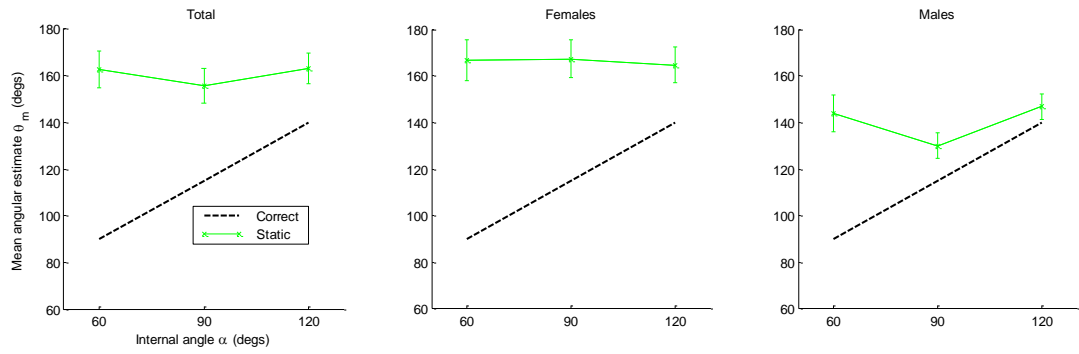


Distance: S-L

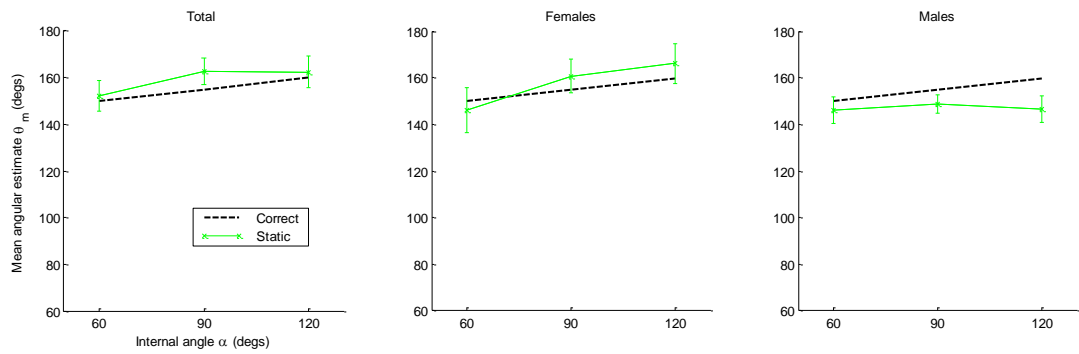
Figure 5.2. Mean directional estimates for the three internal angles and three distances in the Ur-N environment, combined (left) and separately by gender



Distance: L-L

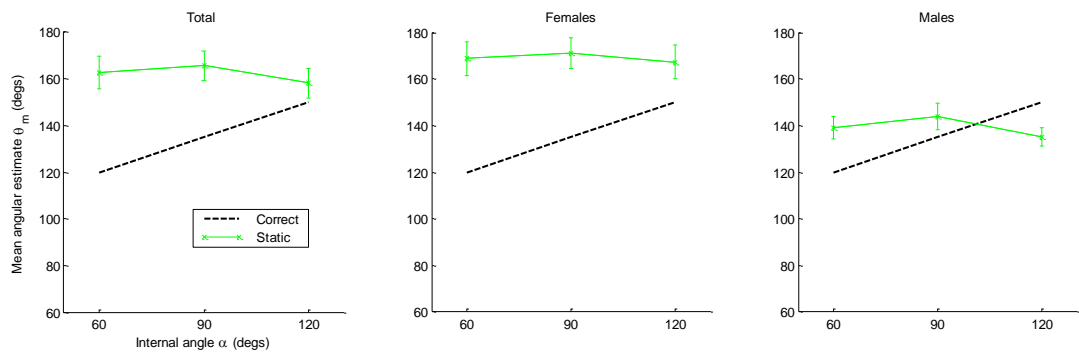


Distance: L-S

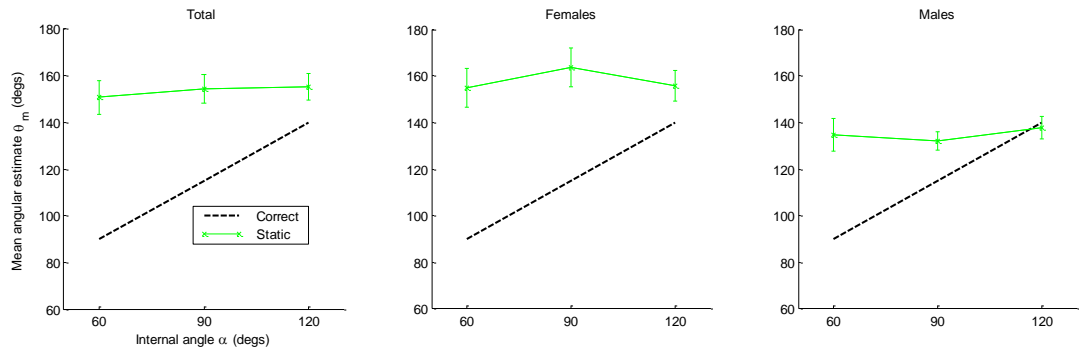


Distance: S-L

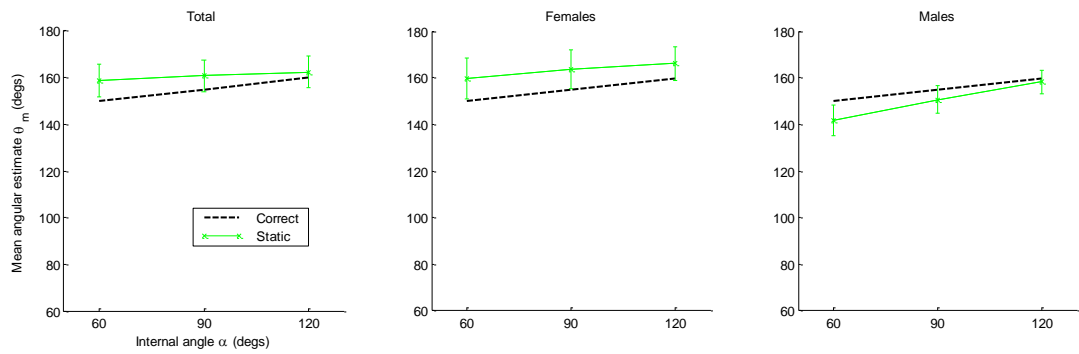
Figure 5.3. Mean directional estimates for the three internal angles and three distances in the Rur-S environment, combined (left) and separately by gender



Distance: L-L



Distance: L-S



Distance: S-L

Figure 5.4. Mean directional estimates for the three internal angles and three distances in the Rur-N environment, combined (left) and separately by gender

by males. Thus, the green line appears above the black dotted line for females, and below it for males. Male estimates, again, tended to be more accurate, on average, than female estimates.

On the L-L and L-S layouts, females uniformly overestimated the final angle on trials for all three internal angles: to a very great degree on the 60° and 90° angle trials, and less on the 120° angle trials. Males uniformly overestimated the final angle on the 60° and 90° angle trials as well, but tended to mostly underestimate it on the 120° angle trials. Both genders were more accurate on the S-L layouts; and females generally overestimated the final angle, whilst males uniformly underestimated it.

Table 5.2.

*Mean directions and mean angular deviations (in brackets) of the directional estimates, by distance and by environment*

$\alpha$	Dist comb.	$\theta$	Ur-S	Ur-N	Rur-S	Rur-N
60°	L-L	120°	162.57° (39.12°)	156.50° (35.77°)	151.83° (30.47°)	162.65° (36.11°)
	L-S	90°	149.50° (40.01°)	157.19° (35.45°)	162.78° (40.87°)	150.72° (37.78°)
	S-L	150°	170.07° (32.27°)	157.11° (31.59°)	152.01° (34.03°)	158.68° (36.49°)
90°	L-L	135°	158.12° (41.88°)	163.75° (29.21°)	160.07° (32.42°)	165.67° (33.28°)
	L-S	115°	160.75° (37.58°)	161.61° (36.87°)	155.76° (38.19°)	154.33° (32.26°)
	S-L	155°	163.03° (33.25°)	163.71° (31.25°)	162.61° (30.05°)	160.79° (35.32°)
120°	L-L	150°	163.67° (32.55°)	156.28° (34.96°)	159.52° (34.52°)	158.11° (33.21°)
	L-S	140°	160.27° (38.35°)	151.02° (40.65°)	163.07° (34.65°)	155.23° (30.07°)
	S-L	160°	162.15° (33.41°)	163.62° (33.60°)	162.42° (35.52°)	162.48° (34.35°)

These patterns were broadly similar across the four environments, with mean directions for males tending to be closer to the correct values, especially on the S-L route layouts. The error bars in the figures indicate that variability was generally higher, overall, for females than males.

The similar pattern and large magnitude of the mean error on the 60° and 90° angle trials, regardless of the layout, suggests that participants were guessing, as it appears that they responded, on each condition, as if all the angles were exactly the same. The estimate is extremely inaccurate in all conditions: the very high mean error indicates that participants struggled to ascertain the correct direction. Very similar patterns of error were observed across all four environments.

Turn type (the degree of rotation) did not greatly influence the responses. It can be seen from figure 5.5 that, for the combined male and female data, there is a very similar pattern of results, and similar levels of accuracy, on the roundabout and intersection trials, on each of the three route layouts across the four environments. The lines representing the data for the two turn types converge quite closely, which indicates that differences in accuracy are very small. The final angle is consistently overestimated, by a considerable amount on the L-L and S-L layouts, and by a lesser amount on the S-L layout (which is quite accurate): the red and blue lines are both above the dotted line, representing the correct response, on the graph of each layout; and closer to the dotted line on the S-L layout than on the L-S and L-L layouts.

Turn type not have a great effect on male responses: the red and blue lines converge on the graphs for each route layout. However, turn type had some effect on female responses: on the graphs for the L-L and L-S route layouts, the lines diverge, especially on the L-S trials. This indicates some differences between estimates on the roundabout and intersection trials, on routes with a longer outbound path.

Thus, no large systematic differences are discernible between the responses on trials of the two turn types: similar patterns and levels of accuracy are apparent, in general (apart from female responses on the L-S layouts).

### **5.3.5 Analysis of the Absolute Error Data: Effects of Internal Angle $\alpha$ and Environment**

The means of the absolute error of the directional estimates were analysed with Watson-Williams tests for circular data (Watson & Williams, 1956; Batschelet, 1981), for the factors *internal angle* (three levels: 60°, 90°, and 120°) and *environment* (four levels: Ur-S, Ur-N, Rur-S, and Rur-N), using the MATLAB CircStats toolbox (Berens, 2009; Berens & Velasco, 2009). This test is analogous to the one-factor ANOVA.

Table 5.3.

Mean directions and mean angular deviations (in brackets) of the directional estimates by turn type

Distance	$\theta$	Environment	Roundabout	Intersection
L-L	135°	Ur-S	158.12° (41.88°)	162.33° (41.37°)
		Ur-N	163.75° (29.20°)	156.86° (34.18°)
		Rur-S	160.07° (32.42°)	158.83° (32.31°)
		Rur-N	165.67° (33.28°)	151.75° (27.61°)
L-S	115°	Ur-S	160.75° (37.58°)	157.12° (45.60°)
		Ur-N	161.61° (36.87°)	150.48° (34.41°)
		Rur-S	155.76° (38.19°)	154.59° (42.29°)
		Rur-N	154.33° (32.26°)	148.61° (27.80°)
S-L	155°	Ur-S	163.04° (33.25°)	169.67° (34.51°)
		Ur-N	163.71° (31.25°)	166.37° (38.86°)
		Rur-S	162.61° (30.05°)	156.28° (36.33°)
		Rur-N	160.79° (35.32°)	163.36° (38.96°)

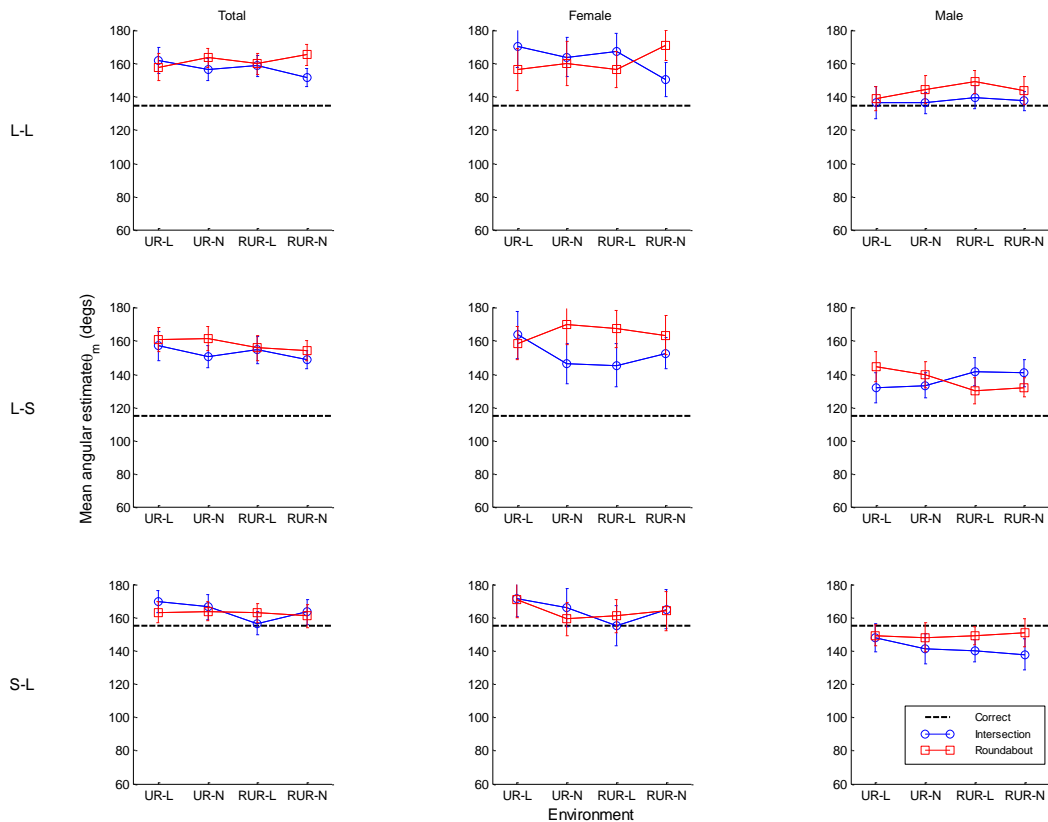


Figure 5.5. Mean directions of directional estimates across environments, by turn type, distance, and gender

### 5.3.5.1 Effects of Internal Angle $\alpha$

There was no significant effect of *internal angle* ( $F_{(2,1077)} = 0.74, p = 0.479$ ). The mean directions and angular deviations, averaged across environments, are shown in table 5.4. The means and standard deviations of the signed error data, also averaged across environments, are shown in table 5.5.

It can be seen from table 5.4 that the measured angle is similar for all three internal angles  $\alpha$  (within  $4^\circ$  of each other); as is the level of variability. Participants tended to select a similar angle each time, regardless of the actual value of the internal angle. Thus, participants generally behaved as though all the angles were the same, and larger than they actually were: much larger in the case of the  $60^\circ$  and  $90^\circ$  angles, and slightly larger in the case of the  $120^\circ$  angle. The participants were responding as if all the angles were  $120^\circ$ : mean estimated values tended to be closest to the value for the  $120^\circ$  angle.

This effect can be clearly seen in figures 5.1, 5.2, 5.3, and 5.4. The green error line for the total (combined male and female) data is in a similar position on all the graphs, regardless of the correct value, at around  $140^\circ - 160^\circ$  on the y-axis: this is the correct range for the  $120^\circ$  angle. Thus, the data points for the  $120^\circ$  angle are close to the black dotted line, whilst the data points for the other two angles are far from the dotted line.

The effect is also seen on the S-L layouts, for which the correct response varies between  $150^\circ$  and  $160^\circ$ : the error line is close to this range ( $150^\circ - 170^\circ$ ), so that the data points for all three angles are close to the correct dotted line.

The tendency for participants to respond as though all the angles were  $120^\circ$ , that is, larger than their actual value, may have reflected a reliance on a heuristic of the shortest distance, or the shortest time, to the exit road. Participants may have adopted such a heuristic to compensate for their impaired ability to estimate how far they had rotated around the roundabout, due to the lack of self-motion information.

Table 5.4.

*Mean directions and mean angular deviations (in brackets) of directional estimates by angle*

$\alpha$	$\theta$	$\theta_m$
$60^\circ$	$120^\circ$	$152.81^\circ$ (38.82°)
$90^\circ$	$135^\circ$	$157.01^\circ$ (37.02°)
$120^\circ$	$150^\circ$	$156.63^\circ$ (36.78°)

Table 5.5.

*Means and standard deviations (in brackets)  
of signed angular error by angle*

$\alpha$	Error
60°	-33.36° (41.83°)
90°	-20.80° (38.03°)
120°	-6.19° (36.60°)

The 120° angle exit-road was the closest of the three exit-roads to the approach road. Both the distance to the exit-road, and the duration of travel, were shorter, because participants experienced a smaller degree of rotation on the curved segment and consequently spent less time rotating.

As can be seen from table 5.5, the magnitude of the error decreases with increasing magnitude of angle  $\alpha$ , with the magnitude of the error for the 60° angle trials being five times that for the 120° angle trials. The mean error for 120° angle trials is quite small, at only 6.20°. There was consistent overestimation of the correct heading direction in the estimates, indicating overestimation of the underlying angle; and, therefore, underestimation of the internal  $\alpha$  angle. The very similar standard deviations indicate similar levels of variability (a difference of only 5.23°) between participants across the angles. Variability was also very high. Thus, taken together, the data indicates that the level of accuracy was greatest on 120° angle trials, and lowest on 60° angle trials, across all angles, for all environments and distances.

The difference in accuracy between the 60° and 120° angle trials may have reflected a difference in susceptibility to the effects of the lack of reliable self-motion information, due to the different degree of rotation experienced in each case. The 60° angle turn required the most rotation, as participants had to travel further around the roundabout to reach the exit-road, compared with the other angles. The 120° turn required the least rotation, as a shorter distance was travelled around the roundabout to reach the exit-road, compared with the other angles. Thus, participants reached the exit road more quickly on 120° angle trials, and less quickly on 60° trials, and the lack of self-motion information may have affected performance accordingly. On the 120° angle trials, the shorter distance, and consequent reduction in travel time on the route, may have compensated for the lack of accurate rotation information.

The greater accuracy on the 120° angle trials may also have reflected the use of a heuristic of shortest distance, or shortest time, to the exit road. If participants were using such a heuristic, the proximity of the exit road to the approach road, on

the 120° angle route layouts, may have made it easier to ascertain the final angle on these trials. This strategy may have been less susceptible to disruption from the lack of self-motion information.

### 5.3.5.2 Effects of Environment

There was no significant effect of *environment* ( $F_{(3,1436)} = 0.25, p = 0.863$ ). The mean directions and angular deviations are shown in table 5.6. The means and standard deviations of the signed error are shown in table 5.7. From table 5.6, it is apparent that there is a similar measured angle across all four environments. It is clear from table 5.7 that error was slightly higher in the Rur-N environment, and slightly lower in the Rur-S environment. However, the difference between environments is small. The correct heading direction is underestimated in all the environments, indicating a consistent tendency to underestimate the required angle, and, therefore, to overestimate the internal angle  $\alpha$ .

### 5.3.6 Analysis of the Absolute Error Data: Effects of Internal Angle and Triangle Layout by Gender

Harrison-Kanji tests for circular data (Harrison, Kanji & Gadsden, 1986; Harrison & Kanji, 1988) were performed on the absolute error means of the directional estimates, for the factors *internal angle* (three levels: 60°, 90° and 120°) x *gender* (two levels); and for the factors *triangle layout* (nine levels) x *gender* (two levels). This test is analogous to the two-way ANOVA.

Table 5.6.

*Mean directions and mean angular deviations (in brackets) of directional error by environment*

Environment	$\theta_m$
Ur-S	155.36° (38.87°)
Ur-N	155.44° (36.73°)
Rur-S	156.33° (36.62°)
Rur-N	151.62° (37.57°)

Table 5.7.

*Means and standard deviations (in brackets) of directional error by environment*

Environment	Error
Ur-S	-25.49° (38.87°)
Ur-N	-25.19° (36.73°)
Rur-S	-24.30° (36.62°)
Rur-N	-29.72° (37.57°)

### 5.3.6.1 Internal Angle by Gender

There was no significant effect of *internal angle* ( $F_{(2,1074)} = 0.80, p = 0.45$ ). However, there was a significant effect of *gender* ( $F_{(1,1074)} = 84.02, p < 0.001$ ). Mean directions and angular deviations can be seen in table 5.8, and the means and standard deviations in table 5.9. It is clear that estimates by males had consistently lower mean error than estimates by females; they also showed less variability. All the estimates were close to the correct value of 120°: this reflects a tendency for participants to respond to all the angles as though they were 120°, and, thus, often larger than the actual value. A difference was seen between male and female estimates of 17.19° for the 60° angle, 17.42 for the 90° angle, and 17.0 for the 120° angle. Whilst both genders consistently overestimated the direction, and showed a tendency for decreasing levels of error with increasing angle, male estimates were consistently more accurate, and showed less variability, than female estimates.

Table 5.8.

*Mean directions and mean angular deviations (in brackets) of the directional estimates for angle by gender*

$\alpha$	$\theta$	Female	Male
60°	120°	162.19° (42.76°)	144.99° (31.71°)
90°	135°	165.94° (41.79°)	148.52° (29.36°)
120°	150°	165.36° (41.70°)	148.36° (29.85°)

Table 5.9.

*Means and standard deviations of the signed error (in brackets) of the directional estimates for angle by gender*

$\alpha$	Female	Male
60°	- 41.61° (46.02°)	- 24.49° (35.95°)
90°	- 29.20° (43.18°)	- 11.72° (30.59°)
120°	- 14.49° (41.97°)	2.25° (29.62°)

Thus, participants of both genders displayed the general tendency to respond as though all the angles were 120°. This effect may have resulted from a reliance on a heuristic of the shortest distance, or the shortest time, to the exit road, as participants attempted to compensate for the effects of the unreliable self-motion information on their ability to estimate how far they had rotated around the roundabout.

The greater accuracy shown on the 120° angle trials, by both genders, may have been because the proximity of the exit road to the approach road assisted participants to more accurately perceive the distance they had travelled, and the degree of rotation they had experienced: thereby enabling more successful compensation for the lack of self-motion information. Participants travelled a shorter distance around the curved segment of the route on the 120° angle route layouts, compared with the other route layouts, because the exit-road was the closest of the three to the approach road. They also, consequently, arrived at the exit road more quickly. Thus, participants experienced less rotation on 120° angle trials compared with trials on the other angle layouts.

### **5.3.6.2 Layout by Gender**

There was a significant effect of *gender* ( $F_{(1,1062)} = 83.52, p < 0.001$ ), but no effect of *layout* ( $F_{(8,1062)} = 0.57, p = 0.80$ ). Mean directions and angular deviations can be seen in table 5.10; and means and standard deviations in table 5.11. It is, again, apparent that mean error for females is consistently much higher than for males. It is also clear that mean error for both genders is higher on the 60° and 90° angle trials than on the 120° angle trials; and that mean error is much higher on the L-L and L-S layouts than on the S-L layout.

Table 5.10.

*Mean directions and mean angular deviations (in brackets) of the directional estimates for layout by gender*

Layout	Configuration: $\alpha$ + leg-length	$\theta$	Male	Female
1	60°+ L-L	120°	145.85° (31.70°)	160.85° (44.64°)
2	60°+ L-S	90°	139.11° (36.79°)	155.57° (42.95°)
3	60°+ S-L	150°	145.72° (34.96°)	161.94° (45.96°)
4	90°+ L-L	135°	149.53° (30.15°)	165.85° (41.07°)
5	90°+ L-S	115°	136.01° (24.42°)	165.77° (43.57°)
6	90°+ S-L	155°	148.56° (26.15°)	163.32° (43.09°)
7	120°+ L-L	150°	148.94° (28.60°)	164.51° (41.31°)
8	120°+ L-S	140°	141.43° (26.97°)	157.60° (34.54°)
9	120°+ S-L	160°	160.40° (27.28°)	166.49° (38.43°)

### 5.3.7 Analysis of the Signed Error Data: Combined Effects of Environment, Internal Angle, Distance, and Gender

A mixed-design 4-way ANOVA (4 *environments* x 3 *angles* x 3 *distance-combinations* x *gender*) was performed on the means of the signed error of the directional estimates, in order to assess any higher-level effects. There were three within-participants factors, *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), *internal angle* (60°, 90°, and 120°), and *distance-combination* (L-L: long-long, L-S: long-short, and S-L: short-long). There was one between-participants factor, *gender*. Since the signed error is constrained within 180° on either side of the correct value, a linear ANOVA was appropriate for the analysis.

There was a main effect of *angle* ( $F_{(2,56)} = 121.86$ ,  $p < 0.001$  partial  $\eta^2 = 0.81$ ) and *distance-combination* ( $F_{(2,56)} = 70.92$ ,  $p < 0.001$ , partial  $\eta^2 = 0.72$ ). There was also an interaction effect between *angle* x *distance-combination* ( $F_{(4,112)} = 18.04$ ,  $p < 0.001$ , partial  $\eta^2 = 0.39$ ). There was no significant effect of *environment* ( $F_{(3,84)} = 0.88$ ,  $p = 0.457$ ) or *gender* ( $F_{(1,28)} = 3.39$ ,  $p = 0.076$ ), and there were no other significant interaction effects. Bonferroni-adjusted pairwise comparisons showed that all three angles differed significantly from each other, all  $p < 0.001$ . A polynomial contrast also revealed a significant linear tendency for angle ( $F_{(1,28)} = 255.34$ ,  $p < 0.001$ , partial  $\eta^2 = 0.90$ ). Thus, error increased linearly with angle. Bonferroni-

Table 5.11.

*Means and standard deviations (in brackets) of the directional estimates for signed error for layout by gender*

Layout	Configuration: $\alpha$ + leg length	$\theta$	Male	Female
1	60°+ L-L	120°	-25.61° (35.44°)	-39.03° (47.20°)
2	60°+ L-S	90°	-45.61° (36.79°)	-62.06° (42.95°)
3	60°+ S-L	150°	1.12° (34.96°)	-17.03° (45.97°)
4	90°+ L-L	135°	-13.00° (31.09°)	-28.11° (42.51°)
5	90°+ L-S	115°	-16.94° (24.42°)	-46.82° (43.57°)
6	90°+ S-L	155°	3.61° (26.15°)	-11.28° (43.07°)
7	120°+ L-L	150°	1.59° (28.96°)	-13.38° (41.35°)
8	120°+ L-S	140°	-0.81° (26.97°)	-15.49° (34.57°)
9	120°+ S-L	160°	1.18° (27.28°)	-7.35° (38.41°)

adjusted pairwise comparisons on *distance-combination* showed that all three distance combinations also differed significantly from each other, all at  $p < 0.001$ .

Table 5.12 shows the means for the signed error of the directional estimates by angle and distance, averaged across the environments. It can be seen that the greatest mean error occurred on trials with the 60° angle and L-S distance combination, and that the mean error is also high on trials with the 60° angle and L-L distance combination, and the 90° angle with the L-S distance combination. Mean error is smaller on trials with all three angles and the S-L distance combination.

Tables showing mean angular directions, separately by gender, are included in Appendix C. Means and standard deviations of the signed error of the directional estimates by angle, distance and environment are displayed in Appendix D.

### 5.3.8 Analysis of the Signed Error Data: Combined Effects of Turn-type, Environment, Distance, and Gender

A 4-way mixed-design ANOVA (2 *turn types* x 4 *environments* x 3 *distance-combinations* x *gender*) was conducted on the signed error means of the directional estimates from the 90° angle roundabout and intersection trials, in order to test for any effects of turn type. There were three within-participants factors: *turn type* (intersection or roundabout), *environment* (Ur-S, Ur-N, Rur-S, Rur-N), and *distance-combination* (L-L: long-long, L-S: long-short, and S-L: short-long); and the between-participants factor, *gender*. A linear ANOVA was appropriate for the analysis, as the

Table 5.12.

*Means of the signed error of the directional estimates by angle and distance, averaged across environments*

Distance Comb.	$\alpha = 60^\circ$	$\alpha = 90^\circ$	$\alpha = 120^\circ$
L-L	-39.35°	-28.06°	-10.79°
L-S	-61.21°	-39.62°	-16.21°
S-L	-16.84°	-11.91°	-4.35°

signed error was constrained within 180° on either side of the correct value. Means and standard deviations are summarised in table 5.13, and, averaged across the four environments, in table 5.14.

There was a significant effect of *distance-combination* ( $F_{(2,56)} = 55.45$ ,  $p < 0.001$ , partial  $\eta^2 = 0.66$ ) but no significant effect of *turn type* ( $F_{(1,28)} = 5.39$ ,  $p = 0.469$ ) or of *environment* ( $F_{(3,84)} = 2.39$ ,  $p = 0.075$ ). There was also no significant effect of *gender* ( $F_{(1,28)} = 2.99$ ,  $p = 0.094$ ). Pairwise comparisons on distance-combination showed that all three distances differed significantly from each other, and all at  $p < 0.001$ .

Table 5.13.

*Means and standard deviations (in brackets) of the signed error of the directional estimates by turn type*

Distance	Environment	Roundabout	Intersection
L-L	Ur-S	-31.93° (42.29°)	-31.43° (47.93°)
	Ur-N	-28.08° (30.81°)	-24.90° (36.72°)
	Rur-S	-23.59° (34.12°)	-24.74° (33.62°)
	Rur-N	-28.65° (35.09°)	-18.28° (29.16°)
L-S	Ur-S	-41.83° (39.33°)	-44.11° (45.66°)
	Ur-N	-43.73° (39.30°)	-34.36° (36.91°)
	Rur-S	-36.41° (40.48°)	-36.79° (44.06°)
	Rur-N	-36.53° (33.72°)	-32.51° (28.96°)
S-L	Ur-S	-11.53° (35.09°)	-16.86° (36.39°)
	Ur-N	-14.35° (30.97°)	-14.46° (41.83°)
	Rur-S	-10.81° (31.36°)	-4.22° (38.54°)
	Rur-N	-10.93° (38.16°)	-12.60° (41.78°)

Table 5.14.

*Means of the directional estimates (signed error) by turn type, averaged across environments*

Leg-length	$\theta$	Roundabout	Intersection
L-L	135°	-28.06°	-24.84°
L-S	115°	-39.62°	-36.94°
S-L	155°	-11.91°	-12.04°

### **5.3.9 The Virtual Experience: Presence and Authenticity**

Scores on the four factors of the ITC-SOPI (Lessiter, Freeman, Keogh, & Davidoff, 2001), and responses to a questionnaire created by the researcher, were used to assess the virtual environments, in terms of their effectiveness in evoking presence and immersion, their authenticity, and any negative aspects. Participants completed both questionnaires immediately after their experience in the virtual environments.

#### **5.3.9.1 Presence and Immersion in the Virtual Environments**

A mean score was calculated for each participant, on each of the four presence factors, by averaging their responses to the items which constitute the factor. A sample mean was then calculated for each factor. The mean factor scores and standard deviations are displayed in table 5.15. The data for each factor were analysed individually, as the scores can not currently be combined into an overall score. Additional comments, grouped according to each of the factor's main themes, are included in Appendix E.

Lower scores were found on all the factors in this experiment, compared with those observed in Experiments 1 and 2. Participants reported feeling a lower sense of spatial presence (2.47), and less engagement (2.61). The lack of continuous motion had clearly affected the virtual experience. The score for ecological validity / naturalness was relatively high (the highest of the four scores) at 2.76: participants perceived the virtual environments as being fairly realistic, despite the absence of natural movement. The negative effects factor also received a lower score (in fact, the lowest here) at 2.01, indicating a lower prevalence of cybersickness symptoms, and of other negative aspects of the virtual experience.

Variability was again high, especially for engagement, for which it was higher than in Experiment 1, and in both conditions of Experiment 2. Variability on the spatial presence factor was comparable to both conditions of Experiment 2, but

Table 5.15.

*ITC-SOPI: Mean factor scores and standard deviations*

Factor	Score
Spatial Presence	2.47 (0.75)
Engagement	2.61 (0.67)
Ecological Validity / Naturalness	2.76 (0.72)
Negative effects	2.01 (0.68)

lower than in Experiment 1; whilst for ecological validity / naturalness and negative effects, variability was comparable to the Passive condition, but lower than in both Experiment 1 and the Active condition of Experiment 2.

The additional comments emphasise the strong impression which was made by the disrupted self-motion. There are many comments about the absence of natural movement: several participants found it strange and felt frustrated by it, which was also observed by the experimenter during the experiment and during conversation afterwards.

### **5.3.9.2 Analysis of the Signed Error Data: Combined Effects of Presence, Environment, Internal Angle, and Distance**

Participants were divided into two groups (*high* and *low* presence), according to their scores, on each of the four factors which make up Sense of Presence on the ITC-SOPI scale (Lessiter et al., 2001): that is, spatial presence, engagement, ecological validity, and negative effects. The *low* presence group included participants with scores from 1.00 to 2.99, whilst the *high* presence group included participants with scores from 3.00 to 5.00.

The signed error means of the directional estimates were analysed with a 4-way mixed-design ANOVA (2 *presence levels* x 4 *environments* x 3 *angles* x 3 *distance-combinations*), in order to test for any effects of sense of presence. There was one between-participants factor, namely, *sense of presence* (*High* and *Low*); and there were three within-participants factors, which were *environment* (Ur-S, Ur-N, Rur-S, and Rur-N), *angle* (60°, 90°, and 120°) and *distance combination* (L-L: long-long, L-S: long-short, and S-L: short-long). Tests were carried out on each of the four presence factors separately. A linear ANOVA was appropriate for the analysis, as the signed error was limited to 180° on either side of the correct value. Means and standard deviations of the signed error by presence group and layout, averaged across the environments and gender, are summarised in Appendix F. Appendix G shows the sample size of the *high* and *low* presence groups on each factor.

There was a main effect of *negative effects* ( $F_{(1,28)} = 5.11, p < 0.05$ , partial  $\eta^2 = 0.154$ ). There were no other significant effects: *spatial presence* ( $F_{(1,28)} = 0.18, p = 0.677$ ), *engagement* ( $F_{(1,28)} = 1.29, p = 0.265$ ), *ecological validity / naturalness* ( $F_{(1,28)} = 2.04, p = 0.164$ ). Thus, sense of presence did not affect path integration performance, in general, apart from negative effects. However, this result needs to be treated with caution, as very few participants experienced any negative effects in this experiment. The sample sizes of the *high* and *low* groups on this factor were very disproportionate, therefore, with a very small *high* group (only three participants) and a very much larger *low* group (27 participants), as can be seen from Appendix G.

### **5.3.9.3 Authenticity of the Virtual World**

The qualitative data were grouped into categories for analysis, using the same set of structural frames (Kitchin, 1997) that were used in Experiments 1 and 2. The frequency of occurrence of items related to these themes was tallied, and the corresponding percentages within each theme were calculated. Data from all 30 participants were included.

The major categories of features found to be authentic (shown in Appendix H) were mountains (16.67%), countryside / rural areas (16.67%), and houses (15.15%); followed by structures and road aspects (12.12% and 10.61%). Participants in this experiment were more divided than those in Experiments 1 and 2 about which features they would change, or add to the environments, in order to create a more authentic character: these data are shown in Appendix I. In contrast with the previous experiments, the comments did not reveal any dominant category of features, but were instead more evenly spread over the entire list. Typical landscape features (such as farms, rivers, detail in the centre of the roundabouts) received the highest percentage of responses at 10.61%, followed by farm animals, trees / forest, road signs / markings, and details of houses, each with 9.09% of the responses.

## **5.4 Discussion**

### **5.4.1 Path Integration Performance**

*Hypothesis 1:* Restricted optic flow information would result in lower overall accuracy of path integration performance, compared with Experiments 1 and 2, and with previous studies

*This hypothesis was met.* Participants were able to perform path integration, but with lower overall accuracy than in Experiments 1 and 2, and compared with previous studies conducted in virtual environments. High accuracy was observed only on S-L layouts, and reasonably high accuracy was also found on 120° angle trials. A pattern of consistent overestimation of the final angle was evident. The intermittent manner of presenting the visual information, apparently, reduced the beneficial effects of using a small-screen display, which had been observed in Experiment 2.

Overestimation of the final angle was also found in Experiment 2, in which a small screen was used; but not in Experiment 1, in which a large screen was used, and in which a consistent tendency for underestimation was found. This suggests that the display influenced performance, and contributed to the difference in the error pattern which was seen in Experiments 2 and 3, compared with Experiment 1.

Strong underestimation of the final angle was also observed in previous studies of visual path integration, in which the virtual world was presented on large projection screens, measuring 2.05m wide by 1.65m high (Wartenberg, May, & Péruch, 1998; Péruch, May, & Wartenberg, 1997). Similarly, Schulte-Pelkum, Riecke, von der Heyde, and Bühlhoff (2004) found that participants tended to underrun simulated target angles on a large curved screen, but to overturn them on a flat screen.

In Experiments 2 and 3, overestimation of the final angle was found. However, not only overestimation, but also underestimation, was found in Experiment 2, depending on route layout (internal angle and outbound path length). The final angle was consistently underestimated on 120° angle trials and S-L layout trials, in contrast with the overestimation on trials with all three internal angles in Experiment 3. Thus, the different displays cannot fully account for the differences in the pattern of results. The geometric properties of the route layouts also exerted an effect, possibly in conjunction with properties of the virtual environments (especially the limited visual cues to depth and distance). Thus, the difference may be due to an interaction between the screen size and the geometric properties of the route layouts, possibly together with the limited visual cues to depth and distance in the virtual display.

The results observed on the L-L layout trials used in Experiment 3, that is, on routes with equal-length first and second straight roads, can be directly compared with the results observed on the L-L layout trials in Experiment 2, and on all the trials in Experiment 1. This enables these effects to be examined more closely. Differences in the overall pattern of results on these equivalent trials are clear from comparing the figures for the three experiments. Consistent overestimation was found in Experiment 3, with considerable inaccuracy on the 60° and 90° angle trials, but much greater accuracy on the 120° angle trials (figures 5.1., 5.2., 5.3., and 5.4.). This

contrasts with Experiment 1, in which participants' responses showed consistent underestimation of the final angle, on trials across all three internal angles (figures 3.10 and 3.11). It also contrasts with Experiment 2, in which the final angle was consistently underestimated on the 120° angle trials, but consistently overestimated on the 60° and 90° angle trials (figures 4.2, 4.3, 4.4 and 4.5). Thus, the final angle was underestimated on the 60° and 90° angle trials in Experiment 1, but it was overestimated in Experiment 2. However, the final angle was underestimated on the 120° angle trials, in both experiments. Higher overall accuracy on the L-L layouts in Experiments 1 and 2, compared with Experiment 3, is also clear from the figures. However, the 120° angle was more accurate in Experiment 3 than in Experiment 1.

*Hypothesis 2: Accuracy would differ as a function of route layout (internal angle and leg-length combination)*

*This hypothesis was met.* Performance on the 60° and 90° angle trials, combined with the L-L and L-S route layouts, was extremely inaccurate; however, it still reflected stereotyped responses. Performance on the 120° angle trials was more accurate. Responses on the S-L layout trials were also very accurate, with all three internal angles, often *more* so than in Experiment 2. Thus, the disrupted self-motion cues interfered with the ability to estimate distance, through estimation of self-velocity or travel duration, in the 60° and 90° angle trials on L-L and L-S layouts; but not on the 120° angle trials, or on the S-L layout. Participants were able to compensate for the unreliable optic flow information on 120° angle trials and on the S-L layout.

The internal angle, by itself, did not affect performance: the measured angle was almost identical for all three internal angles  $\alpha$ , and across all four environments; and it was close to the correct value for the 120° angle trials. The level of accuracy was, therefore, greatest for the 120° angle, and lowest for the 60° angle, across all environments and leg-length combinations. The magnitude of the error decreased with increasing magnitude of angle  $\alpha$ . The error for 120° is quite small, and much larger for the 60° and 90° angles. Thus, participants responded as though all the internal angles were similar, and large (120°); and therefore larger than the actual value for the 60° and 90° angles trials. There was a consistent overestimation of the final angle, and, thus, the correct heading direction, in the estimates, indicating that the internal  $\alpha$  angle was underestimated. Variability was very high, and very similar levels were apparent between participants across layouts with the three internal angles.

Although the internal angle alone had no effect on performance, the route layout (that is, the leg-length combination and the internal angle, together) had an

effect. This suggests that it was the length of the legs on the outbound route which was the critical factor for task performance in the route layout, rather than the angle.

The accuracy of performance on the 120° angle and S-L layout trials in this experiment suggests that continuous visual information is not always required for path integration; and that participants were able to obtain sufficient (visual or other) information from other aspects of the environment, which enabled them to perform fairly accurate path integration on these trials.

It is also possible that participants were able to navigate by using some strategy other than path integration. As self-motion information was too unreliable, and difficult to use, for accurate path integration, participants may have used other visual information, which was available in the virtual environments. It is possible that not all potential landmark cues from the environment were eliminated in the experiment, and that participants were able, therefore, to make use of information from these external references to navigate.

During path integration, navigators can keep track of the direction in which they are moving, by using a stable distal landmark with a known bearing as a directional reference (O'Keefe & Nadel, 1978): for example, by using a very distant environmental feature, directly sensed through vision, as an azimuthal reference (Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001). Participants may have been able to use incidental features from the texture maps of real environments, which were used to create the distant background scenes: for example, several participants mentioned three factory chimneys, which were very faintly visible in the distance. These were an artefact of the photograph used for the background, but participants may have found them helpful. These features may have been sufficient to support accurate performance over the shorter distances, but not the longer ones.

It is also possible that some participants were able to use the structures as proximal landmarks. The actual structures were inter-changed, in order to prevent their use as landmarks. However, there was a stability to their presence, as there were always four structures occupying roughly the same positions around the roundabout.

It is to be expected that participants would attempt to use other strategies than path integration to perform the task, when faced with the difficulties of using the optic flow cues in this experiment. Navigation by both path integration and the use of landmarks together is usual, and participants would be accustomed to switching their strategies according to the conditions. Typically, landmark information and self-motion cues interact during navigation, in a complementary fashion. Information from the environment, and from self-motion estimation, is integrated, with preference given to one or the other, according to how salient or reliable it is. This enables navigators

to use the most appropriate source of information for their purpose. Although stable landmark information is preferred, landmarks are not always available; and path integration by itself is not always accurate enough to be used instead. Visual cues are the most commonly-used environmental spatial references; however, navigators are accustomed to relying on other types of external information, together with self-motion cues, when visual references are not available (Etienne & Jeffery, 2004).

Alternatively, participants may have relied on some heuristic, such as the shortest distance travelled, or the shortest travel time, for all angles and layouts. This would have resulted in more accurate performance on the S-L layouts and 120° angle trials, since less distance and, hence, less travel time was required on these, compared with the 60° and 90° angle trials on the L-L and L-S route layouts.

Finally, repeated trials may have enabled participants to form a cognitive map of the route layouts, which they used to navigate instead.

However, the absence of continuous visual information did lead to a deterioration of performance on the 60° and 90° angle trials on the L-L and L-S route layouts in this experiment: performance was more accurate on the equivalent trials in Experiments 1 and 2, in which participants had access to continuous visual information. This is evident from comparing the L-L and L-S route layout data in figures 5.1, 5.2, 5.3, and 5.4 for Experiment 3, with that in figures 4.2, 4.3, 4.4 and 4.5 for Experiment 1. In the figures for Experiment 3, the green line, joining the data points for the mean estimates on the 60° and 90° angle trials, is further above the black dotted (correct) line than the corresponding red and blue lines, in the figures for Experiment 2.

The data for the L-L layouts in Experiment 3, shown in figures 5.1 - 5.4, can also be compared with figures 3.10 and 3.11, which show the results for Experiment 1. Again, it can be seen that, in the figures for Experiment 3, the green line, which joins the data points for the mean estimates on the 60° and 90° angle trials, is much further away from the black dotted (correct) line than the equivalent line, in the figures for Experiment 1.

Greater accuracy was observed on the S-L route layout and the 120° angle trials. This can also be seen in the figures. The data point for the 120° angle is closer to the correct line, in the figures for Experiment 3, than the corresponding data point in the figures for Experiments 1 and 2; and the line for the S-L layouts is closer to the correct line than the corresponding line in Experiment 2.

The S-L layout and the 120° angle routes are similar: in both, there is a shorter distance between the exit-road and the start point of the route, and, therefore, a shorter duration of travel time on the outbound route, compared with the other angles and layouts. On the S-L route, the approach road is shorter than on the other

layouts, resulting in participants travelling a shorter distance on the straight segment of the route, thereby spending less time translating. Participants experienced less translational flow on this route, therefore. On the 120° angle trials, participants experienced less rotational flow: the exit road is closer to the approach road than in the case of the other angles, resulting in participants travelling a shorter distance around the curved segment of the route, thereby turning through fewer degrees of rotation. Thus, participants spent less time rotating on these trials. In both cases, participants arrived at the exit road more quickly than on the other routes.

It may be that, in the case of the shorter journey on the 120° angle trials, and on the S-L layouts, the inter-stimulus interval was not long enough to completely prevent the perception of self-motion. Several participants refer to motion or movement in additional comments made in response to the ITC-SOPI (Appendix E): this suggests that at least some of the participants perceived motion. Thus, the inter-stimulus interval may have been too short. Participants may have been able to track their self-motion over the shorter distances on the outbound routes on S-L layout and 120° angle trials, despite the reduced optic flow information. Longer distances on the outbound route may be more susceptible to the effects of disrupted optic flow. This would account for the fact that participants were still able to perform path integration on the 120° angle trials and on the S-L layouts, despite the degraded visual stimulus.

The S-L layout and 120° angle routes may also show similar results, because the range of correct response values was very narrow on the S-L layouts (150°, 155°, and 160°, for the 60°, 90°, and 120° internal angles, respectively), and very close to the correct value for the 120° internal angle (150°). Thus, these angles may have been perceived by participants as being the same.

*Hypothesis 3:* Path integration performance on 90° angle routes would be particularly inaccurate with a small turn (intersection) compared with a large turn (roundabout)

*This hypothesis was not met.* No effect of turn type was found (that is, no differences between roundabout and intersection trials). This suggests that for both turn types, the ability to estimate distance and, especially, rotation was equally adversely affected by the reduced self-motion information, such as about velocity. An effect of turn type was found in Experiment 2, which mostly affected responses by female participants in the Passive condition: accuracy was more divergent between intersection and roundabout trials, in comparison with the responses of Active females, and of males in both conditions; this also depended on route layout. This difference in the results between Experiments 2 and 3 may have been due to a

particular sensitivity, by female participants, to the inability to rely on the rotational self-motion information in the Passive condition of Experiment 2.

*Hypothesis 4:* Female performance would be less impaired than male performance by the disrupted optic flow

*This hypothesis was not met.* Gender was very influential in this experiment. The effect was not in the expected direction, however. Estimates by male participants were consistently more accurate than those by female participants, and also showed less variability. This indicates that female performance was more disrupted by the lack of smooth self-motion: females were less able to compensate for the unreliable optic flow information than males. This suggests that female participants may have been more dependent on the optic flow information, generally, or that it was difficult for them to use other visual information, such as the additional depth information provided by the structures. This may have been because of the lack of motion: a structure, or structures, on the route could have been missed, for example, due to the presentation of intermittent snapshot views.

The trends in the data were similar for both genders, however: consistent overestimation of the final angle, and decreasing error with increasing values of the internal angle; higher mean error on 60° and 90° angle trials than on 120° angle trials; and much higher mean error on the L-L and L-S layouts than on the S-L layout.

The finding that female participants exhibited lower accuracy than male participants is contrary to expectations, based on the results of previous studies suggesting that females are less dependent than males on visual information, such as optic flow (Kearns, Warren, Duchon, & Tarr, 2002; Fortenbaugh, Chaudhury, Hicks, Hao, & Turano, 2007). However, responses in the study by Kearns et al. (2002) may also have reflected a bias towards equilateral triangles, in addition to the use of sensory information: there was a tendency for participants to produce stereotyped responses across all triangle layouts. Sample size was also very small, and there was a high female attrition rate, due to simulator sickness: women who completed the experiment may have been less visually dependent, as sensory conflict may have led to a higher rate of sickness symptoms in women who relied on optic flow. In the current study, there were larger samples of males and females, and the groups were equivalent in size, making the findings more representative.

*Hypothesis 5:* Performance would be more accurate in environments with added structures, as these would compensate for the absence of reliable optic flow, by providing additional visual cues (depth)

*This hypothesis was not met.* There was no effect of environment. The final angle, and, thus, the correct heading direction, was underestimated, to a similar degree, in all the environments: this indicates a consistent tendency for participants to overestimate the internal angle  $\alpha$ . The additional depth information, provided by the structures, was insufficient to compensate entirely for the absence of reliable optic flow information. Route layout was much more influential than the presence or absence of structures.

*Hypothesis 6:* Sense of presence would be lower than in Experiments 1 and 2, as the experience would be less immersive, due to the manner of presenting the visual information

*This hypothesis was met.* Participants experienced less presence in the virtual environments, and less engagement with the virtual experience, compared with participants in Experiments 1 and 2. It seems likely that these effects were due to the disrupted motion. The virtual environments were also judged as having lower ecological validity than in the previous experiments, as shown by the lower mean ratings they received: slightly lower than in the Active condition of Experiment 2, but considerably lower than in Experiment 1 and the Passive condition of Experiment 2. Smooth motion is, therefore, influential for the experience of presence. Thus, the beneficial effects of the small-screen display, which were observed in Experiment 2, were reduced by the intermittent presentation of the visual information.

However, participants mostly still found the environments quite natural and lifelike, even with reduced motion; albeit to a lower degree than the participants who had experienced realistic motion simulation, on both the large and small screens. This is, perhaps, surprising, given the unusual nature (even strangeness) of the stimulus presentation in this experiment: viewing a navigated route as a series of snapshots is completely unrealistic, and probably could never happen in the real world. It is possible that the participants focused their attention on each snapshot when it was on the screen, and looked at it carefully, while waiting for the next snapshot. The lack of motion may, thus, have accentuated some aspects of the environments. Compared with the previous two experiments, participants would have had more time to consider each snapshot image.

The lack of simulated image motion contributed to an alleviation of the disorientation and other adverse reactions, such as cybersickness symptoms, experienced by many participants in the previous two experiments. Despite this, some participants commented on feeling disoriented in the environments. The feedback comments show that the disrupted motion made a strong impression on

many participants; and that many were aware that it was affecting their task performance, and felt powerless about the situation. This was very clear to the experimenter in conversation with some of the participants afterwards.

The major categories of features found to be authentic were mountains, countryside / rural areas, and houses, as in the previous two experiments. There was less consensus in this experiment than in the previous ones, about which features participants would change, or add to the environments, in order to increase their authenticity. In contrast to Experiments 1 and 2, no particular category stood out. The comments were fairly equally divided between typical landscape features, farm animals, trees / forest, road signs / markings, and details of houses. The interrupted motion may have made it difficult for the participants to think of the environments as actual places, due to the lowered overall realism.

*Hypothesis 7:* A lowered sense of presence and engagement would result in less accurate path integration performance compared with Experiments 1 and 2

*This hypothesis was not met.* There was no effect of sense of presence on path integration performance, in general: accuracy did not depend on the level of presence that was experienced by participants. Thus, the lower overall accuracy, which was observed in this experiment, was not due to a lower sense of presence. Of the four factors on the ITC-SOPI presence scale, there was an effect of negative effects only. However, it should be stressed that the sample sizes for the *high* and *low* groups on this factor were very different; and that the *high* negative effects group was very small, as very few participants experienced any adverse effects in this experiment. This is clear from Appendix G. Thus, this result needs to be treated with caution, as there may not have been any real effect of this factor, in common with the other three factors. No effect of any of the four presence factors was found in Experiment 2, in which the two groups were larger, and more similar in size. The method used to form the groups may also have been an issue. Most of the presence scores were around the mid-point of the scale, making it difficult to form a *high* and *low* group which were clearly differentiated, and resulting in a rather arbitrary cut-off point: that is, participants with scores of up to 2.99 were included in the *low* group, and participants with scores of 3.00 or above in the *high* group. More polarisation of the scores would have resulted in two groups which differed from each other to a much greater extent.

## 5.4.2 Explanatory Models and Predictions

Two explanatory models have been proposed, in chapters 2, 3, and 4, to account for the error observed in this study. Overestimation of the final angle, indicated by participants turning the pointer on the dial too far (resulting in *negative* errors), was attributed to either overestimation of rotation at the end of the first leg, combined with correct perception of distance; or to overestimation of distance on the outbound path, together with correct perception of rotation. The two types of error are illustrated in figures 4.8 and 4.9: the data indicate a particular class of error through the position of the red line, representing error, relative to the solid blue line, representing a correct response from the perceived final position. The red line positioned above the blue line indicates overestimation of the final angle.

This is analogous to the position of the lines showing mean participant responses, and correct responses, in figures 5.1, 5.2, 5.3, and 5.4 for Experiment 3. The values of the mean responses are represented by the green line, and the correct responses by the black dotted line. The data illustrate consistent overestimation of the final angle, which can be attributed to misperception (overestimation) of either rotation or distance. It is also possible that the error resulted from a combination of rotation and distance overestimation. However, as previously discussed, the current data cannot be used to ascertain this, or to distinguish between the rotation and distance error models. Further refinement of the models would be required for this, together with the collection of more data.

Participants are assumed to be capable of making the correct directional response towards the final position at the end of the second leg. In the case of correct rotation perception, participants are also assumed to perceive equal-length first and second legs: incorrectly, in this experiment, as legs of different lengths were included on some layouts. The error is, thus, assumed to result from misperception of either distance or rotation on the outbound path: participants overestimated either how far along the outbound path they had travelled, or the degree to which they had rotated between the two outbound legs.

It has been assumed, in the previous two experiments, that error in the final angle estimates is likely to have resulted from misperception of distance, rather than of rotation. Overestimation of distance has been found in several previous studies (Redlick, Jenkin, & Harris, 2001; Lappe, Jenkin, & Harris, 2007; Kearns et al., 2002; Bakker, Werkhoven, & Passenier, 2001); and it was also found in Experiment 2 of this study, on the 60° and 90° trials with L-L and L-S route layouts.

The overestimation of the final angle is, therefore, assumed to indicate that participants overestimated the distance of their self-motion along the outbound path.

Participants may have perceived that they had travelled further along the second leg than they actually had, because they perceived the speed of their self-motion to be faster than the actual speed. There are several possible factors which may have contributed to participants perceiving that they were travelling more quickly than they really were, such as limited depth cues and inappropriate oculomotor responses. These will be discussed in chapter 6.

Thus, participants' ability to estimate distance was affected by the lack of smooth self-motion, which disrupted the optic flow and made it difficult to estimate velocity. The effect of presenting the visual information intermittently may have been to make it appear to participants that they were travelling more quickly. It is possible that the .33 Hz presentation rate gave the impression of a series of 'jerks' of very fast forward motion followed by a stop. This is, indeed, reflected in some of the additional comments made in response to the ITC-SOPI (Appendix E): several participants refer to motion or movement, describing it as *jerky*, *stilted*, *staccato*, "*jumpy jolty*", or as lacking smoothness or continuity. Other comments make references to pauses, lags, and transitions between movements or frames.

### 5.4.3 Comparison Between Experiments

Performance on the L-L layout trials used in Experiments 2 and 3 (that is, on the routes with equal-length first and second straight roads) can be directly compared with performance on the trials in Experiment 1 (in which all routes had equal-length outbound roads): in terms of both accuracy and the pattern of error.

In Experiment 1, performance across the three internal angles showed consistent underestimation of the final angle. A pattern of consistent underestimation was also observed by Wartenberg et al. (1998), Péruch et al. (1997), and Kearns et al. (2002), in studies of human visual path integration. Accuracy in Experiment 1 was also similar to that observed in the previous studies, that is, a mean underestimation of between approximately 7.1° and 24°. Mean error on the 60°, 90°, and 120° angle trials indicated underestimation by 14.92°, 21.94°, and 30.71°, respectively. Accuracy was, therefore, approximately within the range typically found; although estimates were a little less accurate for the 120° angle. The mean error of 30.71° for the 120° angle is similar to the mean underestimation by 29.6° for 180° angles, which was found by Péruch et al. (1997).

In contrast with Experiment 1, a pattern of overestimation on the L-L + 60° and LL + 90° angle trials was found in both the Active and Passive conditions of Experiment 2; and underestimation on the L-L + 120° angle trials. In the Active condition, accuracy for all three internal angles was higher than in Experiment 1:

mean error showed overestimation by  $9.87^\circ$  and  $0.18^\circ$ , on the  $60^\circ$  and  $90^\circ$  angle trials, respectively; and underestimation by  $8.10^\circ$  on the  $120^\circ$  angle trials. Accuracy was mostly higher in the Passive condition than in Experiment 1, as well: mean error on the  $60^\circ$  and  $90^\circ$  angle trials showed overestimation by of  $25.23^\circ$  and  $15.16^\circ$ , respectively; and underestimation on the  $120^\circ$  angle trials by  $1.74^\circ$ .

Active participants showed a level of accuracy, for all three angles, that was similar to that found by Kearns et al. (2002), but considerably higher than in the studies by Wartenberg et al. (1998), and Péruch et al. (1997). Performance by Passive participants was less consistent. Their responses showed higher accuracy on the  $120^\circ$  angle trials than in the three earlier studies. However, whilst passive estimates were comparable to those observed by Wartenberg et al. (1998), and by Péruch et al. (1997), on the  $60^\circ$  angle trials, and slightly more accurate on the  $90^\circ$  angle trials, they were less accurate, on both the  $60^\circ$  and  $90^\circ$  angle trials, compared with Kearns et al. (2002).

A pattern of consistent overestimation was found on the L-L layout trials in Experiment 3, in contrast with both previous experiments. Performance on the  $60^\circ$  trials was much less accurate than in both Experiments 1 and 2; on the  $90^\circ$  angle trials, accuracy was similar to Experiment 1, but lower than in both the Active and Passive conditions of Experiment 2. On the  $120^\circ$  angle trials, participants performed more accurately than in Experiment 1, but less accurately than in both conditions of Experiment 2. The mean error for the L-L +  $60^\circ$ , L-L +  $90^\circ$ , and L-L +  $120^\circ$  trials showed overestimation by  $39.35^\circ$ ,  $28.06^\circ$ , and  $10.79^\circ$ , respectively.

Compared with previous studies of visual path integration, conducted in virtual environments, Experiment 3 showed less accurate performance on the  $60^\circ$  and  $90^\circ$  angle trials. On the  $120^\circ$  trials, however, it was more accurate than in the studies with minimal optic flow by Wartenberg et al. (1998), and by Péruch et al. (1997); but less accurate than in the study by Kearns et al. (2002), in which both rotational and translational optic flow were available. Underestimation by  $20.3^\circ$  for isosceles triangles, and by  $20.9^\circ$  overall, was observed by Péruch et al. (1997), and by  $19^\circ$  and  $24^\circ$  by Wartenberg et al. (1998). Underestimation of  $7.1^\circ$  was observed by Kearns et al. (2002).

Thus the overall level of accuracy found in this study was generally similar to, or better than, that found in previous experiments (Péruch et al., 1997; Wartenberg et al., 1998; Kearns et al., 2002), when uninterrupted optic flow cues from smooth self-motion were available to participants; and even when optic flow cues were disrupted, through intermittent presentation of self-motion, on shorter routes. However, accuracy dropped considerably, in relation to previous experiments, on longer routes, with disrupted optic flow cues.

## **Chapter 6. General Discussion**

The aim of this thesis has been to extend previous research on human visual path integration, by examining performance in ecologically-valid, large-scale virtual environments. The effects of several factors have been examined: characteristics of the display; variations in route (triangle) layout, specifically, the lengths of the path legs and the value of the angle between them; the large curve on the roundabout; optic flow and depth cues contextualised within authentic environments; disrupted optic flow information from intermittent self-motion; immersion and sense of presence; navigation mode; and gender. The findings will now be discussed in detail.

The results are of interest from the perspective of practical applications of virtual environment systems: such as their use for navigational training in professions in which a high level of navigational skills, including path integration skills, is required.

### **6.1 Effects of Visual Context on Path Integration**

#### **6.1.1 General Overview of Results**

The overall results show that participants in this study were able to perform path integration on the basis of optic flow cues alone. Participants displayed systematic patterns of error, and levels of accuracy, which were generally comparable to those observed in previous studies of human visual path integration, conducted in virtual environments with triangle-completion tasks (Kearns, Warren, Duchon, & Tarr, 2002; Wartenberg, May, & Péruch, 1998; Péruch, May, & Wartenberg, 1997). Performance was reasonably accurate, overall, when optic flow cues were available, and sensitivity to route layout parameters was apparent: specifically, to the different lengths of the first and second leg on the outbound path, in conjunction with the angle between the legs (the internal angle). Performance was also affected by display size and type, as well as by the availability of optic flow and other visual information, such as depth. Gender and navigation mode were also influential, to some extent. There was sometimes a compression of the range of responses relative to the correct values, which is a common finding in triangle-completion studies, conducted both in virtual worlds (Kearns et al., 2002; Wartenberg et al., 1998; Péruch et al., 1997), and in the real world (Loomis et al., 1993; Klatzky et al., 1990).

The current study can be compared with similar triangle-completion studies conducted in virtual environments, that is, with those in which a similar range of internal angles (60°, 90°, and 120°), and route types (two- or three-leg outbound

paths), were employed. In studies of visual path integration performed in conditions of sparse optic flow information, Wartenberg et al. (1998) reported underturning by 24° and 19° in two separate experiments; whilst Péruch et al. (1997) documented a mean underturn of 20.9° overall, and of 20.3° for isosceles triangles. Kearns et al. (2002) observed mean underturning by 7.1°, when both rotational and translational optic flow were available. Thus, in general, underestimation of the final angle, by a mean signed error of between about 7° and 24°, could be considered typical for human performance in virtual environments. This overall level of performance, whilst not very accurate, is well above chance and systematic (Loomis, Klatzky, Golledge, & Philbeck, 1999).

In Experiment 1 of the current study, in which the virtual environments were displayed on large projection screens in a driving simulator, performance exhibited a level of accuracy which was comparable to that observed in the previous studies; at least, on 60° and 90° angle trials. In Experiment 2, in which the virtual environments were displayed on small desktop monitor screens, performance in both the Active and Passive conditions was, in general, within a similar range of accuracy, or higher, than in the previous studies. Even in Experiment 3, in which optic flow information from self-motion was disrupted, performance displayed similar or higher accuracy than in the previous studies, on 120° angle and S-L layout trials. However, on trials along routes with the 60° and 90° angle and L-L and L-S layouts, performance was considerably less accurate, compared with the previous studies.

Overall, performance in the current study did not show the very high level of accuracy of rotational estimates, and small variance, which were observed in studies of visual path integration, based on optic flow, by Riecke, van Veen, and Bühlhoff (2000, 2002), and by Gramann, Müller, Eick, and Schönebeck (2005). However, this may have been due to differences in both the experimental apparatus, and the virtual environments, which were used. A large half-cylindrical projection screen was used in both of the previous studies, whilst the screens used in the current study were flat (and tilted backwards in Experiment 1). Participants in the study by Gramann et al. (2005) travelled through a tunnel, whilst the setting in the current study was a large outdoor space. Riecke et al. (2000, 2002), who found almost perfect visual rotation, provided feedback to participants on their performance, which may account for the elevated accuracy; whilst no feedback was given to participants in the current study.

Cornell and Bourassa (2007), and Cornell and Greidanus (2006), on the other hand, observed much lower performance accuracy on routes with large gradual curves. In the current study, decreased accuracy was found when the availability of optic flow cues was reduced in Experiment 3; rather than from the presence of the

large curve on the roundabout, apart from female responses in the Passive condition. Thus, there was not a large effect of the gradual curve.

The results of this study are consistent with previous studies, which have shown that information from optic flow alone can support path integration (Kearns et al., 2002; Wartenberg et al., 1998; Péruch et al., 1997; Riecke et al., 2000, 2002; Gramann et al., 2005). The findings do not, therefore, support studies indicating that additional proprioceptive and vestibular cues from physical turning are required for updating self-rotations during path integration (Chance, Gaunet, Beall, & Loomis, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Bakker, Werkhoven, & Passenier, 1999; 2001; Lathrop & Kaiser, 2002; Sadalla & Montello, 1989). The conditions in the present study were not detrimental to performance.

However, it was also found that the overall accuracy of performance can be increased, through the addition of some active participant control; and through manipulation of the route layout. The combination of leg-lengths on the outbound route, together with the internal angle, has a very powerful effect. The use of less intrusive apparatus, and attention to gender effects, can also heighten accuracy.

### **6.1.2 Effects of the Display**

The first experiment examined the effects of presenting visual information on three large projection screens, arranged so that the participant was partially enclosed. This display provided a wide forward field of view (175° horizontal by 41° vertical), which enabled the presentation of peripheral visual information; and enhanced depth. This display was expected to increase the accuracy of task performance, in comparison with previous studies; either through direct effects on path integration, or through a heightened sense of presence and immersion, in the absence of other immersive features. The second experiment investigated the effects of presenting visual information on three smaller, standard desktop computer monitors, again arranged to partially enclose the participant. A wide forward field of view was also provided by this display (107.2° horizontal by 39.3° vertical). In both experiments, the three-screen display was expected to compensate for the absence of information from head movements during the simulated motion, and thereby to enhance accuracy. In all three experiments, the effects of the display on performance were found to be direct, rather than through a sense of presence.

It was found that the experimental apparatus in the first experiment did not lead to very accurate path integration performance: the required degree of rotation was consistently underestimated, and responses were compressed into a narrow range. However, performance was similar to that found in other studies of visual path

integration using large screens (Péruch et al., 1997; Wartenberg et al., 1998). Very pronounced gender differences in performance were also observed in Experiment 1, with female estimates tending to be less accurate than male estimates.

This result contrasts with those of several studies, in which it was found that large screens, providing a wide field of view, enhanced navigational performance, including path integration, in virtual environments (Tan, Gergle, Scupelli & Pausch, 2003, 2004, 2006; Tyndiuk, Lespinet-Najib, Thomas, & Schlick, 2007; Patrick et al., 2000), and that the effect is especially large for the rotational component (Riecke et al., 2002; Schulte-Pelkum, Riecke, von der Heyde, & Bühlhoff, 2004). Large displays have been found to be particularly beneficial for females, leading to reduced gender differences (Czerwinski, Tan, & Robertson, 2002; Tan, Czerwinski, & Robertson, 2003). However, in the current study, gender differences were found in Experiment 1, in which large screens were used; whilst they were reduced in Experiment 2, in which the small-screen desktop monitor arrangement was used.

This difference in results may be because the large screens used in the current study were not stand-alone projection screens, as in the previous studies, but also part of a driving simulator: this may have influenced performance separately. The experimental display used in Experiment 1 was very nauseogenic, and provoked at least some simulator sickness symptoms in the majority of the participants. This may have impacted negatively on task performance. Some participants, especially females, also found the simulator intrusive and somewhat intimidating. Thus, some female participants, in particular, may have been further negatively affected by feelings of apprehension about the driving simulator. These adverse effects may have negated any beneficial effects of using the large display screens: such as accentuation of the optic flow, and other visual cues, available from the environment; or increased immersion, leading to an enhanced sense of presence.

Most of the previous studies also used a curved, or semi-curved, panoramic display; whilst the large screens used in the current study were flat. Whilst both types of display partially surround the user, and are, thus, more immersive, large screens may also need to be curved in order to have beneficial effects on navigation performance. This is possibly because curved screens increase realism, and thereby support a more convincing illusion of immersion in the virtual world. The split screens may interfere with the perception and use of visual information: for example, important details may be obscured at the point where the screens meet. The curved surfaces may also help to correct, or compensate for, some perceptual distortions that can occur with projection screens.

More accurate performance was, in fact, observed in Experiment 2, with the standard desktop monitors. The small-screen display countered some of the adverse

effects of the large screens: it reduced cybersickness, and may, also, have reduced apprehension in females, because it was more familiar, and less technically daunting. The effect of other factors, such as accommodation distance to the screen or active participant control, may also have been important. Accuracy showed particular improvement in the Active condition in Experiment 2. Active control might also have increased the accuracy of performance in the driving simulator, which was used in Experiment 1; this was not tested, however, as only passive trials were conducted.

The different pattern of results in Experiments 1 and 2 may have been due to effects of the displays on velocity and distance estimation. Firstly, the overall size of the virtual world, which was perceived by the participants, may have depended on the size of the display. The smaller display, on which the virtual environments were presented in Experiment 2, resulted in a reduced field of view, compared with Experiment 1. A restricted field of view may make the world appear smaller, by reducing peripheral information (Dolezal, 1982), which can limit context and texture-gradient information available in the environment; and by creating an artificial frame around the world (Kuhl, Thompson, & Creem-Regehr, 2009). In the real world, a reduced field of view can lead to compression of perceived distance (Dolezal, 1982; Hagen, Jones, & Reed, 1978) and size (Alfano & Michel, 1990). It may also influence distance judgments in virtual environments.

In Experiment 2, the virtual world may have seemed to be in miniature, due to the use of the smaller screens: it may have appeared that everything had shrunk, including dimensions such as length. Scaling effects possibly made the roundabout seem very small (as with a model), which could have led participants to perceive that they were travelling faster, and covering more ground, than they really were. Thus, participants possibly perceived that they had travelled further along the first leg than they actually had: that is, they overestimated the true distance. Perception of faster self-motion speed may, thus, have led to the distance covered seeming longer than it truly was. This may explain the overestimation of distance on the routes with a longer outbound distance (that is, on the L-L and L-S layouts with the 60° and 90° angles).

In Experiment 1, in contrast, the virtual world may have seemed to be much larger than it actually was, because of the use of the large screens. It may have appeared that everything had been magnified, including dimensions such as length. Due to scaling effects, the roundabout may have seemed enormous, leading participants to perceive that they were travelling more slowly, and covering less ground than they actually were: thus, they perceived the true distance covered to be shorter than it was, and requiring more time to travel than it really did. They perceived, therefore, that they had not gone as far along the first leg as they really

had: that is, they underestimated the true distance. Perception of slower self-motion speed may, thus, have led to the distance covered seeming shorter than it truly was.

However, the final angle was also underestimated on the 120° angle routes, and on the S-L layouts, in Experiment 2. Thus, on the shorter outbound distances, participants perceived that they had gone less far than the true distance, as in the first experiment. This may have been because self-motion along the shorter distance minimised the effects of perceived size: it is possible that such effects are more likely to occur, or are stronger, over longer distances, and that the distance was too short on these routes. Thus, there may be an interaction between the distance on the outbound routes, and the perception of self-motion speed, and hence, distance travelled, which produces different effects for long and short routes.

Misjudgement of travelled distance may have been due to misperception of the velocity of simulated translation in the virtual world. Visual speed perception may have been influenced by an interaction between effects of the display characteristics, such as the field of view, and effects of enhanced peripheral vision from the textured environments. Both underestimation (Baumberger, Flückiger, Paquette, Bergeron, & Delorme, 2005; Törnros, 1998; Recarte & Nunes, 1996) and overestimation (Godley, Triggs, & Fildes, 2004, 2002, 2000) of speed have been found in virtual environments presented in a driving simulator. Driving speed in a simulated road tunnel was higher than in its real-world equivalent, due to underestimation of perceived speed (Törnros, 1998). Reduced driving speed resulted from overestimation of perceived speed, on straight sections of a narrowed road (Godley et al., 2004, 2000): this was due to road markings with highly textured and contrastive patterns, such as hatched striping or transverse lines, which enhanced peripheral visual stimulation (Triggs, 1986).

The effect of the high-contrast textured road marking patterns was not found on curves (Godley et al., 2004); this is probably because curves provide less stimulation of peripheral vision, resulting in minimal, if any, enhancement of speed perception. This could have affected the results in Experiment 2, since different route layouts included different distances, hence different travel duration, on the straight section versus the curved section of the route. On routes with long straight segments on the approach road (the L-L and L-S layouts), more time was spent on the straight section than on the route with a short straight segment (the S-L layout): thus, speed may have seemed faster on the L-L and L-S routes than on the S-L routes.

Similarly, the 120° angle exit-road was relatively close to the straight-through exit-road at 180° from the approach road, so this route may have seemed to have one long straight segment. Thus, participants may have perceived that they were travelling straight through the roundabout on these routes, and not turning at all: some participants did informally indicate this in the debriefing after the experiment.

This may account for the overestimation of distance on the L-L and L-S routes with 60° and 90° angles, versus the underestimation on the S-L and 120° angle routes.

Speed estimation may also have interacted with navigation mode in Experiment 2. Recarte and Nunes (1996), in a study of real-world driving on a closed circular track, observed a tendency for speed to be underestimated, particularly at lower speeds. However, underestimation systematically decreased as speed increased, particularly under active conditions, and especially by women, compared with passive conditions.

Effects of the perceived size of the virtual world on velocity and distance estimation may have interacted with participants' oculomotor responses to the displays; specifically, with the accommodation response of the eye to the screen, and vergence. The distance of the participants from the display screens differed in Experiments 1 and 2, resulting in different visual accommodation distances: participants were seated further away from the screen in Experiment 1 than in Experiment 2. Thus, different effects of participants' oculomotor responses, on their perception of the distance travelled on the outbound path, would be expected.

In the visual accommodation (focusing) response of the eye, the lens brings objects at different distances into focus, so that they can be seen clearly. As an observer fixates on objects at different distances, the vergence angle between the lines of sight of the eyes changes, to maintain alignment of the object image on the two retinæ. The accommodation response and vergence may interact, whereby as one changes, so does the other. Accommodation can serve as a depth or distance cue, through the registration of changes in apparent distance for objects of constant angular size (Roscoe & Acosta, 2008). The perception of size and distance depends partly on the accommodation distance of the eyes (Hull, Gill, & Roscoe, 1982; lavecchia, lavecchia, & Roscoe, 1988, 1983; Simonelli, 1979).

Accommodation may be influenced by perceived distance, which may, in turn, be influenced by the depth plane in a virtual image display. The influence of the perceived distance of a stimulus on the accommodation response is illustrated by a phenomenon known as instrument myopia: stimuli viewed through instruments such as microscopes, despite their optical distance, are perceived as being closer (Edgar, 2007). Conversely, the perceived distance of objects may also be affected by accommodation. The effects of accommodation and vergence on perceived size and / or distance may occur as part of an interaction with other distance cues, such as visual texture gradients (Roscoe, 1998).

Oculomotor responses can be influenced by the design features of virtual displays. Misperception of size and distance, such as violations of size-distance invariance, are common (Roscoe & Acosta, 2008; Acosta, 1997; Roscoe, 1998,

1984; Roscoe, Hasler, & Dougherty, 1966; Roumes, Meehan, Plantier, & Menu, 2001). This may be partly due to inappropriate oculomotor responses involving accommodation, possibly in conjunction with changes in eye vergence and focal distance of the eyes when using a virtual display (Iavecchia et al., 1988; Roscoe, 1998; Edgar, 2007).

The visual field commonly appears to shrink in virtual displays, which may be associated with focal distance. In flight simulators, for example, compression in simulated airport scenes causes runways and other surface features to be perceived as smaller or narrower, more distant, and closer to the horizon, compared with viewing them directly. Consequently, the approach angle appears shallower, and the distance to the aimpoint farther away, than they actually are (Roscoe, 1998, 1984; Roscoe et al., 1966). Focal distance and apparent size are highly correlated: apparent size increases with focal distance; concomitantly, apparent distance decreases with focal distance (Roscoe & Acosta, 2008; Roscoe, 1998, 1977; Acosta, 1997; Roscoe, Olzak, & Randle, 1976). Roscoe et al. (1976) found that the size of circular disks was consistently judged to increase with outward shifts in focus, and to decrease with inward shifts.

Randle, Roscoe and Petitt (1980) found that focal distance was related to professional pilots' judgments of whether they would overshoot or undershoot the landing aimpoint on the final approach to a virtual airport scene, during simulated flights. Such misjudgements in simulated landing approaches may be corrected through image magnification, so that the images appear the same size as a natural view of the same scene. This can compensate for violations of size-distance invariance, and support more accurate distance estimation (Roscoe & Acosta, 2008; Meehan & Triggs, 1988; Roscoe, 1984; Randle et al., 1980).

In Experiment 2, the pattern of participants' responses differed on the shorter and longer outbound routes. Underestimation of the final angle was observed on the S-L and 120° angle routes, and overestimation on the L-L and L-S routes with the 60° and 90° angles. This difference may have been due to an interaction between the perceived distance on the outbound routes, and oculomotor responses to the display. It has been shown previously that accommodation and vergence can affect perceived distance through interaction with distance cues in virtual displays. Accommodation may influence, or be influenced by, perceived distance. Different perceptual biases resulting from this interaction may have led to different effects on distance estimation, and, ultimately, on the directional estimates.

The different patterns of error, and levels of accuracy, in Experiments 1 and 2 may also have resulted from other differences between the displays. The screen in Experiment 1 was slightly sloping, whilst the screen in Experiment 2 was not; the

former also had a wider horizontal field of view than the latter (a difference of almost 68°). Previous studies have found that the use of different display types can produce different patterns of results. Schulte-Pelkum et al. (2004) observed that participants tended to underturn target angles on a curved screen, but to overturn them on a flat screen; whilst Bakker et al. (1999, 2001) found a pattern of underturning with a horizontal field of view of 24°, but overturning with a horizontal field of view of 48°. Schulte-Pelkum et al. (2004) argue that differences in display *type* are more critical than the field of view *per se* for perception of self-rotations.

Finally, differences between the results in Experiments 1 and 2 may have been partly attributable to the presence of particular features in one experiment, which were absent from the other: these concerned, for example, framing effects and the contrast level of the stimulus. The simulator car in Experiment 1 provided a strong reference frame, whilst such a surround was absent in Experiment 2, in which no car was used. A spatial reference frame may support estimation of egocentric angles, leading to higher accuracy, by suggesting a polar coordinate system (Riecke et al., 2000, 2002). The low-contrast screens in Experiment 1 were absent from Experiment 2, in which higher-contrast screens were used leading to different effects on the estimation of self-motion velocity.

### **6.1.3 Effects of Route (Triangle) Layout: Internal Angle and Leg-length**

The route layout parameters (the leg-lengths on the outbound path and the internal angle between them) had a powerful effect on path integration performance.

*Effect of Internal Angle:* The internal angle exerted a very clear and strong effect on the final turn angle estimates: this was evident from the magnitudes and patterns of error, which differed according to the value of the internal angle, across the three experiments. This is consistent with other studies which have found strong effects of angle (Kearns et al., 2002; Péruch et al., 1997; Wartenberg et al., 1998; Bakker et al., 1999, 2001).

In the first experiment, consistent underestimation of the final angle was observed. The mean error tended to increase with increasing size of the internal angle  $\alpha$ , from the small (60°) to the large (120°) angle, which is a common finding in path-completion studies. Responses for the 60° angle were the most accurate, therefore, and responses for the 120° angle were the least accurate, with the 90° responses intermediate. Participants tended to respond to the 120° angle as though they perceived that they had turned a smaller (60°) angle. Estimates on the 90° and 120° angle trials showed very similar values of the mean error. A compressed range

of responses across the set of angles was seen, with a very small difference between the values for all three angles: this suggests that the participants did not perceive the angles to be very different from each other. Variability was rather high overall, and similar across all three angles. The responses on the 90° angle trials show the least variability, and those on the 60° responses show the most.

In the second experiment, the final turn angle was generally overestimated on the 60° and 90° angle trials, and underestimated on the 120° angle trials, in both the Active and Passive conditions. Participants in the Active condition treated all the internal angles as 90° angles, showing the least mean error in responses to the 90° angle, and the greatest mean error in responses to the 120° angle. This effect is consistent with previous research (Loomis et al., 1993; Loomis, Klatzky, Golledge, & Philbeck, 1999; Kearns et al., 2002). In the Passive condition, responses to the 120° angle were the most accurate, and responses to the 60° angle the least accurate. In the Passive condition, there is greater error on the 60° and 90° angle trials, but considerably less error on the 120° angle trials, than in the Active condition.

In the third experiment, consistent overestimation of the final angle was observed. Responses on the 60° and 90° angle trials were extremely inaccurate, with estimates on the 90° angle trials being the least accurate. However, responses were considerably more accurate on the 120° angle trials.

*Effect of Leg-Lengths on Outbound Path:* To assess whether performance in the first experiment had been influenced by the simple and repetitive triangle geometry used, greater variations in the route layout were included in the second experiment. The underlying triangle shapes were not all equilateral or isosceles, which led to a wider range of values of the required angle of rotation in the response. Nine different route layouts were produced, through different combinations of the internal angle  $\alpha$  and the lengths of the first and second straight section of the route. It was found that participants responded differently on the various layouts: thus, it is unlikely that any regular properties of the equilateral and isosceles triangles used in Experiment 1 had resulted in predictable or easily represented responses.

Thus, participants' responses demonstrated sensitivity to differences in outbound path (triangle) shape. The differences found, according to route layout, in Experiment 2 indicate that the simplicity of the equilateral or isosceles triangles was not a determining factor for accuracy in Experiment 2. This supports the explanation of error as resulting from misperception of distance on the outbound route, rather than from misperception of the (internal) angle of rotation at the end of the second outbound leg. However, there was also some bias towards stereotyped responses, indicated by the tendency of participants to assume that all the internal angles were

the same in some conditions. In the Active condition, for example, participants treated all angles as 90°, whilst in the Passive and Static conditions, all angles were treated as 120°.

Participants' performance was very strongly influenced by the different leg-length combinations, that is, by the lengths of the approach and exit roads, on the outbound path in the route layouts. Different response patterns and levels of error were found according to route layout: specifically, responses on routes with a short approach road and long exit road tended to show different patterns to responses on the other two layouts (long-long and long-short), which both had a long approach road. It appears that the length of the first leg exerts a critical influence on error.

In view of the finding that manipulations of the leg-lengths led to systematic changes in the directional estimates, it is unlikely that the observed errors are the result of underestimation or overestimation of the rotation at the end of the second leg of the route, as proposed in explanatory model 1. This is shown in figures 3.12 and 4.8 (at the top of pages 99 and 156). Rather, this finding indicates a greater likelihood that it is underestimation or overestimation of the length (distance) of the outbound legs which is the important influence on the errors, as proposed in model 2. This is illustrated in figures 3.13 and 4.9 (at the bottom of pages 99 and 156).

The effect of distance on the estimates is very clear from the data in Experiment 2. The internal angles used in Experiments 1 and 2 were the same; however, the patterns of error were quite different. This suggests that the error is unlikely to have resulted from misperception of the rotation (the internal angle). Similarly, in Experiment 3, leg-length (distance) had a very clear effect on the directional estimates. Again, the same set of angles was used as in the previous experiments.

The effect of the distance manipulations is illustrated by comparing the pattern and magnitude of the mean signed error, averaged across environments, for the nine route layouts (angle and leg-length configurations) used in Experiments 2 and 3. Error in Experiment 2, in both the Active and Passive conditions, showed overestimation of the final angle, on both of the route layouts which combined a long approach road with either of the two smaller internal angles: that is, on the L-L and L-S layouts (those with equal-length approach and exit roads, and a long approach road and short exit road, respectively), with the 60° and 90° angles. On the other hand, underestimation of the final angle was observed on the layout with a short approach road and long exit road, (the S-L layout), with all three internal angles; and on the other two layouts with the larger (120°) angle. This contrasts with the consistent underestimation of the final angle on the comparable trials in Experiment 1; and with the general overestimation of the final angle on all trials in Experiment 3.

Thus, the length of the approach road (that is, the first leg of the triangle on the outbound path), combined with the size of the internal angle, has a decisive influence on the type of error which is observed. The patterns of error can be predicted by assuming that participants misperceive the distance on the first road, and assume that both roads are of equal length. Perceiving a shorter or longer distance travelled on the approach road will lead to different kinds of error when estimating the final angle.

Error patterns were often similar in Experiments 2 and 3, in which optic flow cues were disrupted due to the intermittent self-motion. This observation suggests that participants were able to use cues besides optic flow to navigate, or that their visual perception was overridden by cognitive processes, while performing the path-completion task in Experiment 3.

The effects of angle and distance in the Experiments 1 and 2 will be considered in more detail, and some explanatory factors proposed, in the next two sections.

#### **6.1.4 Effects of Internal Angle: *Experiment 1***

In Experiment 1, participants consistently underestimated the final turn angle, particularly on 120° internal angle trials. A pattern of underestimation of the required degree of rotation in purely visual human path integration performance, particularly with larger turn angles on the outbound path, was also found in previous studies by Péruch et al. (1997), Wartenberg et al. (1998), and Kearns et al. (2002).

The level of accuracy was also comparable to that observed in these previous studies (or higher, in the case of the 60° angle). The results of Experiment 1 are very similar to those of Wartenberg et al. (1998), who obtained underestimation by 19° and 24°; and to those of Péruch et al. (1997), who found underestimation by 20.3° (for isosceles triangles) and 20.9 (overall). These studies were conducted in simple virtual environments, with limited optic flow, using large projection screens. The Experiment 1 results are less accurate than those of Kearns et al. (2002), who observed underestimation by 7.1°, in virtual environments in which both rotational and translational optic flow were available, using a head-mounted display.

The underestimation in Experiment 1 has been attributed to underestimation of distance on the outbound legs of the route, in line with an explanatory model which has been proposed. Distance underestimation is common in virtual environments, and may result from a number of factors. In this experiment, it may have been due, for example, to visual misperception of the virtual world, or to low contrast of the

display, leading to underestimation of the velocity of self-motion. Several possible explanations for the observed distance underestimation will now be considered.

Firstly, distance underestimation may have been due to misperception of depth, resulting from the limited depth cues in the display. Restricted availability of monocular depth cues in the projected images in flight training simulators, for example, has been shown to impair distance estimation. The accuracy of size and distance estimation from displays should increase, as the number of available depth cues increases, and the more veridical these cues are (Meehan, 1993; Roumes, Meehan, Plantier, & Menu, 2001).

Secondly, it is possible that the underestimation of distance was due to a failure of size constancy, whereby the apparent physical size of objects did not remain constant as they were approached, as their visual size projected onto the retina changed. This failure may have resulted from the effect of a strong surrounding reference frame, which was provided by the car in which participants were seated: the virtual world was viewed through the windscreen during the simulated motion. Riecke et al. (2000, 2002) attributed the excellent turning accuracy they observed to the screen providing a spatial reference frame, which, they suggest, may have aided estimations of egocentric angles, by suggesting a polar coordinate system.

Perception of an object's physical size, and distance from the observer, can be strongly influenced by its relative size within a fixed visual frame of space: failure of size constancy can result from perception of this frame around the object (Konkle & Oliva, 2011). Rock and Ebenholtz (1959) found that, when observers adjusted the length of a line framed in a large rectangle, to match the length of a standard line framed in a smaller rectangle, they made it much longer than the standard; thereby showing a strong bias to preserve the ratio of the line within the frame (the relative framing ratio). Participants in Experiment 1 may have perceived the scale of the space as larger, and, therefore, the speed of their self-motion as slower, due to framing effects.

A *vista paradox* illusion may also have occurred: that is, a framing effect in which large distant objects seem to shrink in physical size, and recede into the distance, when approached through the view of a naturally-occurring corridor, such as a street scene (Konkle & Oliva, 2011). The visual size of both the frame and the object increase on the retina as one approaches, as both get physically closer: however, the ratio of the object in the frame decreases, due to the frame growing much more quickly than the more distant object. A similar effect may have been produced in this experiment, as a result of the long straight street scenes along the route. This could have made the world appear larger, and, hence, the self-motion speed could have been perceived as slower.

A third possibility is that a cognitive distortion, resulting from the use of the large screens, may have led participants to perceive that they were travelling more slowly than their true speed, or that they had travelled a shorter distance than the actual one. The near-lifesize images of the virtual world, projected onto the large display screens, may have given the impression of a world that was larger than it really was: an effect possibly enhanced by sitting in a real (hence, lifesize) car, with another person present. This may also have increased the sense of immersion and presence, both of which were reported by participants as being quite high in this experiment. Together, these effects may have enhanced perception of the large scale of the virtual environments.

Finally, it is possible that perception in the virtual world was incidentally affected by a confounding variable, which resulted from an artefact of the driving simulator projection system: the display screens were found to have a low level of contrast. This may have influenced participants' sense of the speed at which they were travelling, and, hence, how far they had travelled along the outbound paths.

The effect of contrast on perceived speed is well-documented. Reducing the contrast of a slow-moving stimulus, such as a moving-grating pattern, reduces its apparent speed. At slow speeds, low-contrast gratings are perceived to be moving more slowly than high-contrast gratings moving at the same speed. Thus, slow-moving low-contrast patterns appear to be moving more slowly than they actually are (Thompson, 1982; Stone & Thompson, 1992; Brooks, 2001). Other stimulus patterns, such as a single dot, disc, or random dots, also demonstrate a change in speed as a function of contrast (Blakemore & Snowden, 1999, 2000). The opposite effect is found at high speeds. Low-contrast gratings are perceived as moving faster than high-contrast gratings moving at the same speed; thus, reduced contrast increases apparent speed. Fast-moving stimuli can appear to move faster than their true speed at low contrasts (Thompson, Brooks, & Hammett, 2006; Thompson, 2003).

This illusion of reduced speed is also found in real-life situations, such as driving in fog: drivers perceive their driving speed to be far slower than it actually is, and so they often increase their speed as a result (Snowden, Stimpson, & Ruddle, 1998). In a driving simulator study, in which the view from a vehicle moving along a road, through a virtual environment, was simulated, Snowden et al. (1998) found that foggier scenes were perceived to be moving more slowly than clear scenes. The same effect on perception of driving speed was found in a more realistic task, in which participants "drove" a simulated vehicle at set speeds along a winding road: as fog in the scene increased, thereby reducing the contrast of the driver's image, participants drove at faster speeds, exceeding the target speed. Thus, drivers'

perceptual judgment of their speed was erroneous in low-contrast situations: they perceived their movement to be slower than it actually was.

The low contrast of the driving simulator display screens, combined with the relatively slow speed of the self-motion, which simulated a maximum of 50 km/h (and was sometimes lower than this), may have produced the same effect in Experiment 1; whereby the participants perceived the speed of their self-motion as being slower than its true speed.

### **6.1.5 Effects of Route Layout: Internal Angle and Leg-length: *Experiment 2***

In Experiment 2, there was a general tendency for overestimation of the final turn on the 60° and 90° internal angle trials, and underestimation of the final turn on the 120° internal angle trials. Thus, participants tended to overestimate the required degree of rotation for the right angle, and for the acute angle (or smaller turn); and they generally underestimated it for the obtuse angle (or larger turn). A pattern of overestimation of small angles, and underestimation of large angles, is a typically-observed general tendency in path integration studies (Kearns et al., 2002; Loomis et al., 1993; Klatzky et al., 1990; Péruch et al., 1997; Bakker et al., 1999). There was also considerable variation between participants, which, again, is commonly found. Accuracy was highly influenced by route layout, in both the Active and Passive conditions; and it was generally higher in the Active condition than in both the Passive condition and Experiment 1.

In the model proposed earlier, overestimation and underestimation of the final angle were attributed to misperception (both overestimation and underestimation) of the distance on the legs of the outbound route. Distance misperception in Experiment 2 may have been influenced by several factors, some of them the same as those which affected the results in Experiment 1. However, these factors would have operated differently (potentially in opposing ways) in the two experiments, due to differences in the experimental design, which resulted in environments of different perceived scale.

Both overestimation and underestimation of distance have been found in previous studies of human path integration conducted in virtual environments. Observers are able to use optic flow to estimate the distance of visually-simulated forward self-motion, but their performance is prone to systematic patterns of error (Frenz & Lappe, 2005, 2006; Frenz, Lappe, Kolesnik, & Bührmann, 2007; Lappe, Jenkin, & Harris, 2007).

In a move-to-target task, perceived travelled distances were consistently overestimated, especially longer distances (Redlick, Jenkin, & Harris, 2001; Lappe et

al., 2007; Frenz & Lappe, 2005): that is, participants indicated a distance towards a previously-seen location, which was longer than the correct distance. In this task, participants were shown a static visual target in a corridor, which was then removed: they reported when they believed they had arrived at the target position, during simulated forward self-motion along the corridor towards it, on the basis of optic flow information. Participants typically responded too early, indicating that they felt they had reached the target location before they had traversed the whole distance. With a true travel distance of 12m, for example, participants perceived that they had covered the distance to a target that had been 16m away. Thus, they perceived that they had travelled further, and covered more ground, than they actually had, in moving towards the target. Short distances, however, were underestimated.

Thus, the move-to-target task produced overestimation or underestimation of distance, depending on the required distance. The finding that longer target distances were overestimated, and shorter target distances underestimated, parallels the pattern of results obtained in Experiment 2. Both overestimation and underestimation of the final angle were found, depending on the length of the approach road to the roundabout (that is, the first leg of the outbound route). The final angle was overestimated on the outbound routes with a longer first leg, and underestimated on the outbound routes with a shorter first leg. These errors have been attributed to misperception of distance on the outbound routes.

Both types of error have been explained with a leaky path integration model (Lappe et al., 2007; Lappe & Frenz, 2009), in which it is assumed that humans can estimate travelled distance from visual motion cues alone, through integration; but that the integration process is leaky. The model proposes that misperception of distance occurs, partly, because the integration leaks over the course of self-motion; and because when visual motion is transformed into travel distance, there is a gain factor. As the leak increases with distance travelled, longer and shorter distances are affected differently.

Both overestimation and underestimation in the move-to-target task are predicted by the leaky integration model, using a single mechanism (that is, integration), and the same parameters (that is, the leak, the gain, and the task type). The integration is assumed to leak by the same leakage factor in both conditions. The model proposes that human path integration from visual motion takes place over space, rather than over time; and that the leak is, therefore, accumulated as space is traversed, rather than while time passes (Lappe et al., 2007; Lappe & Frenz., 2009; Lappe, Stiels, Frenz, & Loomis, 2011).

The leaky path integration model accounts for the overestimation of distances, especially long distances, which were found in the move-to-target task. A

different task was used in the current study, as participants indicated direction with a dial, and there was no self-motion towards the start point. Distance estimates have been inferred from the data, therefore, rather than directly measured. However, it has been assumed, in the current study, that error in the final turn on the triangle-completion task results from misperception of distance on the outbound legs, rather than from erroneous execution of the response at the end of the second leg. A further assumption is that the same process of integration operates on the outbound legs of the path, regardless of the response method: that is, whether participants physically walk the distance to the origin afterwards, experience simulated self-motion towards it, or indicate the direction to it. Thus, leaky path integration could explain the pattern of results seen in Experiment 2.

In Experiment 2, a critical effect on error was exerted by the distance travelled on the outbound route as far as the exit-road: that is, the distance travelled on the first straight road, together with the distance travelled along the curved segment on the roundabout. This distance can be shorter, due to either a short first straight segment, or a short curved segment on the roundabout; or it can be longer, because of either a long first straight segment, or a long curved segment on the roundabout. Thus, the distance travelled on the roundabout curve was reflected in the final angle estimates, and could be considered a third leg of the outbound route. This distance depended on the value of the internal angle.

The 120° angle routes and the S-L layouts have the shortest outbound path lengths. The 120° angle exit-road is positioned the shortest distance from the approach road on the roundabout, and is reached more quickly, compared with the 90° and 60° angle exit-roads, especially the 60° angle exit-road. Similarly, the S-L route entails the shortest distance on the first straight segment, and the exit-road is consequently reached more quickly, than on the L-L and L-S layouts, which both have a long first straight segment. The 60° and 90° angle routes and the L-L and L-S routes have longer outbound path lengths: the 60° and 90° angle routes have longest stretch on the curve, the L-L and L-S layouts have a long first straight section.

The combination of the length of the first road, together with the distance between the first road and the exit-road along the curve on the roundabout, will be referred to as the *approach segment* of the outbound route. Routes with a short approach segment included those with a short first road (S-L routes), or the 120° angle exit-road; whilst routes with a long approach segment included those with a long first road (L-L or L-S routes), and the 60° or 90° angle exit-road. The 60° and 90° exit-roads were positioned further around the roundabout from the approach road than the 120° angle exit-road. The 120° angle exit-road was located quite close to the

approach road on the roundabout, whilst the 60° and 90° angle exit-roads were located far from the approach road on the roundabout.

The approach segment length was more important than both the length of the second road, and the degree of rotation experienced at the end of the first road. This may also help to explain the lack of a strong effect of turn type (gradual curve versus sharp turn) on performance: the *distance* traversed on the curve is more influential than the degree of rotation involved. This finding suggests that the task in the current study is more appropriately considered as a complex path-completion task, along a route with three outbound legs, one of which is the curved section of the route on the roundabout; rather than as a triangle-completion task in the strict sense (that is, a route with two outbound legs).

According to the leaky path integration model, leaking of the integration leads to overestimation of longer distances and underestimation of shorter distances, due to the relative proportional amount of leakage over long and short distances. This could help to explain the results in the current study. Overestimation of the final angle was displayed on layouts with a long approach segment on the outbound path in Experiments 2 and 3 (that is, on the L-L and L-S routes, in combination with 60° and 90° angles); and underestimation was shown on layouts with a short approach segment (that is, on the S-L layout and 120° angle routes). It has been assumed, in the proposed explanatory models, that error in the final angle estimates is due to misperception of distance on the outbound route: it can, thus, be further assumed that distance was overestimated on outbound routes with long approach segments, and underestimated on those with short approach segments.

The observed patterns and levels of error in the response depended on route layout, and the length of the approach segment on the outbound path had very strong effects on the error. Accuracy was generally higher on route layouts with a short approach segment on the outbound path than on routes with a long approach segment. The combination of a long first road together with the 60° or 90° angle exit-road produced the most error, especially in the Passive and Static conditions. Thus, participants' responses demonstrated great sensitivity to differences in route layout (triangle shape).

### **6.1.6 Effects of Disrupted Optic Flow Cues: *Experiment 3***

Experiment 3 examined the effects of presenting visual information intermittently on path integration, by disrupting smooth self-motion through the environments. The limited availability of optic flow information for performing the task enabled the importance of optic flow cues for path integration to be assessed. Otherwise, the

visual information was presented in the same natural contexts, and authentic virtual environments, that were used in the previous experiments. The experimental apparatus was the same as in Experiment 2.

The final angle was consistently overestimated in Experiment 3, and participants tended to respond as though all the internal angles were 120°. Accuracy was, therefore, highest on the 120° angle trials, and lowest on the 60° angle trials, on all three route layouts. Accuracy was also high on the S-L layout with all three internal angles. Performance was much less accurate on routes with the 60° and 90° angles combined with the L-L and L-S layouts; this suggests that it was much more difficult for participants to perform path integration on these routes, with disrupted self-motion cues, than it was on the 120° angle and S-L layout trials. Overall, performance was less accurate than in Experiments 1 and 2. However, accuracy was sometimes higher on the 120° angle and S-L layout trials, compared with the other two experiments, particularly in comparison with Experiment 1.

The overestimation of the final angle in Experiment 3 has been attributed to overestimation of the distance travelled on the outbound section of the route. It may have been especially difficult for participants to estimate distance, by using self-velocity information, on the routes with a longer outbound section (that is, on routes with 60° and 90° angles combined with the L-L and L-S layouts). However, on the routes with a shorter outbound section (that is, on those with 120° angles and S-L layouts), it may have been possible for participants to compensate for the disrupted optic flow information, by using other cues. Alternatively, the effects of disrupted optic flow may be cumulative, making velocity estimation more difficult and, hence, less accurate, over longer distances.

Overestimation of the final angle, attributed to overestimation of distance on the outbound path, was also found on layouts with longer approach segments in Experiment 2: that is, on L-L and L-S routes with 60° and 90° angles. Overestimation of distance has been observed in previous studies of human path integration conducted in virtual environments, especially with longer distances (Redlick et al., 2001; Lappe et al., 2007; Frenz & Lappe, 2005; Kearns et al., 2002).

However, underestimation of the final angle, on layouts with shorter approach roads on the outbound route, was not found in Experiment 3, in contrast with Experiment 2. This is an intriguing finding. Increased *accuracy* is expected on shorter routes, compared with longer ones, as error accumulates with distance during path integration. However, it is unclear why the *pattern* of error would differ from that found on shorter routes in the previous experiments, especially Experiment 2, which used the same display and route layouts. It may be that the response pattern is less stable over shorter distances, when optic flow cues from self-motion are unreliable.

The misperception of distance in Experiment 3 may have been influenced by the same effects of the display as in Experiment 2, such as erroneous estimation of the velocity of self-motion due to the perceived size of the virtual world, limited depth cues in the virtual environments, and accommodation distance to the screen. Overestimation of the final angle was also found in Experiment 2, in which the same apparatus was used as in Experiment 3; but it was not found in Experiment 1, in which different apparatus was used.

The greater accuracy on the S-L layouts and 120° angle routes may have resulted from the use of a heuristic by participants, to compensate for the lack of reliable optic flow information, such as shortest travel time or shortest distance. Since these routes had the shortest approach segment on the outbound route and, hence, travel time, compared with the other angles and layouts, this would have produced more accurate estimates. The possible use of a shortest distance or shortest travel time heuristic in Experiment 3, thereby by-passing any attempt to use distance cues, may also explain why performance was sometimes more accurate on the 120° angle and S-L layout trials, compared with Experiments 1 and 2. Participants may have attempted to use estimated velocity or distance information, only, to perform the task, in Experiments 1 and 2, without resorting to heuristics (which they did not need to use, as the optic flow information was more reliable).

It is also possible that other objects in the environment were used as landmarks, or as other aids to performing the task (such as the structures or artefacts of the simulation that were inadvertently present), which participants were better able to take advantage of in these conditions; perhaps because they were less distracted on the shorter routes by the confusion caused by having to cope with the disrupted optic flow cues.

The results of Experiment 3 do not, therefore, provide unequivocal support for previous research, showing either that continuous smooth optic flow promotes more accurate path integration than intermittent optic flow (Kirschen, Kahana, Sekuler, & Burack, 2000); or that continuous dynamic presentation of visual information is not required for path integration (Gaunet, Vidal, Kemeny, & Berthoz, 2001; Péruch, Vercher, & Gauthier, 1995; Mestre, 1988).

There were clear gender effects on performance in Experiment 3. Smooth optic flow promoted more accurate path integration by females than intermittent optic flow. Female responses were strikingly less accurate in Experiment 3 than in the Active and Passive conditions of Experiment 2, across environments and angles; especially on routes with equal-length roads or the S-L layout (which combined a short approach road and a long exit road). Responses by males in Experiment 3, however, did not greatly differ from their responses in the Active and Passive

conditions of Experiment 2, across all environments, angles and layouts. Thus, male responses showed less overall variability than female responses across the three conditions. The intermittent manner of presentation clearly had a more detrimental effect on female performance than on male performance.

There were also very different response patterns for females and males in Experiment 3. Females consistently overestimated the required angle, across environments, angles, and layouts. In contrast, males tended to underestimate the required angle on routes with a short approach road and long exit road, with all angles; as well as on all routes with the 120° angle, across all environments. However, males generally overestimated the final angle on routes with either equal-length roads or on S-L layouts (which combined a long approach road and short exit road) with a 60° or 90° angle, across environments.

Lathrop and Kaiser (2005) note that good interface fidelity (that is, a faithful depiction of changes in the user's position and orientation during navigation, including velocity and acceleration changes) can reduce any advantage during path integration of a more immersive interface, such as a head-mounted display which provides idiothetic information. Good interface fidelity was provided by smooth self-motion in the first two experiments. When fidelity was compromised in Experiment 3, by replacing the smooth self-motion with a sequence of still frames, performance deteriorated on the 60° and 90° angle trials with L-L and L-S layouts, especially for females, but not on the S-L layouts and 120° angle trials. Thus, interface fidelity may be more supportive of distance estimation performance on longer outbound routes, and by females.

Thus, the overall picture is rather complex, and the results are intricately entwined with issues of gender and route layout, making it hard to extricate trends and patterns purely in terms of whether image presentation was intermittent or continuous. This may help to account for the inconsistencies in previous studies, as gender was not considered in these studies, and mostly very simple route layouts were used, with no systematic variations of parameters, such as angles and distances, across conditions.

### **6.1.7 Effects of the Large Curve**

A large gradually curving section was included on the roundabout, in order to more accurately replicate path integration in real-world conditions: this added a large degree of rotation to the route. The effect of this curve on path integration was examined in Experiments 2 and 3, in which performance on roundabout and intersection routes was compared. A subset of 90° angle route layouts was included

in these experiments, in which the roundabout had been replaced with a crossroads intersection, which had a curve with a smaller, sharper degree of rotation. Cornell and Bourassa (2007) proposed that the degree of rotation (that is, turn versus curve) is important in path integration.

The 90° angle was selected for the comparison, as this was the angle with which participants were expected to have the least difficulty, and to show the greatest accuracy. It was expected, therefore, that this angle would provide clearer and less ambiguous data. Participants' directional estimates, typically, tend to be biased towards 90° angles; and to be most accurate near orthogonal directions, such as 90° (Sadalla & Montello, 1989; Moar & Bower, 1983; Waller, Beall, & Loomis, 2004; Montello, Richardson, Hegarty, & Provenza, 1999; Loomis et al., 1993; Klatzky et al., 1990). This suggests that directional knowledge may be organised using an internalised orthogonal reference system (Montello et al., 1999). The response bias may also arise from a distorted mental representation (Sadalla & Montello, 1989). The bias is especially prevalent when directional estimates are indicated with a dial, and may, indeed, be partly an artefact of this response method (Waller et al., 2004; Montello et al., 1999).

Turn type was not very influential on task performance in the current study. Error in the final angle estimates showed no effect of turn type, in general. Patterns of error were similar between trials with the roundabout curve, and the intersection turn. It was not the case that consistently more accurate performance was shown on either the intersection or the roundabout trials. Both types of turn showed very strong effects of the outbound road-length combination, and of gender.

There was an effect of turn type on the directional estimates in Experiment 2, mainly in the Passive condition, especially those of female participants. Differences in accuracy were observed between the roundabout and intersection trials, which also depended on route layout. A different pattern of results was also found on routes with longer and shorter outbound roads, whereby estimates on roundabout trials were less accurate on L-L and L-S layouts, and estimates on intersection trials less accurate on S-L layouts. Turn type did not greatly influence the responses in the Active condition by males or females, or male responses in the Passive condition: the relative accuracy of intersection and roundabout trials was very similar.

Turn type did not have an effect at all in Experiment 3. Estimates were very similar on intersection and roundabout trials on each route layout, and showed less overall accuracy than in Experiment 2. The lack of motion impaired participants' ability to accurately estimate rotation, on both the gradual curve and the sharp curve.

These findings do not support real-world studies of path integration along longer, gradually curved paths (Cornell & Bourassa, 2007; Cornell & Greidanus,

2006); in which path completion performance was less accurate than that typically observed on shorter straight paths in smaller real-world environments (Klatzky et al., 1990; Sadalla & Montello, 1989). The different findings may be due to methodological differences between the earlier studies and the current one. The previous studies were conducted in real, large-scale, outdoor environments, with blindfolded participants who walked. The current study, on the other hand, investigated visual path integration in virtual environments, which, while they were intended to replicate such environments, would not have been exactly equivalent. Self-motion was also simulated on-screen. The turn in the current study was also a complex rotation, which combined several directions, rather than being one gradual curve.

However, the *distance* which was traversed along the curve was influential. This is related to the angle between the two outbound roads. This suggests that the task in the current study is appropriately considered as a complex path-completion task along a route with three outbound legs, one of which is curved; rather than as a triangle-completion task in the traditional sense, along a route layout with a very large degree of rotation.

### **6.1.8 Effects of Optic Flow Manipulation and Depth Cues**

In all three experiments, optic flow information was available from textures within lifelike contexts. Environments contained either combinations of complex textures from buildings; or simple textures from the ground, or from natural elements, such as grass and trees. Visual path integration performance has been shown to be more accurate, equalling or even surpassing performance of non-visual path integration, when optic flow cues are available from more extensive texture (Riecke et al., 2000, 2002; Kearns et al., 2002; Gramann et al., 2005). Depth cues were also available from the textures, and from additional structures positioned around the roundabout.

The availability of optic flow was controlled through the level of texture displayed in the virtual environments. The intention was to replicate the effects found in visual path integration studies which used random patch textures, but with more contextualised flow from familiar naturalistic textures commonly found in the real world. During rotation, angular speed and direction are specified by the rate of optic flow from distant features in the surrounding visual environment. It has been shown that humans can perceive their self-motion, and estimate the angles that they have turned, from pure optic flow information (Bremmer & Lappe, 1999; Ellmore & McNaughton, 2004; Warren, Kay, Zosh, Duchon, & Sahuc, 2001; Warren & Wertheim, 1990). This study examined whether they would also be able to extract this information from the more naturally-textured virtual environments.

No overall benefits were found to result from the additional information provided by the more complex environments. Participant responses tended to be rather similar across the four environments, in general. Manipulation of the environmental textures had no effect on accuracy. The geometric features of the environment were more influential: that is, the lengths of the two outbound legs on the route and the intervening angle.

There was an effect of environment in Experiment 2, but this was small, and not as expected. Performance had been expected to be more accurate in the more detailed urban environments than in the rural ones, as the urban environments were richly-textured and provided both translational and rotational flow. Greater accuracy had also been expected in the environments with additional structures, than in those without them, as the structures provided further depth information. However, more accurate overall performance was observed in the environments with *less* depth information, especially by Active participants; and Passive participants performed more accurately in the environments with *less* optic flow information. Thus, *fewer* visual cues promoted more accurate performance; and the kind of cues which were more salient depended on navigation mode.

Active participants' performance exhibited higher overall accuracy in the urban and rural environment without added structures, than in the equivalent environments with structures. Thus, Active participants performed more accurately overall in environments with *less* depth information (Ur-N and Rur-N), than they did in the same environments with added depth information (Ur-S and Rur-S). Error was lowest in the environment with a high level of optic flow but no additional depth cues: that is, in the urban environment with no structures (Ur-N).

Passive participants, on the other hand, displayed greater accuracy in the rural environments than in the urban environments (one of which also contained additional structures, in each case). Thus, Passive participants performed with greater accuracy in an environment with very simple structure and less flow, than they did in in the same environment with additional flow information. Error was lowest in the simplest environment, with the least amount of visual information, from both optic flow and depth cues: that is, the rural environment without structures (Rur-N).

Thus, lower overall performance accuracy was shown by Active participants in both of the environments with added structures (Ur-S and Rur-S); and by Passive participants in one of the environments with added structures (Ur-S). Both Active and Passive participants showed the greatest level of accuracy in an environment with fewer depth cues (Ur-N and Rur-N, respectively). This seems counter-intuitive: it would be expected that the extra depth information provided by the structures would

improve accuracy of performance. This suggests that participants were using the structures in some way other than as a source of depth information.

Performance may have been less accurate, in the conditions with structures, due to participants attempting to keep track of their position and direction of travel, by using one or more of the structures as a landmark. Humans prefer to navigate by piloting when salient landmarks are available. However, the structures did not provide a reliable source of information for tracking position and direction, as they were not stable. Their positions were interchanged in each of the environments: thus, the attempted use of one or more of the structures as a fixed visual reference would have lowered the accuracy of performance.

Participants may have tried to combine piloting and path integration, by attempting to integrate information from the optic flow, the structures (which they perceived to be landmarks), and, in the Active condition, proprioception (physical feedback from steering). Piloting and path integration are normally complementary processes: information from landmarks and self-motion cues usually interact continuously during navigation; with one or other source of information being preferred, according to salience or reliability. This enables navigators to use the most suitable source of information for a particular purpose.

Active participants showed more accurate performance in the environments with no structures. This is likely to be because they were able to judge their speed more accurately by relying solely on the optic flow information, together with the additional basic proprioception information from the steering. Hence, Active participants performed most accurately in the Ur-N environment, as this provided the most reliable self-motion cues: it was the most detailed and visually informative environment, and it also had some non-visual (idiothetic) information; whilst there was no influence of the structures. Passive participants, however, were unable to benefit, to the same extent, from the complex visual information available in the urban environments, as they could not estimate their speed as accurately from the self-motion cues. Due to their mode of navigation, passive participants did not have non-visual information available, and so they had to rely completely on the optic flow cues. Thus, they performed more accurately in the simpler visual environments, which were provided by the rural environments.

Péruch, Vercher, and Gauthier (1995) also observed a beneficial effect of active navigation on human path integration performance. Active participants in their study reached specified targets, by the shortest path, more quickly and accurately than passive participants; in a small-scale simple virtual environment which was presented on a large display screen. Participants also found it easier to perform path

integration under active conditions (that is, with self-initiated movement, and the ability to change viewpoints with a joystick) than under passive conditions.

There was no effect of environment on the performance of participants in Experiment 1, however, who were also passive. This may be because the effect of environment interacts with display parameters, as well as with route layout parameters. The more varied layouts in the second experiment included routes with non-equivalent lengths of the two outbound roads.

Thus, the overall findings differed from those of Kearns et al. (2002), who observed a differential effect of the amount of optic flow available, from more textured virtual environments, on rotational estimates in a triangle-completion task. In that study of path integration during walking, participants tended to turn more or less, depending on the amount of optic flow information available. Reduced rotational flow, (achieved through exclusion of wall texture), significantly reduced participants' ability to estimate how far they had turned, resulting in lower accuracy of estimates. Higher accuracy was observed when participants could access both translational and rotational flow, in a richly-textured environment (with both wall and floor texture).

It is possible that the amount of optic flow was not varied enough in the environments in the present study, resulting in all of the environments providing sufficient visual information for path integration, instead of two of them being the intended "low" optic flow environments. It is quite difficult to create a virtual environment with minimal optic flow information, using naturalistic textures. This may also explain the sometimes excellent performance in Experiment 3, in which optic flow cues had supposedly been disrupted: more optic flow information may have been available than was intended, which may have assisted performance on the routes with shorter approach sections to the roundabout.

The finding that additional complex textures did not benefit performance indicates that even quite simple environments, such as the rural ones used in this study, can be sufficient for human path integration. The very basic rural environment, without structures, supported path integration performance, at a level of accuracy which is typically observed. This finding is important from the perspective of virtual environment design. It may be possible to dispense with more complex features, without greatly detrimental effects on task performance, and, thereby, create virtual environments relatively quickly, easily and cost-effectively. Gramann et al. (2005) also demonstrated that sparse optic flow information, provided by a tunnel navigation task, which was presented in simple desktop virtual environments, enabled participants to perform path integration relatively accurately.

### 6.1.9 Effects of Sense of Presence

In this study, direct effects were exerted on task performance by features of the display, virtual environments, and experimental apparatus, as well as navigation mode. However, a sense of presence did not exert indirect effects on performance.

A moderately high sense of presence was experienced by participants, in general, in this study, despite the absence of several features which are typically employed to enhance immersion: such as multi-sensory stimulation, stereopsis and head tracking (Witmer & Singer, 1998; Slater & Usoh, 1993; Slater & Wilbur, 1997; Hendrix & Barfield, 1996; Snow & Williges, 1998); as well as very limited navigator control over the self-motion, and opportunities for interaction with the environments.

Witmer and Singer (1998) contend that a head mounted display is more effective than a 2D flat-screen display in eliciting presence, as it creates a greater sense of isolation from the outside world. However, participants' ratings on the ITC-SOPI indicate that the displays used in this study were also quite effective at eliciting presence. Mean presence scores were around the mid-point of the scale in both Experiment 1, conducted in the driving simulator, and in the Active condition of Experiment 2; and they were only a little lower in the Passive condition of Experiment 2. A rather lower score was found in Experiment 3: this was expected, in view of the disrupted optic flow. This finding is also inconsistent with research indicating that immersion requires direct interaction with the virtual environment, and stimulation of a range of senses (Witmer & Singer, 1998; Slater & Wilbur, 1997; Welch, Blackmon, Liu, Mellers, & Stark, 1996; Steuer, 1992). A reasonably immersive experience was provided in the current study, despite the absence of interactivity and sound.

The experimental apparatus incorporated several alternative features which are believed to enhance feelings of immersion, and sense of presence, in virtual environments. These features successfully compensated for the missing elements, to some extent. Smooth self-motion along the routes was convincingly simulated; and the interface device (the steering wheel and pedals) was realistic and non-intrusive. The semi-surrounding displays provided a panoramic scene with a wide field of view; and update rates were quite fast, due to the general lack of interactivity, apart from some limited interaction in the Active condition (Witmer & Singer, 1998; Slater & Usoh, 1993; Slater, 1999; Snow & Williges, 1998; Prothero & Hoffman, 1995; Slater & Wilbur, 1997; Barfield & Hendrix, 1995). A convincing impression of depth resulted from realistic depth cues (Wilson, Nichols, & Haldane, 1997; Darken & Sibert, 1996). The novelty factor may have fostered an increased sense of presence, especially in the driving simulator, which was a new experience for most participants.

Authenticity of the virtual world was achieved through a trade-off between various design features. Peripheral visual cues available from the wide field of view provided by the three-screen display, for example, compensated for the fixed accommodative distance of the display, and for the lack of physical user movement. Participants indicated that authenticity could be further increased through the addition of a few features, such as farm animals, trees or forest, other vehicles, more detailed houses, typical landscape features, and road signs and markings.

The ITC-SOPI scores and comments indicate that participants generally found the task and their overall virtual experience meaningful. They also found the virtual world reasonably realistic, and responded to it as an actual place. Most participants barely noticed various design faults and inaccuracies in the virtual environments, and they were very tolerant of the omission of many real-world details: these aspects also did not greatly impede task performance. These findings are consistent with observations from other studies that goal-directed activity is often unaffected by display defects (Wilson, 1997; Smets & Overbeeke 1995).

The moderately realistic virtual environments, even the basic rural ones with their quite simple visual appearance, supported task performance in this study. The results support the findings of studies which indicate that moderately realistic, less-immersive desktop virtual environments can be effective for learning spatial knowledge, such as developing a representation of the layout of a large-scale environment (Waller et al., 2001; Waller, Hunt, & Knapp, 1998; Péruch, Belingard, & Thinus-Blanc, 2000; Chabanne, Péruch, & Thinus-Blanc, 2003; Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002; Welch, 2003).

However, sense of presence did not, in general, have an effect on path integration performance in this study. A high level of presence did not generally increase accuracy on the path completion task; apart from the engagement factor in the driving simulator. However, as ITC-SOPI presence scores, overall, tended to be around the mid-point of the scale in this study, it was difficult to accurately separate and categorise participants into high and low presence groups. The groups may not have been sufficiently distinct to test the effects of presence adequately.

Furthermore, although the results indicate that the absence of features thought to be important for immersion did not greatly reduce presence, the addition of very limited interactivity led to greater accuracy in the Active condition of Experiment 2. Even a limited degree of control over the self-motion was sufficient to raise the level of accuracy of the directional estimates in the current study.

There was also a very high level of variability between participants, which may have reflected their different experiences, for example, of adverse aspects, such

as simulator sickness and disorientation. This may have affected task performance. The simulated motion was also influential.

## 6.2 Effects of Navigation Mode on Path Integration

In Experiment 2, navigation mode was manipulated, in order to assess the effects of navigator autonomy on path integration performance. One group of participants controlled their own simulated self-motion along the route, using a steering wheel and foot pedals (the Active group). Another group watched pre-recorded motion along the route, over which they had no control (the Passive group).

Navigation mode had an effect on path integration performance. Performance in the Passive condition was uniformly more accurate than in the Active condition, on all route layouts with the 120° angle; and on routes which combined a short approach road with a long exit road (S-L layouts), with all internal angles, and across all environments. Passive observers may have been able to benefit more from the shorter outbound routes, and been better able, therefore, to register flow indicating how far they had moved along the road on these routes, as they were not driving. Active participants may have been less able to do so, because they were focusing their attention on controlling their self-motion.

On the other hand, performance was consistently more accurate in the Active condition than in the Passive condition, on routes which combined a long approach road (L-L or L-S layouts) with either the 60° or 90° angle. The longer outbound routes may have provided Active participants with more opportunities to obtain information about the velocity and duration of their self-motion, partly from the action of using the steering wheel, which provided some basic proprioceptive feedback; the shorter routes may have been too short for Active participants to obtain this information.

Females showed a general tendency for Active responses to be more accurate than Passive responses, on routes with a long outbound path, that is on routes with equal-length roads, or with a combination of a long approach road and short exit road, with all three internal angles (but a little less consistently for the 120° angle). In contrast, there was a general tendency for males to show greater accuracy in the Passive condition than in the Active condition, or for only very small differences between the two conditions, on routes with all three angles.

Navigation mode did not influence the general patterns of error: these were the same in both the Active and Passive conditions. The final angle was consistently overestimated on routes which combined a long outbound distance with a smaller internal angle, that is, on L-L and L-S layouts with a 60° or 90° internal angle.

However, consistent underestimation of the final angle was observed on routes with a short outbound distance, that is, on S-L layouts, and on routes with a larger internal angle, that is, the 120° angle.

The results for the L-L layout trials in Experiment 2 can be compared with all trials in Experiment 1, since the layouts were the same. The Passive condition of Experiment 2 is directly comparable with Experiment 1, as participants in both were passive. The pattern of results on the 60° and 90° angle routes showed consistent overestimation of the final angle in Experiment 2, but underestimation in Experiment 1. However, the final angle was underestimated, in both experiments, on routes with the 120° angle.

Accuracy was higher in the Passive condition than in Experiment 1 on the 90° angle routes, and, especially, on the 120° angle routes, on which the difference in accuracy between the two experiments was extreme. On the 60° angle routes, however, accuracy was much lower in the Passive condition than in Experiment 1. Greater accuracy was found in the Active condition than in Experiment 1 on routes with all three angles. Thus, active navigation led to more accurate performance, overall, than passive navigation, particularly when the small-screen desktop monitors were used.

Active participants in the current study displayed a level of accuracy that was comparable to that observed by Kearns et al. (2002), and generally greater than that found by Péruch et al. (1997), and by Wartenberg et al. (1998), especially on the L-L and S-L layouts, and on L-S layouts combined with the 120° angle. On L-S layouts, responses on the 60° angle trials were less accurate than in the other three studies, however. Passive participants' performance on routes which combined a long outbound route (L-L and L-S layouts) with a 60° or 90° angle was comparable to that observed by Wartenberg et al. (1998) and Péruch et al. (1997), but less accurate than that found by Kearns et al. (2002). However, performance on routes with a short outbound distance (S-L layouts and the 120° angle exit-road) showed generally higher accuracy than in all three of the previous visual studies.

Under impoverished viewing conditions, in which some types of depth cues are less informative, unreliable, or absent altogether, other types of depth cues may become more salient (Roumes, Meehan, Plantier, & Menu, 2001). Active participant control may improve distance estimation, on the basis of a particular type of depth cue. Participants showed more accurate distance estimation with a stereoscopic display, for example, when they had active manual control of an aircraft during a simulated flight (Roumes, Plantier, & Menu, 1992), and during a simulated automated refuelling sequence (Woodruff, Hubbard, & Shaw, 1986), compared with passive distance estimation in the same environment.

In the present study, active control may have helped participants to obtain more information about the speed or duration of their self-motion, from the optic flow cues, over the longer outbound distance on route layouts which combined a long approach road (L-L or L-S) with either the 60° or 90° angle. The longer distance (and associated travel time) may have supported more accurate perception of the flow, and / or more thorough processing of the information it provided. This additional information, in turn, would have assisted distance estimation, and, ultimately estimation of the final angle. This would account for the greater accuracy of performance on those routes in the Active condition, compared with the Passive condition.

The findings of the current study, therefore, do not completely support previous research, indicating a facilitative effect of active navigation on human path integration (Péruch, Vercher, & Gauthier, 1995). Neither do they completely support previous studies showing no influence of navigation mode on human path integration performance (Gaunet, Vidal, Kemeny, & Berthoz, 2001; Wilson, Foreman, Gillett, & Stanton, 1997; Wilson, 1999). There are systematic differences in task performance, which indicate an effect of navigation mode; but these are closely intertwined with effects of gender and route layout. Thus, it is difficult to extract effects purely in terms of navigation mode, without considering gender and route layout.

### **6.3 Effects of Gender on Path Integration**

There were clear gender effects across the three experiments, but they were quite complex; and they did not indicate consistently greater accuracy by either gender, compared with the other. The effect of experimental design was important. Females performed less accurately than males in the driving simulator (Experiment 1), and when optic flow was disrupted (Experiment 3). However, gender differences were reduced when optic flow cues were available from smooth self-motion, and the virtual environments were presented on a smaller desk-top display, especially when some active participant control was possible (Experiment 2).

There were many similarities between male and female performance, such as similarly high levels of variability, and the same tendencies in the pattern of results: for example, underestimation of the final angle in Experiment 1, which increased with increasing size of the angle; and overestimation of the final angle in Experiment 3, together with decreasing error with increasing size of angle.

In Experiment 1, many female participants (unlike male participants) seemed to find the driving simulator off-putting, which may explain the lower overall accuracy

of female task performance. The lower accuracy of female estimates in Experiment 3, on the other hand, may have reflected a greater dependence, compared with males, on optic flow information, and less ability to compensate for its disruption through the use of other visual information, such as static depth cues. The intermittent motion may also have prevented, or hindered, the use of other strategies that women were using to complete the task; such as timing, or reliance on a cognitive map.

In Experiment 2, reduced gender differences in accuracy may have been due to the use of a small-screen desktop display, which would have been more familiar to participants than the driving simulator; or to the greater variety of route layouts, which provided a wider range of test conditions. The differences may also have reflected effects of the navigation mode, as females tended to perform more accurately than males, on some layouts, in the Active condition. A combination of these factors is also possible. This finding highlights the need to ensure that the experimental design does not mask female abilities, or create, or contribute to, *apparent* gender differences.

Thus, the results did not indicate consistently more accurate path integration performance by either gender, in comparison with the other. Consistent overall trends are difficult to discern. On routes with a short approach road and a long exit-road, for example, females consistently performed more accurately in the Passive condition, while males generally performed more accurately in the Active condition, compared with the other gender. Female performance in the Passive condition, on routes with a short approach road and a long exit-road, was very accurate; and more accurate than male performance on the same routes in the Active condition.

These results are consistent with previous research which also found complex gender effects, with no clear advantage for either gender, in path integration (Kearns, Warren, Duchon, & Tarr, 2002); and with studies in which greater navigational accuracy was shown by one gender, or the other, depending on the context (Galea & Kimura, 1993; Moffatt, Hampson, & Hatzipantelis, 1998).

The results of Experiment 1 appear initially to support research showing that females are disadvantaged in navigation in virtual environments (Lawton & Morrin, 1999; Tlauka, Brolese, Pomeroy, & Hobbs, 2005), as female performance was consistently less accurate than male performance. However, it is of note that the *pattern* of error was identical for males and females (consistent underestimation of final angles), suggesting the influence of other factors on both genders. This was confirmed in Experiment 2, in which gender differences were greatly reduced, and females showed higher accuracy than males on many trials.

This suggests that it was not spatial ability, adeptness with technology, or the use of virtual reality *per se*, but some aspect of the technology itself which was

the critical factor. The display seems to have affected female performance, in particular. Females were more accurate when using the small-screen equipment in Experiment 2, possibly because they found it less threatening, or because they felt more comfortable with the smaller-scale model. However, females tended to be less accurate than males in Experiment 3 (except on routes with a short approach road and a long exit road), in which the same apparatus was used. This indicates that females were more affected by the lack of motion than males, since conditions were otherwise the same as in Experiment 2: this may have overridden the beneficial effects of the display.

Females seem to be especially affected by parameters of the technology, as well as by manipulations of the availability of optic flow; males, perhaps, are more able to compensate for these conditions, by using other cues. Fortenbaugh, Chaudhury, Hicks, Hao, and Turano (2007) found that males were able to use different types of cues in environments with minimal texture and photorealistic textures, whereas women found it more difficult to do this.

Overall, the results of the current study do not support findings of consistently more accurate performance by males than females, on a range of human navigation tasks in virtual mazes (Moffatt et al., 1998; Lawton & Morrin, 1999; Foreman, Sandamas, & Newson, 2004; Tlauka et al., 2005). The results also cast doubt on the contention by Waller, Hunt, and Knapp (1998), and by Waller, Knapp, and Hunt (2001) that virtual environments are especially challenging for women. In Experiment 2, women performed more accurately than men on many trials, in the same virtual environments, and on the same task, as those used in the other experiments. This suggests that aspects of the experimental apparatus contributed to the deterioration in female performance in the first experiment, compared with the second.

The contention by Waller (2000), that gender influenced spatial knowledge acquisition from a desktop virtual environment through association with navigational interface proficiency, is also not borne out in this study. Women in the driving simulator did not need to be proficient with the interface, as they did not actively navigate; whereas women in the Active condition of Experiment 2 did need such proficiency, in order to control their own self-motion through the virtual environments. However, women in the Active condition displayed the more accurate performance.

The results of Experiment 2 are consistent with studies conducted in more realistic and ecologically-valid virtual environments, which reported no gender effects (Wilson, Foreman, & Tlauka, 1997; Rossano & Moak, 1998; Darken & Sibert, 1996). However, the difference seems to be attributable, less to the type of virtual environment used, as suggested by Tlauka et al. (2005); and more to the apparatus used to display it. The evidence suggests that the display has a large effect.

The gender difference also did not appear to be due to a simple distinction between males and females, in the use of geometric versus landmark information, in performing path integration (Moffat et al., 1998; Sandstrom, Kaufman, & Huettel, 1998; Dabbs, Chang, Strong, & Milun, 1998; Galea & Kimura, 1993; Astur, Tropp, Sava, Constable, & Markus, 2004; Levy, Astur, & Frick, 2005; O'Laughlin & Brubaker, 1998; Saucier et al., 2002). Neither gender had access to landmarks in the environments, but women still performed as well as, or even more accurately than, men in Experiment 2.

Thus, females did not seem to be particularly disadvantaged by the lack of landmarks in performing path integration: in fact, they performed more accurately than males on some routes, such as those with a short approach road and a long exit road. This indicates an ability by females to use geometric route layout parameters, that is, the internal angle and outbound road-lengths, for path integration. Thus, if females do have a preference for landmarks, rather than distance and angular information, it appears that they can change strategies, or otherwise compensate for an absence of landmarks, during path integration.

## **6.4 Potential Bias Resulting From the Use of the Dial**

It is possible that the use of a dial in this study may have led to bias in the results. Directional knowledge is commonly assessed by requiring participants to manipulate a line on a circle, in order to indicate a direction to a target. Using a manual dial for this purpose is one of the most widely-used techniques in real-world studies, and, more recently, this traditional method of testing has also been adapted for computers (Waller, Beall, & Loomis, 2004; Montello, Richardson, Hegarty, & Provenza, 1999). However, testing methods that use depictions of circles can lead to response biases (Waller et al., 2004).

Categorical bias is one typical pattern of bias. Directional estimates are influenced by the category organisation of the surrounding spatial frame, as people divide the frame along the major axes of symmetry and use the resulting categories in making their estimates: this produces systematic bias toward the centres (prototypes) of those spatial categories. In reports of memories for the location of objects presented within a circular display, for example, a tendency has been found for responses to be biased towards the centre of the quadrants that can be formed, by superimposing horizontal and vertical axes through the centre of the circle (Waller et al., 2004; Huttenlocher, Hedges, & Duncan, 1991). Evidence for a categorical response bias towards a 45° angle was found by Waller et al. (2004).

Distortion bias is another common pattern of bias, resulting from an incorrect mental representation. Responses tend to be biased towards the horizontal axis of the circle, suggesting that directions are perceived as being more horizontal than they actually are. Participants' directional estimates, for example, are typically biased towards 90°, that is, directions are estimated as being closer to right angles than they really are (Waller et al., 2004; Sadalla & Montello, 1989; Moar & Bower, 1983).

Waller et al. (2004) suggest that such biases in pointing performance may be partly an artefact of using a circular stimulus as the response method. A stimulus-driven response bias may be especially likely to result from tasks which require participants to respond to a circular stimulus, such as a dial, which can be easily organised in terms of orthogonal axes. It is also possible that such tasks place particularly high demands on cognitive resources, such as working memory; and that they may, thus, cause greater reliance on heuristics that result in biased responses. This is because using a dial is an indirect pointing method, which requires the participant to imagine both the learned environment and the appropriate heading.

Evidence of the use of an underlying orthogonal reference system, as a means of organising egocentric space, was found by Sadalla and Montello (1989): they observed that directional estimates tended to be most accurate near the orthogonal directions of 0°, 90°, 180° and 270°. Montello et al. (1999) found that error increased for directions to targets that were further away from the closest orthogonal axis (ahead, behind, right, left).

Montello et al. (1999) note that when directions are estimated using a physical manual dial for pointing, an orthogonal reference system of ahead, behind, left, and right is used to estimate egocentric directions. Participants employ the four orthogonal directions as reference axes for their estimates: directions are first estimated as being closest to one of the four axes, and then an adjustment is made within the four quadrants of egocentric space, in order to estimate the direction to a target within that quadrant. The adjustment process adds extra error to the estimate of any target direction, which is not close to one of the four orthogonal directions. This is an internalised organizing system, which does not require the perception of any external cues (such as an orthogonal pattern) on the dial or the floor, or in the environment, in order to operate.

Montello et al. (1999) point out that, despite the potential for response bias, using a manual dial produces acceptably low levels of error in research which concerns effects on directional estimation of the order of 20° or more. This is common in research on large-scale or environmental spatial knowledge, including the current study.

## 6.5 Practical Applications

The current experimental findings have implications for the use of virtual reality for spatial training. The use of moderately immersive authentic virtual environments, displayed on projection screens, supported human visual path integration, at a typically-observed level of accuracy, or higher; especially when the environments were displayed on small-screen desktop computer monitors.

Path integration facilitates navigation in environments where reliable landmarks are not available. This includes unfamiliar environments of any kind, in which useful landmarks have not yet been identified; expanses of undifferentiated terrain; or spaces where landmarks are, for various reasons, not visible. Path integration is, thus, a particularly important and useful skill for fire-fighters and search-and-rescue teams, who are constantly required to enter unknown terrain and quickly find their way around. Their work frequently involves navigating under immense pressure in unfamiliar environments, and often in extremely challenging circumstances, such as near-darkness or thick smoke; or in landscapes which have been altered through the effects of natural disasters, such as earthquakes. They may have to work in caves, tunnels, or mine shafts; or in large natural outdoor areas such as forests, or deserts. Well-developed path integration skills are essential.

It is not always feasible for such professionals to train in appropriate real-life environments, due to safety and ethical considerations, as well as economic and practical issues. However, the environmental conditions which they may face, and the tasks they need to perform, can be replicated using virtual reality technology. Virtual environments are, therefore, potentially particularly appropriate for the kind of spatial training required in these professions (Durlach et al., 2000). They have, indeed, already been used successfully to train fire-fighters (Bliss, Tidwell, & Guest, 1997; Tate, Sibert, & King, 1997).

However, there are also drawbacks to the use of virtual reality for training in this context. Realistic, highly detailed virtual environments are very time-consuming to create, and also extremely expensive; this is due to the software and programming expertise needed in their design, as well as the hardware required to generate and display them. Sophisticated immersive systems, with features such as head-tracking and head-mounted displays, are also expensive; in addition, they are intrusive, and can be nauseogenic for some users. Virtual reality systems require a great deal of (usually dedicated) space. The technology quickly becomes obsolete. Limited funds may be more usefully spent on other, often equally costly, equipment. Justification for the use of such technology for training in these professions, therefore, depends on a clear demonstration of actual benefits from its use.

In developing virtual environments for training, it is important to ascertain the level of similarity to the real world which is required, in order for the environments to be effective (Waller, Knapp, & Hunt, 2001). There is a constant need to compromise between realism and computer processing power; this is also related to cost. Kearns, Warren, Duchon, and Tarr (2002), and Riecke, van Veen, and Bühlhoff (2000, 2002), showed that path integration is possible on the basis of visual cues alone, using state-of-the-art immersive virtual technology. The findings of this study show that visual path integration performance can also be supported with less sophisticated virtual reality technology; provided that the system incorporates features which can compensate for the absence of the immersive features typically included in more expensive systems, such as head-mounted display units and head-tracking. The system may need to overcome, for example, a lack of interactivity and physical cues, due to an absence of real movement; a small field of view; or limited photorealism and detail in the virtual environments.

Alternative design features in the current study included moderately authentic virtual environments, in which the optic flow and depth cues were contextualised; thereby increasing the task-relevance of the available visual information, by making its source more ecologically valid. Realistic complex route layouts further added to the overall ecological validity, as did a “driving” task and interface (especially in the Active condition, in which this interface was also interactive).

This study, therefore, supports the feasibility of using moderately immersive virtual environments displayed on a projection screen, or on a desktop or laptop monitor, using an ordinary computer, for training in which path integration skills are required. Virtual environments, of the kind used in this study, could be used to train, for example, search-and-rescue and fire-fighting personnel, who are frequently required to navigate through novel environments, and to quickly develop a cognitive representation of them. This methodology would considerably reduce costs; the training mode would be less intrusive and the apparatus more familiar; and less programming expertise would be required.

The level of accuracy achieved in the current study may be acceptable for spatial training in which path integration is not the focus. However, in contexts in which the purpose of training is to improve path integration skills, accuracy would need to be increased, through the inclusion of features such as active control. The addition of even a very limited degree of control over the self-motion, and some very basic interactivity, was sufficient to raise the level of accuracy of the directional estimates in the Active condition in this study. The results also indicate that a small-screen display would be preferable to one with large screens, as it would reduce gender effects and cybersickness symptoms. Smooth self-motion is also important.

Participants found the experience of trying to perform the path completion task with intermittent self-motion frustrating; which led to a reduced sense of presence, and, possibly, lower accuracy.

The findings are consistent with previous studies indicating that spatial knowledge, such as a representation of an environment, can be acquired in non-immersive, low-fidelity (even wireframe or schematic) virtual environments (Waller et al., 2001; Waller, Hunt, & Knapp, 1998; Péruch, Belingard, & Thinus-Blanc, 2000; Chabanne, Péruch, & Thinus-Blanc, 2003). Spatial training is not necessarily enhanced by the use of highly realistic virtual environments and interfaces, or by increased resolution of the visual imagery and field of view (Durlach et al., 2000). Aircraft simulators, for example, are a successful training method for pilots, despite their often relatively crude and unrealistic graphic displays (Welch, 2003), especially in the past. Greater fidelity from a variety of textured surfaces was recognised and appreciated by participants in a study of route learning, but it did not influence learning (Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002). Waller et al. (2001) found that the effect of visual fidelity was small, compared to individual differences. Thus, lower-fidelity desktop virtual environments, such as those used in this study, are not necessarily detrimental to navigation performance.

## **6.6 Limitations**

The study has considered only directional estimates in the response (not path distance), as this was the focus of the investigation. In interpreting the results, assumptions have been made about the role of distance estimates, in line with the proposed explanatory models. However, to obtain a more complete picture of human path integration capabilities, the translational and rotational components of the response should be studied together, and distance estimates measured; preferably in an experimental design which allows participants to move within the virtual world. The present study has demonstrated that path integration performance is possible within even quite simple virtual environments. Thus, a limited amount of interactivity could be introduced to such environments, without expending too much power computationally, in order to enhance their effectiveness.

A further limitation of this study is that the virtual dial was not an ideal measurement tool: it did not measure behaviour directly, and introduced an intervening cognitive level. It is an abstract representation of a physical action, and it was assumed that this representation was accurate. It was also assumed that participants fully understood the function of the dial, and used it correctly. Its use required abstract thinking and mental rotation ability. It is possible that there were

individual differences in the ability to use the dial correctly, and that this may have introduced error, which was unrelated to the pointing task. Use of the dial is also likely to have resulted in response biases, such as categorical and distortional biases (Waller, Beall, & Loomis, 2004; Montello, Richardson, Hegarty, & Provenza, 1999; Huttenlocher, Hedges, & Duncan, 1991); these may have influenced the results in some conditions. However, as participants could not physically turn and point in the virtual world, it was difficult to devise a more direct method in the current study.

There were also issues concerning the best way to represent a virtual dial on-screen: for example, from an abstract viewpoint, whether the dial should be presented as being *inside* the virtual world, and, therefore, a part of the events within that world; or as an object in the external world, used to measure events within the virtual world from the outside. From a more practical perspective, there were questions concerning whether the dial should be lying flat on the virtual ground or slightly raised; and, crucially, where the pointer should be placed on the dial, when it first appeared on each trial, in order to avoid influencing participants into thinking that it provided any information, in itself, about direction. Some participants mentioned, after the first simulation, that they had assumed that placing the pointer at the top of the dial represented pointing north, although they had not been told this. In the subsequent simulations, participants were explicitly informed that the dial did not represent compass directions.

## **6.7 Suggestions for Future Studies**

Two separate models have been proposed, in order to account for the two classes of error found in the results of the current study: that is, positive error, resulting from underestimation of either rotation or distance; and negative error, resulting from overestimation of either rotation or distance. Due to the experimental design, in line with the specific aims of this study, the data obtained from the experiments are not sufficient to discriminate between the proposed rotation error model and the distance error model, in the analysis of the results; nor whether the data could be better explained by a mixture of the two models (combined rotation and distance underestimation, or overestimation).

Therefore, in view of the large existing body of experimental evidence supporting distance underestimation in virtual environments, it has been assumed that error in this study resulted from underestimation of distance, rather than of rotation. Further theoretical development of the models, together with evidence obtained from psychophysical experiments, would support increased understanding of the observed error; as well as a more definitive explanation, which would allow

discrimination between misperception of rotation and distance as a source of error. The possibility that a mixture of the two models (misperception of both rotation and distance) could explain the error could then also be explored.

It was also found that the distance travelled on the roundabout was reflected in the final angle estimates, and that the long gradual curve could, therefore, be considered a third leg of the outbound route. Further work on integrating this finding into the models is required, in order to provide greater insight into the effects of distance on the outbound route on task performance. The current models are based on a triangular route, and it is not clear how a third leg, particularly a curved one, on the outbound path affects the predictions.

It has also been proposed that the leaky path integration model (Lappe, Jenkin, & Harris, 2007) may be relevant, in accounting for the overestimation and underestimation of distance, which has been assumed to underlie the error in the angular estimates observed in the current study. This model has been developed, based on experimental tasks other than the one which was used in the current study. Further work on combining the two basic models outlined here with the leaky path integration model would be valuable.

In the current study, there were often quite complex effects of several factors, simultaneously, on path integration performance. Distance and angle effects were closely related to gender effects, for example, and it was difficult to separate these. Although these interactions did not usually reach statistical significance, their combined effect on path integration performance is clear from the graphs, and from the analysis generally. The problem of drawing conclusions about the effect of one factor, when it is so closely combined with the effects of another, was noted by Kearns, Warren, Duchon, and Tarr (2002), with respect to the joint effects of gender and triangle layout. A better understanding of the separate influence of each of these variables would be facilitated by a study, in which the effects of different variables are more effectively separated. One way to do this might be to study path integration performed by one gender at a time, rather than studying males and females together.

A study which includes a more direct way for participants to indicate their estimates, perhaps using the virtual reality technology itself, would also be beneficial. A method could be devised which allows participants to make their estimates from within the virtual world, instead of introducing the outside world into the task. Finally, allowing participants to control their viewpoint within the virtual world, so that simulated movement towards the origin is possible, rather than using a virtual dial as a pointing analogue, would allow closer examination of rotation and translation together. This may require participants to undergo some initial training in rotation of objects in 3D space, in order to eliminate any individual differences in ability.

## Chapter 7. Conclusions

### 7.1 Effects of Visual Context on Path Integration Performance

#### 7.1.1 Visual Display

The use of different display types resulted in different patterns of error. The final angle was uniformly underestimated, when large projection screens were used in a driving simulator. However, the use of small-screen desk-top computer monitors led to the final angle being overestimated on longer outbound routes, but underestimated on shorter outbound routes. Performance was also much more accurate on shorter outbound routes, when the small screens were used, than in the driving simulator. These effects may have been related to differences between the two displays, such as the field of view, accommodation distance to the screen, whether depth and distance cues were enhanced, and whether perceptual illusions, such as framing effects, were present. The effects on performance were direct, rather than through a sense of presence from immersion.

Use of the small-screen display improved overall accuracy, and reduced gender differences, when optic flow was available, especially in the Active mode. This may have been due to a reduction in simulator sickness symptoms; and / or because the equipment was perceived as being less intrusive, especially by female participants, due to prior familiarity with desktop computers. The small screens had an additional positive impact, as they were less likely to cause adverse effects. Large screens may need to be curved, in order to achieve performance benefits, whereas the ones used in this study were flat. The use of smaller flat screens on conventional computer monitors could be effective for spatial training systems.

#### 7.1.2 Route Layout Parameters: Internal Angle and Leg-length

Performance was very strongly influenced by the geometric parameters of the route layouts: the length of the first road on the outbound path (that is, the first leg of the triangle), together with the size of the angle between the two outbound roads (that is, the internal angle). Errors were predictable according to route layout.

The length of the first road, combined with the distance between the first road and the exit-road along the curve on the roundabout, has been referred to, in this study, as the *approach segment* of the outbound route. The size of the internal angle

determined the distance which was travelled around the roundabout. Route layouts with a short approach segment included those with a short first road (S-L routes), and those with the 120° angle exit-road; whilst route layouts with a long approach segment included those with a long first road (L-L or L-S routes), combined with the 60° or 90° angle exit-road. The location of the 120° angle exit-road was quite near to the approach road on the roundabout, whilst the 60° and 90° angle exit-roads were located a long distance around the roundabout from the approach road. Thus, the 60° and 90° exit-roads were positioned further around the roundabout from the approach road than the 120° angle exit-road.

The length of the approach segment on the outbound path exerted a very powerful effect on error. Both the pattern and the magnitude of error, which was observed in the response, depended on route layout. Accuracy was generally higher on route layouts with a short approach segment on the outbound path, than on routes with a long approach segment. The combination of a long first road, together with the 60° or 90° angle exit-road, produced the most error, especially in the Passive and Static conditions. Thus, participants' responses demonstrated great sensitivity to differences in route layout (triangle shape).

Performance on each of the route layouts was also influenced by the availability of optic flow cues, the level of participant control over their self-motion, and gender. Greater accuracy of responses was observed on layouts with shorter approach segments, when optic flow cues were disrupted. Responses in the Passive condition were more accurate than Active responses on routes with a shorter approach section; whilst responses in the Active condition were more accurate than Passive responses on routes with a longer approach segment. Female angular estimates were generally more accurate on layouts with shorter approach sections on the outbound routes.

### **7.1.3 Misperception of Distance**

The observed performance errors on the non-regular triangle layouts indicate how participants perceived the distances that they had travelled, along the outbound roads. A model has been proposed, which attributes the observed overestimation and underestimation of the final angle to navigator misperception of the distance travelled on the outbound section of the route (the first and second legs of the triangle). According to this model, the observed errors are predictable from an assumption that participants misperceive the distance travelled on the outbound path: they either underestimate or overestimate the distance, and this is reflected in

their final angle estimates. Thus, error depends on whether the travelled distance on the outbound path is perceived to be shorter, or longer, than the true distance.

The distance travelled on the roundabout curve can also be considered as part of the outbound route: the combination of the length of the first straight section and the length of the curved section has been referred to as the *approach segment*. The effects of different-length approach segments on estimation of the final angle can also be predicted, if it is assumed that participants misperceive how far they have travelled along the straight sections of the route; and that this misperception leads to either overestimation or underestimation of the final angle. It is likely that participants also misperceive the distance they have travelled on the curved section; however, this was not considered in the present model, and further investigation is required in order to confirm that misperception of distance also occurs on the curve. The combined effect of misperception of distance on both the straight and curved segments of the route also warrants further examination.

The experimental results confirm the predictions of the model. Different patterns and levels of error were observed on layouts with long and short first roads. Different patterns and levels of error were also observed on layouts with long and short approach segments on the outbound routes. Thus, misperception of distance on the outbound route accounts for the error.

Distance estimation may have been affected by the ability to estimate velocity and / or duration of travel; which, in turn, could have been influenced by the design features of the display and virtual environments, especially where these affected the available visual cues. Limited depth and distance cues, for example, may have resulted in misperception (overestimation or underestimation) of velocity and / or duration of the simulated self-motion, and hence of distance; leading to error in the directional estimates.

#### **7.1.4 Optic Flow**

Optic flow cues are more important for path integration over longer distances on the outbound route, and for path integration by females. Disruption of the optic flow cues was detrimental to performance on routes with long approach segments on the outbound path: that is, on layouts with a long first road (L-L and L-S) and a 60° or 90° internal angle. However, performance was much less impaired on routes with short approach segments: that is, on layouts with a short first road (S-L), and on routes with a 120° internal angle. Female responses were also more affected than male responses by limited optic flow information, suggesting a greater dependency by females on optic flow to perform path integration.

### 7.1.5 Size of the Curve

The large gradual curve, which was included on the roundabout segment of the route, did not greatly influence the results. There was an effect of turn type on directional estimates only in the Passive condition, especially on the performance by female participants: some divergence in accuracy was seen between responses on roundabout and intersection trials, which also depended on route layout. Turn type had no effect on angular estimates in the Active condition, in the driving simulator, or when optic flow information was disrupted.

However, the *distance* travelled along the curve on the roundabout, between the approach-road and the exit-road, contributed to the overall distance of the approach segment on the outbound route. This did have an important influence on the directional estimates. The degree of curvature is, thus, less important than the distance covered by the forward motion on the curved segments. The task in the current study is, therefore, appropriately regarded as a complex path-completion task along a route with three outbound legs, one of which is curved; rather than as a triangle-completion task in the strict sense, that is, along a route with two outbound legs, with a large degree of rotation between them.

### 7.1.6 Environment

The level of environmental detail did not have a great effect on accuracy of task performance. When the availability of optic flow and depth cues was controlled, similar patterns and magnitudes of error were found, in general, in both complex urban and simple rural environments, which contained different amounts of texture; and regardless of the presence or absence of additional structures. Thus, very detailed structured environments are not required for path integration. Environment had an effect on angular estimates in Experiment 2, but not in Experiments 1 or 3. This suggests that the effects of environment depend on the navigation mode and manner of presenting the visual information; and possibly also on the display type.

In Experiment 2, accuracy was higher, overall, in environments without the added structures, especially in the Active condition: increased depth information did not lead to increased performance accuracy. Participants may have attempted to perform the task by using the structures as landmarks for piloting, which would have reduced accuracy, as the structures were not stable: their position changed in each environment, therefore, they did not provide reliable information for tracking location and heading. Active participants could benefit from the extra proprioceptive information provided by steering, in addition to the optic flow cues, in estimating the

speed of their self-motion. Passive participants were able to benefit from the simpler rural environments, which had less optic flow.

### **7.1.7 Immersion and Presence**

The novel, minimally immersive virtual environments which were used in the current study successfully elicited a sense of presence, whether they were presented on the small-screen desktop display, or on the large-screen simulator display. However, task performance did not depend on presence: accuracy was not enhanced through higher levels of presence. This may have been because the environments were not immersive enough: presence scores were concentrated around the mid-range of the scale. This also made it difficult to form highly differentiated, similar-size high and low presence groups for comparison.

The inclusion of features, such as a wide field of view, compensated for reduced immersiveness and limitations of the visual display, such as limited detail and photorealism. Some basic participant control further enhanced these effects. The virtual world was also perceived as fairly authentic. Authenticity could be further enhanced through the addition of various features, such as flora and fauna, other vehicles, or road signs and markings.

The moderately realistic virtual environments supported reasonably accurate path integration performance, at a level of accuracy which was generally within the range typically found in studies of human visual path integration, or higher. Even with disrupted optic flow, performance on some route layouts (those with a short approach segment) displayed comparable or higher accuracy. This level of accuracy may be acceptable for spatial training in contexts in which a high level of precision is not required; and in which path integration is not the primary focus of training. The virtual environments would need refinement for use in training path integration skills. The overall accuracy of performance can be enhanced through the addition of features such as active participant control, or the use of less intrusive apparatus.

## **7.2 Effects of Navigation Mode on Path Integration Performance**

The general pattern of results was not influenced by navigation mode: this was the same in the Active and Passive conditions. There was an effect on accuracy, however. Performance in the Passive condition was consistently more accurate, compared with the Active condition, on all routes with a short approach segment on the outbound path: that is, on routes with the 120° angle and on S-L layouts.

Consistently more accurate performance was observed in the Active condition, compared with the Passive condition, on routes with a long approach segment on the outbound path: that is, on routes which combined a long first road (L-L or L-S layouts) with either the 60° or 90° internal angle. Active participants may have been able to obtain more information about the velocity and duration of their self-motion on the longer outbound routes, from their control of the self-motion: for example, from the rudimentary proprioceptive feedback provided by the steering wheel and pedals.

Female responses were generally more accurate in the Active condition than in the Passive condition, on routes with long approach roads. For males, however, greater overall accuracy was displayed in the Passive condition than in the Active condition, or there were only very small differences between the two. Females may benefit from active control of the self-motion over longer distances, as they may be better able to calibrate their speed of self-motion to the scale of the environment.

The findings are relevant to training applications. As the active mode has some benefits for navigation in virtual environments, at least some active participant control is desirable in the design of the training task, even if it is only of a very basic kind, as in the current study. This may be particularly beneficial for female trainees.

### **7.3 Effects of Gender on Path Integration Performance**

Gender is influential and its effects are complex. The experimental design can have important implications. Females performed less accurately than males in the driving simulator, and when optic flow was disrupted. However, gender effects were reduced when optic flow cues were available from smooth self-motion, and when the virtual environments were presented on a small desk-top display, especially when some active participant control was possible. The accuracy of female performance matched, or exceeded, that of male performance in these conditions. This indicates the importance of the experimental design, which may mask female abilities, and, thereby create, or contribute to, apparent gender differences. This may have been an issue in previous studies. Gender effects were also implicated in the effects of the visual display, and navigation mode.

### **7.4 Final Conclusions**

In a simulation of real-world navigation, the use of authentic large-scale complex virtual environments, together with a realistic task, supported human path integration, using optic flow cues from simulated self-motion, along routes with a large

roundabout. Performance on a realistic path-completion task exhibited systematic errors, which were similar to those observed in studies conducted in less realistic virtual environments: specifically, underestimation and overestimation of angular estimates of the start point of the route. These errors can be explained as resulting from misperception of distance on the outbound route. Optic flow cues are especially important for path integration over longer distances on the outbound route, especially by females.

Route layout has a very important influence on performance: particularly the length of the first road on the outbound route, together with the distance travelled around the roundabout (which depends on the angle between the two outbound roads). The degree of curvature on the roundabout is not very influential, but the distance covered by the curve is. Route layout interacts with navigation mode (active versus passive), and gender, to affect accuracy.

The use of flat-screen desktop monitors enhanced performance accuracy, and led to different error patterns, compared with the use of large projection screens in a driving simulator; especially when participants had some active control of the simulated self-motion. This effect was especially pronounced for women.

Gender has complex effects on path integration performance: it interacts with experimental apparatus, the availability of optic flow cues, navigation mode, and route layout. Careful attention to these factors in experimental design could reduce apparent gender differences.

Virtual environments do not need to be highly detailed or photorealistic to support path integration, or to evoke a sense of presence, even in the absence of standard immersive design features. Task performance in virtual environments can be enhanced, through the presentation of the required visual information in natural contexts; and through the partial enclosure of navigators within a three-screen display, which provides a wide field of view.

Authentic virtual environments presented on ordinary desk-top computers could provide a low-technology method for spatial skills training for fire-fighters and search-and-rescue personnel: both the environmental conditions in which they work, and the tasks which they need to perform, can be recreated in virtual reality. Such environments would be especially effective if they are combined with wide screens and some basic participant control of motion.

## References

- Acosta, H.M. (1997). *Multifactor determinants of visual accommodation as a critical intervening variable in the perception of size and distance: Phase I report*. (Tech. Rep. AL/HR-TR-1996-0137). Brooks AFB, TX: Armstrong Laboratory.
- Alfano, P.L., & Michel, G.F. (1990). Restricting the field of view: Perceptual and performance effects. *Perceptual and Motor Skills*, 70, 35-40.
- Arleo, A., & Gerstner, W. (2000). Spatial cognition and neuro-mimetic navigation: A model of hippocampal place cell activity. *Biological Cybernetics*, 83, 287-299.
- Arthur, K. W. (2000). Effects of field of view on performance with head-mounted displays. *Dissertation Abstracts International*, 61(5B), 2614.
- Astur, R.S., Ortiz, M.L., & Sutherland, R.J. (1998). A characterization of performance by men and women in a virtual Morris water task: A large and reliable sex difference. *Behavioural Brain Research*, 93, 185-190.
- Astur, R.S., Tropp, J., Sava, S., Constable, R.T., & Markus, E.J. (2004). Sex differences and correlations in a virtual Morris water task, a virtual radial arm maze, and mental rotation. *Behavioural Brain Research*, 151, 103-115.
- Ayaz, H., Allen, S.L., Platek, S.M., & Onaral, B. (2008). Maze Suite 1.0: A complete set of tools to prepare, present, and analyze navigational and spatial cognitive neuroscience experiments. *Behaviour Research Methods*, 40 (1), 353-359.
- Bakker, N.H., Passenier, P.O., & Werkhoven, P.J. (2003). Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments. *Human Factors*, 45(1), 160-169.
- Bakker, N.H., Werkhoven, P.J., & Passenier, P.O. (1999). The effects of proprioceptive and visual feedback on geographical orientation in virtual environments. *Presence*, 8(1), 36-53.

- Bakker, N.H., Werkhoven, P.J., & Passenier, P.O. (2001). Calibrating visual path integration in VEs. *Presence*, 10(2), 216-224.
- Barfield, W., & Hendrix, C. (1995). The effect of update rate on the sense of presence within virtual environments. *Virtual Reality: Research, Development, and Applications* 1(1), 3-16.
- Barfield, W., Zeltzer, D., Sheridan, T.B., & Slater, M. (1995). Presence and performance within virtual environments. In W. Barfield & T.A. Furness (Eds.), *Virtual environments and advanced interface design* (pp. 473-541). Oxford: Oxford University Press.
- Batschelet, E. (1981). *Circular statistics in biology*. Academic Press, New York.
- Baumberger, B., Flückiger, M., Paquette, M., Bergeron, J., & Delorme, A. (2005). Perception of relative distance in a driving simulator. *Japanese Psychological Research*, 47(3), 230-237.
- Benhamou, S., Sauvé, J.P., & Bovet, P. (1990). Spatial memory in large-scale movements: Efficiency and limitation of the egocentric coding process. *Journal of Theoretical Biology*, 145, 1-12.
- Berens, P. (2009). CircStat: A MATLAB Toolbox for circular statistics. *Journal of Statistical Software*, 31(10), 1-21.
- Berens, P., & Velasco, M.J. (2009). *The circular statistics toolbox for Matlab*. Technical Report No. 184, Max-Planck-Institute for Biological Cybernetics, 1-7.
- Billinghurst, M., & Weghorst, S. (1995). The use of sketch maps to measure cognitive maps in virtual environments. In *Proceedings of the 1995 Virtual Reality Annual International Symposium (VRAIS) 1995*, 40-47. Piscataway, NJ: IEEE Press.
- Blakemore, M.R., & Snowden, R.J. (1999). The effect of contrast upon perceived speed: A general phenomenon? *Perception*, 28, 33-48.

- Blakemore, M.R., & Snowden, R.J. (2000). Textured backgrounds alter perceived speed. *Vision Research*, 40, 629-638.
- Bliss, J.P., Tidwell, P.D., & Guest, M.A. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence*, 6(1), 73-88.
- Bowman, D.A. (2002). Principles for the design of performance-oriented interaction techniques. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications* (pp.277-300). Mahwah, NJ: Lawrence Erlbaum Associates.
- Bremmer, F., & Lappe, M. (1999). The use of optical velocities for distance discrimination and reproduction during visually simulated self motion. *Experimental Brain Research*, 127(1), 33-42.
- Brooks, K. (2001). Stereomotion speed perception is contrast dependent. *Perception*, 30, 725-731.
- Bullinger, A.H., Roessler, A., & Mueller-Spahn, F. (1998). From toy to tool: The development of immersive virtual reality environments for psychotherapy of specific phobias. In G. Riva, B.K. Wiederhold, & E. Molinari (Eds.), *Virtual environments in clinical psychology and neuroscience* (pp. 103-111). Amsterdam, Netherlands: IOS Press.
- Bülthoff, H.H., & van Veen, H.A.H.C. (1999). *Vision and action in virtual environments: Modern psychophysics in spatial cognition research*. Technical Report No. 77, Max Planck Institute, Tübingen, Germany (pp. 1-13).
- Bystrom, K.E., Barfield, W., & Hendrix, C. (1999). A conceptual model of the sense of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, 8(2), 241-244.
- Chabanne, V., Péruch, P., & Thinus-Blanc, C. (2003). Virtual to real transfer of spatial learning in a complex environment: The role of path network and additional features. *Spatial Cognition and Computation*, 3(1), 43-59.

- Chance, S.S., Gaunet, F., Beall, A.C., & Loomis, J.M. (1998). Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence*, 7, 168-178.
- Christou, C., & Bühlhoff, H.H. (2000). Perception, representation and recognition: A holistic view of recognition. *Spatial Vision*, 13(2, 3), 265-275.
- Christou, C., & Bühlhoff, H.H. (2000). Using realistic virtual environments in the study of spatial encoding. In C. Freksa, W. Brauer, C. Habel, & K.F. Wender (Eds.), *Spatial Cognition II: Integrating abstract theories, empirical studies, formal methods and practical applications* (pp. 317-331). Berlin: Springer-Verlag.
- Cobb, S.V.G., Nichols, S., Ramsay, A., & Wilson, J.R. (1999). Virtual reality-induced symptoms and effects (VRISE). *Presence*, 8(2), 169-186.
- Collett, M., & Collett, T.S. (2000). How do insects use path integration for their navigation? *Biological Cybernetics*, 83, 245-259
- Collett, T.S., & Collett, M. (2000). Path integration in insects. *Current Opinions in Neurobiology*, 10, 757-762.
- Cornell, E.H., & Bourassa, C.M. (2007). Human non-visual discrimination of gradual turning is poor. *Psychological Research / Psychologische Forschung*, 71(3), 314-321.
- Cornell, E.H., & Greidanus, E. (2006). Path integration during a neighbourhood walk. *Spatial Cognition and Computation*, 6(3), 203-234.
- Cornell, E.H., & Heth, C.D. (2004). Memories of travel: Dead reckoning within the cognitive map. In G.L. Allen (Ed.), *Human spatial memory: Remembering where* (pp.191-215). Mahwah, NJ: Lawrence Erlbaum Associates.
- Crawford, L.E., & Duffy, S. (2010). Sequence effects in estimating spatial location. *Psychonomic Bulletin & Review*, 17(5), 725-730.

- Cruz-Neira, C., Sandin, D.J., Defanti, T.A., Kenyon, R.V., & Hart, J.C. (1992). *The CAVE: Audio-visual experience automatic virtual environment*. SIGGRAPH '92 Showcase. Association for Computing Machinery Inc. Communications of the ACM, 35(6), 64-72.
- Cutting, J.E., Springer, K., Braren, P.A., & Johnson, S.H. (1992). Wayfinding on foot from information in retinal, not optical, flow. *Journal of Experimental Psychology: General*, 121(1), 41-72.
- Czerwinski, M., Tan, D.S., & Robertson, G. (2002). Women take a wider view. In *Proceedings of the CHI 2002 Conference on Human Factors in Computing Systems*, 195-202.
- Dabbs, J.M., Chang, E. L., & Strong, R.A., & Milun, R. (1998). Spatial ability, navigation strategy and geographic knowledge among men and women. *Evolution and Human Behavior*, 19, 89-98.
- Darken, R.P., & Sibert, J. L. (1996). Navigating large virtual spaces. *International Journal of Human-Computer Interaction*, 8, 49-71.
- Deisinger, J., Cruz-Neira, C., Riedel, O., & Symanzik, J. (1997). The effect of different viewing devices for the sense of presence and immersion in virtual environments: a comparison of stereoprojections based on monitors, HMDs, and screens. In M. Smith, G. Salvendy, & R. Koubek (Eds.), *Advances in Human Factors / Ergonomics (21B). Design of computing systems: Social and ergonomic considerations* (pp. 881-884). Amsterdam: Elsevier.
- Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: Effects on self-motion perception and postural control. In R. Held, H.W. Leibowitz, & H.L. Teuber (Eds.), *Perception: Handbook of sensory physiology, vol VIII* (pp. 755-804). New York: Springer-Verlag.
- Dolezal, H. (1982). The restricted field of view: a neglected factor in adaptation research. In H. Dolezal (Ed.), *Living in a world transformed* (pp 69-117). . New York: Academic Press.

- Duffy, S., Huttenlocher, J., Hedges, L.V., & Crawford, L.E. (2010). Category effects on stimulus estimation: Shifting and skewed frequency distributions. *Psychonomic Bulletin and Review* 17(2), 224-230.
- Durlach, N., Allen, G., Darken, R., Garnett, R. L., Loomis, J., Templeman, J., & von Wiegand, T.E. (2000). Virtual environments and the enhancement of spatial behaviour: Towards a comprehensive research agenda. *Presence*, 9(6), 593-615.
- Edgar, G.K. (2007). Accommodation, cognition, and virtual image displays: A review of the literature. *Displays*, 28, 45-59.
- Ellmore, T.E., & McNaughton, B.L. (2004). Human path integration by optic flow. *Spatial Cognition and Computation*, 4, 255-272.
- Etienne, A.S. (1992). Navigation of a small mammal by dead reckoning and local cues. *Current Directions in Psychological Science*, 1, 48-52.
- Etienne, A.S. (1998). Mammalian navigation, neural models, and biorobotics. *Connection Science*, 10(3-4), 271-289.
- Etienne, A.S., & Jeffery, K.J. (2004). Path integration in mammals. *Hippocampus*, 14, 180-192.
- Etienne, A.S., Maurer, R., & Saucy, F. (1988). Limitations in the assessment of path dependent information. *Behavior*, 106, 81-111.
- Etienne, A.S., Maurer, R., & Séguinot, V. (1996). Path integration in mammals and its interaction with visual landmarks. *Journal of Experimental Biology*, 199, 201-
- Fisher, N.I. (1995). *Statistical analysis of circular data. Revised edition*. Cambridge University Press.
- Fisher, R. (1953). Dispersion on a sphere. *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*, 217 (1130), 295-305.

- Foo, P., Warren, W.H., Duchon, A., & Tarr, M.J. (2005). Do humans integrate routes into a cognitive map? Map- versus landmark-based navigation of novel shortcuts. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 31, 195-215.
- Foreman, N., Sandamas, G., & Newson, D. (2004). Distance underestimation in virtual space is sensitive to gender but not activity-passivity or mode of interaction. *CyberPsychology & Behaviour*, 7(4), 451-457.
- Fortenbaugh, F.C., Chaudhury, S., Hicks, J.C., Hao, L., & Turano, K.A. (2007). Gender differences in cue preference during path integration in virtual environments. *ACM Transactions on Applied Perception*, 4(1), 1-18.
- Frenz, H., Bremmer, F., & Lappe, M. (2003). Discrimination of travel distances from "situated" optic flow. *Vision Research*, 43, 2173-2183.
- Frenz, H., & Lappe, M. (2005). Absolute travel distance from optic flow. *Vision Research*, 45, 1679-1692.
- Frenz, H., & Lappe, M. (2006). Visual distance estimation in static compared to moving virtual scenes. *Spanish Journal of Psychology*, 9(2), 321-331.
- Frenz, H., Lappe, M., Kolesnik, M., & Bührmann, T. (2007). Estimation of travel distance from visual motion in virtual environments. *ACM Transactions on Applied Perception*, 4(1), Article 3, 1-18.
- Fujita, N., Loomis, J.M., Klatzky, R.L., & Golledge, R.G. (1990). A minimal representation for dead reckoning navigation: Updating the homing vector. *Geographical Analysis*, 22, 326-335.
- Galea, L.A.M., & Kimura, D. (1993). Sex differences in route learning. *Personality and Individual Differences*, 14, 53-65.
- Gallistel, C.R. (1990). *The organization of learning*. Cambridge, M.A.: Bradford / MIT Press.

- Garris-Reif, R., & Franz, T.M. (1995). Simulator sickness and human task performance in conventional and virtual environments. In A.C. Bittner & P.C. Champney (Eds.), *Advances in industrial ergonomics and safety VII*, (pp.219-223). Taylor & Francis.
- Gaunet, F., Vidal, M., Kemeny, A., & Berthoz, A. (2001). Active, passive and snapshot exploration in a virtual environment: Influence on scene memory, reorientation and path memory. *Cognitive Brain Research*, *11*, 409-420.
- Gibson, J.J. (1950). *Perception of the visual world*. Boston: Houghton Mifflin.
- Gibson, J.J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.
- Gibson, J.J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
- Godley, S.T., Triggs, T.J., & Fildes, B.N. (2000). Speed reduction mechanisms of transverse lines. *Transportation Human Factors*, *2*(4), 297-312.
- Godley, S.T., Triggs, T.J., & Fildes, B.N. (2002). Driving simulator validation for speed research. *Accident Analysis and Prevention*, *34*, 589-600.
- Godley, S.T., Triggs, T.J., & Fildes, B.N. (2004). Perceptual lane width, wide perceptual road centre markings and driving speeds. *Ergonomics*, *47*(3), 237-256.
- Golledge, R.G. (1999). *Wayfinding behavior*. Baltimore: Johns Hopkins University Press.
- Gothard, K.M., Skaggs, W.E., & McNaughton, B.L. (1996). Dynamics of mismatch correction in the hippocampal ensemble code for space: interaction between path integration and environmental cues. *Journal of Neuroscience*, *16*, 8027-8040.

- Gramann, K., Müller, H.J., Eick, E., & Schönebeck, B. (2005). Evidence of separable spatial representations in a virtual navigation task. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 1199-1123.
- Hagen, M.A., Jones, R.K., & Reed, E. (1978). On a neglected variable in theories of pictorial perception: Truncation of the visual field. *Perception & Psychophysics*, 23, 326-330.
- Harrison, D., & Kanji, G.K. (1988). The development of analysis of variance for circular data. *Journal of Applied Statistics*, 15(2), 197.
- Harrison, D., Kanji, G.K., & Gadsden, R.J. (1986). Analysis of variance for circular data. *Journal of Applied Statistics*, 13(2), 123.
- Hartmann, G., & Wehner, R. (1995). The ant's path integration system: A neural architecture. *Biological Cybernetics*, 73, 483-497.
- Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators and Virtual Environments* 1(2), 262-271.
- Held, R., & Durlach, N. (1992). Telepresence. *Presence: Teleoperators and Virtual Environments* 1(1), 109-112.
- Hendrix, C., & Barfield, W. (1996). Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperators and Virtual Environments* 5(3), 274-289.
- Henry, D., & Furness, T. (1993). *Spatial perception in virtual environments: Evaluating an architectural application*. Technical Report No. FU-20, Human Interface Technology Laboratory, University of Washington, Seattle, WA.
- Hettinger, L.J. (2002). Illusory self-motion in virtual environments. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp. 471-491). Hillsdale, NJ: Lawrence Erlbaum Associates.

- Hettinger, L.J., & Haas, M.W. (Eds.). (2003). *Virtual and adaptive environments: Applications, implications, and human performance issues*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Hettinger, L.J., & Riccio, G.E. (1992). Visually-induced motion sickness in virtual environments. *Presence: Teleoperators and Virtual Environments*, 1(3), 306-310.
- Hildreth, E.C., & Royden, C.S. (1998). Computing observer motion from optical flow. In T. Watanabe (Ed.), *High-level motion processing: Computational, neurobiological, and psychophysical perspectives* (pp. 269-293). Cambridge, MA: MIT Press
- Huang, M.P., & Alessi, N.E. (1998). Current limitations into the application of virtual reality to mental health research. In G. Riva, B.K. Wiederhold, & E. Molinari (Eds.), *Virtual environments in clinical psychology and neuroscience* (pp.63-66). Amsterdam, Netherlands: IOS Press.
- Hull, J.C., Gill, R.T., & Roscoe, S.N. (1982). Locus of the stimulus to visual accommodation: Where in the world, or where in the eye? *Human Factors*, 24, 311-319.
- Huttenlocher, J., Hedges, L.V., & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, 98(3), 352-376.
- Huttenlocher, J., Hedges, L.V., Lourenco, S.F., Crawford, I.E., & Corrigan, B. (2007). Estimating stimuli from contrasting categories: Truncation due to boundaries. *Journal of Experimental Psychology: General*, 136(3), 502-519.
- lavecchia, J.H., lavecchia, H.P., & Roscoe, S.N. (1983). The moon illusion revisited. *Aviation, Space, and Environmental Medicine*, 54, 39-46.
- lavecchia, J.H., lavecchia, H.P., & Roscoe, S.N. (1988). Eye accommodation to head-up virtual images. *Human Factors*, 30, 689-702.
- Jammalamadaka, S.R., & Sengupta, A. (2001). *Topics in Circular Statistics*. World Scientific.

- Jeffery, K.J. (1998). Learning of landmark stability and instability by hippocampal place cells. *Neuropharmacology*, 37, 677-687.
- Jeffery, K.J., Donnett, J.G., Burgess, N., & O'Keefe, J.M. (1997). Directional control of hippocampal place fields. *Experimental Brain Research*, 117, 131-142.
- Kaiser, M.K., Montegut, M.J., & Proffitt, D.R. (1995). Rotational and translational components of motion parallax: Observers' sensitivity and implications for three-dimensional computer graphics. *Journal of Experimental Psychology: Applied*, 1(4), 321-331.
- Kalawsky, R.S. (1993). *The science of virtual reality and virtual environments*. Wokingham, U.K.: Addison-Wesley.
- Kalawsky, R.S. (1999). VRUSE - a computerised diagnostic tool: for usability evaluation of virtual/synthetic environment systems. *Applied Ergonomics*, 30, 11-25.
- Kearns, M.J., Warren, W.H., Duchon, A.P., & Tarr, M.J. (2002). Path integration from optic flow and body senses in a homing task. *Perception*, 31, 349-374.
- Kennedy, R.S., Lilienthal, M.G., Berbaum, K.S., Baltzley, D.R., & McCauley, M.E. (1989). Simulator sickness in U.S. Navy flight simulators. *Aviation, Space, and Environmental Medicine*, 60, 10-16.
- Kessler, G.D. (2002). Virtual environment models. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.255-276). Mahwah, NJ: Lawrence Erlbaum Associates.
- Kirschen, M.P., Kahana, M.J., Sekuler, R., & Burack, B. (2000). Optic flow helps humans to navigate through synthetic environments. *Perception*, 29, 801-818.
- Kitchin, R.M. (1997). Exploring spatial thought. *Environment and Behaviour*, 29(1), 123-156.

- Kitchin, R.M., & Blades, M. (2002). *The cognition of geographic space*. London: Tauris.
- Klatzky, R.L., Beall, A.C., Loomis, J.M., Golledge, R.G., & Philbeck, J.W. (1999). Human navigation ability: Tests of the encoding-error model of path integration. *Spatial Cognition and Computation*, 1, 31-65.
- Klatzky, R.L., Loomis, J.M., Beall, A.C., Chance, S.S., & Golledge, R.G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science*, 9, 293-298.
- Klatzky, R.L., Loomis, J.M., & Golledge, R.G. (1997). Encoding spatial representations through nonvisually guided locomotion: Tests of human path integration. *The Psychology of Learning and Motivation* 27, 41- 84.
- Klatzky, R.L., Loomis, J.M., Golledge, R.G., Cicinelli, J.G., Doherty, S., & Pellegrino, J.W. (1990). Acquisition of route and survey knowledge in the absence of vision. *Journal of Motor Behaviour*, 22(1), 19-43.
- Knapp, J.M., & Loomis, J.M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators and Virtual Environments*, 13, 572-577.
- Kolasinski, E.M. (1995). *Simulator sickness in virtual environments*. Technical Report 1027, Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.
- Konkle, T., & Oliva, A. (2011). Canonical visual size for real-world objects. *Journal of Experimental Psychology: Human Perception and Performance*, 37(1), 23-37.
- Kuhl, S.A., Thompson, W.B., & Creem-Regehr, S.H. (2009). HMD calibration and its effects on distance judgments. *ACM Transactions on Applied Perception*, 6(3), Article 19, 1-20.

- Lampton, D.R., Bliss, J.P., & Morris, C.S. (2002). Human performance measurements in virtual environments. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.701-720). Mahwah, NJ: Lawrence Erlbaum Associates.
- Lappe, M., Bremmer, F., & van den Berg, A.V. (1999). Perception of self-motion from visual flow. *Trends in Cognitive Sciences*, 3, 329-336.
- Lappe, M., & Frenz, H. (2009). Visual estimation of travel distance during walking. *Experimental Brain Research*, 199, 369-375.
- Lappe, M., Jenkin, M., & Harris, L.R. (2007). Travel distance estimation from visual motion by leaky path integration. *Experimental Brain Research*, 180, 35-48.
- Lappe, M., Stiels, M., Frenz, H., & Loomis, J.M. (2011). Keeping track of the distance from home by leaky integration along veering paths. *Experimental Brain Research*, 180, 35-48.
- Lathan, C.E., Tracey, M.R., Sebrechts, M.M., Clawson, D.M., & Higgins, G.A. (2002). Using virtual environments as training simulators: measuring transfer. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.403-414). Mahwah, NJ: Lawrence Erlbaum Associates.
- Lathrop, W.B., & Kaiser, M.K. (2002). Perceived orientation in physical and virtual environments: Changes in Perceived orientation as a function of idiothetic information available. *Presence*, 11, 19-32.
- Lathrop, W.B., & Kaiser, M.K. (2005). Acquiring spatial knowledge while travelling simple and complex paths with immersive and non-immersive interfaces. *Presence*, 14(3), 249-263.
- Lawson, B.D., Graeber, D.A., Mead, A.M., & Muth, E.R. (2002). Signs and symptoms of human syndromes associated with synthetic experiences. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.589-618). Mahwah, NJ: Lawrence Erlbaum Associates.

- Lawton, C.A., & Morrin, K.A. (1999). Gender differences in pointing accuracy in computer-simulated 3D mazes. *Sex Roles, 40*, 73-92.
- Lee, D. N. (1974). Visual information during locomotion. In R.B. MacLeod, & H. Pick (Eds.), *Perception: Essays in honor of J.J. Gibson* (pp.250-267). Ithaca, NY: Cornell University Press.
- Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. *Presence, 10* (3), 282-297.
- Levy, L.J., Astur, R.S., & Frick, K.M. (2005). Men and women differ in object memory but not performance of a virtual radial maze. *Behavioral Neuroscience, 119*, 853-862.
- Loomis, J.M., Blascovich, J.J., & Beall, A.C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments and Computers, 31*, 557-564.
- Loomis, J.M., Klatzky, R.L., Golledge, R.G., Cicinelli, J.G., Pellegrino, J.W. & Fry, P.A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General, 122*, 73-91.
- Loomis, J.M., Klatzky, R.L., Golledge, R.G., & Philbeck, J.W. (1999). Human navigation by path integration. In R.G. Golledge (Ed.), *Wayfinding behaviour: Cognitive mapping and other spatial processes* (pp.125-151). Baltimore: Johns Hopkins University Press.
- Loomis, J.M., & Knapp, J.M. (2003). Visual perception of egocentric distance in real and virtual environments. In L.J. Hettinger & M.W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 21-46). Mahwah, NJ: Lawrence Erlbaum Associates.
- Maguire, E.A., Burgess, N., Donnett, J.G., Frackowiak, R.S., Frith, C.D., & O'Keefe, J. (1998). Knowing where and getting there: A human navigation network. *Science, 280*, 921-924.

- Mania, K., & Chalmers, A. (2001). The effects of levels of immersion on memory and presence in virtual environments: A reality centred approach. *CyberPsychology & Behaviour, 4*(2), 247-262.
- Maurer, R. (1998). A connectionist model of path integration with and without a representation of distance to the starting point. *Psychobiology, 26*, 21-35.
- Maurer, R., & Séguinot, V. (1995). What is modelling for? A critical review of the models of path integration. *Journal of Theoretical Biology, 175*(4), 457-475.
- May, M., & Klatzky, R.L. (2000). Path integration while ignoring irrelevant information. *Journal of Experimental Psychology: Learning, Memory and Cognition, 26*(1), 169-186.
- May, M., Péruch, P. & Savoyant, A. (1995). Navigating in a virtual environment with map-acquired knowledge: Encoding and alignment effects. *Ecological Psychology, 7*(1), 21-36.
- McNaughton, B.L., Barnes, C.A., Gerrard, J.L., Gothard, K.M., Jung, M.W., Knierim, J.J., Kudrimoti, H., Qin, Y., Skaggs, W.E., Suster, M., & Weaver, K.L. (1996). Deciphering the hippocampal polyglot: The hippocampus as a path integration system. *Journal of Experimental Biology, 199*, 173-185.
- Meehan, J.W. (1993). Apparent minification in an imaging display under reduced viewing conditions. *Perception, 22*, 1076-1084.
- Meehan, J.W., & Triggs, T.J. (1988). Magnification effects with imaging displays depend on scene content and viewing conditions. *Human Factors, 30*, 487-494.
- Meehan, J.W., & Triggs, T.J. (1992). Apparent size and distance in an imaging display. *Human Factors, 34*, 303-311.
- Mestre, D. (1988). Visual control of displacement at slow speeds. *Human Factors 30*(6), 663-676.
- Mittelstaedt, H. (1985). Analytical cybernetics of spider navigation. In F.G. Barth (Ed.), *Neurobiology of arachnids* (pp. 298-316). Berlin: Springer-Verlag.

- Mittelstaedt, H. (2000). Triple-loop model of path control by head direction and place cells. *Biological Cybernetics*, 82, 261-270.
- Mittelstaedt, H., & Mittelstaedt, M.-L. (1982). Homing by path integration. In F. Papi & H.G. Walraff (Eds.), *Avian navigation* (pp.290-297). New York: Springer.
- Mittelstaedt, M.-L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften*, 67, 566-567.
- Moar, I., & Bower, G.H. (1983). Inconsistency in spatial knowledge. *Memory and Cognition*, 11, 107-113.
- Moffatt, S.D., Hampson, E., & Hatzipantelis, M. (1998). Navigation in a "virtual" maze: Sex differences and correlation with psychometric measures of spatial ability in humans. *Evolution and Human Behaviour*, 19, 73-87.
- Montello, D.R., & Frank, A.U. (1996). Modelling directional knowledge and reasoning in environmental space: Testing qualitative metrics. In Portugali, J. (Ed.), *The construction of cognitive maps* (pp. 321-344). Dordrecht, Netherlands: Kluwer Academic.
- Montello, D.R., Richardson, A.E., Hegarty, M., & Provenza, M. (1999). A comparison of methods for estimating directions in egocentric space. *Perception*, 28, 981-1000.
- Morris, R.G., Garrud, P., Rawlins, J.N., & O'Keefe, J. (1982). Place navigation impaired in rats with hippocampal lesions. *Nature*, 297, 681-683.
- Müller, M., & Wehner, R. (1988). Path integration in desert ants, *cataglyphis fortis*. *Proceedings of the National Academy of Sciences, USA*, 85, 5287-5290.
- Muller, R. (1996). A quarter of a century of place cells. *Neuron*, 17, 813-822.
- Nadel, L. (1999). Neural mechanisms of spatial orientation and wayfinding: An overview. In R.G. Golledge (Ed.), *Wayfinding behavior* (pp. 313-327). Baltimore, MD: Johns Hopkins University Press.

- Newman, E.L., Caplan, J.B., Kirschen, M.P., Korolev, I.O., Sekuler, R., & Kahana, M.J. (2007). Learning your way around town: How virtual taxicab drivers learn to use both layout and landmark information. *Cognition*, *104*, 231-253.
- O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. *Brain Research* *34*, 171-175.
- O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford: Clarendon Press.
- O'Keefe, J., Burgess, N., Donnett, J.G., Jeffery, K.J., & Maguire, E.A. (1998). Place cells, navigational accuracy, and the human hippocampus. *Philosophical Transactions of the Royal Society (London), B, Biological Science* *353*, 1333-1340.
- O'Keefe, J., & Speakman, A. (1987). Single unit activity in the rat hippocampus during a spatial memory task. *Experimental Brain Research*, *68*, 1-27.
- O'Laughlin, E.M., & Brubaker, B.S. (1998). Use of landmarks in cognitive mapping: Gender differences in self-report versus performance. *Personality and Individual Differences*, *24*, 595-601.
- Patrick, E., Cosgrove, D., Slavkovic, A., Rode, J.A., Vewatti, T., & Chiselko, G. (2000). Using a large projection screen as an alternative to head-mounted displays for virtual environments. In *Proceedings of the CHI 2000 Conference on Human Factors in Computing Systems*, 478-485.
- Perrone, J.A., & Stone, L.S. (1994). A model of self-motion estimation within primate extrastriate visual cortex. *Vision Research*, *34*, 2917-2938.
- Péruch, P., Belingard, L., & Thinus-Blanc, C. (2000). Transfer of spatial knowledge from virtual to real environments. In C. Freksa, W. Brauer, C. Habel, & K.F. Wender (Eds.), *Spatial Cognition II: Integrating abstract theories, empirical studies, formal methods and practical applications* (pp. 253-263). Berlin: Springer-Verlag.

- Péruch, P., & Gaunet, F. (1998). Virtual environments as a promising tool for investigating human spatial cognition. *Current Psychology of Cognition / Cahiers de Psychologie Cognitive*, 17(4-5), 881-899.
- Péruch, P., May, M., & Wartenberg, F. (1997). Homing in virtual environments: Effects of field of view and path layout. *Perception*, 26, 301-311.
- Péruch, P., Vercher, J. L., & Gauthier, G.M. (1995). Acquisition of spatial knowledge through visual exploration of simulated environments. *Ecological Psychology*, 7, 1-20.
- Philbeck, J.W., Klatzky, R.L., Behrmann, M., Loomis, J.M., & Goodridge, J. (2001). Active control of locomotion facilitates nonvisual navigation. *Journal of Experimental Psychology: Human Perception and Performance*, 27(1), 141-153.
- Prothero, J.D., & Hoffman, H.G. (1995). *Widening the field of view increases the sense of presence in immersive virtual environments*. Human Interface Technology Laboratory Technical Report, University of Washington, Seattle, WA, R-95-4.
- Prothero, J.D., & Parker, D.E. (2003). A unified approach to presence and motion sickness. In L.J. Hettinger & M.W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp.47-66). Mahwah, NJ: Lawrence Erlbaum Associates.
- Randle, R.J., Roscoe, S.N., & Pettitt, J. (1980). *Effects of accommodation and magnification on aimpoint estimation in simulated landings with real and virtual image displays*. (Tech. Paper NASA-TP-1635). Washington, DC: National Aeronautics and Space Administration.
- Recarte, M.A., & Nunes, L.M. (1996). Perception of speed in an automobile: Estimation and production. *Journal of Experimental Psychology: Applied*, 2(4), 291-304.
- Redlick, F.P., Jenkin, M., & Harris, L.R. (2001). Humans can use optic flow to estimate distance of travel. *Vision Research*, 41(2), 213-219.

- Regenbrecht, H., Schubert, T., & Friedmann, F. (1998). Measuring the sense of presence and its relations to fear of heights in virtual environments. *International Journal of Human-Computer Interaction, 10*(3), 233-249.
- Richardson, A.E., Montello, D.R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory and Cognition, 27*, 741-750.
- Riecke, B.E., Schulte-Pelkum, J., Avraamides, M.N., von der Heyde, M. & Bülthoff, H.H. (2006). Cognitive factors can influence self-motion perception (vection) in virtual reality. *ACM Transactions on Applied Perception, 3*(3), 194-216.
- Riecke, B.E., van Veen, H.A.H., & Bülthoff, H.H. (2000). *Visual homing is possible without landmarks*. Technical Report No. 82, Max Planck Institute, Tübingen, Germany (pp. 1-29).
- Riecke, B.E., van Veen, H.A.H., & Bülthoff, H.H. (2002). Visual homing is possible without landmarks: A path integration study in virtual reality. *Presence, 11*, 443-473.
- Riecke, B.E., von der Heyde, M., & Bülthoff, H.H. (2001). How real is virtual reality really? Comparing spatial updating using pointing tasks in real and virtual environments. *Journal of Vision 1*(3), 321a.
- Rieger, J.H., & Toet, L. (1985). Human visual navigation in the presence of 3D rotations. *Biological Cybernetics, 52*, 377-381.
- Rock, I., & Ebenholtz, S. (1959). The relational determination of perceived size. *Psychological Review, 66*(6), 387-401.
- Roscoe, S.N., (1977). *How big the moon, how fat the eye?* (Tech. Rep. ARL-77-9 / AFOSR-77-8). Savoy, IL: University of Illinois at Urbana-Champaign.
- Roscoe, S.N. (1984). Judgments of size and distance with imaging displays. *Human Factors, 26*, 617-629.
- Roscoe, S.N. (1985). *Aviation Psychology*. Ames, IA: Iowa State University Press.

- Roscoe, S.N. (1989). The zoom-lens hypothesis. In M. Hershenson (Ed.), *The moon illusion* (pp.31-57). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Roscoe, S.N. (1998). Size-distance variance and eye accommodation: The ways of an investigator. *The International Journal of Aviation Psychology*, 8(1), 75-81.
- Roscoe, S.N., & Acosta, H.M. (2008). A flight by periscope and where it landed. *Human Factors*, 50(3), 361-367.
- Roscoe, S.N., Hasler, S.G., & Dougherty, D.J. (1966). Flight by periscope: Making takeoffs and landings: the influence of image magnification, practice, and various conditions of flight. *Human Factors*, 8, 13-40.
- Roscoe, S.N., Olzak, L.A., & Randle, R.J. (1976). Ground-referenced visual orientation with imaging displays: Monocular versus binocular accommodation and judgments of relative size. *Proceedings of the AGARD Conference on Visual Presentation of Cockpit Information* (pp. A5.1-A5.9). Neuilly-sur-Seine, France: North Atlantic Treaty Organization.
- Rossano, M.J., & Moak, J. (1998). Spatial representations acquired from computer models: Cognitive load, orientation specificity and the acquisition of survey knowledge. *British Journal of Psychology*, 89, 481-497.
- Roumes, C., Meehan, J.W., Plantier, J., & Menu, J. P. (2001). Distance estimation in a 3-D imaging display. *The International Journal of Aviation Psychology*, 11(4), 381-396.
- Roumes, C., Plantier, J., & Menu, J.P. (1992). *Evaluation d'informations présentées en stéréoscopie en cours d'une tâche de pilotage. Influence of stereoscopic information on flight performance*. Tech. Rep. No. CERMA 92-07. Paris: Centre d'Études et de Recherches de Médecine Aérospatiale.
- Royden, C.S., Banks, M.S., & Crowell, J.A. (1992). The perception of heading during eye movements. *Nature*, 360, 583-585.
- Royden, C.S., Crowell, J.A., & Banks, M.S. (1994). Estimating heading during eye movements. *Vision Research*, 34, 3197-3214.

- Ruddle, R.A., & Lessels, S. (2006). For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological Science*, 17, 460-465.
- Ruddle, R.A., Payne, S.J., & Jones, D.M. (1997). Navigating buildings in “desk-top” virtual environments: Experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied*, 3(2), 143-159.
- Sadalla, E.K., & Montello, D.R. (1989). Remembering changes in direction. *Environment and Behaviour*, 21(3), 346-363.
- Sadowski, W., & Stanney, K. (2002). Presence in virtual environments. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.791-806). Mahwah, NJ: Lawrence Erlbaum Associates.
- Samsonovich, A., & McNaughton, B.L. (1997). Path integration and cognitive mapping in a continuous attractor neural network model. *Journal of Neuroscience*, 17, 5900-5920.
- Sandstrom, N.J., Kaufman, J., & Huettel, S.A. (1998). Males and females use different distal cues in a virtual environment navigation task. *Cognitive Brain Research*, 6, 351-360.
- Saucier, D.M., Green, S.M., Leason, J., MacFadden, A., Bell, S., & Elias, L.J. (2002). Are sex differences in navigation caused by sexually dimorphic strategies or by differences in the ability to use the strategies? *Behavioral Neuroscience*, 116, 403-410.
- Schubert, T., Friedmann, F., & Regenbrecht, H. (1999). Embodied presence in virtual environments. In R. Paton & I. Neilson (Eds.), *Visual representations and interpretations* (pp.268-278). London: Springer-Verlag.
- Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence*, 10(3), 266-281.

- Schulte-Pelkum, J., Riecke, B.E., von der Heyde, M., & Bühlhoff, H.H. (2004). *Influence of display device and screen curvature on perceiving and controlling simulated ego-rotations from optic flow*. Technical Report No. 122, Max Planck Institute, Tübingen, Germany (pp. 1-10).
- Sebrechts, M.M., Lathan, C., Clawson, D.M., Miller, M.S., & Trepagnier, C. (2003). Transfer of training in virtual environments: Issues for human performance. In L.J. Hettinger & M.W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp.67-90). Mahwah, NJ: Lawrence Erlbaum Associates.
- Séguinot, V., Cattet, J., & Benhamou, S. (1998). Path integration in dogs. *Animal Behavior*, *55*, 787-799.
- Séguinot, V., Maurer, R., & Etienne, A.S. (1993). Dead reckoning in a small mammal: the evaluation of distance. *Journal of Comparative Physiology, A*, *173*, 103-113.
- Sharples, S., Cobb, S., Moody, A., & Wilson, J.R. (2008). Virtual reality induced symptoms and effects (VRISE): Comparison of head-mounted display (HMD), desktop and projection display symptoms. *Displays*, *29*, 58-69.
- Sheridan, T.B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments* *1*(1), 120-126.
- Sholl, M.J. (1989). The relation between horizontality and rod-and-frame and vestibular navigational performance. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *15*, 110-125.
- Simonelli, N.M. (1979). Apparent size and visual accommodation under day and night conditions. *Proceedings of the Human Factors Society 23<sup>rd</sup> Annual Meeting* (pp. 374-378). Santa Monica, CA: Human Factors and Ergonomics Society.
- Singer, M.J., & Witmer, B.G. (1999). On selecting the right yardstick. *Presence*, *8*(5), 566-573.

- Slater, M. (1999). Measuring presence: A response to the Witmer and Singer presence questionnaire. *Presence*, 8(5), 560-565.
- Slater, M., Steed, A., McCarthy, J., & Maringelli, F. (1998). The influence of body movement on presence in virtual environments. *Human Factors*, 40(3), 469-477.
- Slater, M., & Usoh, M. (1993). Representation systems, perceptual position, and presence in immersive virtual environments. *Presence: Teleoperators and Virtual Environments* 2(3), 221-233.
- Slater, M., Usoh, M., & Steed, A. (1994). Depth of presence in virtual environments. *Presence: Teleoperators and Virtual Environments* 3(2), 130-144.
- Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators and Virtual Environments* 6(6), 603-616.
- Smets, G.J.F., & Overbeeke, C.J. (1995). Trade-off between resolution and interactivity in spatial task performance. *IEEE Computer Graphics & Applications*, 15, 46-51.
- Snow, M.P., & Williges, R.C. (1998). Empirical models based on free-modulus magnitude estimation of perceived presence in virtual environments. *Human Factors*, 40(3), 386-402.
- Snowden, R.J., Stimpson, N., & Ruddle, R.A. (1998). Speed perception fogs up as visibility drops. *Nature*, 392, 450.
- Stanney, K.M., Mollaghasemi, M., Reeves, L., Breaux, R., & Graeber, D.A. (2003). Usability engineering of virtual environments (VEs): Identifying multiple criteria that drive effective VE system design. *International Journal of Human-Computer Studies*, 58, 447-481.
- Stanney, K.M., Salvendy, G., Deisinger, J., DiZio, P., Ellis, S., Ellison, J., & Witmer, B. (1998). Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda. Report sponsored by the Life Sciences Division at NASA Headquarters. *International Journal of Human-Computer Interaction*, 10(2), 135-187.

- Stappers, P.J., Overbeeke, K., & Gaver, W. (2003). Beyond the limits of real-time realism: Moving from stimulation correspondence to information correspondence. In L.J. Hettinger & M.W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 91-110). Mahwah, NJ: Lawrence Erlbaum Associates.
- Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication, 42*(4), 73-93.
- Stone, L.S., & Perrone, J.A. (1997). Human heading estimation during visually simulated curvilinear motion. *Vision Research, 37*(5), 573-590.
- Stone, L.S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Research, 32*, 1535-1549.
- Stringer, S.M., Trappenberg, T.P., Rolls, E.T., & de Araujo, I. (2002). Self-organizing continuous attractor networks and path integration: One-dimensional models of head-direction cells. *Network, 13*, 217-242.
- Sun, H.J., Campos, J.L., & Chan, G.S. (2004). Multisensory integration in the estimation of relative path length. *Experimental Brain Research, 154*, 246-254.
- Sutcliffe, A.G., & Kaur, K.D. (2000). Evaluating the usability of virtual reality interfaces. *Behaviour Information Technology, 19*(6), 415-426.
- Tan, D.S., Czerwinski, M., & Robertson, G. (2003). Women go with the (optical) flow. In *Proceedings of the CHI 2003 Conference on Human Factors in Computing Systems*, 209-215.
- Tan, D.S., Gergle, D., Scupelli, P.G., & Pausch, R. (2003). With similar visual angles, larger displays improve spatial performance. In *Proceedings of the CHI 2003 Conference on Human Factors in Computing Systems*, 217-224.
- Tan, D.S., Gergle, D., Scupelli, P.G., & Pausch, R. (2004). Physically large displays improve path integration in 3D visual navigation tasks. In *Proceedings of the CHI 2004 Conference on Human Factors in Computing Systems*, 439-446.

- Tan, D.S., Gergle, D., Scupelli, P.G., & Pausch, R. (2006). Physically large displays improve performance on spatial tasks. *ACM Transactions on Computer-Human Interaction*, 13(1), 71-99.
- Tarr, M.J., & Warren, W.H. (2002). Virtual reality in behavioral neuroscience and beyond. *Nature Neuroscience Supplement*, 5, 1089-1092.
- Tate, D.L., Sibert, L., & King, T. (1997). Virtual environments for shipboard firefighting training. *Proceedings of the VRAIS*, 61-68.
- Taube, J.S. (1998). Head direction cells and the neurophysiological basis for a sense of direction. *Progress in Neurobiology*, 55, 225-256.
- Taube, J.S., Muller, R.U., & Ranck, J.B., Jr (1990). Head-direction cells recorded from the postsubiculum in freely moving rats. II. Effects of environmental manipulations. *Journal of Neuroscience*, 10, 436-447.
- The MathWorks, Inc. (2007). *MATLAB – The language of technical computing, Version 2007b*. The MathWorks, Inc., Natick, Massachusetts.
- The MathWorks, Inc. (2008). *MATLAB – Statistics Toolbox, Version 7.2*. The MathWorks, Inc., Natick, Massachusetts.
- Thompson, P. (1982). Perceived rate of movement depends on contrast. *Vision Research*, 22, 377-380.
- Thompson, P. (2003). Reducing contrast really can speed up faster-moving stimuli. *Journal of Vision*, 3, 400a.
- Thompson, P., Brooks, K., & Hammett, S.T. (2006). Speed can go up as well as down at low contrast: Implications for models of motion perception. *Vision Research*, 46, 782-786.
- Thompson, W.B., Willemsen, P., Gooch, A. A., Creem-Regehr, S.H., Loomis, J.M., & Beall, A.C. (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence*, 13, 560-571.

- Tlauka, M., Brolese, A., Pomeroy, D., & Hobbs, W. (2005). Gender differences in spatial knowledge acquired through simulated exploration of a virtual shopping centre. *Journal of Environmental Psychology, 25*, 111-118.
- Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55*, 189-208.
- Törnros, J. (1998). Driving behaviour in a real and a simulated road tunnel – a validation study. *Accident Analysis and Prevention, 30*(4), 497-503.
- Triggs, T.J. (1986). Speed estimation. In G.A. Peters & B.J. Peters (Eds.), *Automotive engineering and litigation (vol. 1, supplement)*. New York: Garland Press, 95-124.
- Turano, K., & Wang, X. (1994). Visual discrimination between a curved and straight path of self-motion: effects of forward speed. *Vision Research, 34*, 107-114.
- Tyndiuk, F., Lespinet-Najib, V., Thomas, G., & Schlick, C. (2007). Impact of tasks and users' characteristics on virtual reality performance. *CyberPsychology & Behaviour, 10*(3), 444-452.
- Usoh, M., Catena, E., Arman, S., & Slater, M. (2000). Using presence questionnaires in reality. *Presence, 9*(5), 497-503.
- Van den Berg, A.V. (1992). Robustness of perception of heading from optic flow. *Vision Research, 32*(7), 1285-1296.
- van Veen, H.A.H.C., Distler, H.K., Braun, S.J., & Bühlhoff, H.H. (1998). Navigating through a virtual city: Using virtual reality technology to study human action and perception. *Future Generation Computer Systems, 14*, 231-242.
- van Veen, H.A.H.C., Riecke, B.E., & Bühlhoff, H.H. (1999). Visual homing to a virtual home. *Investigative Ophthalmology & Vision Science 40*(4), 798.
- Waller, D. (2000). Individual differences in spatial learning from computer-simulated environments. *Journal of Experimental Psychology: Applied, 6*(4), 307-321.

- Waller, D., & Bachmann, E.R. (2006). The borderline of science: On the value of factor analysis for understanding presence. *Presence*, 15(2), 235-244.
- Waller, D., Beall, A.C., & Loomis, J.M. (2004). Using virtual environments to assess directional knowledge. *Journal of Environmental Psychology*, 24, 105-16.
- Waller, D., Hunt, E., & Knapp, D. (1998). The transfer of spatial knowledge in virtual environment training. *Presence*, 7(2), 129-143.
- Waller, D., Knapp, D., & Hunt, E. (2001). Spatial representations of virtual mazes: The role of visual fidelity and individual differences. *Human Factors*, 43(1), 147-158.
- Waller, D., Loomis, J.M., & Haun, D.B. (2004). Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin and Review*, 11, 157-163.
- Waller, D., Loomis, J.M., & Steck, S.D. (2003). Inertial cues do not enhance knowledge of environmental layout. *Psychonomic Bulletin and Review*, 10, 987-993.
- Wann, J.P., & Rushton, S.K. (1995): The use of virtual environments in perception action research: Grasping the impossible and controlling the improbable .In D.J. Glencross & J.P. Piek (Eds.), *Motor control and sensory motor integration: Issues and directions. Advances in Psychology*, 111 (pp. 341-360). Amsterdam, Netherlands: North Holland/Elsevier Science.
- Warren, W.H. (1995). Self-motion: Visual perception and visual control. In W. Epstein & S. Rogers (Eds.), *Handbook of perception and cognition, vol 5: Perception of space and motion* (pp. 263-325). San Diego, CA: Academic Press.
- Warren, W.H., & Hannon, D.J. (1988). Direction of self-motion is perceived from optical flow. *Nature*, 336, 162-163.
- Warren, W.H., & Hannon, D.J. (1990). Eye movements and optical flow. *Journal of the Optical Society of America, Series A*, 7, 160-169.

- Warren, W.H., Kay, B.A., Zosh, W.D., Duchon, A.P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, 4, 213-216.
- Warren, W.H., Mestre, D.R., Blackwall, A.W., & Morris, M.W. (1991). Perception of circular heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 28-43.
- Warren, W.H., Morris, M.W., & Kalish, M. (1988). Perception of translational heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 646-660.
- Warren, R., & Wertheim, A.H. (1990). *Perception and control of self-motion*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Wartenberg, F., May, M., & Péruch, P. (1998). Spatial orientation in virtual environments: Background considerations and experiments. In C. Freksa, C. Habel, & K.F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 469-489). Berlin, Germany: Springer Verlag.
- Watson, B., Walker, N., Hodges, L., & Worden, A. (1997). Managing level of detail through peripheral degradation: Effects on search performance with a head-mounted display. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 4(4), 323-346.
- Watson, G.S., & Williams, E.J. (1956). On the construction of significance tests on the circle and the sphere. *Biometrika*, 43, 344-352.
- Wehner, R., & Wehner, S. (1986). Path integration in desert ants. Approaching a long-standing puzzle in insect navigation. *Monitore Zoologico Italiano*, 20, 309-331.
- Welch, R.B. (1999). How can we determine if the sense of presence affects task performance? *Presence: Teleoperators and Virtual Environments*, 8, 574-577.

- Welch, R.B. (2003). Adapting to telesystems. In L.J. Hettinger & M.W. Haas (Eds.), (2003). *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 129-167). Mahwah, NJ: Lawrence Erlbaum Associates.
- Welch, R.B., Blackmon, T.T., Liu, A., Mellers, B.A., & Stark, L.W. (1996). The effects of pictorial realism, delay of visual feedback, and observer interactivity on the subjective sense of presence. *Presence: Teleoperators and Virtual Environments*, 5, 262-273.
- Welch, R.B., & Sampanes, A.C. (2008). Adapting to virtual environments: Visual-motor skill acquisition versus perceptual recalibration. *Displays*, 29, 152-158.
- Whishaw, I.Q., McKenna, J.E., & Maaswinkel, H. (1997). Hippocampal lesions and path integration. *Current Opinion in Neurobiology*, 7, 228-234.
- Willemsen, P., Colton, M.B., Creem-Regehr, S.H., & Thompson, W.B. (2009). The effects of head-mounted display mechanical properties and field-of-view on distance judgments in virtual environments. *ACM Transactions on Applied Perception*, 6(2), 8:1 – 8:14.
- Wilson, J.R., Eastgate, R.M., & D'Cruz, M. (2002). Structured development of virtual environments. In K.M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications. Human factors and ergonomics* (pp.353-378). Mahwah, NJ: Lawrence Erlbaum Associates.
- Wilson, J.R., Nichols, S.C., & Haldane, C. (1997). Presence and side effects: Complementary or contradictory? In M. Smith, G. Salvendy, & R. Koubek (Eds.), *Design of computing systems: Social and ergonomic considerations* (pp.889-892). Amsterdam: Elsevier.
- Wilson, M.A., & McNaughton, B.L. (1993). Dynamics of the hippocampal ensemble code for space. *Science*, 261, 1055-1058.
- Wilson, P.N. (1997). Use of virtual reality computing in spatial learning research. In N. Foreman & R. Gillett (Eds.), *A Handbook of spatial research paradigms and methodologies, Vol 1* (pp. 181-206). Psychology Press Ltd., Hove, East Sussex, U.K.

- Wilson, P.N. (1999). Active exploration of a virtual environment does not promote orientation or memory for objects. *Environment and Behaviour*, 31(6), 752-763.
- Wilson, P.N., Foreman, N., Gillett, R., & Stanton, D. (1997). Active versus passive processing of spatial information in a computer-simulated environment. *Ecological Psychology*, 9(3), 207-222.
- Wilson, P.N., Foreman, N., & Tlauka, M. (1997). Transfer of spatial information from a virtual to a real environment. *Human Factors*, 39, 526-531.
- Wilson, P.N., & Péruch, P. (2002). The influence of interactivity and attention on spatial learning in a desk-top virtual environment. *Cahiers de Psychologie Cognitive / Current Psychology of Cognition*, 21, 601-633.
- Witmer, B.G., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence*, 14(3), 298-312.
- Witmer, B.G., & Kline, P.B. (1998). Judging perceived and traversed distance in virtual environments. *Presence* 7, 144-167.
- Witmer, B.G., & Singer, M.J. (1994). *Measuring immersion in virtual environments*. ARI Technical Report 1014, Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.
- Witmer, B.G., & Singer, M.J. (1998). Measuring presence in virtual environments: A Presence Questionnaire. *Presence*, 7(3), 225-240.
- Woodruff, R.R., Hubbard, D.C., & Shaw, A. (1986). Comparison of helmet-mounted visual displays for flight simulation. *Displays*, 7, 179-185.
- Worchel, P. (1951). Space perception and orientation in the blind. *Psychological Monographs*, 65, 1-28.
- Zar, J.H. (1999). *Biostatistical Analysis*, 4th edition. Prentice Hall.

## Appendices

### Appendix A. Mean Vector Lengths ( $R$ ) for Three Angles by Environment and Leg-length, Separately by Gender

Table A.1

*Experiment 2: Mean vector lengths for three angles by environment and leg-length, separately by navigation mode and gender*

Distance	Environment	Gender	ACTIVE			PASSIVE		
			60°	90°	120°	60°	90°	120°
L-L	Ur-S	F	0.80	0.84	0.82	0.69	0.81	0.74
		M	0.91	0.87	0.86	0.81	0.87	0.84
	Ur-N	F	0.72	0.83	0.80	0.72	0.64	0.73
		M	0.84	0.90	0.91	0.87	0.82	0.84
	Rur-S	F	0.77	0.80	0.81	0.53	0.63	0.77
		M	0.87	0.85	0.89	0.70	0.84	0.84
	Rur-N	F	0.74	0.74	0.78	0.70	0.77	0.81
		M	0.86	0.84	0.84	0.86	0.87	0.90
L-S	Ur-S	F	0.74	0.82	0.72	0.66	0.66	0.78
		M	0.83	0.85	0.87	0.82	0.83	0.87
	Ur-N	F	0.72	0.79	0.82	0.69	0.63	0.73
		M	0.81	0.92	0.88	0.79	0.79	0.82
	Rur-S	F	0.77	0.74	0.85	0.58	0.71	0.77
		M	0.87	0.80	0.92	0.75	0.84	0.83
	Rur-N	F	0.68	0.73	0.73	0.73	0.71	0.72
		M	0.85	0.81	0.84	0.85	0.81	0.80
S-L	Ur-S	F	0.69	0.79	0.75	0.71	0.74	0.71
		M	0.82	0.86	0.83	0.84	0.88	0.85
	Ur-N	F	0.76	0.80	0.77	0.71	0.72	0.78
		M	0.87	0.90	0.83	0.84	0.87	0.85
	Rur-S	F	0.74	0.85	0.82	0.70	0.70	0.79
		M	0.87	0.88	0.87	0.86	0.85	0.88
	Rur-N	F	0.68	0.72	0.77	0.68	0.68	0.65
		M	0.87	0.80	0.84	0.84	0.81	0.86

Table A.2

*Experiment 3: Mean vector lengths for three angles by environment and leg-length, separately by gender*

Leg-length	Environment	Gender	60°	90°	120°
L-L	Ur-S	F	0.77	0.73	0.84
		M	0.76	0.84	0.84
	Ur-N	F	0.81	0.87	0.81
		M	0.82	0.83	0.84
	Rur-S	F	0.86	0.84	0.82
		M	0.85	0.85	0.82
	Rur-N	F	0.80	0.83	0.83
		M	0.81	0.81	0.86
	L-S	Ur-S	F	0.76	0.79
M			0.76	0.81	0.83
Ur-N		F	0.81	0.79	0.75
		M	0.80	0.80	0.79
Rur-S		F	0.75	0.78	0.82
		M	0.72	0.80	0.81
Rur-N		F	0.78	0.84	0.86
		M	0.80	0.83	0.86
S-L		Ur-S	F	0.84	0.83
	M		0.82	0.87	0.83
	Ur-N	F	0.85	0.85	0.83
		M	0.83	0.87	0.87
	Rur-S	F	0.82	0.86	0.81
		M	0.90	0.87	0.84
	Rur-N	F	0.80	0.81	0.82
		M	0.84	0.84	0.85

**Appendix B. Mean Vector Lengths (*R*) by Turn-type (Intersection / Roundabout)**

Table B.1

*Experiment 2: Mean vector lengths (*R*) by turn-type (intersection / roundabout), separately by navigation mode and gender*

Leg-length	Environment	Gender	Roundabout		Intersection	
			Active	Passive	Active	Passive
L-L	Ur-S	F	0.84	0.81	0.74	0.79
		M	0.87	0.87	0.88	0.90
	Ur-N	F	0.83	0.64	0.81	0.80
		M	0.90	0.82	0.89	0.93
	Rur-S	F	0.80	0.63	0.76	0.84
		M	0.85	0.84	0.87	0.91
	Rur-N	F	0.74	0.77	0.81	0.83
		M	0.84	0.88	0.88	0.93
L-S	Ur-S	F	0.82	0.66	0.76	0.76
		M	0.85	0.83	0.89	0.91
	Ur-N	F	0.79	0.63	0.76	0.76
		M	0.92	0.79	0.90	0.88
	Rur-S	F	0.74	0.71	0.83	0.86
		M	0.80	0.84	0.90	0.94
	Rur-N	F	0.73	0.71	0.78	0.81
		M	0.81	0.81	0.93	0.90
S-L	Ur-S	F	0.79	0.74	0.75	0.86
		M	0.86	0.88	0.87	0.90
	Ur-N	F	0.80	0.72	0.83	0.79
		M	0.90	0.87	0.86	0.86
	Rur-S	F	0.85	0.70	0.86	0.85
		M	0.88	0.85	0.88	0.93
	Rur-N	F	0.72	0.68	0.80	0.81
		M	0.80	0.81	0.87	0.88

Table B.2

*Experiment 3: Mean vector lengths (R) by turn type  
(intersection / roundabout)*

Leg-length	Environment	Gender	Roundabout	Intersection
L-L	Ur-S	F	0.73	0.74
		M	0.84	0.80
	Ur-N	F	0.87	0.82
		M	0.83	0.86
	Rur-S	F	0.84	0.84
		M	0.85	0.84
Rr-N	F	0.83	0.88	
	M	0.81	0.91	
L-S	Ur-S	F	0.79	0.68
		M	0.81	0.80
	Ur-N	F	0.79	0.82
		M	0.80	0.84
	Rur-S	F	0.78	0.73
		M	0.80	0.80
Rur-N	F	0.84	0.88	
	M	0.83	0.87	
S-L	Ur-S	F	0.83	0.82
		M	0.87	0.78
	Ur-N	F	0.85	0.77
		M	0.87	0.77
	Rur-S	F	0.86	0.80
		M	0.87	0.85
Rur-N	F	0.81	0.77	
	M	0.84	0.80	

## Appendix C. Mean Angular Directions and Signed Error, Separately by Gender

Table C.1

*Experiment 2: Mean directions and mean angular deviations of the directional estimates by distance, environment, gender, and navigation mode*

$\alpha$	Dist. comb.	$\theta$	Environment	Gender	Active	Passive
60°	L-L	120°	Ur-S	F	134.74° (33.50°)	138.43° (50.29°)
				M	123.47° (31.82°)	131.93° (33.82°)
			Ur-N	F	132.03° (37.69°)	140.66° (44.47°)
				M	133.07° (30.53°)	135.43° (36.73°)
			Rur-S	F	119.60° (38.90°)	165.68° (59.91°)
				M	131.73° (35.72°)	131.71° (41.19°)
	Rur-N	F	119.68° (33.75°)	139.94° (48.71°)		
		M	129.82° (39.25°)	130.63° (35.09°)		
	L-S	90°	Ur-S	F	129.54° (43.06°)	128.69° (53.95°)
				M	135.36° (41.51°)	120.38° (34.38°)
			Ur-N	F	132.06° (33.58°)	137.85° (48.83°)
				M	120.41° (37.25°)	134.15° (36.26°)
			Rur-S	F	118.31° (36.32°)	135.28° (51.19°)
				M	123.02° (28.98°)	127.41° (43.47°)
	Rur-N	F	121.45° (42.17°)	140.39° (41.09°)		
		M	116.47° (46.25°)	124.37° (38.35°)		
	S-L	150°	Ur-S	F	124.73° (42.36°)	143.91° (36.25°)
				M	139.15° (31.48°)	136.43° (44.19°)
Ur-N			F	136.89° (35.03°)	151.98° (47.36°)	
			M	140.68° (40.58°)	138.24° (38.65°)	
Rur-S			F	120.91° (32.49°)	142.28° (47.95°)	
			M	137.78° (34.23°)	147.61° (32.44°)	
Rur-N	F	137.53° (32.44°)	152.94° (49.37°)			
	M	134.13° (43.49°)	141.29° (35.80°)			
90°	L-L	135°	Ur-S	F	136.71° (31.86°)	157.95° (33.44°)
				M	148.21° (28.77°)	142.45° (30.05°)
			Ur-N	F	131.72° (29.02°)	134.76° (50.85°)
				M	128.63° (31.64°)	139.47° (46.92°)
			Rur-S	F	129.39° (31.33°)	147.82° (52.05°)
				M	137.50° (33.10°)	142.78° (33.17°)
Rur-N	F	127.30° (42.42°)	157.73° (44.74°)			
	M	143.10° (36.88°)	140.37° (31.79°)			

	L-S	115°	Ur-S	F	143.44° (30.32°)	146.61° (51.23°)
				M	139.13° (34.14°)	137.13° (22.99°)
			Ur-N	F	124.55° (28.74°)	142.82° (57.43°)
				M	132.14° (33.60°)	135.34° (30.87°)
			Rur-S	F	120.59° (34.64°)	150.17° (43.50°)
				M	135.13° (39.44°)	132.10° (37.12°)
			Rur-N	F	129.31° (34.07°)	138.76° (50.51°)
				M	146.64° (42.19°)	131.62° (33.28°)
	S-L	155°	Ur-S	F	135.62° (36.96°)	153.28° (33.14°)
				M	149.21° (29.27°)	150.14° (36.25°)
			Ur-N	F	137.49° (27.58°)	153.27° (46.54°)
				M	133.34° (36.78°)	145.11° (31.87°)
			Rur-S	F	127.04° (33.95°)	148.81° (37.53°)
				M	143.33° (25.62°)	149.25° (31.39°)
			Rur-N	F	138.01° (39.63°)	153.95° (42.03°)
				M	130.50° (34.49°)	147.49° (37.80°)
120°	L-L	150°	Ur-S	F	139.10° (23.84°)	147.33° (43.76°)
				M	147.16° (37.49°)	140.35° (36.21°)
			Ur-N	F	140.42° (25.38°)	158.78° (38.35°)
				M	141.18° (30.97°)	147.19° (34.65°)
			Rur-S	F	131.44° (27.21°)	161.34° (37.83°)
				M	144.11° (34.13°)	148.41° (32.77°)
			Rur-N	F	132.54° (24.39°)	140.62° (42.56°)
				M	144.37° (43.76°)	133.89° (24.16°)
	L-S	140°	Ur-S	F	132.75° (32.35°)	159.32° (35.93°)
				M	140.41° (39.97°)	135.50° (31.05°)
			Ur-N	F	137.20° (26.75°)	130.91° (39.78°)
				M	128.83° (32.11°)	149.88° (41.12°)
			Rur-S	F	125.37° (29.04°)	135.08° (37.21°)
				M	123.35° (23.03°)	147.74° (29.69°)
			Rur-N	F	134.03° (34.23°)	145.52° (46.18°)
				M	122.60° (34.48°)	135.87° (32.50°)
	S-L	160°	Ur-S	F	139.17° (29.29°)	163.16° (38.93°)
				M	152.08° (36.85°)	143.28° (32.08°)
			Ur-N	F	136.13° (39.04°)	169.30° (37.18°)
				M	148.43° (36.43°)	146.29° (37.38°)
			Rur-S	F	129.87° (30.44°)	160.78° (41.21°)
				M	141.28° (36.11°)	149.84° (31.47°)
			Rur-N	F	136.17° (32.72°)	169.76° (45.49°)
				M	150.90° (38.46°)	159.02° (36.32°)

Table C.2

*Experiment 2: Means and standard deviations of the signed error of the directional estimates by distance, environment, gender, and navigation mode*

$\alpha$	Dist. comb.	$\theta$	Environment	Gender	Active	Passive
60°	L-L	120°	Ur-S	F	13.88° (37.56°)	25.44° (58.96°)
				M	3.90° (34.58°)	14.89° (37.05°)
			Ur-N	F	11.56° (41.22°)	26.36° (54.08°)
				M	15.75° (31.00°)	19.29° (41.02°)
			Rur-S	F	6.06° (39.96°)	52.23° (68.97°)
				M	16.40° (37.12°)	19.59° (44.40°)
	Rur-N	F	1.25° (35.18°)	30.80° (58.16°)		
		M	10.11° (48.68°)	16.45° (40.99°)		
	L-S	90°	Ur-S	F	36.25° (48.14°)	42.14° (66.80°)
				M	47.10° (47.44°)	27.47° (36.65°)
			Ur-N	F	31.46° (37.11°)	49.81° (56.90°)
				M	23.70° (43.13°)	43.45° (39.29°)
			Rur-S	F	23.59° (41.35°)	53.30° (55.27°)
				M	26.54° (42.36°)	38.67° (48.33°)
	Rur-N	F	22.99° (36.70°)	47.43° (49.26°)		
		M	39.98° (39.84°)	32.38° (43.37°)		
	S-L	150°	Ur-S	F	-9.44° (53.00°)	3.32° (42.22°)
				M	-8.02° (27.81°)	2.97° (52.40°)
Ur-N			F	-15.54° (33.89°)	20.78° (57.91°)	
			M	-1.74° (54.43°)	-3.67° (42.16°)	
Rur-S			F	-23.42° (35.10°)	11.09° (59.12°)	
			M	-6.95° (35.54°)	7.55° (41.60°)	
Rur-N	F	-4.81° (28.76°)	11.56° (57.63°)			
	M	-5.14° (51.60°)	7.66° (44.77°)			
90°	L-L	135°	Ur-S	F	2.37° (33.62°)	25.89° (36.89°)
				M	6.94° (39.09°)	6.39° (31.77°)
			Ur-N	F	-8.88° (41.59°)	11.44° (64.00°)
				M	-3.85° (35.79°)	17.46° (53.85°)
			Rur-S	F	-6.02° (33.81°)	24.65° (65.09°)
				M	0.50° (39.64°)	7.82° (36.16°)
Rur-N	F	1.22° (49.13°)	24.84° (52.11°)			
	M	9.15° (45.62°)	5.30° (34.82°)			

	L-S	115°	Ur-S	F	26.58° (32.74°)	33.17° (61.35°)
				M	24.48° (37.86°)	18.45° (24.09°)
			Ur-N	F	7.18° (30.13°)	30.42° (68.94°)
				M	18.13° (40.29°)	18.12° (33.03°)
			Rur-S	F	4.73° (34.84°)	29.31° (51.14°)
				M	22.78° (40.84°)	13.31° (40.96°)
			Rur-N	F	7.15° (36.38°)	32.34° (59.97°)
				M	28.35° (45.24°)	11.74° (37.41°)
	S-L	155°	Ur-S	F	-11.20° (35.75°)	1.29° (37.00°)
				M	-1.59° (31.69°)	-3.78° (42.56°)
			Ur-N	F	-11.65° (31.51°)	3.52° (54.40°)
				M	-15.45° (41.67°)	-5.39° (34.71°)
			Rur-S	F	-14.15° (31.64°)	0.08° (43.63°)
				M	-8.95° (27.19°)	-0.74° (33.09°)
			Rur-N	F	-12.74° (41.89°)	2.28° (49.25°)
				M	-11.98° (41.76°)	-1.65° (43.16°)
120°	L-L	150°	Ur-S	F	-10.64° (25.25°)	9.26° (54.22°)
				M	3.47° (43.52°)	-6.59° (39.34°)
			Ur-N	F	-14.04° (32.81°)	10.17° (43.27°)
				M	-7.31° (32.56°)	-1.47° (37.47°)
			Rur-S	F	-17.08° (26.78°)	12.72° (42.15°)
				M	-5.65° (37.13°)	0.14° (35.44°)
			Rur-N	F	-17.39° (26.26°)	8.73° (60.44°)
				M	3.88° (51.29°)	-15.84° (25.38°)
	L-S	140°	Ur-S	F	-11.96° (34.77°)	20.03° (40.68°)
				M	7.31° (47.98°)	-4.57° (33.88°)
			Ur-N	F	-4.46° (26.44°)	-5.51° (47.21°)
				M	-9.69° (35.21°)	7.56° (46.38°)
			Rur-S	F	-13.29° (28.13°)	-6.89° (40.53°)
				M	-8.06° (39.88°)	6.48° (31.37°)
			Rur-N	F	-4.91° (29.53°)	5.02° (52.48°)
				M	-12.04° (38.98°)	-2.02° (35.15°)
	S-L	160°	Ur-S	F	-19.39° (31.65°)	5.24° (44.09°)
				M	-1.95° (45.68°)	-13.73° (35.17°)
			Ur-N	F	-27.51° (45.11°)	14.15° (42.48°)
				M	-10.10° (31.21°)	-10.40° (40.39°)
			Rur-S	F	-32.69° (41.41°)	6.59° (47.22°)
				M	-21.53° (35.44°)	-8.07° (33.94°)
			Rur-N	F	-24.16° (36.00°)	24.86° (56.32°)
				M	-2.19° (44.66°)	9.16° (46.87°)

## Appendix D. Means and Standard Deviations by Triangle Layout, and Environment

Table D.1

*Experiment 2: Means and standard deviations (in brackets) of the signed error of the directional estimates by triangle layout, navigation mode, and environment*

$\alpha$	Dist. comb.	$\theta$	Environment	Active	Passive
60°	L-L	120°	Ur-S	8.89° (35.99°)	19.90° (48.34°)
			Ur-N	13.66° (36.06°)	22.65° (47.18°)
			Rur-S	11.23° (38.43°)	35.09° (58.98°)
			Rur-N	5.68° (42.16°)	23.26° (49.75°)
	L-S	90°	Ur-S	41.68° (47.49°)	34.44° (52.94°)
			Ur-N	27.58° (39.91°)	46.47° (47.92°)
			Rur-S	25.06° (41.35°)	45.62° (51.60°)
			Rur-N	31.48° (38.77°)	39.53° (46.29°)
	S-L	150°	Ur-S	-8.72° (41.78°)	3.14° (47.23°)
			Ur-N	-8.64° (45.30°)	7.94° (51.11°)
			Rur-S	-15.18° (35.85°)	9.23° (50.04°)
			Rur-N	-4.97° (41.23°)	9.51° (50.64°)
90°	L-L	135°	Ur-S	4.66° (36.06°)	15.65° (35.26°)
			Ur-N	-6.37° (38.38°)	14.60° (58.20°)
			Rur-S	-2.76° (36.52°)	15.82° (51.95°)
			Rur-N	5.18° (46.97°)	14.58° (44.41°)
	L-S	115°	Ur-S	25.53° (34.95°)	25.44° (45.72°)
			Ur-N	12.65° (35.55°)	23.96° (52.84°)
			Rur-S	13.75° (38.57°)	20.91° (46.14°)
			Rur-N	17.75° (41.92°)	21.53 (49.87°)
	S-L	155°	Ur-S	-6.40° (33.70°)	-1.37° (39.59°)
			Ur-N	-13.55° (36.51°)	-1.16° (44.77°)
			Rur-S	-11.55° (29.24°)	-0.35° (37.95°)
			Rur-N	-12.36° (41.29°)	0.22° (45.59°)
120°	L-L	150°	Ur-S	-3.59° (35.83°)	0.94° (47.06°)
			Ur-N	-10.67° (32.44°)	4.06° (40.23°)
			Rur-S	-11.36° (32.47°)	6.12° (38.79°)
			Rur-N	-6.76° (41.64°)	-4.17° (46.59°)
	L-S	140°	Ur-S	-2.32° (42.49°)	7.12° (38.82°)
			Ur-N	-7.07° (30.85°)	1.35° (46.64°)
			Rur-S	-10.67° (34.17°)	0.13° (36.17°)
			Rur-N	-8.47° (34.33°)	1.32° (43.79°)
	S-L	160°	Ur-S	-10.67° (39.79°)	-4.72° (40.29°)
			Ur-N	-18.80° (39.29°)	1.26° (42.70°)
			Rur-S	-27.11° (38.46°)	-1.11° (40.93°)
			Rur-N	-13.17° (41.55°)	16.62° (51.51°)

Table D.2

*Experiment 3 Means and standard deviations (in brackets) of the signed error of the directional estimates by angle, distance and environment*

$\alpha$	Dist- ance	$\theta$	Ur-S	Ur-N	Rur-S	Rur-N
60°	L-L	120°	-43.04° (41.71°)	-36.36° (37.14°)	-33.20° (32.25°)	-44.73° (37.91°)
	L-S	90°	-54.80° (43.71°)	-64.66° (37.22°)	-65.61° (41.04°)	-59.78° (40.57°)
	S-L	150°	-29.84° (39.02°)	-13.16° (33.43°)	-9.80° (38.43°)	-14.56° (38.99°)
90°	L-L	135°	-31.93° (42.29°)	-28.08° (30.81°)	-23.59° (34.12°)	-28.65° (35.09°)
	L-S	115°	-41.83° (39.33°)	-43.73° (39.30°)	-36.41° (40.48°)	-36.53° (33.72°)
	S-L	155°	-11.53° (35.08°)	-14.35° (30.97°)	-10.81° (31.36°)	-10.93° (38.16°)
120°	L-L	150°	-14.38° (34.20°)	-7.25° (37.11°)	-11.81° (35.95°)	-9.74° (35.49°)
	L-S	140°	-19.95° (40.79°)	-10.43° (43.43°)	-20.93° (36.14°)	-13.53° (31.27°)
	S-L	160°	-3.44° (34.98°)	-4.86° (36.29°)	-4.59° (37.81°)	-4.50° (36.14°)

## Appendix E. ITC-SOPI: Additional Comments

Table E.1

*Experiment 1: ITC-SOPI: Additional comments*

Factor	Comment
Spatial Presence	I felt pre-occupied by my inability to “solve” the puzzle, rather than concentrating on the reality of the environment
Ecological Validity / Naturalness	<p><i>VEs</i></p> <p>Overall, the simulator was very realistic, although it was very quiet, which made it slightly less realistic</p> <p>Found the VE unreal, which sometimes distracted me from focussing on/performing the task</p> <p><i>Interface</i></p> <p>The simulation made me feel as though I was stopping a car in real life (my head felt as though it was jolting forwards) like it does when braking</p>
Negative effects	<p><i>Disorientation</i></p> <p>Because the vision wasn’t 360°, I couldn’t work out where I was.</p> <p><i>Simulator sickness</i></p> <p>I tried to look around while we were moving to get a better idea of space, but I couldn’t keep it up because I felt nausea and dizziness</p>

Table E.2

*Experiment 2: Active condition: ITC-SOPI: Additional comments*

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*Spatial Presence*

I found it a bit hard to pay attention to the environment, as I was concentrating on driving the car, if I didn't, I would drive off the road (like in the real world!)

---

*Engagement*

After a while, I became more interested in the various buildings, vehicles, trees than in the road-trip.

A more graphically detailed VE would invite a greater mental response from participants

---

*Ecological Validity / Naturalness*

*1. VEs*

The display environment is quite realistic, but still needs more subtle detail

Driving sounds from some traffic would make it more realistic

Environmental physics were off sometimes

The hills in the background seem to repeat themselves in a 360° loop?

The road markings were greyed out on one situation in the urban roundabout , so couldn't see where I was going

*2. Interface*

The car driving is very realistic

Very awkward controls. Controls unresponsive.

The turning of the vehicle seemed slow, especially during the intersections: The vehicle cannot make a proper 90° turn in those situations.

*3. Task*

Found it very difficult to mediate speed

It was hard to judge my speed

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*Negative effects*

It made me car-sick

Extremely nauseating

Strains eyes

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Table E.3

*Experiment 2: Passive condition: ITC-SOPI: Additional comments*

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*Spatial Presence*

I was aware of the artificiality of the experience, but enjoyed it for that reason:  
particularly the graphics of the buildings  
I was aware of phones ringing and people chatting elsewhere  
Some glitches with the computer program, such as road turning a very light grey  
colour within the roundabouts, would bring me back to the sensation that it is not real,  
and I am simply watching a screen

---

*Engagement*

I liked the detail of the shops, petrol station, car wash, etc  
I liked the richer context, with the old-style houses and FoodWorld and gas station  
The corner-turning was thrilling  
Great fun  
More interaction would have kept interest  
Was quite repetitive, but wasn't that boring  
Very repetitive  
The game was a bit too long

---

*Ecological Validity / Naturalness*

*1. VEs*

The white lines [road markings] stood out, especially when crossing over them.  
The lights on the road verge stood out when coming to a halt

*2. Interface*

Some of the driving was erratic  
The flashing stop sign was distracting  
The blurry graphics was disorientating  
The road with no marking/the supermarket forecourt blending into the road, was alien

---

*Negative effects*

I moved my head counter to the direction the "vehicle" was moving, to combat  
disorientation and nausea  
I sometimes shut my eyes as soon as the orange cones came into view, to stop the  
dizziness: I didn't want to "view" the braking at the cones, as it caused a lurching  
feeling  
I felt like I really had no idea where the start point was: it was very intense and I felt  
frustrated that I couldn't visualise in my mind where to point the arrow

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Table E.4

*Experiment 3: ITC-SOPI: Additional comments*

Factor	Comment
<i>Spatial Presence</i>	Would Pacific Petrol Co. cross the road to modernise? Would FoodWorld build on top of an old petrol station?
<i>Engagement</i>	My focus improved about 2/3 into the session, I was tired before that I enjoyed the experience and would have liked it to continue if there had been more development I got frustrated I didn't enjoy myself because there was not enough interaction: I had no control.
<i>Ecological Validity / Naturalness</i>	<p>1. <i>VEs</i> The scenes were realistic in that they could happen, but not in appearance It lacked continuity, otherwise the graphics were believable It seemed like some important parts of a "film" had been cut out, and overlapping pictures you would have seen in real life were gone The sky doesn't get involved: the sunset should "move"</p> <p>2. <i>The lack of movement/motion</i> I felt that the "speed" of movement was somewhat jerky and stilted Quite long pauses in the movement (staccato) Why does it move frame by frame? Too slow moving, a bit jumpy jolty The lag between movements was frustrating and confusing to begin with, but I soon got used to it Very jerky model Maybe smoother transitions would feel more natural Frustrating, because I had to just wait and couldn't speed up movement</p>
<i>Negative effects</i>	I was unable to really control the direction of my vision within the stimulation, and likewise my speed I felt that in a lot of scenarios I was coming from the same direction, but before the end of the scenarios, I was beginning to struggle with my perceptions It was sometimes hard to get a clear indication of the direction the car was going in, especially on some of the roundabouts After ¾ of it, I started to doubt sense of direction, and had to draw it to satisfy myself that I was right I was quite disoriented on the first few [trials] Took a while to realise which way the turns went, didn't realise there was a roundabout

## Appendix F. Means and Standard Deviations by Presence and Triangle Layout

Table F.1

*Experiment 1: Presence by Angle (averaged across trials, environments, and gender)*

Angle	Pres. Group	Mean (Std. Deviation)			
		Spatial Presence	Engagement	Ecological Validity	Negative Effects
60°	Low	-2.25° (28.03°)	2.68° (26.25°)	4.36° (31.98°)	16.35° (12.97°)
	High	21.77° (21.69°)	25.95° (20.54°)	19.55° (20.86°)	12.73° (30.03°)
90°	Low	9.21° (29.48°)	8.54° (26.11°)	15.21° (32.13°)	24.69° (17.10°)
	High	27.09° (20.73°)	34.97° (14.19°)	24.78° (19.60°)	19.70° (27.67°)
120°	Low	19.37° (29.11°)	16.89° (25.68°)	23.49° (29.36°)	37.36° (25.71°)
	High	32.87° (22.05°)	40.99° (17.04°)	31.37° (22.19°)	24.77° (24.30°)

Table F.2

*Experiment 2: Presence by Angle and Distance (averaged across environments and gender)*

Layout	Pres. Group	Mean (Std. Deviation)			
		Spatial Presence	Engagement	Ecological Validity	Negative Effects
60°/LL	Low	11.57° (39.57°)	16.99° (37.80°)	10.67° (35.30°)	14.63° (28.07°)
	High	21.96° (36.06°)	18.10° (38.07°)	23.17° (39.05°)	25.24° (55.88°)
60°/LS	Low	34.95° (37.86°)	37.08° (39.03°)	31.08° (38.31°)	32.32° (29.03°)
	High	37.62° (38.35°)	35.89° (37.29°)	40.90° (37.47°)	47.45° (54.31°)
60°/SL	Low	-3.20° (35.42°)	-2.11° (37.82°)	-3.63° (39.25°)	-1.65° (26.78°)
	High	0.69° (36.41°)	0.18° (34.14°)	1.22° (33.05°)	0.85° (53.62°)
90°-LL	Low	1.05° (36.01°)	4.94° (37.00°)	0.12° (36.66°)	5.90° (25.15°)
	High	12.57° (31.39°)	10.40° (30.28°)	13.85° (30.11°)	12.33° (50.26°)
90°/LS	Low	11.42° (34.76°)	16.80° (37.40°)	14.01° (37.34)	15.94° (27.25°)
	High	26.67° (33.67°)	23.57° (32.01°)	25.25° (32.03°)	31.41° (48.44°)
90°/SL	Low	-8.21° (31.08°)	-4.15° (28.22°)	-10.90°(29.84°)	-6.93° (24.19°)
	High	-4.04° (30.18°)	-7.48° (32.78°)	-1.65° (30.63°)	-2.89° (43.41°)
120°/LL	Low	-9.52° (34.36°)	-5.70° (33.14°)	-9.35° (35.03°)	-5.85° (24.27°)
	High	1.50° (29.13°)	-0.66° (30.46°)	1.87° (28.15°)	3.87° (46.00°)
120°/LS	Low	-5.24° (32.60°)	-5.09° (33.32°)	-7.42° (34.91°)	-4.39° (25.29°)
	High	-0.18° (28.52°)	0.43° (26.92°)	1.84° (25.43°)	3.11° (40.73°)
120°/SL	Low	-13.60°(36.52°)	-11.55°(34.33°)	-14.37°(34.80°)	-7.37° (26.00°)
	High	-2.49° (29.98°)	-2.88° (31.79°)	-1.35° (30.94°)	-6.78° (47.99°)

Table F.3

*Experiment 3: Presence by Angle and Distance (averaged across environments)*

Lay-out	Group	Mean (Std. Deviation)			
		Spatial Presence	Engagement	Ecological Validity	Negative Effects
60°/LL	Low	39.37° (27.35°)	42.78° (28.73°)	42.68° (32.15°)	35.45° (29.52°)
	High	39.30° (38.71°)	32.49° (34.25°)	34.99° (28.83°)	74.42° (9.94°)
60°/LS	Low	61.96° (29.36°)	64.28° (31.43°)	65.69° (32.38°)	55.71° (32.19°)
	High	59.47° (47.26°)	55.08° (41.92°)	55.36° (38.29°)	110.77°(3.06°)
60°/SL	Low	18.28° (30.03°)	20.48° (29.89°)	21.51° (36.02°)	13.91° (32.32°)
	High	13.48° (38.70°)	9.55° (37.09°)	10.73° (26.68°)	43.18° (18.58°)
90°/LL	Low	27.80° (23.31°)	29.59° (25.06°)	33.29° (27.29)	25.66° (26.25°)
	High	28.69° (33.73°)	25.02° (29.63°)	21.23° (24.14°)	49.68° (15.90°)
90°/LS	Low	42.34° (28.86°)	45.37° (29.85°)	50.09° (29.32°)	35.66° (31.02°)
	High	33.28° (39.17°)	28.13° (34.21°)	25.94° (30.82°)	75.28° (9.89°)
90°/SL	Low	13.63° (23.55°)	17.22° (25.62°)	18.08° (26.51)	8.26° (25.10°)
	High	7.89° (34.25°)	1.28° (26.92°)	3.84° (25.74°)	44.68° (17.89°)
120°/LL	Low	12.22° (26.51°)	15.18° (27.78°)	16.60° (31.13°)	6.75° (27.22°)
	High	7.46° (34.71°)	2.02° (29.86°)	3.21° (24.19°)	47.23° (8.66°)
120°/LS	Low	20.32° (30.71°)	19.58° (29.28°)	26.87° (29.09°)	12.88° (30.76°)
	High	6.63° (34.91°)	9.48° (37.78°)	2.27° (31.34°)	46.21° (33.10°)
120°/SL	Low	5.30° (24.72°)	10.63° (28.33°)	10.00° (31.54°)	1.64° (28.46°)
	High	2.14° (37.75°)	-8.21° (25.98°)	-3.05° (23.31°)	28.68° (18.10°)

## Appendix G. ITC-SOPI: Size of High and Low Groups on Each Factor

Table G.1

*Experiment 1: ITC-SOPI: Size of High and Low Groups on each factor*

Factor	High	Low
	<i>n</i> =	<i>n</i> =
Spatial Presence	14	7
Engagement	10	11
Ecological Validity / Naturalness	13	8
Negative effects	15	6

*N* = 21

Table G.2

*Experiment 2: ITC-SOPI: Size of High and Low Groups on each factor*

Factor	High	Low
	<i>n</i> =	<i>n</i> =
Spatial Presence	46	34
Engagement	40	40
Ecological Validity / Naturalness	44	36
Negative effects	22	58

*N* = 80

Table G.3

*Experiment 3: ITC-SOPI: Size of High and Low Groups on each factor*

Factor	High	Low
	<i>n</i> =	<i>n</i> =
Spatial Presence	9	21
Engagement	10	20
Ecological Validity / Naturalness	13	17
Negative effects	3	27

*N* = 30

## Appendix H. Features of VEs Considered Authentic

Table H.1

*Experiment 1: Features of VEs considered by participants to be authentic*

Feature	%	Freq.
Mountains, hills	19.67	12
Houses	18.03	11
Structures (supermarket, shops, church, petrol station)	14.75	9
The countryside / rural areas	13.11	8
Trees	8.20	5
Road aspects (markings, lights, signs, roundabout)	8.20	5
Colours (e.g., green grass)	8.20	5
General appearance	4.92	3
Vehicles	3.28	2
Others: the sunset	1.64	1
<b>Total</b>	<b>100</b>	<b>61</b>

Table H.2

*Experiment 2: Features of VEs considered by participants to be authentic:  
Active condition*

Feature	%	Freq.
Road aspects (markings, street lights, signs, roundabout)	18.68	17
Mountains, hills	17.58	16
Houses	15.38	14
The countryside / rural areas	13.19	12
Structures (supermarket, church, shops, petrol station)	8.80	8
Buildings (general)	6.59	6
Colours (e.g., green grass)	6.59	6
Driving on left hand side of road	4.40	4
Trees	3.30	3
Vehicles	2.20	2
The landscape / scenery (general)	1.10	1
Others: horizon, lack of other traffic	2.20	2
<b>Total</b>	<b>100</b>	<b>91</b>

Table H.3

*Experiment 2: Features of VEs considered by participants to be authentic:  
Passive condition*

Feature	%	Freq.
The countryside / rural areas	15.75	20
Structures (supermarket, shops, church, petrol station)	15.75	20
Road aspects (markings, street lights, signs, roundabout)	14.96	19
Houses	13.39	17
Mountains, hills	12.60	16
Buildings (general)	7.87	10
Vehicles	5.51	7
Trees	5.51	7
The landscape / scenery (general)	3.94	5
Colours (e.g., green grass)	3.94	5
Others: sky	0.79	1
Total	100	127

Table H.4

*Experiment 3: Features of VEs considered by participants to be authentic*

Feature	%	Freq.
Mountains, hills	16.67	11
The countryside / rural areas	16.67	11
Houses	15.15	10
Structures (supermarket, shops, church, petrol station)	12.12	8
Road aspects (markings, lights, signs, roundabout)	10.61	7
New suburbs	7.58	5
Colours (e.g., green grass)	6.06	4
Vehicles	4.54	3
The horizon	4.54	3
Trees	3.03	2
Others: speedometer and rpm meters, sunset	3.03	2
Total	100	66

## Appendix I. Additional Features Which Would Make VEs More Authentic

Table I.1

*Experiment 1: Additional features to make VEs more authentic*

Feature	%	Freq.
Farm animals / livestock (especially cows/cattle, sheep)	15.85	13
Trees / forest (especially native NZ trees)	14.63	12
People (drivers, pedestrians)	9.76	8
Typical landscape features (e.g., farms, traffic lights, detail in centre of roundabouts)	9.76	8
Vehicles / traffic	7.31	6
Familiar NZ names (of supermarket, shops, petrol station)	6.10	5
Recognisable NZ elements (e.g., fish & chip shop, beach)	6.10	5
Road signs / markings: junction approach / give way signs	6.10	5
Fences, hedges	4.87	4
Details of houses: more windows, mailboxes, not all new, further back from road, more garden / front lawns	4.87	4
Mountains, hills	3.66	3
Movement, activity: of traffic, people, objects, hazards	3.66	3
More variety: environments too similar	2.44	2
Sound / noises	2.44	2
Others (e.g., clouds)	2.44	2
Total	100	82

Table I.2

*Experiment 2: Additional features to make VEs more authentic: Active condition*

Feature	%	Freq.
Farm animals / livestock (especially cows / cattle, sheep)	20.45	18
Familiar NZ names (of supermarket, shops, petrol station)	11.36	10
Road signs / markings: junction approach / give way signs	9.09	8
Trees / forest (especially native NZ trees)	7.95	7
Mountains, hills	7.95	7
Typical landscape features (e.g., farms, traffic lights, detail in centre of roundabouts)	7.95	7
Vehicles / traffic	6.82	6
People (drivers, pedestrians)	6.82	6
Details of houses: more windows, mailboxes, not all new, further back from road, more garden / front lawns	6.82	6
More variety: environments too similar	4.55	4
Fences, hedges	4.55	4
Movement, activity: of other traffic, people, objects, hazards	2.27	2
Fewer foreign-seeming elements (e.g., car makes)	1.14	1
Others: Possibly use video instead of CGI, mid-day city traffic	2.27	2
Total	100	88

Table I.3

*Experiment 2: Additional features to make VEs more authentic: Passive condition*

Feature	%	Freq.
Farm animals / livestock (especially cows / cattle, sheep)	21.51	20
Trees / forest (especially native NZ trees)	11.83	11
Vehicles / traffic	11.83	11
People (drivers, pedestrians)	9.68	9
Details of houses: more windows, mailboxes, not all new, further back from road, more garden/front lawns	9.68	9
More realism (e.g., preserve relative sizes of buildings)	7.53	7
Mountains, hills	5.38	5
Familiar NZ names (of supermarket, shops, petrol station)	5.38	5
More variety: environments too similar	4.30	4
Road signs / markings: junction approach / give way signs	3.23	3
Movement, activity: of other traffic, people, objects, hazards	3.23	3
Typical landscape features (e.g., farms, river, detail in centre of roundabouts)	2.15	2
Fewer foreign-seeming elements (e.g., car makes)	2.15	2
Others: Sound / noises, weather	2.15	2
Total	100	93

Table I.4

*Experiment 3: Additional features to make VEs more authentic*

Feature	%	Freq.
Typical landscape features (e.g., farms, river, detail in centre of roundabouts)	10.61	7
Farm animals (esp. cows / cattle, sheep)	9.09	6
Trees / forest (especially native NZ trees)	9.09	6
Road signs / markings: junction approach / give way signs	9.09	6
Details of houses: more windows, mailboxes, not all new, further back from road, more garden / front lawns	9.09	6
Fences, hedges	7.58	5
Familiar NZ names (of supermarket, shops, petrol station)	6.06	4
People (drivers, pedestrians)	6.06	4
Vehicles / traffic	6.06	4
Mountains, hills	6.06	4
More variety: environments too similar	6.06	4
Recognisable NZ elements (e.g., signs of Maori culture: marae)	3.03	2
Less perfection (e.g., houses, object textures too perfect): imperfections seem more real	3.03	2
Movement / activity: other traffic, people, objects, hazards	3.03	2
Sound / noises	3.03	2
Others: Make road shoulder wider; clouds	3.03	2
Total	100	66

