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**The Influence of Analogy Instructions on Motor Skills:  
Processing, Preference and Performance**

A thesis  
submitted in fulfilment  
of the requirements for the degree  
of

**Doctor of Philosophy in Health, Sport and Human Performance**

at  
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by  
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THE UNIVERSITY OF  
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## Abstract

When teaching a movement to novices, communicating knowledge about the movement by comparison with a similar, well-known concept (an analogy) may be effective, as no other verbal instructions or rules need to be provided. The aim of this PhD thesis was to investigate the potential underlying mechanisms that influence motor performance after analogy instruction. This may help guide the development of appropriate and useful analogies in clinical and other practical settings. Five chapters discuss experiments conducted in early learning of complex motor skills. In order to investigate the mechanism of analogy learning in children, Chapter 2 investigated children's acquisition of a golf-chipping task. We asked whether an analogy presented after initial, explicit practice has an influence on performance, and whether this effect is moderated by the propensity to consciously control the mechanics of one's movements (movement specific reinvestment). Movement-specific reinvestment predicted improvement in chipping accuracy after introduction of the analogy, indicating that children's motor learning by analogy may depend on personal characteristics associated with conscious control.

A reliable and objective measure to deduct underlying conscious processes during movement is electroencephalography (EEG). Chapter 3 explored the relationship between working memory (WM) capacity, cortico-cortical communication (EEG high-alpha power and coherence), and propensity for conscious control of movement (movement specific reinvestment) during novice performance of a complex motor task. Results revealed that the capacity for short-term storage and processing of visuo-spatial information is an important factor in early motor control.

Analogies allegedly reduce reliance on verbal information processes during motor planning, which is a feature of psychomotor efficiency. In Chapter 4, we investigated whether analogy instructions promote higher psychomotor efficiency, characterised by greater high-alpha power in the left hemisphere of the brain and reduced coactivation between the verbal processing (T7) and motor planning regions of the brain (Fz) during motor performance. Hockey push-pass accuracy during a combined task (passing coupled with decision-making) was significantly better following practice using an analogy instruction compared to explicit instructions, and left-temporal EEG high-alpha power was significantly higher in the analogy condition. The analogy instruction may have influenced

verbal aspects of information processing without impacting on efficiency of motor planning, and may thus promote cognitive, rather than psychomotor, efficiency.

Individual characteristics of information processing may have an influence on how analogy instructions are interpreted and used. Chapters 5 and 6 investigated the associations between analogy learning and verbal or visuomotor processing as measured by EEG coherence, visual-verbal instruction preference, and performance. While Chapter 5 tentatively suggests that analogy learning may be of greater benefit to people who tend to rely on visual processes during motor planning, Chapter 6 suggests that changes in information processing (measured by EEG high-alpha power) and in performance after analogy instruction, depended on verbal preference. The findings are discussed with respect to the implicit motor learning framework and theories of movement automaticity. The thesis is rounded off by suggesting future studies and providing some guidelines for the use of analogy instructions in different groups of learners.

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# Thesis Outline

## Chapter organization

Chapter 1 summarises the state of the art in analogy motor learning and gives an overview of concepts related to information processing in motor learning, such as movement specific reinvestment, working memory, structure mapping. The use of electroencephalography in motor skill acquisition, specifically in implicit motor learning, is also reviewed. Chapters 2 to 6 present experiments that have been conducted to investigate the mechanisms underlying early motor performance and analogy motor learning. The final chapter (Chapter 7) summarises the key findings and discusses implications for future research.

## Outline of experimental chapters

The aim of this PhD thesis was to investigate the potential underlying mechanisms that lead to benefits in motor performance after analogy instruction. Experiments included measures of working memory capacity (the maximum amount of information that a person can store and process at the same time), of movement specific reinvestment (a person's propensity to consciously control their movements), instruction preference, electroencephalographic measures indicating activation of verbal, visual and motor processing regions of the brain, as well as performance outcomes at different far-aiming tasks.

A first study (Chapter 2) investigated the mechanism of analogy learning in an exploratory way by testing children's acquisition of a golf chipping task. Performance was measured in a pretest, after practice using explicit instructions, and after the introduction of an analogy instruction. Children who showed a low score on the Movement Specific Reinvestment Scale generally benefited from the analogy, whereas children with a high score deteriorated. Learning a movement by analogy may be related to personal characteristics of information processing associated with conscious control of movements. This study also showed that children may not be ideal participants when investigating general cognitive processes during learning of motor skills.

To date, studies investigating analogy instructions in motor learning have used subjective measures, such as questionnaires or dual task paradigms to gain insight into

underlying conscious processes during the learning process or performance. However, a more reliable and objective measure is electroencephalography (EEG), which allows the assessment of brain activity. The remaining experiments include measurements of EEG power and coherence in verbal (T7), visual (T8) and motor planning areas (Fz) of the brain to get better insight into underlying processes. Based on finding in the first study that reinvestment was related to performance improvement after analogy instruction, Chapter 3 investigated how movement specific reinvestment, working memory capacity and brain activity (EEG power and coherence) interacted to predict performance in uninstructed, early performance of a hockey push-pass. The results indicated that capacity for short-term storage and processing of visuo-spatial information may be of central importance in early motor control.

After confirming the importance of conscious processing ability during motor performance, it was of interest to determine the effect of the same variables when different instructions were used during motor learning. Based on previous findings that implicit motor learning leads to increased psychomotor efficiency, Chapter 4 investigated whether analogy instructions promoted higher psychomotor efficiency in a similar way. Psychomotor efficiency is characterised in the brain by greater high-alpha power in the left hemisphere and reduced coactivation between the verbal processing (T7) and motor planning regions (Fz) during motor performance. Results of the experiment in Chapter 4 indicated that an analogy instruction influenced verbal aspects of information processing without impacting on efficiency of motor planning, suggesting that an analogy instruction may promote efficiency of cognitive processes.

Based on results in the previous studies, preferences or individual characteristics of information processing may have an influence on how analogy instructions are taken up and used. Finding out which characteristics identify people who do or do not benefit from analogy instructions may help determine the underlying mechanism of analogy motor learning. In Chapter 5, data from the previous study were re-analysed in order to investigate whether EEG coherence during baseline performance of a motor task predicted change in performance when an analogy or explicit instructions were used. The results suggested that analogy learning may be of greater benefit to people who tend to rely on visual processes during motor planning. This finding gives some support to a visual processing explanation of analogy motor learning.

However, EEG coherence has not been linked to stable trait preferences in many studies. If information processing moderates the benefit of analogy instructions, then preference for processing and using verbal as opposed to visual instructions may be a better measure. The experiment described in Chapter 6 was designed to investigate whether preference for verbal instructions was related to changes in performance and information processing (EEG high-alpha power and coherence) after instruction by analogy. Results were in line with Chapter 3, suggesting that analogy reduces verbal processing demands. It is likely that motor adaptation in response to analogy instruction depends on personal aspects of information processing; however, the results stand at odds with Chapter 5 - if analogies are simply visual instructions, visualisers should benefit more than verbalisers, but the results of Chapter 5 showed that people with high verbal preference benefited from analogy. This last study supports a chunking explanation of analogy motor learning.





## **Publication status of the work generated by this thesis**

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**van Duijn, T.**, Masters, R. S. W. (in preparation). Chipping in on the role of reinvestment in children's motor learning by analogy.

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# Chapter 1

## General Introduction

*"We are like dwarfs standing upon the shoulders of giants, and so able to see more and see farther than the ancients."*

Bernard of Chartres, ca. 1130.

### Analogy in concept learning<sup>1</sup>

#### Introduction

As Bernard of Chartres said, we can see further than our predecessors (the giants upon whose shoulders we sit), not because we have sharper vision, but because we are carried up to a higher level of understanding by basing our work on theirs (Troyan, 2004). Most of our understanding is based on existing knowledge. This is also true within the individual: when we learn about a new concept, we often draw parallels with other, already familiar, concepts, which facilitates our understanding. This process is often referred to as learning by analogy.

Learning by analogy is the cognitive process of "[...] understanding a novel situation in terms of one that is already familiar" (Gentner & Holyoak, 1997, p. 1). For example, the hydrogen atom can be compared with the solar system to aid understanding and learning of the elements within the atom and their relationships among each other.<sup>2</sup> Similarly, a learner who knows what a cookie jar is can easily make a correct free-throw in basketball if instructed to "move as if they are putting cookies into a cookie jar on a high shelf". Analogy motor learning involves learning a motor skill using one analogical instruction about how to move. Movement analogies hold information about the to-be-learned concept (the movement) in reference to a well-known concept (Koedijker et al., 2011; Liao & Masters, 2001; Masters, 2000). Motor learning research has demonstrated that

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<sup>1</sup> This is an attempt to review the portion of the analogy learning literature relevant to this thesis. It does by no means cover the complete literature on the subject.

<sup>2</sup> Rutherford proposed a scientific model of the hydrogen atom that was in essence an analogy comparison with the solar system (Tilton, 1996).

analogies provide a powerful tool for instructing motor skills effectively and efficiently (Masters & Poolton, 2012). Analogy learning was first described and investigated in terms of learning concepts in physics, chemistry, biology and mathematical problems (Gentner, 1983). In the following sub-section, early research on analogy learning of concepts is summarised, after which a review of research in the motor learning field follows.

### **Definition and etymology**

The word analogy stems from Latin *analogia*, based on the ancient Greek word αναλογία, which meant proportionality and indicated an identity of relations between any two pairs (*ana* "upon, according to" + *logos* "ratio, word, speech, reckoning"). Aristoteles proposed that analogies were four-part structures that may be represented by the form "A:B::C:D" or "A is to B as C is to D". This Aristotelean proportion framework was a rigid and narrow definition of analogy (e.g., see review by Sternberg, 1977)<sup>3</sup>. The modern meaning of "partial agreement, likeness or proportion between things" has only been attributed to the term in the late middle ages, where analogical reasoning was widely used in Christian theology (e.g., Cajetan, 2009). The first use of analogy to convey a scientific concept was the likening of sound propagation to the propagation of waves in water by Vitruvius in the first century BC (Vitruvius, 1960). For reviews on the history of analogy, see Holyoak, Gentner, and Kokinov (2001) or Shelley (2003).

In cognitive psychology, analogy has been described as "a comparison in which relational predicates, but few or no object attributes, can be mapped from base to target" (Gentner, 1983, p. 159). Analogy is a key concept in the psychology of problem-solving and knowledge-based learning. It has even been argued that analogy is the core of cognition (Hofstadter, 2001). Analogy is a similarity term, it refers to a similarity between two things. It is important to differentiate the term from other similarity terms or domain comparisons (Gentner & Clement, 1988, p. 315, see also Bowdle & Gentner, 2005 and Gentner & Grudin, 1985 – see Figure 1):

- Literal similarity: A comparison where two things are exactly mapped onto each other, e.g., "the X12 star system in the Andromeda galaxy is like our solar system" (Gentner, 1983, p.159).

---

<sup>3</sup> It would later lead to SAT "analogy questions" such as "Hand is to palm as foot is to \_\_\_\_?" etc.

- Abstraction: a comparison where the base domain is an abstract relational structure. All predicates from the abstract base domain are mapped into the target domain, there are no non-mapped predicates (e.g., the hydrogen atom is a central force system).
- Metaphor: The term metaphor is often applied loosely, it can convey surface similarity, structural similarity, or both
  - Relational metaphors: metaphors that convey common relational structure (e.g., “standing on the shoulders of giants”). Relational metaphors are factually analogies, as both are non-literal similarity comparisons.
  - Attributional metaphors: mere-appearance matches that focus on common object attributes, or surface similarities (e.g., "Her arms were like twin swans").

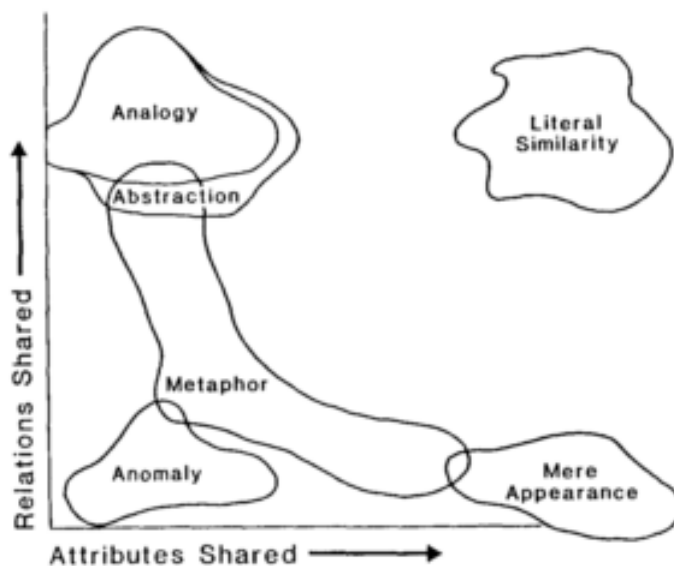


Figure 1. Similarity terms and their shared attributes and relations.

Reprinted with permission from Gentner & Clement (1988), p.314.

### Use of analogies in reasoning, problem solving and concept learning

Analogies are wide spread in everyday experience, taking the form of simple analogical comparisons (“Life is like a box of chocolates: you never know what you are going to get” – *Forrest Gump’s* mother) and witticisms (“A good speech should be like a woman's skirt: long enough to cover the subject and short enough to create interest” - Winston Churchill) or complex scientific concepts (e.g., the heart works like a pump, the hydrogen atom is like our solar system, electricity flows as water does). Analogies even take the form of

expressive comparisons (“the white mares of the moon rush along the sky - beating their golden hoofs upon the glass heavens” - Amy Lowell, *Night Clouds*). Whenever phrases, such as, ‘and so on’, ‘and the like’, ‘as if’, or the word ‘like’ are used, an analogical comparison in the wider sense is made (Oppenheimer, 1956). Likeness between different situations has been used as a literary form since the first preserved literary works, including the Babylonian epic of Gilgamesh (written about 4000 years ago, Ferry, 1993). Especially in poetry, analogy was often used to communicate emotions (Thagard & Shelley, 2001). Greek philosophers in the third and fourth century BC, including Plato and Socrates, saw that analogous objects cannot only communicate a relation, but also an idea, a pattern, a regularity, an attribute, an effect or a philosophy. The philosophers used analogy in their essays to impart understanding and knowledge. For example, Plato used multiple analogies in his scriptures. He made use of an analogy between a ‘just soul’ and a ‘just city’ in order to elaborate and visualise what justice means for the soul. He assumed that by looking at a larger-scale example, he would gain insight into the smaller, less decipherable one (Williams, 1997).

*“So the just man in his turn, simply in terms of his justice, will be no different from a just city. He will be like the just city.” - (Plato, 2000, 435B)*

Analogy as a teaching method plays a significant role in education as it is used for communication and explanation of new materials as well as for conceptualization. The use of analogies has beneficial effects on recall, understanding and also recognition of knowledge, which is why it lends itself to teaching environments (Glynn & Takahashi, 1998). Analogies have been shown to be superior to instruction by extensive explanatory text or instruction, as cueing a learner to prior (existing) knowledge has a positive effect on memory of newly learned information (Schustack & Anderson, 1979), and may even provide the opportunity for learning superior, general schemas that encompass both concepts (Gentner & Holyoak, 1997). Research in teaching subjects such as language and grammar learning (Falkenhainer, 1988; Gentner, Anggoro, & Klibanoff, 2011; Goswami, 1986, 1988; Nagao, 1984) as well as memory and retelling of stories (Gentner & Landers, 1985; Gentner & Toupin, 1986; Markman & Gentner, 1993; McDaniel & Donnelly, 1996; Schustack & Anderson, 1979; Vosniadou & Schommer, 1989; White, 2005) showed that analogies affect memory and learning, inference and argumentation in children as well as in adults. Teachers may also use analogies to explain scientific concepts. For example, Ernest Rutherford used the analogy of our solar system to explain the hydrogen atom in the now well-known Rutherford Model (Tilton, 1996). Research has been conducted to

apply analogies systematically in the teaching of science (Donnelly & McDaniel, 1993; Klein, Piacente-Cimini, & Williams, 2007; Shapiro, 1985; Taber, 2001), electricity (Duit, 1991; Gentner & Gentner, 1983; Heywood & Parker, 1997; Paatz, Ryder, Schwedes, & Scott, 2004; Shipstone, 1984), physics (Glynn & Takahashi, 1998; Podolefsky & Finkelstein, 2006; VanLehn, 1998), chemistry (Orgill & Bodner, 2004; Orvis et al., 2016; Supasorn & Promarak, 2015) and mathematics (Alvarez et al., 2017; Ngu & Yeung, 2012; Richland & McDonough, 2010; Richland, Zur, & Holyoak, 2007; Ross & Kennedy, 1990; Ruchikachorn & Mueller, 2015; Schoenfeld, 1992). Analogies have been shown to be useful for children of almost any age from 3 years and upwards (Gentner et al., 2016; Gentner & Toupin, 1986; Glynn & Takahashi, 1998; Goswami, 1986, 1988; Rattermann & Gentner, 1998; see Gentner & Hoyos, 2017, for a recent overview on children's and adults' learning by analogy).

Furthermore, analogy is of central importance in problem solving and decision-making (e.g., Carbonell, 1986). Analogous problems with a known solution are often used as a model for unsolved problems (Gick & Holyoak, 1980, 1983; Hayes & Broadbent, 1988; Reed, 1987). If a partial mapping between two concepts is found, this mapping can then be extended by retrieving additional information, which generates new knowledge about the unsolved problem (Gick & Holyoak, 1980, 1983). In reasoning and argumentation, analogies are often used as references and illustrations (DeRaedt & Bruynooghe, 1992; Goldschmidt, 2001; Kolodner, 1997; Sternberg, 1977; see Holyoak, 2012, for an overview on the use of analogy in reasoning).

Analogies are also pervasive in other cognitive processes, such as invention and creativity, emotion, humour and empathy (Thagard & Shelley, 2001), translation (Hofstadter, 2001; Nagao, 1984), scientific reasoning, political debate, economics and advertising (El Houssi, Morel, & Hultink, 2005; Gregan-Paxton & John, 1997; Jehiel, 2005), and organization theory (Ketokivi, Mantere, & Cornelissen, 2017).

### **The structure mapping model of analogy learning**

Gentner (1983) proposed a *structure mapping model* of analogy learning to explain how analogies may be used to gain knowledge about a complex concept. The model is now widely applied by contemporary cognitive scientists and although it has been adapted and extended it is still used in current research. The model is based on the notion of analogy in the wide sense (similar to Plato and Aristotle), as a comparison of shared abstractions



(Shelley, 2003). According to the model, an analogy instruction refers the learner to a concept that they are familiar with. This concept represents the knowledge base or *base concept*, providing information about a *target concept* by mapping the relationships between structures of the concepts. In the example of the hydrogen atom mentioned above, the learner infers that, just like the sun, the nucleus is larger than the electron, that it attracts the electron, and that this causes the electron to revolve around the nucleus. The stages of analogical learning have been described as follows (Gentner, 1987; Gentner & Clement, 1988; Gentner & Landers, 1985):

- 1) Accessing the base concept; finding the relevant concept stored in long-term memory
- 2) Performing the mapping between a familiar base and novel target concept to identify systematic correspondences between the two and aligning the corresponding parts
- 3) Making and storing inferences about the target concept; creating new knowledge
- 4) Judging the soundness of the match, evaluating and adapting inferences
- 5) Extracting the commonalities, generating new schemas, updating old schemas, addition of new instances to memory

The term “analogical” refers to a similarity between relationships of components within the concepts (e.g., the propagation of sound through the air is analogically similar to the propagation of waves at sea), rather than between surface features of the concepts (e.g., sound does not look like water; Gentner, 1983; Holyoak et al., 2001; Oppenheimer, 1956). Gentner (1983) observed that people implicitly prefer mapping functional or causal relations when interpreting an analogy, a phenomenon which she called the *systematicity principle*. People would automatically interpret the Rutherford analogy by mapping structural relations based on structural similarity (e.g., “heavier than” or “revolves around”), rather than surface similarity (e.g., the sun is hot, large, yellow; the atom is small). Moreover, the greatest benefit regarding understanding of the target concept is achieved by mapping of higher-order relations – relations between relations. Core assumptions of structure mapping are therefore systematicity (i.e., that matches of structural similarities are preferred over attributional similarities) and that representations of concepts are hierarchically organised (i.e., that higher order relations govern lower-order relations).

The model has been applied in education (e.g., science text, Glynn & Takahashi, 1998), marketing research and consumer learning (Gregan-Paxton & John, 1997), as well as design learning (Goldschmidt, 2001). There is a widespread agreement among researchers about accessing, mapping (i.e., drawing parallels between underlying structures), and inference as the basics of analogical learning (Carbonell, 1986; Hofstadter, 1984; Sternberg, 1977; Winston, 1980). However, the criteria that humans use to select the items to be mapped are not agreed upon. Structure mapping is not the only selection criterion that has been proposed to select what is to be mapped. For example, Winston's (1980) importance-guided matching algorithm, which is a variation of the structure mapping model, suggests that the criteria to select predicates for matching may be based on importance. Hofstadter's (1984) model includes systematicity as the main influence on mapping. A different account opposing the structure mapping model is the pragmatic account proposed by Holyoak (1985). According to this theory, goal attainment is the only criterion for mapping two identities between problems. Holyoak (1985) argued that higher-order relations that are mapped are always causal elements, which are pragmatically important to goal attainment. This model was developed with analogical reasoning in mind and is not applicable to any other forms of analogical mapping (e.g., scientific discovery by analogy, Vosniadou & Ortony, 1989).

Experimental studies have been conducted to investigate the underlying principles of the *structure mapping model* (i.e., systematicity and preference of higher-order over lower-order alignments). For example, Gentner and Clement (1988) conducted a study to investigate whether people indeed fulfil the basic assumptions of structure mapping by including relations and omitting object descriptions when interpreting an analogical comparison. In their study, participants wrote out interpretations of analogical comparisons such as "a cigarette is like a time bomb". These were rated by naïve judges. Results showed that people have a strong focus on relational information, supporting the *systematicity principle* within the model. Gentner, Rattermann, and Forbus (1993) found that subjective soundness of an analogical match depended on the degree of shared relational structure, particularly higher-order structure, such as causal bindings. Memory retrieval, in contrast, was shown to be highly sensitive to surface similarities, such as common object attributes. However, some research pointed out contrasting findings related to the systematicity principle. Structural similarity was not always the learner's preferred mapping criterion. Gentner and Landers (1985), for example, found that people often failed to see higher-order structures - when spontaneously matching past concepts

from memory, participants remembered spurious, superficial similarities better, and Ross (1989) found that both structural and superficial similarities affect how an analogy is accessed and used. Additionally, Gentner and Toupin (1986) found that four to six year old children were likely to use surface similarity rather than structural relations; however, eight to ten year old children were able to map depending on structural similarities when the analogies were transparent enough. Gentner and Toupin (1986) suggested that a relational shift occurs during children's development, from an initial reliance on only surface similarity to the use of relational structure when mapping from analogies. Studies repeatedly have found that literal similarity is helpful in pointing a person to the correct analogical (structural) mappings (Reed, 1987; Ross, 1989). Spiro (1988) pointed out that analogy often leads to misconceptions by reducing the newly learned knowledge to features that the target concept shares with its source concept. Further research showed that the learner has to know which concepts to apply to the target and which to ignore (Gentner & Holyoak, 1997), which sometimes necessitates guidance from a teacher (Gentner et al., 2011; McDaniel & Donnelly, 1996). The lack of guidelines for the use of analogies, causes both teachers and researchers often to use analogies unsystematically, which leads to confusion rather than deeper understanding (Glynn & Takahashi, 1998; Thiele & Treagust, 1991). If and when an analogy breaks down (i.e., the source can only partly be mapped to the target concept), the use of analogy may have a negative effect on learning (Halasz & Moran, 1982; Taber, 2001). Some authors, however, argue that confrontation with an incomplete match may lead to deeper processing and thus to better learning (e.g., Heywood & Parker, 1997). Even if analogical mapping is unsuccessful, a learning benefit may arise from increased analysis of the problem and generation of hypotheses (Duit, 1991; Duit, Roth, Komorek, & Wilbers, 2001).

After almost six decades of research in cognitive psychology, a few practical implications and guidelines for the successful use of analogies can be summarised. First, successful learning by analogy depends on knowledge about the base concept. The more familiar a learner is with the base concept and the more experience they have in using it (e.g., in arguments and reasoning), the more parallels can be drawn between the base and target concepts, resulting in greater knowledge gain and better understanding of the target concept (Duit, 1991; Ngu & Yeung, 2012; Paatz et al., 2004; Taber, 2001). Second, the context has to be clear before the new concept or analogy is presented (Bransford & Johnson, 1972). Third, visual analogies are recalled (memorised) better than verbal analogies and presenting the source concept visually has been shown to be beneficial to

physics problem solving tasks (Podolefsky & Finkelstein, 2006). Better learning performance was documented when the base domain was visible during instruction of the target, when it was included actively by the teacher using visuo-spatial cues and gestures, and when mental imagery and visualization were encouraged (Mayer & Gallini, 1990; Orgill & Bodner, 2004).

Gentner's (1983) *structure mapping model* has found considerable support in computer science, artificial intelligence and machine learning over the last three decades (DeRaedt & Bruynooghe, 1992; Falkenhainer, 1987; Gentner & Landers, 1985; Gregan-Paxton & John, 1997; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997; Winston, 1980). Machines cannot easily simulate the chaotic and implicit cognitive processes ("common sense") that govern inference and learning in humans (Andrade, Bai, Rajendran, & Watanabe, 2016). To capture how humans learn by analogy, how they retrieve concepts and compare knowledge from different representations, a number of computational models have been created. Computer simulations of analogical inference and mapping have been founded on algorithms for constraints satisfaction, including the Structure Mapping Engine (SME; Falkenhainer, Forbus, & Gentner, 1989), Analogical Constraint Mapping Engine (ACME; Holyoak & Thagard, 1989), or Learning and Inference with Schemas and Analogies (LISA; Hummel & Holyoak, 1997). Different models and networks exist to teach machines to learn by analogy (e.g., Andrade et al., 2016; Chan, Hope, Shahaf, & Kittur, 2016; Falkenhainer & Forbus, 1968; Tomlinson & Love, 2006). For a review of computational models, see Gentner and Forbus (2011).

## **Analogy instructions in learning of movement skills**

### **Principles for the use of analogies in teaching movements**

Analogies have also been used to teach movements by, for example, sports teachers, coaches and physiotherapists. In contrast to classic, verbal forms of instruction involving several verbally transmitted rules, the knowledge transfer from well-known concepts to a novel motor skill may have benefits for motor performance. Masters (2000) suggested the systematic use of one single analogy instruction in place of explicit rules as a means of teaching a movement implicitly. In this way, the concept may be imparted with minimal load on information processing resources. It has also been suggested that analogy should be packaged into a visually salient image, or "motor metaphor", that is easy to visualise and apply directly with minimal processing effort (Liao & Masters, 2001). Similar to

concept learning, selection of the base concept that should be used to impart knowledge about the movement has to be done with care. The analogy instruction has to convey all important characteristics of the movement to be learned (Masters & Liao, 2003), it has to be familiar to the learner (Ngu & Yeung, 2012; Taber, 2001) and it has to fit within the cultural context of the learner (Poolton, Masters, & Maxwell, 2007b).

Liao and Masters (2001) provided empirical evidence that analogy learning leads to benefits to performance compared to explicit instruction. In their experiment, table tennis novices were instructed that they should “strike the ball while bringing the bat up the hypotenuse of [a] triangle” (Liao & Masters, 2001, p. 310) in order to learn a topspin forehand. No other information was provided about how the task was to be achieved. Usually, performance at a task deteriorates when a concurrent cognitive task (e.g., tone counting) is performed or when the learner is put in a situation where the psychological pressure is raised. However, performance of participants instructed by analogy was robust in both a dual task situation and under psychological stress, compared to an explicitly instructed group.

Since then, a variety of experiments have presented evidence that supports analogy instructions as a means of teaching movements. All of the studies showed that analogy instructions gave rise to a learning curve similar to the learning curve that occurs in response to classic explicit rules, and that performance after practice was comparable, which suggests that analogy instructions are just as effective as explicit instructions when teaching a movement (e.g., Bobrownicki, Macpherson, Coleman, Collins, & Sproule, 2015; Lam, Maxwell, & Masters, 2009a, 2009b; Law, Masters, Bray, Bardswell, & Eves, 2003; Liao & Masters, 2001; Poolton, Masters, & Maxwell, 2006; Poolton et al., 2007b). Recent research also confirmed benefits of analogy instructions for performance under dual task loading (Bobrownicki et al., 2015; Jie et al., 2016; Lam et al., 2009b; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, Wong, & Masters, 2016; Tse, Wong, & Masters, 2017), under pressure (Lam et al., 2009a; Law et al., 2003; Liao & Masters, 2001; Vine, Moore, Cooke, Ring, & Wilson, 2013) or when decisions have to be made concurrently (Masters, Poolton, Maxwell, & Raab, 2008; Poolton et al., 2006; Schlapkohl, Hohmann, & Raab, 2012). What is more, quality of the movement output has been described as more implicit and natural when participants are taught by analogy compared to explicit instructions (e.g., a more natural speech pattern - Tse, Wong, Ma, Whitehill, & Masters, 2013 or kinematics representing more implicit movement control - Lam et al., 2009b). An

overview of research on analogy instruction in motor learning is provided later in this chapter.

### **Implicit motor learning**

Analogy learning has been termed a means of implicit motor learning (Liao & Masters, 2001). Reber (1989) defined implicit learning as the “process by which knowledge about the rule governed complexities of the stimulus environment is acquired independently of conscious attempts to do so” (p. 220).

In the process of learning a motor skill, usually a mixture of implicit and explicit knowledge is acquired. Explicit knowledge is described as declarative, verbalisable information such as facts or rules, whereas implicit knowledge is present in a subconscious form that is not verbalisable (Masters, 1992). A learning model proposed by Fitts and Posner (1967) describes three successive stages in motor learning: a cognitive phase involves the build-up of explicit knowledge, which leads to slow and rule-bound, declarative learning. An associative phase involves consolidating and stabilizing this knowledge. A third, autonomous, phase sees the movement automation completed with abstract and unconscious knowledge and fast, fluent movement execution (Fitts & Posner, 1967). This last stage involves procedural learning without contribution from consciousness. The gradual reduction of verbal processes that occurs during progression through motor learning stages coincides with an increase in procedural, “unconscious”, knowledge about how to perform the movement, and more fluent motor execution. In declarative stages, explicit instructions and feedback may be functional and lead to faster learning. However, a number of studies show a negative influence of giving feedback or rule instructions to the performer (Baumeister, 1984; Hardy, Mullen, & Jones, 1996; Hodges & Lee, 1999; Schücker, Hagemann, & Strauss, 2013; Wulf & Weigelt, 1997) as well as verbalizations of the movement by the performer (Chauvel, Maquestiaux, Ruthruff, Didierjean, & Hartley, 2013; Flegal & Anderson, 2008; Lane & Schooler, 2004).

Rather than a strict progression from declarative to procedural stages of learning, a parallel processing model of Maxwell, Masters, and Eves (2003) suggested that procedural (implicit) and declarative (explicit) knowledge can be acquired separately (Masters, 1992; Maxwell, Masters, & Eves, 2000; Maxwell et al., 2003). The authors suggested that similar to learning of artificial grammars (Reber, 1992), it is possible to learn a motor skill implicitly, acquiring almost no explicit knowledge about the skill. Implicit learning

generally depends less on conscious processes, as shown in studies where amnesic participants were unable to learn and remember words explicitly, but when primed with word fragments, responded with the previously learned words that they could not explicitly remember (Warrington & Weiskrantz, 1968, 1974). Reber (1989, 1993) suggested that although explicit processes may be affected by some forms of neurological damage, implicit processes may remain intact in some cases. Implicit processes are also thought to be relatively independent of age or intelligence (Maybery, Taylor, & O'Brien-Malone, 1995; Reber, 1992).

The use of implicit learning methods in motor learning has been suggested in order to reduce or prevent declarative, explicit processes in early stages of motor skill acquisition (Hardy et al., 1996; Masters, 1992). Experiments on learning of serial reaction time tasks involving key presses (Nissen & Bullemer, 1987) or movement tracking (Green & Flowers, 1991; Pew, 1974) provide the basis for implicit motor learning. Performance after practice in which a segment of a seemingly random movement pattern was repeated during practice without the participants' knowledge resulted in participants learning the recurring sequence of motor responses; however, learners were often unable to explicitly recall the sequence.

In order to ensure that the learning process is implicit, it does not suffice to only refrain from providing task specific information to the learner. If no information about the execution of a movement is available, a learner might discover how best to achieve the goal by testing hypotheses (Berry & Broadbent, 1984; Hodges & Lee, 1999). They may thus build a large pool of declarative knowledge. Also termed discovery learning, the no-instruction method is an efficient strategy to induce explicit, rather than implicit forms of learning.<sup>4</sup> Research on learning of complex motor skills has used different methods to facilitate implicit learning and to avoid the build-up of explicit rules. Masters (1992) suggested the use of a cognitively demanding secondary task (random letter generation, see Baddeley, 1966) that was performed simultaneously during practice. The aim of this approach was to prevent the learner from testing hypotheses about how best to execute the movement, which was expected to lead to an implicit mode of learning. Results of his study, in which participants learned a golf putt in this manner showed that implicit

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<sup>4</sup> Learning of a coordination task (bimanual coordination task) was improved by this method compared to explicit, rule-based learning and was found to lead to stable performance when a secondary task was performed concurrently, while verbalisable knowledge of the task reported by the uninstructed group was comparable to that of an explicitly instructed group (Hodges & Lee, 1999).

learners acquired fewer declarative rules compared to explicit learners, and that their performance was less likely to break down under pressure (Masters, 1992). These findings have been replicated and extended by Hardy and colleagues (Hardy et al., 1996; Mullen, Hardy, & Oldham, 2007). There are, however, drawbacks to this method (Beek, 2000; MacMahon & Masters, 2002; Maxwell et al., 2003). Secondary task loading leads to a decrement in performance compared to an explicitly instructed group, which makes it hard to compare two experimental groups. Additionally, it is difficult to apply a dual task setting in a natural sports environment (Beek, 2000). Alternatively, a reduced feedback paradigm (Maxwell et al., 2003), subliminal feedback (feedback at an unconscious level; Masters, Maxwell, & Eves, 2009) and errorless learning methods (MacMahon & Masters, 2002; Maxwell et al., 2000) have been developed. The reduced feedback paradigm withholds visual or acoustic outcome feedback from the performer. If no such feedback is available to the performer, the testing of hypotheses is suppressed. The learner cannot distinguish success from failure and has to learn in an implicit way (Maxwell et al., 2003). Subliminal feedback learning involves giving feedback at an unconscious level; for example, by the use of a tachistoscope (Masters, Maxwell, et al., 2009). This method provides feedback to the learner without conscious perception of the feedback, which reduces explicit association processes and conscious error correction. In errorless learning, sensory feedback is provided but the situation is manipulated to avoid or minimise errors. According to Maxwell et al. (2000), hypotheses are tested if the learner is aware of making mistakes; it gives an incentive and direction to improve performance. In an errorless learning study (Maxwell, Masters, Kerr, & Weedon, 2001), this effect was tested on novice learners in golf putting. The errorless condition was achieved by increasing the putting distance only gradually, while an errorful group trained on a fixed distance from the beginning (Maxwell et al., 2001; Poolton, Masters, & Maxwell, 2005). This indicates that verbal, declarative processes were indeed reduced by the method. A different approach that works in a similar fashion is provided by physical guidance methods. A range of experiments have shown a beneficial effect of physically guiding a movement during learning, such as when learning a pursuit tracking task (MacRae & Holding, 1966) or a slalom-type movement on a ski simulator (Wulf, Shea, & Whitacre, 1998), which technically reduces the need for conscious, verbal control and error correction while the “muscle memory” (i.e., implicit knowledge base) is built up. Verbal processes have been shown to play a much smaller role in implicit motor learning (Masters, van der Kamp, & Capio, 2009). Benefits of implicit modes of learning have been



found for performance under pressure (Hardy et al., 1996; Koedijker, Oudejans, & Beek, 2007; Lam et al., 2009a, 2009b; Liao & Masters, 2001; Masters, 1992), fatigue (Masters, Poolton, & Maxwell, 2008; Poolton, Masters, & Maxwell, 2007a) as well as when decisions have to be made concurrently (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006) in various sports such as basketball (Lam et al., 2009a, 2009b), table tennis (Koedijker, Oudejans, & Beek, 2008; Liao & Masters, 2001; Poolton et al., 2007b), soccer (Savelsbergh, Cañal-Bruland, & van der Kamp, 2012), rugby performance (Masters, Poolton, & Maxwell, 2008), golf (Poolton et al., 2005; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011), and outside the sports domain, in laparoscopy (e.g., Zhu, Poolton, Wilson, Hu, et al., 2011), surgery (e.g., Masters, Lo, Maxwell, & Patil, 2008), rehabilitation and balance (e.g., Orrell, Eves, & Masters, 2006b). Performance of implicitly learned tasks remains stable even when a cognitively challenging secondary task (dual task) is added (Koedijker et al., 2007; Maxwell et al., 2003; Poolton et al., 2005). Furthermore, performance of implicitly learned tasks has been shown to remain stable over longer periods of retention (Poolton et al., 2007a).

Although all these implicit learning methods lead to a reduced pool of knowledge about the task, their application to the field of sport poses some practical problems. For instance, errorless learning can only make sense at a very early stage in the learning process (Maxwell et al., 2001) as it is impossible to prevent mistakes as learning proceeds to a higher level. To address these issues, Masters (2000) proposed a different approach, analogy motor learning.

### **Benefits of analogy instructions and suggestions how they might be caused**

Unlike other implicit learning paradigms, analogy learning requires the intention to learn and involves use of instructions (Poolton et al., 2006), but it may work in a similar way to implicit motor learning. The way in which Masters (2000) intended analogy instructions to be used in early motor learning was in the form of a single instruction that establishes a relation to a well-known concept. Comparison with the well-known concept should capture the essential components of the movement. If the analogy is chosen carefully, no additional information needs to be given to the learner. In this way, a minimal number of verbal instructions contains the necessary information to convey a representation of the movement.

### *Rate of learning*

Implicit motor learning paradigms, such as dual task learning and subliminal feedback learning, resulted in slower learning rates compared to explicit learning techniques (Hardy et al., 1996; MacMahon & Masters, 2002; Masters, 1992; Maxwell et al., 2000, 2003). It has been suggested that novices need some information in order to adapt their movements and correct errors. While other implicit paradigms may not allow the correction of errors during learning (Maxwell et al., 2001), analogy instructions give an indication of how a correct movement should occur, allowing for error correction while keeping verbal contributions to motor control relatively low. Analogy instructed participants perform on average equally to explicitly instructed or control participants during acquisition trials and during regular post-test performance (Bobrownicki et al., 2015; Koedijker et al., 2011, 2007, Lam et al., 2009a, 2009b; Law et al., 2003; Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008; Orrell, Eves, & Masters, 2006a; Poolton et al., 2007b, 2006; Schlapkohl et al., 2012; Schücker, Ebbing, & Hagemann, 2010; Tse et al., 2017; Vine et al., 2013). This supports the propositions of Masters (2000) and Liao and Masters (2001) that analogy instructions allow learning at the same rate as regular explicit learning strategies. A study in children's motor learning found immediate effects of analogy instruction even on performance in a regular (single) task (Tse, Fong, et al., 2016). The authors argued that analogy led to greater movement efficiency in children. It is possible that the mechanism underlying use of analogy by children is different than in adults. Children's use of an analogy instruction is investigated in Chapter 2 of this thesis. A contrasting study by Koedijker et al. (2008) found that when practicing over 10,000 repetitions, performance of a group instructed by analogy plateaued sooner, while an explicitly instructed group continued to improve in performance. The authors suggested that, since only one movement-related rule was provided, detecting and correcting errors related to technical execution was limited for people who learned by analogy (Maxwell et al., 2000). According to Koedijker et al. (2008), more opportunities for technical improvement, such as feedback or an increase in task difficulty, need to be included if performance is to be continually improved over a longer period of practice. However, in their particular study, the speed at which the (externally paced) task (table tennis hitting) was performed may have reduced potential for contributions from conscious processes.

### *Verbal knowledge of the skill*

Donnelly and McDaniel (1993) were the first to show that analogy learning leads to accrual of less verbalisable knowledge about a skill, which is one of the defining characteristics of

implicit learning (Berry & Broadbent, 1984; Hayes & Broadbent, 1988). Since then, considerable evidence has substantiated this claim by repeatedly showing that analogy learners report significantly fewer rules compared to explicitly instructed participants (Bobrownicki et al., 2015; Koedijker et al., 2011, 2007, 2008, Lam et al., 2009a, 2009b; Law et al., 2003; Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008; Orrell et al., 2006a; Poolton et al., 2006, 2007b; Schlapkohl et al., 2012; Schücker et al., 2013; Vine et al., 2013). This indicates that the underlying mechanisms of the skill are less verbally accessible compared to explicit learning and discovery learning conditions (Liao & Masters, 2001). What is interesting is that rule reports provided by analogy learners also show less verbal knowledge compared to reports by uninstructed participants (Lam et al., 2009b; Orrell et al., 2006; but see also Schlapkohl et al., 2012, where an uninstructed control group reported similar verbal knowledge to the analogy instructed group). This may be due to the fact that when not given any information about how to move, learners will actively test hypotheses and generate knowledge about the movement in this way (Berry & Broadbent, 1988; Masters, 1992; Maxwell et al., 2000).

*Performance in dual task and decision-making situations: reliance on working memory*

Although performance in a regular task after analogy instruction is usually comparable with performance after explicit learning, differences have been found when a secondary, cognitive task was included. While explicit learners showed a breakdown in performance, analogy learners' performance was stable (Bobrownicki et al., 2015; Jie et al., 2016; Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, et al., 2016; Tse et al., 2017).

Concurrent decision-making and cognitive secondary tasks have been shown to have a similar effect on motor performance (Poolton et al., 2006). Crucially, during a high complexity decision, the additional load created by the decision-making task impaired performance in explicitly instructed groups but not in an analogy instructed group (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006; Schlapkohl et al., 2012). Schlapkohl et al. (2012) found stable performance under decision-making conditions after analogy in novices, but failed to extend the findings to experts. They found that experts benefited more from explicit rules than from a single analogy instruction and did not struggle to perform decision-making tasks concurrently (Schlapkohl et al., 2012). The authors argued that for experts, explicit verbal instructions may be more beneficial,

potentially because some instructions were already well-known and did not result in a high load on cognitive processes.

Unimpaired motor performance under dual task or decision-making loads suggest that the processing capacities required for motor execution are lower compared to explicitly instructed groups (Jie et al., 2016; Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, et al., 2016; Tse et al., 2017)<sup>5</sup>. Information processing during motor control is a function of working memory (WM), a form of “mental workplace” (MacMahon & Masters, 2002), which allows concurrent short-term storage and processing of information that is in use (Baddeley, 1994; Baddeley & Hitch, 1974, 2000). WM has a limited capacity, which makes it difficult to accomplish several tasks at the same time (Baddeley & Hitch, 1974). WM is thus a factor that defines the limits of human performance (Maxwell et al., 2003). A cognitively demanding task uses more WM capacity than a less demanding task. If a motor and a cognitive task are performed at the same time, reduced attention can be directed to the motor task (Hayes & Broadbent, 1988; Masters, 1992). According to the latest model, WM consists of four components. A central executive controls and directs attention through inhibition, shifting and updating of attention. An episodic buffer acts as a modelling space that interfaces between long term memory and two subordinate “slave systems”, the visuospatial sketchpad for visual information processing and the phonological loop for speech-based information (Eysenck, Derakshan, Santos, & Calvo, 2007, see Figure 2). A high load on WM, caused by processing verbal, movement-related information, is initially functional in the learning process, but can later be debilitating for performance (e.g., Schlapkohl et al., 2012). When a motor skill is learned with explicit instructions or by discovery, movement-related variables are associated with each other by the central executive system of WM, whereas implicit motor learning does not involve explicit association of variables and may therefore lead to a reduced load on the central executive of WM (Hayes & Broadbent, 1988). Reducing verbal control of movements (e.g., by analogy learning) may free capacity for information processing during other tasks (Berry & Broadbent, 1984) and allow stable performance under dual task and pressure situations (Maxwell et al., 2003).

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<sup>5</sup> As an alternative explanation, Poolton, Masters, and Maxwell (2006) discussed the possibility that analogy learners may be able to switch between tasks more easily than explicit learners. However, the short time in which their tasks were executed was not sufficient to allow for task-switching behaviour, so the explanation was dismissed.

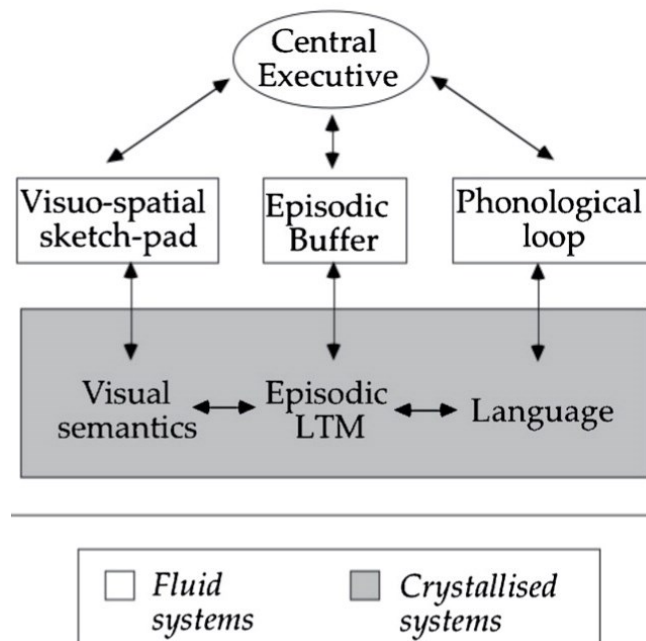


Figure 2. Subsystems of working memory (WM).

Reprinted with permission from Baddeley (2012), p.11.

Lam et al. (2009b) used a probe reaction time (PRT) paradigm to examine differences in attentional resource allocation during a basketball shooting task. They found that an analogy and an explicit group performed the same at the probe reaction time task, which indicates that an equal amount of attentional resources were allocated to the motor task. The explicit group maintained their PRT but did not maintain shooting performance under pressure, which indicates a relatively increased load on WM. Other studies also support the general notion that analogy instructions lead to a reduced load on WM due to limited use of or reliance on verbal rules, which allows correct task execution even if a secondary task competes for WM resources. For example, Tse et al. (2017) taught elderly people in table tennis as well as children in rope skipping (Tse, Fong, et al., 2016) by analogy, and found the same effects when a dual task was performed: a group instructed by analogy maintained their performance, while performance by an explicitly instructed group decreased. One aspect of the study on children’s rope skipping has to be mentioned, however. Instead of using only one analogy in the classical way of previous experiments, children in the analogy group were instructed with two analogies concerning two different parts of the movement (e.g., “hop like a bunny” and “draw circles with your hands”), and were additionally provided with explicit instructions about the rest of the movement (Tse, Fong, et al., 2016). However, the benefit for dual task performance was still present,

indicating that the form rather than the amount of information may be a relevant factor affecting information processing.

A different explanation that also related the benefits of analogy to its form, rather than to the amount of information it contains, was suggested by Masters, Poolton, Maxwell, et al. (2008). They interpreted findings of unimpaired performance in a dual task after analogy learning with reference to the separate domains of WM (e.g., Baddeley, 2000). Demanding decisions and explicit information are processed in the central executive subsystem of WM, while analogy instruction may be processed in a separate, visuospatial domain of WM, which would allow parallel processing of complex decisions and movement-specific content. This explanation is explored further later in this chapter (p. 28).

A contrasting study involving a continuous task was conducted by Orrell et al. (2006a). They tested participants learning a balancing task, in which they found that not only an analogy group but also a non-instructed group showed stable balance performance under dual task conditions, indicating that in a balancing task, both options may lead to relatively implicit motor control. The authors argued that this may be a quality specific to continuous tasks that require little conscious effort to master. Similarly, a pursuit-rotor study by Verdolini-Marston and Balota (1994) did not find improved implicit motor performance after analogy instructions (“think of the pursuit-rotor as stirring in a bowl with a wooden spoon”) compared to a control condition (no instructions) or several elaborative processing conditions (instructions that encourage semantic processes, e.g., “think about each stimulus as a specific song on a record”). Implicit motor performance was measured as pursuit rotor performance (time on target while tracing a pattern on a rotating disc) during trials including stimuli / patterns that had been encountered previously, but were not recognised. While elaborative processing had a positive effect on explicit memory performance (recognition of previously encountered patterns), the control condition was the only condition in which improved implicit motor performance was registered (Experiment 3). The authors suggested that explicit memory performance may benefit from elaborative or semantic processes, whereas implicit memory performance might depend on integrative, spontaneous or nonstrategic processes, which are disrupted when instructions or mental strategies are used (Verdolini-Marston & Balota, 1994). The pursuit-rotor task, similarly to a continuous balancing task and other simple motor tasks (e.g., rod-tracing; Seashore, Dudek, & Holtzman, 1949), may

be too simple for hypothesis testing to be effective (Masters, Polman, & Hammond, 1993). It may simply not be necessary to test different movement strategies to find a successful movement pattern. Implicit motor learning is usually aimed at complex motor tasks that involve several degrees of freedom and in which several different movement solutions may lead to a successful outcome (Masters, 2000; Masters & Poolton, 2012). In complex motor tasks, hypothesis testing is a natural behaviour when participants are not instructed. In order to keep cognitive load low, simple tasks may not need instruction by implicit learning paradigms.

The amount of information available to the learner is affected by using an analogy as opposed to explicit instructions. It seems a straightforward explanation that the number of rules provided may be the decisive factor. In this sense, a single instruction would be superior to a set of 6 instructions as it provides less information to the learner. Bobrownicki et al. (2015) investigated whether purely the amount of information given may be a factor. Additionally to the classic analogy and explicit conditions, they included an “explicit light” condition, in which participants were instructed with 3 technical instructions that were matched to the analogy in information content. Participants in this condition performed similarly to the analogy instructed condition in regular and pressure situations at a high-jumping task, although the analogy was still superior. Bobrownicki et al. (2015) suggested that accumulation of verbal knowledge may be moderated not by the volume of instruction, but by the number of rules or movement components within those instructions. They concluded that control groups in this research should be more realistic and be matched in the number of movement components contained within them. This is also visible in studies where similar benefits were found despite participants in the analogy condition receiving several analogies instead of a single one (Schücker et al., 2010; Tse, Fong, et al., 2016). When learning by analogy, control of movement may simply become more independent of WM processes (Maxwell et al., 2003). In a study of elderly people, WM was found to be a moderator of the relationship between instruction and performance in older adults but not in young adults (Tse et al., 2017). This indicates that WM may be somehow involved. The contribution of WM to motor control is unclear. Chapter 3 explores the involvement of WM and other cognitive factors in early motor performance.

In sum, findings related to performance under dual task or decision making load support the hypothesis that analogy learning may work in a similar manner to implicit

motor learning, by reducing the load on verbal processing or reducing reliance on explicit information for task performance. Reduction of verbal contribution may also be linked to increased efficiency of information processes. Chapter 4 of this thesis explores how analogy instructions may affect the efficiency of verbal processing with the use of electroencephalography (EEG).

#### *Performance under pressure*

In sports, it is generally of interest to perform well. It therefore seems paradoxical that in situations where good performance is of particular relevance, even highly skilled athletes often fall short of their expectations. This phenomenon is well known throughout all sports that involve some kind of precise motor task. Golfers call it the “yips”, basketball players named it the “bricks” (Beilock & Carr, 2001), others speak of “dartitis” and the media often uses the term “choking” (Baumeister, 1984; Beilock & Carr, 2001; Masters & Maxwell, 2008). This problem has been found in many types of sport involving sensorimotor skills, such as darts (e.g., mentioned in Masters, 1992), golf putting (Hardy et al., 1996; Masters, 1992), the golf swing (Schücker et al., 2010), tennis (Farrow & Abernethy, 2002), basketball (Liao & Masters, 2002), table tennis (Law et al., 2003; Liao & Masters, 2001), and many more. The phenomenon also occurs in other sensorimotor tasks, such as typing (Langer & Imber, 1979) and video games (Baumeister, 1984). Baumeister (1984) defined choking under pressure as “performance decrements under circumstances that increase the importance of good or improved performance” (p. 610). Situations of performing, and thus choking in performance, can happen at any stage in the learning process, from novice to expert (Baumeister, 1984).

A proposed mechanism behind choking under pressure is explained by the theory of reinvestment (Masters & Maxwell, 2008). The theory claims that expert knowledge or skills can be de-automated by an over-focus on movement execution, which results in reinvestment of knowledge that has been acquired in earlier stages of learning in order to control the exact movement. This kind of self-focused conscious control increases when a person executing a task becomes conscious of the specific movements related to the task (for example, through psychological pressure or arousal and drive; Paulus & Cornelius, 1974). Reinvestment has been defined by Masters & Maxwell (2004) as the “manipulation of conscious, explicit, rule based knowledge, by WM, to control the mechanics of one’s movements during motor output” (p. 208). Expert knowledge or skills



can therefore be de-automated by a strong focus on movement execution, especially under the influence of pressure to perform well.

Analogy learning may be a solution to the problem of choking under pressure. Findings related to performance under pressure indicate that similarly to implicit learning, analogy instructions may lead to less performance breakdown when conscious monitoring is increased by psychological pressure (Lam et al., 2009a; Law et al., 2003; Liao & Masters, 2001; Vine et al., 2013). In a study of table tennis, performance of participants instructed by analogy was robust to stress over three different psychological stress conditions (neutral, supportive and adversary audiences), while explicit learners' performance was negatively affected in a supportive audience condition (Law et al., 2003). The authors concluded that analogy may lead to less explicit knowledge of the mechanics, which reduces the opportunity to consciously control movements under pressure. Similar findings were evident in basketball (Lam et al., 2009a) and golf putting (Vine et al., 2013). The experiment in golf putting also included a condition where participants were trained to increase their quiet eye duration (QE), which led to similar benefits as analogy instruction (i.e., both the analogy and QE-training groups did not experience choking under pressure). QE is the duration of the last visual fixation before movement initiation and is usually measured by eye-tracking equipment. Longer QE durations have been shown to be connected to superior performance and efficient information processing (for a recent review, see Vine, Moore, & Wilson, 2014), and are seen as highly trainable (e.g., Vine & Wilson, 2010). Vine et al. (2013) suggested that QE training as well as analogy instructions may limit the need for – and accrual of – explicit rules throughout learning, resulting in lower verbal processing during motor control.

Alternatively, Vine et al. (2013) suggested that the constrained action hypothesis (Wulf, McNevin, & Shea, 2001) may be consulted to explain these differences. Analogy, like QE training, may be a means to encourage a more external focus of attention in the learner, which is known to also lead to benefits related to performance under pressure (Wulf et al., 2002). Explicit instructions may shift focus towards movement execution and internal processes, which may 'constrain', or disrupt, motor learning (see Wulf, 2007 for a review). A similar explanation was suggested by Koedijker et al. (2007). In order to test whether that might be an explanation, they tested table tennis novices who practiced using either explicit instructions, analogy instruction, environmental focus instructions, or movement focus instructions. All groups performed comparably during acquisition, but

the explicit instructions group was the only group that performed worse under pressure, which may indicate that the introduction of explicit rules, not the direction of attention, may be the cause of performance breakdown under pressure.<sup>6</sup>

Not all findings related to performance under pressure are unanimous. An exception is found in a study where participants practiced a table tennis topspin over 10,000 repetitions, using either analogy or explicit instructions (Koedijker et al., 2008). No difference between analogy and explicitly instructed groups was found in a pressure condition. Cooke, Kavussanu, McIntyre, Boardley, & Ring (2011) even found increased performance and effort when golf experts performed under pressure<sup>7</sup>. Opposing findings related to performance under pressure can be explained using Eysenck and Calvo's (1992) processing efficiency theory, which proposes that psychological pressure can either reduce performance by decreasing processing efficiency through increased conscious control and diverting attention to task-irrelevant threatening stimuli, or it can improve performance by enhanced effort and by allocating more processing resources to movement output (for an updated model, see Eysenck et al., 2007). A person's maximal performance corresponds to their individual optimal arousal level - either less or more stress will be harmful.

Schücker et al. (2010) investigated the allocation of attention during performance under pressure in a golf swing study. They found differences between analogy and explicit instruction groups at a tone-judgment task that was performed during performance under pressure, which was deemed to reflect self-focus. The difference indicated that explicitly instructed learners were more prone to become aware of their movements when they were under pressure. The authors concluded that analogy leads to different attentional processes under pressure compared to explicit instructions. Along with Masters et al. (2008), they suggested that movement analogies might be processed and stored in a visuospatial rather than verbal form. However, participants in the analogy group were instructed with several analogies, which differs from previously used approaches as it may increase reliance on verbal processes. In a later study Schücker et al. (2013) could not replicate the differences between analogy and explicit groups in task-focus under

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<sup>6</sup> Koedijker and colleagues admit that the manipulation to increase movement focus might not have been effective, as participants in this condition did not report more internal rules than the external focus group.

<sup>7</sup> This paper did not compare two differently instructed groups, however, the results demonstrate the differential effect that pressure may have on performance.

pressure in a golf putting task, although this study included analogy instruction in the form suggested by Masters (2000). They found that analogy learning did not lead to any difference in performance when dual tasking or in a pressure manipulation. This non-result related to the task-focus task was attributed to more attention being allocated to do well in the primary task under pressure. Additionally, the dual task used in the experiment may not have reliably measured skill focus. Koedijker et al. (2008) found that the positive effects of using an analogy instruction (for dual task performance as well as performance under pressure), which are usually found after between 75 and 400 repetitions, were washed out when the task was practiced for 10,000 repetitions. They argued that levels of automaticity may have been achieved by all groups by that stage, allowing for lower cognitive control of movements in both groups. However, there were also limitations to Koedijker et al.'s (2008) study, since only small increases in state anxiety were reported, and the externally paced task did leave enough preparation time between movement repetitions to allow conscious processing. Furthermore, performance after fewer than 1400 trials of practice was not recorded, which makes comparison to other studies difficult.

Not all people are prone to choking under pressure (Masters et al., 1993). Performance disruption may be due to a predisposition for rehearsal of task-relevant explicit knowledge by certain people. Baumeister (1984) also found that individuals high in self-consciousness, as measured by the Self-Consciousness Scale (Fenigstein, Scheier, & Buss, 1975), performed worse than individuals low in self-consciousness during non-pressure practice trials. For the purpose of determining individual differences in the predisposition towards re-investment of previous knowledge under pressure, Masters et al. (1993) devised the Reinvestment Scale. Later, Masters, Eves and Maxwell (2005) developed an adapted questionnaire for the movement context, the Movement Specific Reinvestment Scale (MSRS). The scale comprises 10 questionnaire items that make up two separate subscales: Conscious Motor Processing (CMP), which reflects a person's tendency to control their movement mechanics, and Movement Self-consciousness (MS-C), which reflects a tendency to be self-conscious about movements. High *reinvestors* were shown to experience stronger performance decrements under pressure or self-awareness (Reinvestment scale: Chell, Graydon, Crowley, & Child, 2003; Jackson, Ashford, & Norsworthy, 2006; Masters et al., 1993; Movement Specific Reinvestment Scale: Huffman, Horslen, Carpenter, & Adkin, 2009; Malhotra, Poolton, Wilson, Ngo, & Masters, 2012; Maxwell, Masters, & Poolton, 2006). High reinvestors also showed more constrained

movement kinematics (Cooke et al., 2011; Malhotra, Poolton, Wilson, Omuro, & Masters, 2015). This may be linked to more verbal knowledge (Maxwell et al., 2006) or verbal control of movement as shown by EEG measurements (Zhu, Poolton, Wilson, Maxwell, et al., 2011, Experiment 1). Malhotra et al. (2012) found that the propensity for reinvestment (as measured by the Reinvestment scale) may have a moderating effect on laparoscopic performance under time pressure in medical students, indicating that personality has an effect on responses to stress. Since analogy instructions affect information processing and conscious control of movements, it is likely that they may have a differing effect on people with a high as opposed to a low propensity to consciously monitor and control their movements. In Chapter 2, we explore this relationship in children learning a golf chipping task.

#### *Movement kinematics*

Apart from direct performance measures, a few studies have investigated measures of the quality of execution of a motor skill after learning by analogy. Analysis of table tennis players' technique showed a difference between explicitly and analogy taught participants, with a significantly larger angle of bat movement in the analogy group (Schlapkohl et al., 2012). However, in this specific case, the angle may be a direct consequence of the instruction used, since the analogy required participants to imagine a right-angled triangle and move the bat up its hypotenuse. A similar interpretation was given by Bobrownicki et al. (2015) to explain differences in kinematics of a high-jump between explicitly and analogy instructed participants. The only difference found was in the angle of the knee joint, which may be linked to the analogy instruction ("alternate your legs like scissors to clear the bungee cord"), which implicitly implied straight knees.

Degrees of freedom of a movement execution have been connected with conscious control (Bernstein, 1967). There is weak evidence for an increase in degrees of freedom when analogy instructions are used. During a high complexity decision task in table tennis, a change towards stiffer movement was detected in explicitly instructed participants, but no change in technique was found in an analogy instructed group (Masters, Poolton, Maxwell, et al., 2008). Analogy learners showed higher variability in their movement pattern, which was interpreted as more expert-like and flexible, whereas explicit learners showed stiffening of joint angles and reduction in degrees of freedom, which was connected to conscious, stepwise control of movement, which is characteristic in novices (Masters, Poolton, Maxwell, et al., 2008). Another experiment that investigated kinematic

variables in a seated basketball experiment did not find a significant difference between instruction groups, but a general trend towards a more implicit or automatic mode of movement control was observed in analogy participants (Lam et al., 2009b).

Overall, “naturalness” of skill execution connected with analogy instructions has been mentioned in several studies. For example, speech patterns learned by analogy were perceived as more natural compared to explicitly practiced speech (Tse et al., 2013). Also, a study of stroke patterns in swimming showed that an analogy instruction led to improved coordination patterns in swimming (Komar, Chow, Chollet, & Seifert, 2014) – however, the analogy used in the study (“glide two seconds with your arms outstretched”) did not correspond to motor analogy instructions as defined by Liao and Masters (2001), since it bore no reference to a familiar concept. Nevertheless, Komar et al. (2014) suggested that more efficient movement might be linked to the implicit nature of the instruction, as it did not directly prescribe the movement parameters necessary to comply with the instruction. The instruction might allow learners to flexibly develop their functional patterns of movement in the early coordination stages of learning. According to the constraints-led approach (e.g., Renshaw, Chow, Davids, & Hammond, 2010), explicit instructions are a constraint that shapes behaviour too tightly. Analogy may be a way to shift focus to movement execution without being too prescriptive, opening up constraints during learning to lead to a more flexible pattern of behaviour (Komar et al., 2014; Seifert, Button, & Brazier, 2011).

Kinematic analyses do not give a clear picture of whether movement execution is affected by an analogy instruction. It is likely that although analogy may lead to more implicit control of movement (which may in some cases be visible as more fluent execution), the exact movement will depend on the specific instruction used, as well as on any other constraints posed by the task or inherent to the learner.

### **Thoughts on the use of analogy instructions in different fields of motor learning**

Research generally indicates that novices who practice a motor skill while using a single analogy instruction experience little or no disruption of performance under dual task conditions, under psychological pressure or self-focus, and when making complex decisions while moving. Analogy instruction seems to guide the learning process so that testing of hypotheses during practice is reduced, which leads to reduced accretion of declarative knowledge and reduced reliance on such knowledge while executing a

movement, which seems to place fewer demands on WM. Analogy may allow novices to somehow bypass the need for explicit control of movement execution early in learning. This indicates that this method may be especially useful to people who have deficits in conscious motor control, such as stroke patients, Alzheimer's disease and Parkinson's disease patients, but also children with or without cognitive impairments (Masters, MacMahon, & Pall, 2004). Analogy learning approaches have recently been used in speech therapy (Tse et al., 2013; Tse, Wong, Whitehill, Ma, & Masters, 2016), stroke and Parkinson's Disease patients (Jie et al., 2016; Kleynen et al., 2014), elderly people (Tse et al., 2017) and children with Autism Spectrum Disorder (Tse & Masters, n.d.). A proof-of-principle study in stroke patients showed that this type of instruction is feasible for use in stroke patients in general and reported performance improvement in most participants (Kleynen et al., 2014). A second experiment was conducted using analogy instructions in PD patients (Jie et al., 2016). Although the number of practice trials differed from others in analogy learning (8 repetitions compared to 400 used in other experiments), performance improved significantly and showed trends towards being less impacted by a dual task. The authors argued that participants with PD might take more time to fully assimilate the analogy, but eventually benefit from it.

Even though cognitive capacities may not be impacted in regular physiotherapy clients, giving adequate instructions is also critical in this field (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002; Niemeijer, Smits-Engelsman, Reynders, & Schoemaker, 2003). Since well over a dozen instructions are normally given during a physiotherapy session (Niemeijer et al., 2003), a more efficient way of imparting movement-specific information may reduce the verbal load on patients (Tse et al., 2017), which may have beneficial effects for retention, transfer (e.g., from therapy to real life) and dual task performance (e.g., walking and talking concurrently).

The benefits of using analogy instruction in performance under pressure, in multitasking situations and when making complex decisions concurrently, suggest the use of analogy instruction in fields where these features are of importance, including surgery training (Poolton, Wilson, Malhotra, Ngo, & Masters, 2011), aviation (Wierwille & Eggemeier, 1993), emergency services and military training (Janelle & Hatfield, 2008). Clinical competence of surgeons, for example, not only depends on the technical skill itself but also on the stability of the skill in these conditions (Masters, Lo, et al., 2008; Poolton et al., 2011). Although studies have been conducted in surgery training with other implicit

instruction methods, (i.e., errorless learning; Masters, Lo, et al., 2008; Zhu, Poolton, Wilson, Hu, et al., 2011), analogy has not been included as a means of instruction to date.

Analogy has also been suggested as a method within the framework of nonlinear pedagogy and constraints-led learning (Komar et al., 2014; Renshaw et al., 2010). Nonlinear pedagogy, a form of pedagogy that is increasingly used in PE teaching, is based on Bernstein's (1967) degrees of freedom problem and on the concepts of ecological psychology, and suggests that learners generate individual movement solutions to satisfy the combination of constraints imposed on them, via processes of self-organization (Renshaw et al., 2010). The constraints-led approach aims at harnessing these processes for physical education. Analogy may be a means of opening up constraints during learning to lead to a more flexible pattern, in which participants may find their optimal movement pattern rather than being prescribed with an external one (Komar et al., 2014; Seifert et al., 2011).

### **Mechanisms underlying analogy learning of movements**

Research from the last two decades suggests that analogy instructions have an effect on information processing during movement; specifically, they are thought to reduce reliance on verbal processes during movement planning, which cannot be explained by the mere difference in number of instructions. The underlying processes that may cause these effects have not been determined yet. Insight into the mechanism of analogy instructions in learning may be helpful in driving the generation of better analogies, in informing or optimizing their use in practice, and in extending their use to fields where they add the most benefit. What is more, improving understanding of how the benefits of using analogy instructions in the learning of movements may be caused might challenge and evolve current views of human cognitive motor control.

#### *Effect of analogy on cognitive load: concept learning vs. motor learning*

Gentner's (1983) structure mapping model works well when explaining the benefits of analogy in the learning of concepts (e.g., better inference, memory and problem solving), but fails to explain the benefits related to performance and cognitive processes in motor learning, which are linked to reduced awareness of underlying concepts. When applied to the strongly cognitive, explicit context of concept learning, the use of analogy is a conscious, deliberate process with the goal of increasing explicit knowledge about a new topic. Structure mapping (i.e., matching and mapping of higher-order elements within two

related concepts) and updating of schemas by drawing inferences, are both cognitively challenging and potentially lead to a pool of extant verbalisable knowledge about the concept. These processes are likely to involve a high load on WM, both during the learning process and during later retrieval. Most research in concept learning supports the notion that structure mapping of analogies involves explicit processes which pose a high load on WM (Klein et al., 2007). Sweller and Cooper (1985) found that when the base concept was not present during analogical problem solving, processing load was especially high, potentially because the base concept had to be retrieved from long-term memory and held in WM. Subsequently, the ability to focus on structural similarities and mappings was impaired by this high cognitive load. The authors developed a cognitive load theory based on limited WM capacity, which argues that learners may not learn efficiently if demands of instructional materials and tasks are too high. In a study by Waltz et al. (2000), students showed fewer mappings of structural features compared to surface features in a picture analogy task when a load on WM was added. The authors found that mapping on the basis of relations places greater demands on WM than does mapping on the basis of object attributes, which causes an increased tendency for mapping surface similarities when participants are under a cognitive load. It has also been shown that the ability to reason analogically is closely related to general intelligence (Sternberg, 1977). The cognitive demands of processing a complex analogy might have an increased negative effect on learning by people with limited cognitive resources, such as young children (Richland, Morrison, & Holyoak, 2006) and elderly (Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004). Thibaut, French, and Vezneva (2010) investigated analogy making in children (i.e., the matching of analogous items by using an A:B::C:? paradigm) and found that susceptibility to distraction and false (superficial) matches were a function of the development of executive memory in children, which is known to be central to the inhibition of salient distractions. Richland and McDonough (2010) pointed out that cuing was a helpful tool in teaching by analogy, as it allowed successful mapping without raising demands on WM. Writing, a form of verbalization often used to make participants aware of their thoughts, has also been shown to improve structure mapping and learning by analogies in science (Klein et al., 2007). This suggests that consciously using analogies with the aim of learning structural features of a concept is related to a considerable load on cognitive resources.

In contrast, analogy instruction in motor learning is considered to cause the learner to depend less on WM compared to classic instruction forms such as explicit instruction or



discovery learning. Instead of drawing the learner's attention to parallel features between the source and target analog, learners receive a complete image that allows them to apply the concept without attending to lower order components of the movement. Motor analogy has been described as an "all encompassing, biomechanical metaphor" (Koedijker et al., 2011; Liao & Masters, 2001; Masters, 2000). One could argue that analogy instructions may be a useful way of providing people with a "rule of thumb" or heuristic that conveys the fundamental concepts of the to-be-learned skill in such a way that the correct movement representation can be processed without much effort (Masters, 2000; Todd & Gigerenzer, 2000). Gigerenzer and Goldstein (1996) suggested that heuristics may be *fast and frugal* because they "exploit [...] simple psychological principles that satisfy the constraints of limited time, knowledge, and computational might" (Gigerenzer & Goldstein, 1996; p.651). *Fast and frugal heuristics* have been shown to outperform complicated optimizing models in computer simulations, mathematical models and behavioural experiments because they require less information, do not need to integrate this information, and are more robust to generalization to new cases (Bennis & Pachur, 2006; for an overview on fast and frugal heuristics, see Gigerenzer, 2004). They have also been found to predict decisions in sports environments (de Oliveira, Lobinger, & Raab, 2014; Raab, 2012). Improving the understanding of how the benefits of using analogy instructions in the learning of movements may be caused might build on Todd and Gigerenzer's (2000) idea of heuristic principles in human behaviour.

Traits connected to behaviour that is crucial for survival (such as performance that is not affected by fatigue and remains stable through long retention intervals) are usually phylogenetically older than traits that are less important for survival (e.g., Reber, 1992). Findings showing that implicitly learned tasks are stable under conditions of fatigue, suggesting that implicit processes developed before explicit processes (Masters, Poolton, & Maxwell, 2008; Poolton et al., 2007a). Over time, an increasing need for complex movements and language led to the development of explicit and conscious processes in the human brain; however, implicit processes can still be evoked, e.g., when fast reactions under conditions of fatigue or pressure are needed (Reber, 1992). Analogy learning may be a way to allow the older, more deeply engrained implicit processes to be mobilised during learning, unimpeded by explicit, conscious control processes (Poolton et al., 2007a).

### *Chunking*

One tentative theory that provides a mechanism underpinning benefits of analogy learning is the chunking theory of implicit motor learning (Masters & Liao, 2003). Chunking is a conceptual framework that serves as a basis for our understanding of how humans learn motor skills (Graybiel, 1998). It describes the psychological process of organizing lower-order bits of information by grouping or encoding them into fewer, larger units of a higher organizational level, which is a bottom-up process that runs automatically during learning (Rosenbloom & Newell, 1987). The mechanism was initially proposed by Miller (1956) based on findings related to memory and perception and by De Groot (1978) based on observations and case studies during chess masters' problem solving. Miller (1956) proposed the idea of a "chunk" as an information unit that collates several pieces of information into a single unit (see also Gobet et al., 2001 for a brief overview). Early evidence of chunking is provided in a famous experiment by Chase and Simon (1973), in which a chess master (an expert) and a novice chess player tried to recall positions of chess figures on a chess board. The study found that experts were superior to novices in recall of positions when the positions belonged to a realistic chess situation (structured), but no difference in recall was found when positions were random (unstructured). Apart from providing the first evidence of the principle that skill-specific knowledge is the key to expertise, this experiment substantiated the concept of chunking (Gobet et al., 2001). Miller (1958) showed that unknown letter strings generated by an artificial grammar were memorised better than randomly generated strings. Rosenbaum and et al. (1983) added to this evidence by reporting that finger movement sequences were performed as a group of subsequences, with longer inter-subsequence time intervals. Servan-Schreiber and Anderson (1990) conducted an experiment in which participants were trained on exemplar sentences while being induced to form specific chunks. In a subsequent test of grammatical knowledge, participants were less sensitive to grammatical violations if the previously formed, specific, chunks were preserved than if a grammatical violation disrupted one of the chunks, which further corroborated the notion of chunking. There are several theories of how chunking might work (Gobet & Simon, 1998; Perlman, Pothos, Edwards, & Tzelgov, 2010; Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum et al., 1983; Servan-Schreiber & Anderson, 1990). For example, some computational models suggest that bits of information that co-occur often in the environment are more likely to be chunked together into a single unit (e.g., the competitive chunking hypothesis; Servan-Schreiber & Anderson, 1990). A contrasting

hypothesis stresses that elements need to be organised together in order to be consolidated (Perlman et al., 2010; Rosenbaum et al., 1987; Rosenbaum et al., 1983).

Since this seminal work was conducted, it has been repeatedly shown that chunking naturally occurs during learning of words (Laird, Rosenbloom, & Newell, 1984; Servan-Schreiber & Anderson, 1990), of concepts (see review by Gobet et al., 2001), and of movement sequences (Sakai, Kitaguchi, & Hikosaka, 2003; Schlaghecken, Stürmer, & Eimer, 2000; also see Poolton & Masters, 2014). Most support for chunking as a mechanism in motor learning comes from experiments using the serial reaction time (SRT) task developed by Nissen and Bullemer (1987). The serial reaction time task involves pressing one key, out of a set of four keys, above which a light appears. Similar to Nissen and Bullemer's (1987) experiment, many experiments that tested chunking involved one group receiving a repeating sequence, such that the same short sequence of positions was used through the whole test, and another group receiving a random sequence. Measures of response latency of both groups in Nissen and Bullemer's study indicated that the repeating sequence group showed a reduced latency after practice, and that this reduction reflected primarily the learning of the sequence. Overall, SRT experiments support the view that chunking or unitization is a central mechanism in the learning of motor sequences (Clerget, Poncin, Fadiga, & Olivier, 2012; De Kleine & Verwey, 2009; Hansen, Tremblay, & Elliott, 2005; Klapp, 1995; Kuriyama, Stickgold, & Walker, 2004; Nissen & Bullemer, 1987; Perlman et al., 2010; Rosenbaum et al., 1987, 1983; Sakai et al., 2003; Stöcker & Hoffmann, 2004). SRT's are a practical way to investigate chunking, as chunks become visible in inter-sequence intervals. However, experiments testing performance in SRT tasks do not provide enough insight into underlying processes in complex motor tasks, such as far-aiming tasks, sports movements, and other motor skills. Additional plausibility would be gained by including different implicit learning tasks (e.g., Kaufman et al., 2010)

Related to motor tasks, Keele (1968) suggested that cognitive control is based on an internal sequence representation or "motor program". Chunking in this context refers to the relevant movement information being integrated into long-term memory as a proceduralised representation (Chase & Simon, 1973; Ericsson et al., 1995; Gobet & Simon, 1998; Miller, 1956). Research to date suggests that motor sequences are hierarchically structured into subsequences, which are represented as chunks (Sakai et al., 2003). Research reports patterns of chunking in the learning of visuomotor sequences

(Keele, Jennings, Jones, Caulton, & Cohen, 1995; Nissen & Bullemer, 1987) as a process that may either happen spontaneously (Sakai et al., 2003; Shea, Park, & Braden, 2006) or be imposed (Koch & Hoffmann, 2000). In complex motor skills, it has been suggested that motor skill acquisition is associated with functional adaptations of action-related knowledge in long-term memory (Frank, Land, & Schack, 2013), which indicates that chunking might happen on the level of motor sequence representation. While experts' representational frameworks are organised in a distinctive hierarchical tree-like structure, novices have less structured representations (Schack & Mechsner, 2006; Weigelt, Ahlmeyer, Lex, & Schack, 2011). As continued practice leads to a hierarchical structure, the movement becomes more fluent, while at the same time placing fewer demands on information processing resources.

Chunking may be an important mechanism underpinning implicit learning. Implicit learning allows learning of a skill without conscious knowledge of the underlying principles (Masters, 1992, 2000). Reber (1967) found that following memorization of exemplar sentences, participants efficiently discriminated grammatical from non-grammatical strings, despite being unable to report the underlying grammatical rules. Based on Reber's experiments, Servan-Schreiber and Anderson (1989) proposed that "[...] the resulting knowledge on which grammatical judgments are based is a hierarchical network of chunks that [...] implicitly encodes grammatical constraints" (p. 2). They suggested that the process underlying this implicit form of learning may be chunking.

Masters and Liao (2003) proposed that learning by analogy may be a way to chunk movement related information more effectively than in the long learning process, as the analogy provides "pre-chunked" information that is already on a higher organizational level. This would explain the benefits of analogy instructions for performance in situations where information processing capacities are restricted (Miller, 1956; Newell & Rosenbloom, 1980). According to Miller (1956), information processing is based on units (bits) of information. Not the amount, but the number of items in which information is organised, determines cognitive load. This means that after information has been chunked into fewer bits, it can be processed with relatively less cognitive effort (Newell & Rosenbloom, 1980).

Masters and Liao (2003) argued that the analogy should chunk only technical rules that are encapsulated in the analogy, since chunking can only occur when the discrete "bits" of information are relevant or meaningful to the learning process (Baddeley, Thomson, &

Buchanan, 1975). They tested this premise by teaching table tennis novices using two different sets of explicit instructions (a set that was represented by the analogy and a set that was not). Participants were then provided with the analogy and their performance was examined. They found the same benefits of analogy learning that have been found elsewhere (e.g., Liao & Masters, 2001), but only in the group that had been using the relevant instructions, which supports the chunking hypothesis. However, this theory has not been backed by strong empirical support to date. Gathering sufficient evidence to either corroborate or discard such a chunking hypothesis of implicit motor learning is an important next research step to determine the mechanism of analogy learning.

#### *Visual processing argument*

An alternative explanation for the benefits of analogy learning is a visual processing argument originally stated by Liao and Masters (2001) and reiterated by Masters, Poolton, Maxwell, et al. (2008). Applying a visually salient analogy involves forms of mental animation and visualization (Liao & Masters, 2001). The mountain analogy developed by Poolton et al. (2007b), for example, leads to the visual representation of a mountain in the performer's mind and involves visuospatial processes in movement planning. Based on Baddeley and Hitch's (1974) model of WM, the authors pointed out that analogies might be processed in the visuo-spatial sketchpad rather than in the phonological loop of WM (Baddeley, 1981; Baddeley & Hitch, 1974). Masters, Poolton, Maxwell, et al. (2008) argued that demanding decisions and explicit information are processed in the central executive of WM, whereas analogies may be processed in the visuospatial domain of WM. Based on the assumption that the visuo-spatial sketchpad is responsible for the storage and processing of spatial representations (Shah & Miyake, 1996), it is reckoned that by involving a second subsystem of WM, information processing is rendered more efficient. Consequently, the neuro-motor system can process two tasks (e.g., the instructed movement and a secondary task) simultaneously in different modules within WM without overreaching WM capacity. This would explain superior performance in secondary cognitive tasks or under psychological pressure (Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008). The analogy might serve as a visual capsule which allows information to enter the visuo-spatial sketchpad of WM, where processing is faster and more effortless than in other potential sub-systems of WM.

The premise that visual processes are involved in using analogy is also supported by findings in children's motor learning (Tse, Fong, et al., 2016). Children performed better

when receiving analogies compared to children taught with explicit instructions, both in a single task and in a dual task (counting backwards). Children tend to handle visual instruction forms better; in particular, children between 5-10 years of age rely mostly on visual WM (Hitch, Woodin, & Baker, 1989). Tse, Fong et al. (2016) argued that children may have benefited from the more visual nature of the information presented in analogy instructions (Alloway, Gathercole, Kirkwood, & Elliott, 2008; Alloway, Pickering, & Elizabeth, 2006). Tse, Wong, et al. (2016) provided more support for the visual processing hypothesis. In their study, participants memorised visual or verbal stimuli before reading a text with maximum pitch variation. Recall of the stimuli was used as a measure of visual or verbal WM load. Instructions about achieving maximum pitch variation were presented via visual analogy, verbal analogy, and explicit rules, or without instruction. A reduced load on phonological components of WM was evident when learners were taught by visual analogy. When verbally taught, the analogy loaded both visual and verbal processes; explicit instructions only had a negative effect on recall of verbal objects. The finding that the visually salient form of a piece of information is superior to a purely verbal alternative with the same informational content supports the notion that analogy might involve more visuo-spatial processes. However, whether analogy is indeed used as a purely visual instruction may depend on individual characteristics of the learner. Participants can process the same information in different modalities, optimizing their resources (Irwin & Andrews, 1996; Palmer, 1990; Sperling, 1960; Vogel, Woodman, & Luck, 2001). In Chapter 6, the effect of instruction preference on adaptation of a movement analogy is investigated.

## **Electroencephalographic measurements in motor learning research**

The aim of this PhD is to develop a deeper understanding of the cognitive processes that underlie the use of analogy and explicit instructions during motor adaptation and learning. In order to gain deeper insight into cognitive processes on the brain level, measures of electroencephalography (EEG) are used for the analysis of cortical processes during the preparation and execution of motor tasks. The following subchapter summarises the relevant findings regarding EEG analyses for the investigation of cognitive processes during motor control and motor learning.

### **Electrophysiology and motor performance**

Monitoring the brain's activity via electroencephalography (EEG) provides possibilities to gain insight into cognitive processes during motor adaptation. The electroencephalogram assesses electrical potentials produced by brain cells in the cortex through electrodes placed on the scalp at precisely defined and equally spaced locations. From the detected voltages, cortical activity in different areas can be analysed (for a review on recent research using psycho-physiological measures during sport performance, see Cooke, 2013). Some research in the sport context makes use of event-related potentials (ERP's), which are time-referenced to a certain event in the movement (e.g., to an auditory signal or to the moment of bat-ball contact). Movement-related cortical potentials (MRCPs, i.e., ERP's where the event is a movement) give insight into activity in the brain at a certain time related to movement execution, and are often used in the analysis of preparatory activity in reactive sports.

A different measure of EEG activity is spectral power, which is assessed in the frequency-domain. In the analysis of EEG spectral power, the voltage obtained from the electrodes is fast Fourier transformed and split up into waveforms for each pre-defined frequency band, which allows assessment of spectral power in each band (for a review of different experimental approaches to the spectral analysis of brain oscillations, see Gross, 2014). According to Klimesch (1999), EEG power "reflects the number of neurons that discharge synchronously" (p. 170). Therefore, higher EEG power indicates that more neurons are activated. However, power is related to cognitive and memory performance in a slightly more complex way than that. The conventional notion is that different frequencies reflect functionally different processes (Janelle et al., 2000; Ray & Cole, 1985). The lower and midrange bandwidths (frequencies up to 22 Hz) reflect long- and medium-

range cortico-cortical communication and attentional mechanisms; higher frequency bandwidths represent localised activation of the cortex and indicate spatially constrained regional processing (Crews & Landers, 1993; Nunez, 1995; Nunez & Srinivasan, 2006; Ray & Cole, 1985). In the movement context, most insight is gained from analysing alpha (8-12 Hz), beta (13-30 Hz), and theta (4-8 Hz) power bandwidths, sometimes splitting bandwidths into high- and low- frequency spans (Janelle et al., 2000; Klimesch, 1999). The theta band is often investigated in relation to WM activity (Babiloni et al., 2004; Klimesch, 1999; Krause et al., 2000; Onton, Delorme, & Makeig, 2005). In this PhD thesis, however, we focused on high-alpha power, as most of the movement-specific literature reports findings in this frequency band.

Analysis of EEG power variables has been conducted in different ways. Pfurtscheller (1992; Pfurtscheller, Stancák, & Neuper, 1996) and Klimesch (1999) suggested calculating the difference between the last second before initiation and a baseline, which is measured before the start of each trial (event-related desynchronization, ERD), to reflect electrocortical changes leading up to an action. Cooke et al. (2014, 2015) split EEG signals during the 4s prior to execution of a golf putt (and 1 sec after) into 1-s epochs and analysed each second separately. Most other research on cognitive processes in motor control and motor learning has investigated alpha power averaged over a pre-defined time period during movement preparation, usually between 4 and 7 seconds leading up to movement initiation (Hatfield, Landers, & Ray, 1984). The experiments in the present thesis (Chapters 3-6) investigated EEG power and coherence (see following subchapters) averaged over a 4s pre-shot epoch. This allowed for satisfactory retention of measurement trials after artefact removal and increased reliability of the measurements while giving a good indication of differences between individuals and treatment groups. It also allowed measurement of changes in EEG activity between pretests and retention tests, since inter-individual difference effects were eliminated.

### **Alpha power and performance**

Tonic changes in alpha power happen slowly throughout the lifespan. Alpha power generally increases from early childhood to adulthood and decreases again with increasing age (Pangelinan, Kagerer, Momen, Hatfield, & Clark, 2011). It also decreases with increasing severity of neurological diseases and dementia (Klimesch, 1999). When researching motor control and movement-related information processing, it is more



insightful to investigate intra-individual event-related increases or decreases (phasic changes) rather than differences in tonic alpha power.

EEG alpha power is inversely related to cortical activation - an increase in alpha power reflects decreased cerebral activation and, vice versa, a decrease in alpha power represents a rise in activity (Hillman, Apparies, Janelle, & Hatfield, 2000; see Klimesch, 1999, for a review). A reduction in activity in the seconds leading up to task execution is known as event-related desynchronization (ERD). Event-related desynchronization was initially used as a measure of cognitive load during cognitive and memory tasks (Pfurtscheller, 1992; Pfurtscheller & Lopes da Silva, 1999; Pfurtscheller et al., 1996). With increasing memory performance or increasing task demands, event-related alpha usually decreases (desynchronises; Klimesch, 1999). Vice versa, event-related synchronization, which means an increase in activation, indicates lowered cortical activity or cortical idling (Pfurtscheller et al., 1996). In the movement context, ERD has been used as a direct measure of cognitive involvement or effort during motor control (Babiloni et al., 2008; Hatfield, Haufler, Hung, & Spalding, 2004). Right before movement initiation, alpha power is usually lowered significantly (i.e., desynchronised), which suggests that cortical activity is raised in preparation (Hillman et al., 2000; Janelle et al., 2000; Kerick, Iso-Ahola, & Hatfield, 2000; Loze, Collins, & Holmes, 2001; Salazar et al., 1990). In various expert-novice comparison studies, expertise was reflected by less desynchronization (i.e., higher alpha power in the time course leading up to the movement) and thus lower processing demands – indicating that experts are using fewer brain resources for programming and executing a sports movement than novices (Gentili, Bradberry, Oh, Hatfield, & Contreras Vidal, 2011; Hatfield et al., 2004, 1984; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick, Douglass, & Hatfield, 2004; Landers, Han, Salazar, & Petruzzello, 1994; Wolf et al., 2015). For a review of expert-novice differences in movement-related psychophysiological markers, see Lawton, Hung, Saarela and Hatfield (1998). Studies tracing the development of a skill show an increase in left-hemispheric alpha power after practice, which is associated with better shooting performance (Landers et al., 1994) or golf performance (Kerick et al., 2004). This indicates that nonessential involvement of conscious control mechanisms during performance is gradually reduced (Babiloni et al., 2008, 2009; Del Percio et al., 2010; Zhu et al., 2010). For a review of cortical dynamics of motor skill, see Hatfield et al. (2004).

In shooting, higher alpha power is usually found during the preparation of successful compared to unsuccessful executions (Crews & Landers, 1993; Hillman et al., 2000). However, Babiloni et al. (2008) found alpha power to be lower during the preparatory phase of golf putts, and even more so preceding successful compared to unsuccessful trials. Cooke (2013) suggested that differences in EEG alpha power between shooting and golf may reflect different attentional demands of these tasks. While marksmen are required to allocate resources to monitor proprioceptive and vestibular (i.e., internal) systems, golf putting requires attention to external cues (e.g., the ball, the target) during preparation for action (Janelle & Hatfield, 2008) which has been associated with a decrease in alpha power (Ray & Cole, 1985).<sup>8</sup>

In trials following an error in golf putting, alpha power was found to be reduced, which reflected increased processing demands connected with processing and correction of the error (Cooke et al., 2015). In a study testing the effect of pressure on pistol shooting performance, Hatfield et al. (2013) found that performance remained the same under pressure, but EEG alpha power was raised, indicating relatively greater use of cortical resources. This is consistent with theories of self-focus and increased effort under pressure. Furthermore, age-related differences in motor planning and performance were reflected in electrocortical dynamics - children show less consistent movements as well as increased brain activation (lower EEG power) compared to adults (Pangelinan et al., 2011). These findings support the view that most self-paced movements are preceded by a decrease in alpha power related to an increase in cortical activity required during motor control.

Observations of brain activity during preparation for movement have found that most changes in alpha power during preparation for performance were strongly lateralised. Specifically, the increase in activity found in experts at a skill is often more pronounced over the left temporal region compared to the right temporal region (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Lawton et al., 1998). Hatfield et al. (2004) interpreted this as a shift of activity from the left to the right hemisphere. Lawton et al. (1998) interpreted hemispheric asymmetry during motor execution as a quietening of cortical activity in the left hemisphere in order to decrease interference with visual and

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<sup>8</sup> Ring, Cooke, Kavussanu, McIntyre, and Masters (2015) found that high alpha power can also be trained. The researchers detected that participants could effectively learn to suppress activation of frontal brain regions during preparation for a golf putt (neurofeedback training), even though no effects of neurofeedback training on putting performance were detected.

spatial processes in the right hemisphere, which are necessary for high-level performance. Alpha signals reflect locally specific functional processes. The left hemisphere contains verbal-analytic brain regions such as Broca's area and Wernicke's area and alpha waves in these regions appear to be involved in verbal-analytic processing (Sperry, 1974; Springer & Deutsch, 1998). More specifically, the left temporal lobe has been termed a cognitive association area of the brain (Kaufer & Lewis, 1999). Lowered alpha power in the left temporal region is connected with an increase of conscious engagement in a motor task (Haufler et al., 2000; Kerick et al., 2001). Similarly, alpha band activity in the right temporal lobe has been shown to represent visuospatial mapping of movements (Wolf et al., 2015). The premotor area (located in the frontal midline region) is related to movement planning (Kaufer & Lewis, 1999). It has direct connections to various other areas that are essential in movement execution, such as the motor and visual cortex, allowing for communication between brain regions. Many studies make a distinction with respect to the local specificity of alpha power signals. Depending on which brain areas show increased or decreased power in specific frequency bands, one can deduct more specific cerebral processes during movement preparation or execution.

In this thesis, labelling of brain regions is translated to the nomenclature suggested in the American Electroencephalographic Society's "guidelines for standard electrode position nomenclature" (American Electroencephalographic Society, 1994; Chatrian, Lettich, & Nelson, 1985; Jurcak, Tsuzuki, & Dan, 2007; Klem, Lueders, Jasper, & Elger, 1999). The terms T7 and T8 are used for left and right temporal lobes (whereas other research uses T3 and T4), while Fz, F3 and F4 are used for frontal lobe sites. Odd numbers indicate left hemisphere, even numbers right hemisphere locations (for an overview of the most frequently used locations, see Figure 3). These changes in nomenclature in the literature are due to a change from Jasper et al.'s 10-20 system (1958) to a more spatially accurate system (the 10-10 system) over time.

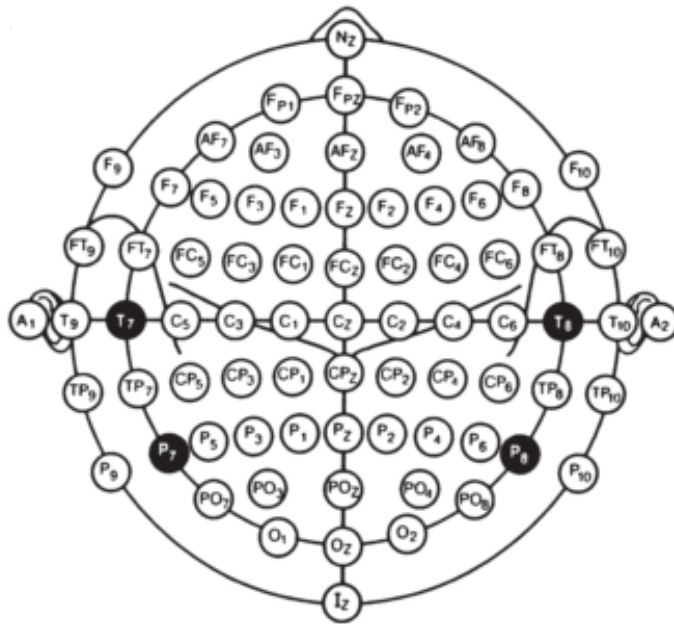


Figure 3. The 10-10 electrode system.

Reprinted with permission from American Clinical Neurophysiology Society (1994, p. 223).

In novices, the preparatory reduction in high-alpha power leading up to a movement has been shown to be more pronounced over the left temporal region, and has been connected to an increase in verbal-cognitive control of a movement (Hauffer et al., 2000). The relative increase of alpha power in the verbal association areas found in experts suggests that verbal-analytical processes may be suppressed during performance (e.g., Hatfield et al., 1984). According to this attribution of cortical activity and cognitive processes, skilled performers employ less verbal-analytical processing during the preparatory period (e.g., aiming period of a shooting task), which may allow a shift to relative engagement of visual-spatial processes in the right hemisphere (Hatfield et al., 1984; Kerick et al., 2004; Wolf et al., 2015).

### Coherence

In order to find out how brain areas cooperate during movement planning and execution, neural coactivation of two areas is investigated by calculating EEG coherence, a quantitative measure of the phase consistency between two signals (Nunez, 1997). Coherence between distinct scalp locations provides a measure of mutual influences or long-range ‘synchrony’ of both regions. Coherence is a function of frequency with values between 0 and 1 indicating how well the signal measured at location  $x$  corresponds to the signal measured at location  $y$  at each frequency. It is calculated using a formula based on

Equation (1), in which  $P_{xx}$  and  $P_{yy}$  represent the power spectral density of signals at location  $x$  and  $y$ , respectively, and  $P_{xy}$  represents the cross power spectral density of  $x$  and  $y$  (e.g., Zhu, Poolton, Wilson, Maxwell, et al., 2011).

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad (1)$$

EEG coherence between regions associated with motor planning (Fz, situated frontal-centrally) and verbal-analytic processing (T7, left temporal lobe) is thought to indicate the involvement of verbal processes in motor performance (Nunez & Cutillo, 1995; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Coherence between Fz and T8 regions represents visuo-spatial processing (Zhu et al., 2010). In the first coherence study in the movement context by Busk and Galbraith (1975) EEG data showed that experts had lower coactivation of verbal-analytic and motor planning regions in the brain during movement execution than novices. Practice was associated with a decrease in coherence at several sites (Oz, C3, C4 and Fz), suggesting that motor learning reduced the demands on task-related information processing (Busk & Galbraith, 1975). Following the seminal work by Busk and Galbraith, several studies comparing novice and expert performers supported the notion that experts display lower coherence and suggested that skilled performance may be associated with a decrease in explicit, verbal processing of the movements (Deeny, Haufler, Saffer, & Hatfield, 2009; Deeny, Hillman, Janelle, & Hatfield, 2003; Gallicchio, Cooke, & Ring, 2016; Reiterer, Hemmelmann, Rappelsberger, & Berger, 2005; Zhu et al., 2010). For example, Gallicchio et al. (2016) found lower frontal-temporal coherence in experts when compared to novices as well as in accurate compared to inaccurate golf putts, confirming the notion that low coherence may represent more efficient processing.

T7-Fz coherence has also been found to increase in conditions of heightened anxiety (Chen et al., 2005; Hatfield et al., 2013). Pressure has been suggested to induce self-focus and lead to conscious control of movements, which is likely to cause increases in explicit, verbal processes (Masters & Maxwell, 2008; Maxwell et al., 2000). Contrary to Chen et al. (2005) and Hatfield et al. (2013), Rietschel et al. (2011) observed a decrease in cortico-cortical communication between the right temporal and the motor planning region when participants performed a line-drawing task during an evaluative condition, which was

accompanied by an improvement in performance. The authors interpreted this as reflective of refinement of cortical communication in visuo-spatial regions, which was functional and led to improved performance rather than the usual pressure-induced decrease in performance. Both findings regarding performance under pressure make sense in light of processing efficiency theory (Eysenck et al., 2007) - pressure may either increase performance by increasing motivation, effort, and efficiency, or it may reduce performance due to heightened self-focus. Zhu et al. (2011) observed higher T7-Fz coherence in participants with a greater propensity to consciously monitor and control their movements (i.e., movement specific reinvestment), which further corroborates that the measure is related to verbal-cognitive motor control. In the same study, Zhu et al. (2011) also found that participants taught by explicit instructions displayed higher T7-Fz coherence compared to participants taught in such a way that they accrued minimal explicit (conscious) knowledge about their movements (implicit motor learning, see Masters, 1992). This indicates that implicit learning decreases the verbal-analytic planning of a movement. Zhu and colleagues (Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011) suggested that EEG coherence between T7-Fz may be a useful yardstick of conscious control in motor performance.

Although findings have on occasion pointed in different directions<sup>9</sup>, the majority of findings investigating skill acquisition report that increasing ability or practice is accompanied by a decrease in coherence between the T7 and Fz regions, which may be explained by a reduction of non-essential cortical activity as a result of skill acquisition (Busk & Galbraith, 1975; Gallicchio, Cooke, & Ring, 2017; Gentili, Bradberry, Hatfield, & Contreras-Vidal, 2009; Gentili et al., 2011; Hatfield et al., 2004; Kerick et al., 2004). Contrary to the left temporal region, increases in coactivation between right temporal and premotor regions (T8-Fz) have been shown to accompany performance improvements in visuospatial aiming tasks (Zhu et al., 2010).

### **Psychomotor efficiency**

As a learner improves at a motor task, the effort involved in performance is reduced even though the requirements remain constant (Rietschel et al., 2014). Similarly to other anatomical properties, the brain is adaptive; as a performer becomes skilled at a task, the

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<sup>9</sup> For example, Kranczioch, Athanassiou, Shen, Gao, and Sterr (2008) found an increase in coherence during practice of a visual power-grip task.

brain increases its efficiency by processing information with less effort (i.e., lower neural activity). During the development of superior performance, brain networks would be expected to adapt to the demands present, becoming refined and more efficient by suppressing non-essential input to the motor planning region (Deeny et al., 2009, 2003; Hatfield et al., 2004; Hatfield & Hillman, 2001). On a neural level, streamlined cortical 'wiring' is an essential constituent of the neural substrate of cognitive skill (Babiloni et al., 2010; Del Percio et al., 2008). *Psychomotor efficiency* is characterised by the co-occurrence of efficient motor output with efficient cognitive processes (i.e., the brain's suppression of non-essential activity, Hatfield & Hillman, 2001). Psychomotor efficiency indicates low conscious processing demands connected to the performed movement and accompanies a higher level of automaticity (Baumeister, Reinecke, Liesen, & Weiss, 2008; Hatfield et al., 2013, 2004; Hatfield & Hillman, 2001). General brain activation patterns, such as higher alpha power (Cooke et al., 2014; Crews & Landers, 1993; Haufner et al., 2000; Hillman et al., 2000), reduced cortico-cortical coherence (Deeny et al., 2009; Hatfield & Hillman, 2001; Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011), regional gating of alpha power (Gallicchio et al., 2017) and event-related potentials (Rietschel et al., 2014) have all been linked to psychomotor efficiency.

Hatfield et al.(2004) suggested that neural efficiency is represented by an appropriate "fit" of neural resources to specific task demands and a consequent reduction in irrelevant processing, which explains why experts (who rely on less verbal-analytic processing for motor control) show reduced T7-Fz (i.e., verbal-motor) coherence compared to novices. However, differences in psychomotor efficiency are not only found between experts and novices, but also among learners with the same level of experience (Hatfield & Hillman, 2001). Rietschel et al. (2014) found that increases in task competence were accompanied by changes in attentional processes (as indexed by the novelty P3, an event-related potential).

Aspects related to psychomotor efficiency (refined attentional processing, absence of effortful cognition, and adaptive and efficient limb movements) resemble those of an implicitly learned movement when compared to explicitly learned movements (for a review on neuroscientific aspects of implicit motor learning, see Zhu, Poolton, & Masters, 2012). Implicitly learned movements may promote higher psychomotor efficiency, measured by lower T7-Fz coherence and higher EEG alpha power at an earlier stage in the learning process. Zhu and colleagues (Zhu et al., 2010; Zhu, Poolton, Wilson, Maxwell, et

al., 2011) corroborated this idea with experimental findings, and promoted neural coactivation as a new yard-stick for psychomotor efficiency in movement learning. Analogy learning shows some similarities with implicit learning techniques, including stable performance under dual tasking and pressure conditions (e.g., Lam et al., 2009a, 2009b; Liao & Masters, 2001). Whether analogy learning works by the same mechanism as errorless or dual task learning paradigms, has not been established yet. Using EEG power and coherence analyses, Chapter 4 investigates psychomotor efficiency in terms of analogy learning.

The aim of this PhD is to determine more closely what affects information processing when analogy instructions are used. In order to investigate the potential underlying mechanisms that lead to benefits in motor performance after analogy instruction, experiments were conducted in which measures of WM capacity, movement specific reinvestment (MSRS), instruction preference, EEG high-alpha power and coherence at frontal and central sites, as well as performance outcomes, during different far-aiming tasks were included.

Chapter 2 represents the first experiment of this PhD. The chapter explored the interaction of analogy instructions, movement specific reinvestment and performance in a field based study in children's analogy learning. This experiment was exploratory and was intended to guide the development of new hypotheses for the following experiments.





## Chapter 2

### Chipping in on the Role of Movement Specific

### Reinvestment in Children's Motor Learning by Analogy<sup>10</sup>

#### Abstract

Little is known about the role of instructions when children acquire skills; however, their ability to process explicit information is a function of working memory capacity that continues to develop throughout childhood. In adult learners, performance at a task learned by analogy is generally comparable to performance after classic, explicit modes of learning, with the added benefit that it remains stable under psychological pressure, in a dual task situation and when complex decisions must be made while moving (whereas performance after explicit learning breaks down). These benefits are likely related to a reduction in cognitive processing required for the adaptation of analogy instructions. In order to investigate whether the same holds for children, we examined children's acquisition of a golf-chipping task that was first practised using explicit instructions, before an analogy was introduced. We tested whether the introduction of the analogy had an effect on performance in regular and dual task conditions, and whether this effect was moderated by (a) the propensity to consciously control the mechanics of one's movements and (b) the type of rules instructed in the explicit practice phase. Thirteen-year-old golf novices performed a pre-test and then learned a golf-chipping task using explicit rules describing one of three different chipping techniques. They performed a set of post-tests (retention, dual task, retention). One week later, an analogy for learning the golf chip was introduced, and an identical set of post-tests was repeated. Movement-specific reinvestment predicted improvement in accuracy (regular task) after the analogy was introduced. However, the different instruction groups did not benefit from the analogy to different extents. Children's motor learning by analogy may depend on personal characteristics of information processing, such as movement specific reinvestment. More research is needed to determine cognitive processes during motor learning in children. Furthermore, due to ongoing cognitive development, children may not be useful participants when investigating the general underlying mechanism of analogy learning.

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<sup>10</sup> Based on: van Duijn, T., Masters, R. S. W. (in preparation). Chipping in on the role of reinvestment in children's motor learning by analogy.

## Introduction

Children's capacity to consciously process complex movement information is a function of their ongoing cognitive development (Baddeley & Hitch, 2000). Working memory (WM), the mental domain for short-term information storage and processing, is accessed differently at different stages of development. Children begin to use verbal processing and phonological loop aspects of WM at about 8 or 9 years of age (Hitch, Halliday, Dodd, & Littler, 1989; Hitch, Woodin, et al., 1989) but Piaget (1953) believed that the ability to formulate and test hypotheses is unlikely to develop until the "formal operational" stage of childhood, which generally begins around the age of 11 years. Processing of movement information during motor performance may differ greatly between different stages in the lifespan, which makes it hard to generalise principles from adults to children. Although cognitive processes accompanying motor learning by adults have been scrutinised for decades, factors that help or hamper children's motor learning are less clear. When investigating cognitive processes during children's motor learning, it makes sense to investigate age groups that are in the process of cognitive development, such as during the early formal operational stage (i.e., 11 -14 years; Piaget, 1953).

When investigating novice motor learning and conscious processing, the use of instructions and their effect on these cognitive processes is of central importance. Coaches in sport often use high levels of explicit correction and instruction (Douge & Hastie, 1993; Ford, Yates, & Williams, 2010). Although providing knowledge about skills is regarded as essential for successful coaching, empirical work has highlighted that more knowledge is not always better (Masters, 1992; Williams & Hodges, 2005). When receiving instructions for motor skill learning, young children, in particular, struggle to process large amounts of explicit, abstract information, preferring instead to deal with images and metaphors (Masters, van der Kamp, et al., 2009). Indeed, evidence suggests that children tend to store information in an implicit form and in visual areas of WM when learning (Hernandez, Mattarella-Micke, Redding, Woods, & Beilock, 2011; Hitch, Halliday, Schaafstal, & Schraagen, 1988). While younger children's memory is better suited to visual stimuli, older children show an increasing use of phonological components when recalling items (Hitch, Woodin, et al., 1989), which may lead to age-related differences in cognitive control of motor performance.

These considerations call for teaching methods that avoid high cognitive load, especially in children. Reducing the amount of explicit information presented to a child at

the earliest stage of learning might lead to a lower load on WM and even have beneficial effects for performance under pressure or when decision making (e.g., Lam et al., 2009a; Masters, 1992; Maxwell et al., 2000). Analogy learning, for example, belongs to a family of implicit learning techniques, which have been shown to reduce the reliance on cognitive information processes during acquisition of a motor skill. Learning by analogy involves the translation of information associated with a well-known (but independent) concept to the concept to be learned (Gentner, 1983). In motor learning, task-relevant rules and knowledge are represented by the analogy. The analogy can be described using a verbal description (e.g., ‘float like a butterfly, sting like a bee’), but it often evokes a visually salient mental image, which the learner can easily relate to and apply. Rules and knowledge that are deemed to be essential for learning the skill properly are covertly present within the analogy and the learner unintentionally uses the rules while implementing the analogy (Liao & Masters, 2001; Masters, 2000).

Liao and Masters (2001) provided empirical evidence in support of Masters’ (2000) argument that analogies can be employed to cause implicit motor learning. Table tennis novices were instructed that they should “strike the ball while bringing the bat up the hypotenuse of a triangle” (p. 310) in order to learn a topspin forehand. No other information was provided about how to achieve the task. After practice, the analogy learners reported minimal explicit knowledge about their movements and their performance of the topspin forehand task was found to be robust in both a dual task situation and under psychological stress. These findings have been replicated on a number of occasions. For instance, analogy learning was shown to lead to stable performance under pressure (e.g., Lam et al., 2009a; Law et al., 2003; Vine et al., 2013), in dual task conditions (Bobrownicki et al., 2015; Jie et al., 2016; Koedijker et al., 2011; Lam et al., 2009b; Poolton et al., 2007b; Tse, Fong, et al., 2016; Tse et al., 2017) and when high-complexity decisions have to be made concurrently (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006; Schlapkohl et al., 2012). Schücker et al. (2010) showed that analogy learning leads to less awareness of skill-related factors under pressure compared to explicit learning. Furthermore, more natural (implicit) behaviours have been found in participants taught by analogy compared to explicit instruction (e.g., naturalness of speech in speech training, Tse et al., 2013; kinematics representing more implicit movement control in basketball, Lam et al., 2009b; and improved inter-limb swimming coordination, Komar et al., 2014). The few studies that did not report significantly better performance under dual task conditions or during pressure manipulations (Koedijker et

al., 2008; Schücker et al., 2013) have been criticised for insufficiently rigorous manipulations (e.g., Lam et al., 2009a).

Few studies to date have investigated analogy learning by children.<sup>11</sup> Tse, Fong, et al. (2016), for example, taught children how to skip a rope either by explicit instructions or by explicit and analogy instructions combined. Analogy learners performed better in normal rope skipping (max. number of skips) and in a multitasking test. The authors concluded that analogy learning may help children's motor learning and potentially reduce cognitive processing requirements when learning.

Analogy instructions have been suggested to reduce conscious, verbal processes related to the control of movements (e.g., Koedijker et al., 2011), so a child's propensity to consciously monitor and control their movements is a factor that may influence the efficacy of analogy instructions. A person's propensity to consciously monitor and control their movements can be assessed using the Movement Specific Reinvestment Scale (MSRS), a 10-item questionnaire developed by (Masters et al., 1993, see also Masters & Maxwell, 2008). The propensity to consciously process movement-related information may be a trait that affects motor performance in children. For example, Ling, Maxwell, Masters, McManus, and Polman (2016) found a weak positive relationship between (subjective measures of) performance and reinvestment in children. Since most studies of adults have showed a negative relationship (e.g., Masters & Maxwell, 2008; Masters et al., 1993), Ling et al. (2015) argued that age might be an important moderator of the relationship between conscious motor processing and motor performance.

Reinvestment may influence how children deal with instructions. Learners with a high propensity to consciously monitor or control their movements may habitually engage in verbal processes such as self-talk or hypothesis testing (Poolton, Maxwell, & Masters, 2004). While explicit, verbal instructions may be more suited to learners with a high propensity for reinvestment as they might be used to verbally control their movements, learners who have a lower propensity for consciously controlling movements may prefer fewer, or less explicit instructions. The degree to which children benefit from analogy

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<sup>11</sup> A handful of other studies found that errorless learning, another form of implicit motor learning had beneficial effects on performance (movement form and accuracy) in a regular task and with a concurrent secondary cognitive task for typically developing children (Capiro, Poolton, Sit, Holmstrom, & Masters, 2013) as well as children with cognitive disabilities (Capiro, Poolton, Sit, Eguia, & Masters, 2013; van Abswoude, Santos-Vieira, van der Kamp, & Steenbergen, 2015).

instructions may be a function of their tendency to consciously control their movements, reflected by movement specific reinvestment.

This field study investigated children's motor performance when they were instructed by explicit rules, but subsequently received an analogy instruction. Performance changes after analogy instruction may reflect changes in cognitive processing related to use of the analogy. The role of propensity for conscious control of movements (measured using the MSRS) in uptake and use of the analogy (i.e., the effect on performance change due to analogy) was explored.

Children were taught by established instructions how to execute a golf chip shot (explicit learning),<sup>12</sup> following which their performance of the shot was assessed in single and dual task tests. Subsequently, they were provided with an analogy instruction that was assumed to encompass the same information as the explicit rules, following which their performance of the shot was again assessed. Performance in a dual task was assumed to be an indirect indicator of conscious processing load (e.g., Poolton et al., 2005). Dual task performance was expected to be inferior to single-task performance after explicit instructions as WM is required to consciously process explicit instructions. However, the dual task effect was expected to dissipate when the analogy was introduced, consistent with reduced demands on WM (Liao & Masters, 2001). A child's propensity for movement specific reinvestment was expected to predict their performance improvement when the analogy was presented to them. Children with a high propensity for reinvestment were expected to benefit less from the analogy (as they might be more habituated to using explicit instructions), whereas children with low reinvestment scores were expected to improve more significantly after the analogy instruction.

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<sup>12</sup> Coaches often use different sets of explicit instructions to teach a golf chip, so we included the three most common techniques for teaching chipping in the explicit learning phase.

## Method

### Participants

Forty-four students from a local school (30 female, 14 male,  $M = 13.02$  years,  $SD = .34$ ) participated in the experiment. The students had no golf experience (i.e., no reported golf lessons, fewer than three games on a golf course, and pre-test error higher than 15m)<sup>13</sup>. Three participants were left handed and 10 showed mixed responses on the Chapman and Chapman (1987) Hand Usage Questionnaire. Informed consent was obtained and parental consent was acquired via an opt-out information letter sent to parents of all participants. Participation in the experiment was part of a sports lesson. Participants were treated in accordance with the local institution's ethical guidelines.

### Apparatus

All participants used a traditional 9-iron golf club appropriate to their height and handedness. Further equipment included standard golf balls, practice balls ( $N = 50$ ), a standard Sony HDR video camera shooting at 920x1080/60p (NTSC) / 50p (PAL) resolution (Sony Corp., Tokyo, JAP), plastic markers and a 1.5m long pole to mark the target. Additional materials included a smart phone with a recorded succession of dual task tones, and speakers. The testing area consisted of a marked starting position with a white target pole positioned 15m from the starting position. A measuring tape was attached to the target pole for measurement of accuracy. A bar was placed horizontally on the ground 4m from the starting position, perpendicular to the chipping direction. A camera was set up facing the participant frontally, and speakers were positioned near the camera, for use during the dual task condition. The practice area was a simple patch of golf green with a rope marking the starting line, another rope marking the 4m-line, and a small pole to mark the target for each participant. Labview Application Builder 2010 (National Instruments, Inc., Austin, TX) was used to create a tone counting task in which high (1000 Hz) and low pitch tones (500 Hz) were played in a randomised order at one-second intervals.

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<sup>13</sup> 15m was set as the minimum average distance from the target in the pre-test, reflecting novice performance; better accuracy was considered to require some experience. See 'Apparatus' for details on how accuracy was measured.

## Procedure

The experiment took place during 4 consecutive weekly PE classes and included a pre-test session (week 1), a practice session (week 2), a pre-analogy session (week 3) and a post-analogy session (week 4). During the pre-test session (week 1), participants provided demographic information and completed the Movement Specific Reinvestment Scale (MSRS, Masters et al., 2005). The MSRS assesses the propensity that a person has to consciously monitor and control their movements. The Scale consists of 10 items such as “I am self-conscious about the way I look when I am moving” and “I am aware of the way my body works when I am carrying out a movement”. Participants indicated to what extent each statement described them using a six-point Likert type scale ranging from ‘strongly disagree’ to ‘strongly agree’ (max. 60 points in total). Participants performed two warm-up trials and a pre-test of 4 trials without instructions. Trials were video recorded and were performed at the participant’s own speed.

Following the pre-test, participants were assigned class-wise to one of three instruction conditions designed specifically to instruct the technique of chipping a golf ball: putting technique (n = 13), ‘y’ technique (n = 12) and bend-and-hold technique (n = 13). In the practice session (week 2), rules specific to each instruction condition (putting technique, ‘y’ technique, bend-and-hold technique) were provided to participants (see Table 1), who then completed 50 practice trials at their own speed. Balls were chipped over a rope placed on the ground at a distance of 4m, and participants were quizzed about the rules at regular intervals to ensure that they attended to them. Rules that were forgotten were repeated to the participant. Participants were also made aware of a video camera filming them, supposedly to control whether they were using the rules in their chipping practice.

Following practice, in a pre-analogy test session (week 3), participants performed a retention test, followed by a dual task test (concurrent tone counting) and then a further retention test. For all of the tests, participants were required to hit the ball so it would land beyond a bar laid out at a distance of 4m and then roll towards the target (a vertical white pole at a distance of 15m). The ball was to stop as close to the pole as possible. Participants completed 4 trials and were allowed to take as much time for each chip as they needed. If a participant failed to hit the ball, the trial was repeated. The dual task test required participants to listen to high pitched (1000 Hz) and low pitched (500 Hz) tones presented in a random order at 1sec intervals, while completing 4 further trials.



They were asked to report the exact number of high-pitched tones that occurred during the test. After each test, participants rested for 2 minutes.

In a post-analogy test session following the pre-analogy test session (week 4), participants were presented with an analogy instruction: “Swing the club head as if it is an airplane landing on a runway that starts where the ball is”. In a test session identical to the pre-analogy test session, participants then performed a retention test, followed by a dual task test (concurrent tone counting) and then a further retention test.

### **Dependent variables and data analyses**

#### *Accuracy*

Performance in the tests was measured as distance to the target in meters (accurate to 2 decimals). A high value indicated poor performance and vice versa. All trials in which the ball did not clear the bar received a standard maximum error score of 22m. Accuracy measurements were obtained for retention 1, dual task and retention 2 in both the pre-analogy and post-analogy test sessions.

#### *Dual task performance*

Counting performance represents the percentage disparity between the reported number of tones and the presented number of tones.

#### *Data analysis*

A one-way analysis of variance (ANOVA) was conducted to compare performance in the three instruction conditions at pre-test, before the instructions had been provided (no differences were expected). In order to examine performance before and after the analogy was presented, a Session (pre-analogy, post-analogy) x Test (retention, dual task, retention) x Instruction condition (putting, ‘y’, bend and hold) repeated measures ANOVA was conducted. Effect sizes were calculated using partial eta squared ( $\eta_p^2$ ) and a significance criterion of  $p < .05$  was adopted. When sphericity was violated, Greenhouse-Geisser corrections were applied. Since a repeated measures ANOVA showed no difference between Retention1 and Retention2 in the pre-analogy session or in the post-analogy session<sup>14</sup>, retention1 and retention2 of each session were averaged into pre-analogy retention and post-analogy retention, respectively, for all further analyses.

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<sup>14</sup> For results of the ANOVA, refer to the results section ‘performance in pre-analogy and post-analogy test sessions’.

Accuracy in the pre-analogy and post-analogy retention tests and score on the Movement Specific Reinvestment Scale (MSRS) were correlated using Pearson product-moment correlations. In order to investigate whether instruction condition moderated the effect of MSRS on pre-analogy or post-analogy performance, two separate regression analyses with moderation were conducted using MSRS as a predictor, performance as a dependent variable, and instruction condition as a moderator.

Table 1. Rules for three instruction conditions

Putting technique	'y' technique	Bend-and-hold technique
General Rule for set-up: Hold the club with your hands close together, the non-dominant hand at the top of the club.		
Stand side-on with your weight even on both feet	Stand with your feet close together, the ball in the middle	Stand with your feet close together, the ball opposite the inside of your left foot
The club should be vertical to the ball	Shift your weight to the left side, angling your club forward	Shift your weight to the left side, angling the club well forward
Backswing distance is equal to through-swing distance	Backswing distance is equal to through-swing distance	Bend your wrists in the backswing
Swing from the arms and shoulders, keeping wrists and elbows locked	Keep the Y shape of your arms and the club locked	Keep your wrists bent on the through swing so that they lead the club head
Lower body and head remain still	Keep your weight on the left side through the strike	Finish with your hands well forward and your weight far left
Analogy: Swing the club head as if it is an aeroplane landing on a runway that starts where the ball is.		

## Results

Figure 4 displays means for accuracy measured as radial error (in meters) over all tests, with a separate line representing each instruction type.

### Pre-test accuracy

One-way analysis of variance (ANOVA) showed no significant accuracy differences between the instruction conditions (putting, 'y', bend-and-hold) prior to presentation of the instructions ( $F(2,41) = .18, p = .84, \eta_p^2 = .01$ ).

### Performance in pre-analogy and post-analogy test sessions

Session (pre-analogy, post-analogy) x Test (retention, dual task, retention) x Instruction condition (putting, 'y', bend-and-hold) repeated measures ANOVA revealed a significant main effect of Session, ( $F(1,41) = 7.4, p = .01, \eta_p^2 = .15$ ). Performance improved between the pre-analogy and post-analogy test sessions. No significant main effect was evident for Instruction condition,  $F(2,41) = .84, p = .44, \eta_p^2 = .03$  or for Test ( $F(2,40) = .25, p = .78, \eta_p^2 = .01$ ). Significant interactions were not evident between Session and Test ( $F(2,41) = .07, p = .94, \eta_p^2 = .00$ ), between Session and Instruction condition ( $F(2,41) = 1.35, p = .27, \eta_p^2 = .06$ ), between Test and Instruction condition ( $F(4,82) = .32, p = .87, \eta_p^2 = .02$ ) or between Session, Test and Instruction condition ( $F(4,82) = .14, p = .97, \eta_p^2 = .01$ ).

These results indicate that the different instruction groups did not benefit from the analogy to different extents. The nonsignificant main effect for Test indicates that the dual task was not effective as a cognitive load, as it did not disrupt performance. Participants made over 31.6% counting errors during the dual task test in the Pre-analogy session (SD = 28%) and 18% (SD = 20%) during the Post-analogy session, indicating that participants may have prioritised motor performance over counting performance. Therefore, these variables will not be analysed further. Since the repeated measures ANOVA showed no effect of Test, both retention tests in each session were collapsed for further analysis.

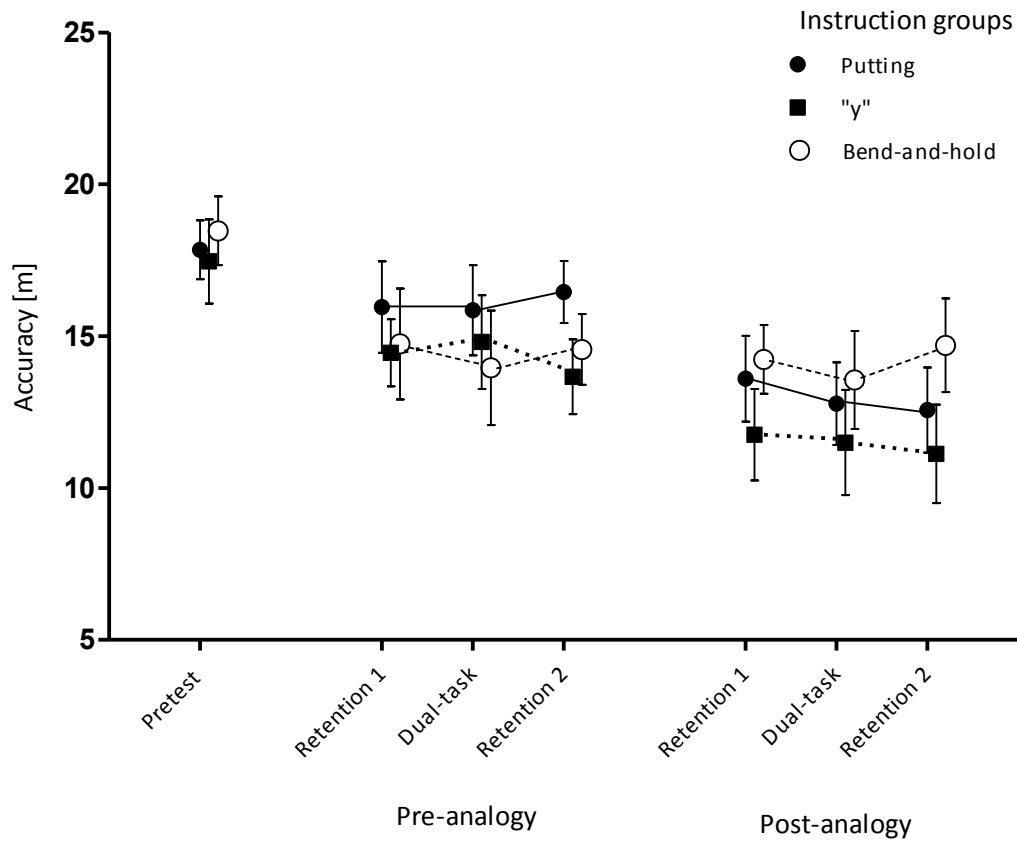


Figure 4. Accuracy measured as mean radial error (m) in each instruction condition during the pre-test and the pre-analogy and post-analogy tests.

Error bars represent one standard error.

### Role of reinvestment in predicting performance

Pearson product-moment correlation analyses were conducted to test the association between score on the Movement Specific Reinvestment Scale (MSRS) and both pre-analogy accuracy and post-analogy accuracy. Dual task performance was not included. The correlation between score on the MSRS and pre-analogy accuracy was negative, but non-significant,  $r(44) = -.09, p = .57$ . The correlation between score on the MSRS and post-analogy accuracy was positive and significant,  $r(44) = .36, p = .018$ , suggesting that higher MSRS scores were associated with less accuracy (greater radial error) after introduction of the analogy. Figures 5 and 6 display a scatter plot of accuracy and MSRS values.

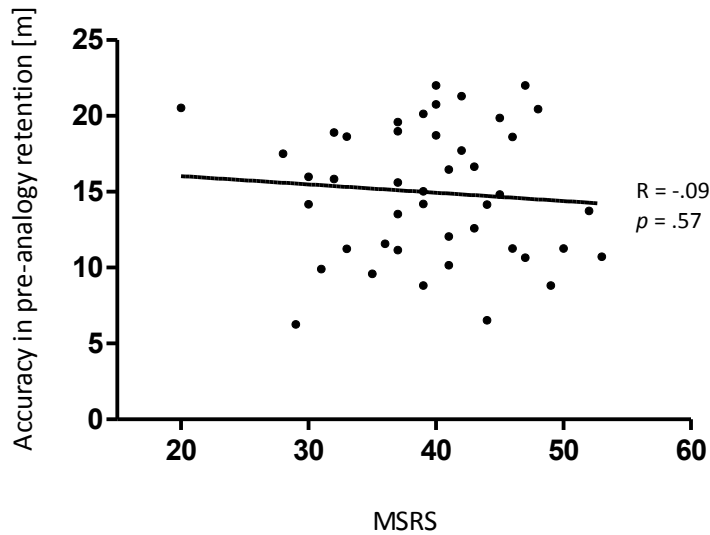


Figure 5. Scatterplot showing score on the Movement Specific Reinvestment Scale (MSRS, x-axis) and pre-analogy retention accuracy (y-axis).

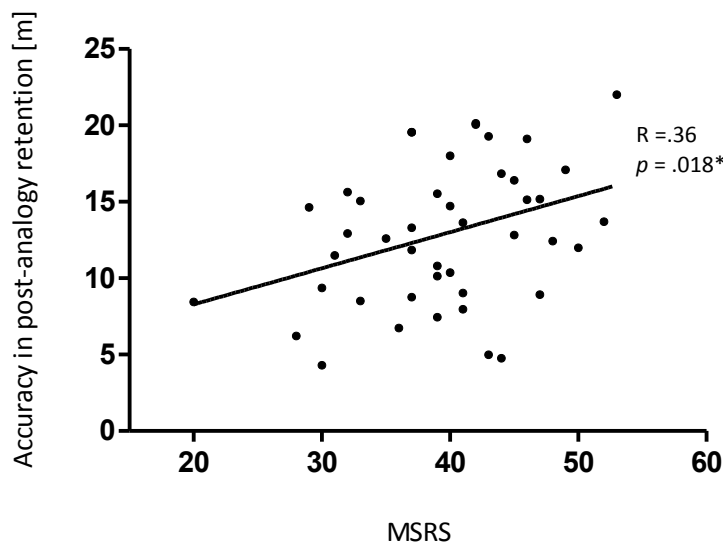


Figure 6. Scatterplot showing score on the Movement Specific Reinvestment Scale (MSRS, x-axis) and post-analogy retention accuracy (y-axis).

To examine whether instruction condition moderated the relationship between MSRS and accuracy in pre- and post-analogy retention, two separate hierarchical multiple regression analyses were conducted (Frazier, Tix, & Barron, 2004). Consistent with recommendations by Frazier et al. (2004), the MSRS variable was standardised so that the mean was 0 and the standard deviation was 1, in order to control for problems associated

with multicollinearity. The categorical moderator variable (instruction condition) was coded using dummy coding (two dummy variables were created for the three categories). Two product terms were created by multiplying the standardised predictor variable (MSRS) by each moderator variable (instruction condition). Variables were entered into a regression equation in a step-wise manner. In the first step, MSRS and instruction condition (as dummy variables) were entered. In the second step, the product terms were entered. A significant  $R^2$  change in the product term would indicate a significant moderator effect. Assumptions for regression analyses were tested and satisfied. Average VIF values were not considerably greater than 1, tolerance values were greater than .17, and the maximum VIF values remained below 6. Durbin-Watson statistics remained in an acceptable range of 1 to 3. The residuals were normally and randomly distributed and none of the cases were found to have a Cook's distance greater than .5. Table 2 shows the results of the analysis at both steps. Nonsignificant interaction terms are also reported as suggested by Brambor, Clark, and Golder (2006).

Results indicated that for pre-analogy accuracy, the first model did not account for a significant amount of variance in the outcome variable,  $R^2 = .06$ ,  $R^2_{adj} = -.01$ ,  $F(3,40) = .81$ ,  $p = .50$ . Adding an interaction term between MSRS and instruction condition did not increase the quality of the model,  $\Delta R^2 = .01$ ,  $\Delta F = .22$ ,  $p = .80$ ,  $F(3,40) = .55$ ,  $p = .74$ .

For post-analogy accuracy, the first model accounted for a significant amount of variance,  $R^2 = .23$ ,  $R^2_{adj} = .17$ ,  $F(3,40) = 3.94$ ,  $p = .015$ . Adding the two interaction terms (one for each dummy variable) did not account for a significantly higher proportion of the variance in accuracy,  $\Delta R^2 = .03$ ,  $\Delta F = .71$ ,  $p = .50$ , although the model remained significant,  $F(3,40) = 2.61$ ,  $p = .040$ .

Table 2. Moderated regression analysis testing the interaction between effects of instruction condition and reinvestment on performance

	Pre-analogy			Post-analogy		
	B	SE B	$\beta$	B	SE B	$\beta$
<b>Step 1</b>						
constant	16.29	1.14		12.78	1.10	
MSRS	-.47	.68	-.11	1.87	.66	.40*
Putt vs. y	-2.20	1.58	-.24	-1.46	1.52	-.15
Putt vs. bend	-1.76	1.70	-.19	2.20	1.63	.22
<b>Step 2</b>						
Constant	16.31	1.18		12.89	1.11	
MSRS	-.60	1.14	-.14	1.20	1.08	.26
Putt vs. y	-2.20	1.63	-.25	-1.63	1.54	-.17
Putt vs. bend	-1.52	1.77	-.16	1.88	1.68	.19
MSRS x y	-.16	1.55	-.02	1.53	1.47	.22
MSRS x bend	1.10	2.00	.11	-.13	1.89	-.01
Step 1, $R^2 = .06$ , $F(3,40) = .81$ , $p = .50$			Step 1, $R^2 = .23$ , $F(3,40) = 3.94$ , $p = .015$			
Step 2, $\Delta R^2 = .01$ , $F(3,40) = .55$ , $p = .74$			Step 2, $\Delta R^2 = .03$ , $F(3,40) = 2.61$ , $p = .04$			

\* Denotes significance at the .05 level.

## Discussion

Children process information differently than adults, due to ongoing development in verbal processing capabilities and other cognitive processes (Hitch, Halliday, et al., 1989; Hitch, Woodin, et al., 1989). These differences have to be kept in mind when interpreting results of the present study.

We did not expect that introduction of an analogy instruction after explicitly instructed practice would facilitate performance of the single task. Research has shown a benefit of analogy instructions on dual task performance while single task performance usually remains unaffected (e.g., Lam et al., 2009b; Liao & Masters, 2001). In this study, however, a significant session effect indicates that participants improved significantly between the pre-analogy and post-analogy session. Children did not practice during that time, so these changes in performance are, in our view, attributable to introduction of the analogy. However, we cannot exclude the possibility of a practice effect, as a major shortcoming of the study's design is the lack of a control group that did not receive the analogy

instruction. While this limits the conclusions we can draw from the data with respect to analogy learning per se, it does not impact on the veracity of our findings regarding the association between movement specific reinvestment and the effect of the analogy.

Improvement in single task performance after introduction of an analogy instruction may indicate that performance became easier after the analogy instruction. We suggest that this might be due to lessened cognitive load by the analogy instruction. The cognitive task of processing and remembering explicit instructions might have been demanding enough to depress performance in the pre-analogy single task. A reduction in performance caused by demands of processing new instructions is realistic and may be due to reduced capacity for movement adjustments (Wulf & Weigelt, 1997). Working memory (WM) is still developing during childhood (e.g. Hitch, Halliday, et al., 1989), and children at the age of 13 may be able to hold fewer items in mind compared to adults. Remembering six complex rules might have led to the same effects in children as a cognitively challenging secondary task would in adults – that is, relatively depressed motor performance due to overloaded working memory. When the analogy was introduced, the necessity to hold each of the six rules in mind became dispensable, since the analogy contained all movement-specific knowledge packaged into one simple unit of information (e.g., Poulton et al., 2006). This would free up WM resources for correction of movements, resulting in better performance.

As shown by Poulton et al. (2005) in a similar design, a cognitively demanding secondary task increases the load on processing resources required for conscious control, leading to performance decrements in explicitly learned tasks, but it does not disrupt motor skill performance of implicit learners. The analogy, if effective as a method of implicit learning in children, was expected to reduce the load on WM and thus allow dual task performance to remain stable. But the underlying assumption that performance in the explicit phase (pre-analogy session) would be disrupted by the secondary task was not confirmed. If performance was already compromised by WM overload (due to processing and remembering of explicit instructions), the effect of adding a second task would be very small. High error rates in the tone counting component of the dual task support this claim, suggesting that either the task was too difficult to perform correctly, or that the children prioritised the chipping task over the counting task, bypassing the bottleneck problem. In a balancing study, Barra, Bray, Sahni, Golding, and Gresty (2006) found that if the concurrent secondary task was too difficult and exceeded attention resources, effort



on one of the tasks was reduced. Often in such cases, preference is given to the motor task, leading to poor performance of the cognitive task (Barra et al., 2006; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). This would effectively explain why motor performance remained almost unchanged in our dual task paradigm.

Not all children benefited equally from the analogy. While there was significant improvement overall, variability in the performance change between pre-analogy to post-analogy sessions remains high. This difference in improvement might reflect differences in personality related to learning and abstract thinking. Analogy learning means mapping features or relations of known situations/tasks to new situations/tasks (Gentner, 1983), which involves abstract thinking processes. The ability to think in abstract terms develops at different speeds during the early-teens (e.g., Masters et al., 2009), which means that some of the 13 year-olds tested in this study were still developing. It is likely, in our view, that only children who were able to reason at a fairly high level of abstraction (i.e., children who were able to map the concept of an airplane landing on a runway to the task of chipping the golf ball to a target) were able to use the analogy effectively (and thus benefit from it). Similarly, personal preference for different types of instructions has been shown to be a predictor of success when using such instructions (for a review, see Cassidy, 2004; but see also Fuelscher, Ball, & MacMahon, 2012 for a summary of the movement context). Therefore it is possible that a higher preference for verbal instructions was an underlying factor determining performance after explicit instructions. This study did not include measures of abstract reasoning ability or instruction preference; however, the wide variability of performance change data (pre-to post-analogy difference) suggests that the analogy was not processed or applied to the movement equally effectively by all children.

A potential predictor of successful from unsuccessful “analogy learners” was found in movement-specific reinvestment. Reinvestment played no role in performance prior to the introduction of the analogy (i.e., when participants were encouraged to use explicit instructions during the chipping task). However, score on the MSRS negatively predicted performance when the students were asked to use the analogy. That is, during post-analogy performance, participants who had a lower propensity for conscious control of their movements displayed more accurate chipping when the analogy was presented. There are two possible reasons for this relationship. First, it is possible that children with a low propensity for conscious control of their movements found it easier to process or

use information that was presented in a less explicit (more visual) form. Such an explanation is consistent with claims that children tend to store information in an implicit form or in visual areas of WM when learning (Hernandez et al., 2011). Children with a high propensity for conscious control of their movements, on the other hand, may have found explicitly presented information easier to deal with and thus not benefited from the analogy. For these children, who presumably relied on higher amounts of explicit information during motor planning and execution (Beilock & Carr, 2001; Gray, 2004; Lewis & Linder, 1997), adding even more information (i.e., the analogy) may not have been helpful (Masters & Maxwell, 2004; Maxwell et al., 2006). A child's tendency to consciously process movement information (reinvestment) may also be indicative of whether that child is used to processing a lot of information. While children with a high reinvestment propensity may be better suited to learning by explicit rules, children with a low propensity may learn better when using less cognitively challenging instructions.

Second, we speculate that WM and its capacity limits might be an important factor underpinning the mechanism by which analogy learning works. Processing of rules during motor performance depends on the capacity of working memory, which, like any aspect of memory, differs among children at different stages of mental development (Baddeley & Hitch, 1974; Bo & Seidler, 2009). WM capacity limits have been shown to affect learning (e.g., categorization tasks and math problem solving, Beilock & Carr, 2005; DeCaro, Thomas, & Beilock, 2008 and motor sequences, Bo & Seidler, 2009). If WM is overloaded, no cognitive resources are available to perform the task at hand, if that task relies on cognitive processes (Masters, van der Kamp, et al., 2009; Rattermann & Gentner, 1998; Richland et al., 2006). This leads to a breakdown in performance of motor and cognitive tasks (Kinrade, Jackson, Ashford, & Bishop, 2010; Laborde, Furley, & Schempp, 2015). Thus, when the number of rules processed by a child reaches their individual capacity limit, adding just one additional instruction can lead to performance breakdown (Baddeley & Hitch, 1974; Marini & Case, 1994). In our study, high reinvesting children, who were more likely to process all the instructions given to them, may have reached their capacity limit in the pre-analogy session. Adding the analogy instruction might have been the straw that broke the camel's back, overloading their WM and leading to performance breakdown. Whether either of these explanations holds in general remains to be investigated.

We don't as yet know the mechanism by which analogy learning works. Chunking has previously been proposed to be the process that underpins the potential benefits of analogy learning (Masters & Liao, 2003). Chunking is a process of compiling discrete "bits" of information into an integrated memory representation. It is a well-documented process in cognitive psychology that naturally occurs during learning of words (Laird et al., 1984; Servan-Schreiber & Anderson, 1990), of concepts (see review by Gobet et al., 2001), or of movement sequences (Sakai et al., 2003; Schlaghecken et al., 2000) also see Poolton & Masters, 2014). Masters and Liao (2003) argued that introducing an analogy should chunk information by integrating complex rules and information about a movement into a single chunk of information; this would place fewer demands on WM resources during motor output (Liao & Masters, 2001; Masters, 2000; Masters & Maxwell, 2004; Masters & Poolton, 2012). Chunking poses a potential framework for the explanation of the benefits of analogy instructions on performance in situations where information processing capacities are restricted (Miller, 1956; Newell & Rosenbloom, 1980). Masters and Liao (2003) argued that analogy should chunk only technical rules that are encapsulated in the analogy, since chunking can only occur when the discrete "bits" of information are relevant or meaningful to the learning process. They taught table tennis novices using two different sets of explicit instructions (a set that was subsumed by the analogy, and a set that was not) and then introduced an analogy to investigate changes in performance. Benefits of analogy learning were apparent (consistent with Liao & Masters, 2001, and others), but only in the group that had learned the task using instructions subsumed by the analogy, which supports the chunking hypothesis. Masters and Liao's (2003) chunking explanation has not been replicated however. Our data does not allow a conclusive answer to the question of chunking, as it does not allow comparison with a control group that did not receive the analogy. Results showed that different instruction groups did not vary in their benefit from analogy learning. Although the rule sets that were instructed to the different groups were expected to naturally differ in "subsumability" (contextual fit with the analogy), this issue was not actively manipulated. As the analogy used in this study was newly developed and has not been tested scientifically before, it is possible that it did not capture all rules that were instructed in either instruction group during the pre-analogy phase. However, the fact that reinvestment predicted how well children improved upon receiving the analogy supports the notion that processing of pre-existing information might play a role in determining how an analogy instruction is taken up and used.

## **Conclusion**

The present study showed that children's motor learning by analogy might depend on personal characteristics of information processing such as propensity for movement specific reinvestment. It also suggests that children may not be ideal participants when investigating general cognitive processes during learning of motor skills. Better insight into the underlying processes of analogy learning may also be gained from objective measures, such as electroencephalography (EEG, measurement of brain activity).

The next chapter (Chapter 3) explores the roles of movement specific reinvestment, working memory capacity and brain activation in the context of uninstructed, early motor performance in adults rather than children. Emphasis was placed on performance without practice or instruction in order to disentangle the roles of these variables without having to accommodate for influences by instruction and practice.



# Chapter 3

## Discerning Measures of Conscious Brain Processes Associated with Superior Early Motor Performance: Capacity, Coactivation, and Character<sup>15 16</sup>

### Abstract

This study explored the relationship between working memory (WM) capacity, cortico-cortical communication (EEG coherence), and propensity for conscious control of movement during the performance of a complex far-aiming task. We were specifically interested in the role of these variables in predicting motor performance by novices. Forty-eight participants completed (a) an assessment of WM capacity (an adapted Rotation Span task), (b) a questionnaire that assessed the propensity to consciously control movement (the Movement Specific Reinvestment Scale), and (c) a hockey push-pass task. The hockey push-pass task was performed in a single task (movement only) condition and a combined task (movement plus decision) condition.

Electroencephalography (EEG) was used to examine brain activity during the single task. WM capacity best predicted single task performance. WM capacity in combination with T8–Fz coherence (between the visuospatial and motor regions of the brain) best predicted combined task performance. We discuss the implied roles of visuospatial information processing capacity, neural coactivation, and propensity for conscious processing during performance of complex motor tasks.

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<sup>15</sup> As previously mentioned, the experiments in this thesis are presented as a series of papers prepared for publication. As a consequence, there is a degree of repetition in the three following chapters – for this, the author apologises.

<sup>16</sup> Based on: van Duijn, T., Buszard, T., Hoskens, M.C.J., & Masters, R.S.W. (2017). Discerning measures of conscious brain processes associated with superior early motor performance: Capacity, coactivation, and character. In: Mark R. Wilson, Vincent Walsh and Beth Parkin (Eds.), *Progress in Brain Research*, Vol. 234, pp. 245-261. Amsterdam: Academic Press.

## Introduction

Mental processes during sport are not easily assessed. Personality characteristics associated with conscious involvement in performance, for example, are often measured subjectively with questionnaires. Capacity to process information is measured using memory and attention tasks, but efficiency in exploiting this capacity can be represented by neural measures, such as cortico-cortical communication between different areas of the brain. Seldom are these approaches considered together when examining the role of the brain in successful performance in sport. Considered in isolation, it is clear that each measure plays an important role in understanding mental processes in sport performance, but evidence of the relationship between the measures is often unclear. Working memory (WM), for instance, provides a “workspace” in which information that is relevant for learning and performance can be manipulated and temporarily stored (MacMahon & Masters, 2002; Maxwell et al., 2003). The amount of information that can be processed is a function of a person’s WM capacity.

Associations have been revealed between WM capacity and various aspects of motor performance. For example, studies have reported positive correlations between WM capacity and performance improvements in motor sequence learning using button-pressing tasks (Bo, Jennett, & Seidler, 2011, 2012; Bo & Seidler, 2009). The tasks typically involve pressing buttons on a keyboard, with a fixed sequence embedded within the movements performed. While these studies have shown that participants with higher WM capacity learn faster, other studies have observed no meaningful correlation between WM capacity and motor sequence learning (Feldman et al. 1995; Kaufman et al. 2010; for discussion of the complex relationship between WM capacity and motor sequence learning, see Janacsek & Nemeth, 2013). WM capacity has also been shown to be positively related to performance during decisive (high pressure) sets in tennis matches (Bijleveld & Veling, 2014) and to shooting accuracy under experimentally induced pressure (Wood et al., 2016). A relationship may exist between WM capacity and movement specific reinvestment, a personality measure of the tendency to consciously process movement related information (Masters & Maxwell, 2008; Masters et al., 1993). For instance, Buszard, Farrow, Zhu, and Masters (2013) reported a positive relationship in a cohort of children and adults. High capacity to process information may provide greater opportunity for a performer to consciously monitor and control their movements; however, Laborde, Furley and Schempp (2015) found that even under psychological

pressure there was no association. Consequently, it is unclear at this stage what the relationship is between WM capacity and movement specific reinvestment.

Our understanding of the relationship between WM capacity, movement specific reinvestment, and motor performance might therefore improve with the inclusion of neurophysiological measures (for a review on recent research using neurophysiological measures in sport performance, see Cooke, 2013). Notably, neural activity can be monitored on-line during execution of experimental tasks at a precise temporal resolution by electroencephalography (EEG). A measure that has become particularly useful for understanding motor performance and learning is EEG coherence—the synchronicity of neural coactivation between different regions in the cerebral cortex. EEG coherence between regions associated with motor planning (Fz, frontal midline) and verbal-analytic processing (T7, left temporal lobe) is thought to indicate the involvement of verbal processes in motor performance (Zhu et al. 2011)<sup>17</sup>. Comparatively, coherence between Fz and the region of the brain associated with visuospatial mapping (T8, right temporal lobe) is thought to indicate the involvement of visuospatial processes in motor performance.

The significance of EEG coherence is revealed by studies investigating skilled performers. In particular, experts display lower coherence between the T7 and Fz regions during movement execution compared to novices (Deeny et al., 2003), suggesting that skilled performance is associated with a decrease in explicit, verbal processing of the movements. T7-Fz coherence has also been found to increase in conditions of heightened anxiety (Chen et al., 2005), and Zhu, Poolton, Wilson, Hu, et al. (2011) observed higher T7-Fz coherence in participants with a greater propensity to consciously monitor and control their movements (i.e., movement specific reinvestment). Zhu et al. (2011) also found that participants taught by explicit instructions displayed higher T7–Fz coherence compared to participants taught in such a way that they accrued minimal explicit (conscious) knowledge about their movements (implicit motor learning; Masters, 1992). Zhu, Poolton, Wilson, Maxwell and Masters (2011) concluded that EEG coherence between T7 and Fz is a useful yardstick of conscious control in motor performance. In an

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<sup>17</sup> In this paper, all labelings are translated to the nomenclature suggested in the American Electroencephalographic Society's "guidelines for standard electrode position nomenclature" (American Electroencephalographic Society, 1994; Chatrian et al., 1985; Jurcak et al., 2007; Klem et al., 1999). The terms T7 and T8 are used for left and right temporal lobes, while Fz, F3, and F4 are used for frontal lobe sites. Odd numbers indicate left hemisphere, even numbers indicate right hemisphere locations.



earlier study, however, Zhu et al., (2010) found that increases in T8–Fz coherence accompanied performance improvements in a visuospatial aiming task, so the information processing required by the task is likely to be an important factor in determining the relationship between T8–Fz or T7–Fz coherence and motor performance.

More recently, the relationship between EEG coherence and WM capacity was investigated in a novel tennis task (Buszard, Farrow, Zhu, & Masters, 2016). Visuospatial WM capacity was negatively correlated with T7–F3 coherence (see Footnote 17), while verbal WM capacity was positively correlated. Buszard and colleagues (2016) speculated that high verbal WM capacity increases the likelihood of a person learning a motor skill explicitly, but high visuospatial WM capacity facilitates nonverbal or implicit motor learning. However, neither WM capacity nor EEG coherence correlated with performance. The purpose of our study was to examine WM capacity, movement specific reinvestment, and EEG coherence during novice performance of a hockey push-pass. A hockey push-pass is a complex motor skill that requires coordination of many degrees of freedom. We were interested in uncovering whether individuals with high WM capacity were better at performing a complex novel motor task. Early motor learning is dominated by effortful processing of information, much of which is conscious, as suggested by stage models of learning (e.g., Fitts & Posner, 1967). High WM capacity is likely to facilitate conscious control of a novice’s movements, so we expected a positive association between WM capacity and performance of the hockey push-pass. We also were interested to know whether WM capacity was associated with the propensity for conscious engagement in performance and/or with concurrent EEG coherence. We expected to find significant correlations between WM capacity and measures of visuospatial and/or verbal–cognitive engagement in the motor task (i.e., T7–Fz and T8–Fz coherence), and between WM capacity and movement specific reinvestment. Performance was also assessed in a more ecologically relevant task in which participants completed the push-pass while making a decision about who should receive the pass (referred to as a combined task). The combined task was expected to increase the demands on the participant, heightening the need for efficient information processing. We therefore expected WM capacity and EEG coherence during the movement only (i.e., single task), which potentially is a marker of efficient motor processing (e.g., Hatfield, Haufler, Hung, & Spalding, 2004), to be associated with performance during the combined task.

## Method

### Participants

Forty-eight novices to hockey (mean age = 21.31 years, SD = 4.96) with normal or corrected-to-normal vision and no movement impairments participated in the study. Participants were recruited from the institution and were incentivized to participate with cafeteria vouchers (value NZD10). Participants with more than 20h of experience were excluded from the study. Ethical permission for the study was received from the Faculty Ethical Committee of the institution. Participants all provided informed consent.

### Materials

Standard field hockey sticks of 92.7 cm (36.5 in.) length were used, and hockey balls were replaced with standard Wilson® tennis balls. The laboratory floor was covered with artificial golf turf. A line on the floor marked the starting position of the ball; a red circle on the wall with concentric circles at 10 cm intervals provided a target for the passes. The distance from the starting position to the target was 340cm. Performance was measured as distance from the target centre and was obtained by manual analysis of video footage from a Sony RX10 pi camera focused on the target. EEG equipment included a wireless EEG/tDCS transmitter, a set of four measuring and two reference electrodes, conducting gel and electrode contact stickers (Neuroelectronics, ESP). The system was connected to a desktop computer using Neurosurfer software for recording (Neuroelectronics, ESP). EEG activity was recorded from six silver/silver chloride (Ag/AgCl) electrodes on the scalp positioned using different sized neoprene caps with predefined holes. Two reference electrodes were placed at the earlobe using a clip. If the earlobe was too small to hold the clip, two sticktrodes were attached to the left mastoid. Caps and electrodes were adjusted to be consistent with a subset of the 10–10 system (Chatrian et al., 1985) and were carefully checked by two technicians before the start of the experiment. Signals were amplified at a sampling rate of 500Hz with 24-bit resolution and 0–125Hz bandwidth. Measurement noise was under 1  $\mu$ V RMS. Prior to commencing the task, impedance needed to reach a satisfactory level (below 15k $\Omega$ ). This was achieved by adjusting electrode positions, the participant's hair and the amount of electrolyte gel. The pre-session criteria were constant across all participants. The pre-session criteria required participants to (a) wash their hair on the evening/morning before testing and (b) not consume caffeine in the 2h preceding testing. A thorough check of the impedances

ensured good quality contacts at all times. Baseline EEG data were collected prior to commencing the experiment. This took place while the participant was seated and not moving during 120s. The first 60s were recorded with the participant's eyes open (blinks were not suppressed), while the second 60s required the eyes to be closed.

### **Procedure**

Participants arrived at the laboratory and completed a demographics sheet plus the Movement Specific Reinvestment Scale (MSRS - Masters & Maxwell 2008; Masters et al. 2005). The MSRS assesses a person's propensity to consciously monitor and control their movements. The scale consists of 10 items and includes items such as "I am self-conscious about the way I look when I am moving" and "I am aware of the way my body works when I am carrying out a movement." Participants indicated to what extent each statement describes them using a six-point Likert-type scale ranging from "strongly disagree" to "strongly agree." The scale has been shown to have a high internal and test-retest reliability (Masters & Maxwell, 2008). After completing the questionnaires, participants were fitted with the Neuroelectrics cap and the EEG electrodes were attached. They then completed a computerised test of WM capacity. The test was an adapted version of the rotation span test (Oswald, McAbee, Redick, & Hambrick, 2015; Shah & Miyake, 1996). The to-be-remembered stimuli in this task were images of arrows that could be differentiated by (a) their length (long or short) or (b) their angle of rotation. Participants were required to remember and recall the specific arrows that were presented (i.e., the length and the angle of rotation) at the conclusion of each trial. After each arrow was presented, participants had to perform a distraction task during which they had to judge the orientation of a letter on the screen.

Participants then performed a hockey push-pass task in two conditions: single task and combined task, with single task always performed first. Both tasks involved one block of 20 trials. The *single task* required participants to push-pass the ball as accurately as possible to the target on the opposing wall. Prior to completing the task, participants were shown an animation that illustrated how the task was to be completed. For the *combined task*, 20 images of hockey players ( $n = 3$ ) standing in different positions were projected onto the opposing wall. Two players were wearing black shirts, and one was wearing an orange shirt. Arrangements of the players varied, with one or two players in the foreground (85% of life size) and the others in the background (70% of life size). Participants were informed that they were a member of the black team and were to push-

pass the ball as quickly and as accurately as possible toward the hockey stick of the player who, in their opinion, was in the best position to receive the ball. Presentation of each image was preceded by a brief countdown on a blank background.

### **Dependent variables and data analysis**

#### *Dependent variables*

Measurements for both performance variables were made using video recordings collected at normal speed (30fps) from the Sony camera focused on the wall. Video clips were played frame by frame in order to determine the time when the ball contacted the wall. *Single task accuracy* was represented by mean contact distance from the target during the single task test (20 trials). *Combined task accuracy* was represented by mean contact distance from the target chosen by the participant. Greater distances therefore represent worse accuracy.

WM capacity measures were calculated via the program “R” using a software script provided by Stone and Towse (2015). The measure *WM capacity* reflects the maximum number of items a participant remembered correctly. Although other measures exist, this variable was considered prior to data collection to be the most informative for our study, as it represents the maximum capacity, rather than general WM ability (Stone & Towse, 2015). Score on the MSRS was calculated by summing the Likert-scale responses, leading to a cumulative range of 10–60 points.

#### *Data reduction*

Raw EEG signals were first filtered at 1–30Hz, and a notch filter was added to exclude 50Hz line noise. Signals were then resampled at 256Hz. Data were reduced to 4-s epochs preceding movement initiation in each trial. Epochs were split into 0.25-s trials for artefact removal. Blinks and eye movements are characterised by high potentials (Boudet, Peyrodie, Gallois, & Vasseur, 2006), so eye artefacts were excluded using an extreme measures approach via EEGLAB. Trials containing signals above 60mV were discarded.

An average 174.70 (SD = 69.33) trials per participant were retained. A fast Fourier transform with a Hamming window taper, 50% overlap with a resolution of 0.49 Hz, was applied. EEG high-alpha (10–12 Hz) power was calculated over the 0.25-s epochs (e.g., Deeny et al. 2003) and averaged for the 4-s epochs preceding each trial. The EEG analyses in this study focused on the high-alpha band. Activity in this bandwidth indicates medium-range cortico-cortical communication and represents task-specific attention processes

(Smith et al. 1999; for a review see Klimesch, 1999). Coherence was analysed for T7–Fz and T8–Fz regional combinations separately, as these areas represent verbal-analytic (T7), visuospatial (T8), and motor planning (Fz) regions (Kaufer & Lewis, 1999; Haufler et al. 2000; Kerick et al. 2001). Matlab scripts were used to calculate EEG outputs. The processing and analysis steps described earlier were implemented with the EEGLAB toolbox (Delorme & Makeig, 2004).

### *Statistical analyses*

Associations between WM capacity, movement specific reinvestment, and EEG coherence were investigated using Pearson’s product-moment correlation coefficient. Regression analyses were conducted to predict performance in both the single task and the combined task. The predictor variables included WM capacity, T7–Fz coherence, T8–Fz coherence, and score on the MSRS. A backward elimination approach was chosen for the regression analyses, with the aim of unpicking the relationships between different measures of conscious processes and performance. Values collected during the single task were also used to predict performance in the combined task. Moderated regression analysis was employed to investigate the joint influence of WM capacity and T8–Fz coherence on performance in the combined task. Alpha value for statistical significance was set to 0.05.

## **Results**

### **Correlation between EEG coherence and performance variables**

Means, standard deviations, and Pearson product-moment correlation coefficients for predictive and outcome variables are presented in Table 3. WM capacity correlated significantly with single task accuracy and combined task accuracy. The relationship was negative, suggesting that larger WM capacity was associated with better push-pass accuracy. A significant correlation was also found between WM capacity and T8–Fz coherence, with larger WM capacity associated with higher coherence. However, WM capacity was not associated with T7–Fz coherence. No significant correlations were observed between push-pass accuracy and T7–Fz or T8–Fz coherence. MSRS score was not significantly correlated with any variable.

Table 3. Means, standard deviations and Pearson Product-Moment correlation coefficients for predictive and outcome variables

	Variable	M	SD	1.	2.	3.	4.	5.
1.	Single task	17.64	8.00	-				
2.	Combined task	25.48	8.24	.26	-			
3.	WM capacity	2.90	0.83	-.33*	-.32*	-		
4.	MSRS	38.08	8.23	.07	.13	-.08	-	
5.	T7-Fz	0.46	0.14	-.03	.12	.24	-.03	-
6.	T8-Fz	0.42	0.15	-.25	.14	.33*	.07	.73**

Note: \*  $p < 0.05$ , \*\*  $p < 0.01$ .

### Predicting single task accuracy

First, a regression analysis was conducted to determine whether gender influenced performance. Gender was not a significant predictor of single task accuracy,  $R^2 = 0.01$ ,  $F(1,47) = 0.53$ ,  $p = 0.47$ , and was therefore not included as a predictor variable in the subsequent analyses. Stepwise regression analysis (backward method) was used to predict single task accuracy. The predictor variables included WM capacity, MSRS score, T7–Fz coherence, and T8–Fz coherence. The threshold value for the predictor variables was  $p = 0.05$  for inclusion and  $p = 0.10$  for exclusion. Results of the regression analysis are presented in Table 4. Model 1, including all variables, was not significant. Consequently, MSRS, which had a  $p$ -value greater than 0.10, was removed to leave a significant model (Model 2). Removal of T7–Fz coherence ( $p > 0.10$ ) further refined the model (Model 3). Finally, removal of T8–Fz coherence ( $p > 0.10$ ) yielded a model (Model 4) in which WM capacity was the only significant predictor of single task accuracy, accounting for 8.8% of the variance (see Figure 7).

Table 4. Regression analyses predicting single task performance

	Model 1		Model 2		Model 3		Model 4	
$R^2_{adj}$	.11		.12		.09		.09	
$p$	.058		.032		.043		.023	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
MSRS	.09	.541	-	-	-	-	-	-
T7-Fz coherence	.34	.100	.33	.110	-	-	-	-
T8-Fz coherence	-.42	.051	-.40	.058	-.16	.277	-	-
WM capacity	-.26	.080	-.27	.066	-.27	.070	-.33	.023

Beta ( $\beta$ ) and  $p$ -values for predictor variables, and  $R^2_{adj}$  values and  $p$ -values for each model.

Abbreviations: WM, working memory; MSRS, Movement Specific Reinvestment Scale score.

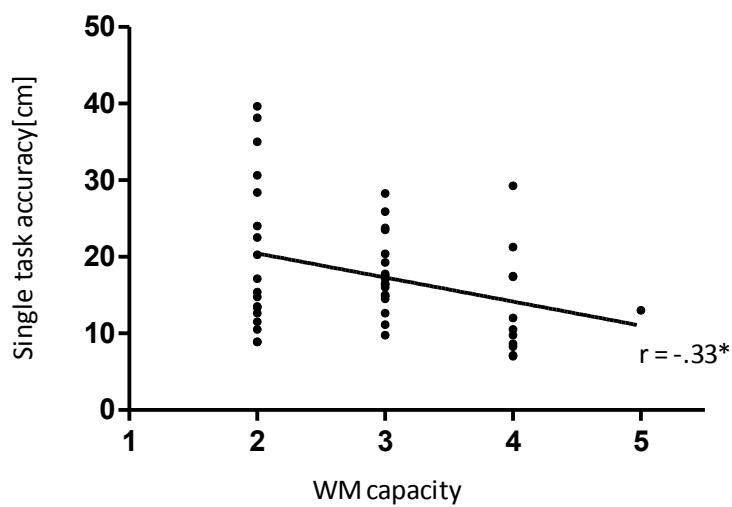


Figure 7. The relationship of WM capacity with performance in the single task.

\* indicates that the variable on the x-axis was a significant predictor of the y-variable in the regression analysis.

### **Predicting combined task accuracy**

Stepwise regression analysis was conducted to predict combined task performance using WM capacity, MSRS score, T7–Fz coherence, and T8–Fz coherence as predictor variables. Results of the analysis are presented in Table 5. A first model, including all variables, was not significant. Consequently, T7–Fz coherence and MSRS ( $p$ 's > 0.10) were eliminated from Models 1 and 2, respectively, to yield a final model (Model 3) in which WM capacity and T8–Fz coherence were an optimal combination of predictors, explaining 13.4% of the variance in combined task performance. Higher WM capacity was associated with more accurate push-pass performance (see Figure 8). Higher T8–Fz coherence during the single task (i.e., movement only) appeared to be associated with less accurate performance during the combined task (movement plus decision); however, the association fell short of significance (see Figure 9).

Moderation analysis was conducted to investigate whether T8–Fz coherence moderated the effect of WM capacity on combined task performance. Variables were entered into the regression equation in a stepwise manner. In the first step, the predictor variable (WM capacity) and potential moderator variable (T8–Fz coherence) were entered. In the second step, a product term created by multiplying WM capacity by the standardised T8–Fz coherence variable was entered. A significant change in  $R^2$  for the product term would indicate a significant moderator effect. Assumptions for regression analysis were tested and satisfied. Results of the analysis are presented in Table 6. A significant moderation effect was not found ( $R^2$  change = 0.01,  $p$  = 0.57).



Table 5. Regression analyses predicting combined task accuracy

	Model 1		Model 2		Model 3	
$R^2_{adj}$	.10		.12		.13	
p	.073		.035		.015	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
T7-Fz coherence	.04	.844	-	-	-	-
MSRS	.08	.571	.08	.580	-	-
T8-Fz coherence	.24	.269	.27	.073	.28	.062
WM capacity	-.40	.009	-.40	.008	-.41	.006

Beta ( $\beta$ ) and p-values for predictor variables, and  $R^2_{adj}$  values and p-values for each model.

Abbreviations: MSRS, Movement Specific Reinvestment Scale score; WM, working memory.

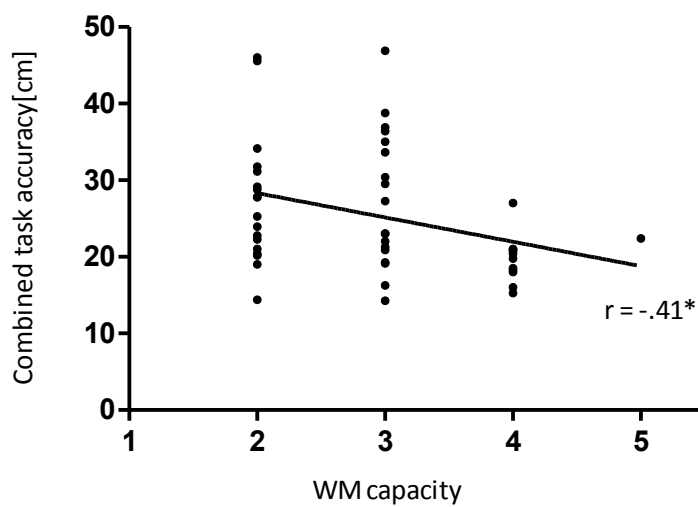


Figure 8. The relationship of WM capacity with performance in the combined task.

\* indicates that the variable on the x-axis was a significant predictor of the y-variable in the regression analysis.

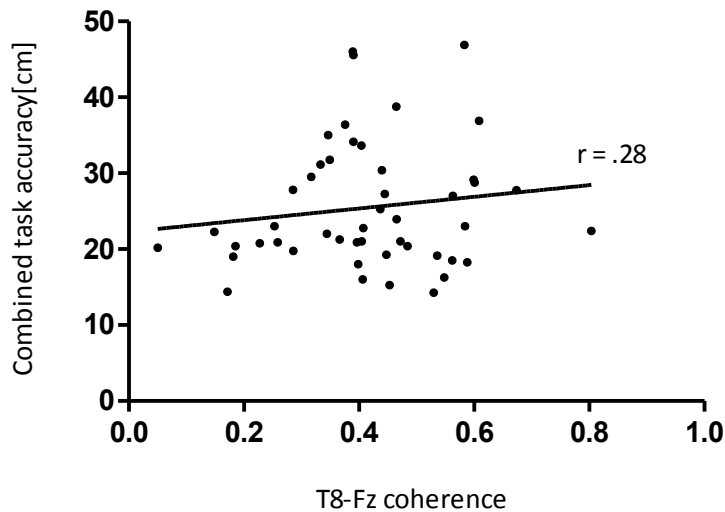


Figure 9. The relationship of EEG T8–Fz coherence with performance in the combined task.

Table 6. Moderation analysis for interaction of WM capacity and T8-Fz coherence in predicting combined task performance

	<i>B</i>	<i>SE B</i>	$\beta$	<i>R</i> <sup>2</sup> <i>Change</i>
<b>Step 1</b>				
WM capacity	-4.08	1.43	-.41*	
T8-Fz coherence	15.21	7.95	.28	.17
<b>Step 2</b>				
WM capacity x T8-Fz coherence	-.52	.90	-.08	.01

Note: \*  $p < 0.05$ .

## Discussion

We explored mental processes associated with performance of a complex far-aiming task by novices, using measures of working memory (WM) capacity, cortico-cortical communication (EEG coherence), and the propensity for conscious control of movement (MSRS).

WM capacity was positively associated with T8–Fz coherence. Our measure of WM capacity uses an adapted version of the Rotation Span task, which involves processing of visuospatial information. People with high visuospatial information processing capacity may be more likely to process their movements visuospatially, culminating in high T8–Fz coherence (i.e., coactivation between visuospatial and motor planning regions of the

brain). Buszard et al. (2016), however, reported a negative association between visuospatial WM capacity and T8–F4 coherence (F4 borders the Fz region). Further work is clearly required to disentangle the functional differences at a neural level.

WM capacity was also positively correlated with accuracy in both the single and combined tasks. For single task accuracy, backward regression analysis revealed a final model that included only WM capacity. For combined task accuracy, backward regression analysis revealed a final model that included WM capacity and T8–Fz, although T8–Fz coherence contributed in the model nonsignificantly. Moderation analysis showed that WM capacity and T8–Fz coherence did not interact to predict performance in the combined task. While WM capacity was positively associated with performance, T8–Fz displayed a trend toward a negative association with performance.

Our data imply that visuospatial WM capacity plays a substantial role in predicting early motor performance. Individuals with larger WM capacity may possess an advantage when solving motor tasks, but typically this has been attributed to verbal rather than visuospatial WM capacity. Maxwell et al. (2003), for example, argued that verbal WM is used to process movement specific information and to correct previous errors in performance. In support of this claim, Lam, Masters and Maxwell (2010) found that people responded more slowly to an audible tone (the probe reaction time paradigm) if they previously had made an error when golf putting. Errors during movement typically are resolved by constructing and testing hypotheses about the most effective way in which to move, which is likely to load verbal rather than visuospatial WM. However, error correction in far-aiming tasks, such as a hockey push-pass, may be more visual than verbal. During a push-pass, the performer attempts to strike a ball toward an often moving target, which can be many meters away. Error correction in this type of task requires the integration of visuospatial information with effector movements (Vickers, 1996), which is likely to make demands on visuospatial WM capacity. Other evidence supports the role of visuospatial WM capacity in early learning. For example, Anguera, Reuter-Lorenz, Willingham and Seidler (2010) found that rate of learning at early stages of motor adaptation depended on visuospatial WM ability and Bo and Seidler (2009) showed that greater visuospatial WM capacity was associated with more rapid learning of a motor sequence.

The role of T8–Fz coherence in predicting early motor performance is less clear in this study. The contribution of T8–Fz coherence to the final model predicting combined task

performance leads us to speculate that people who display low T8–Fz coherence when first performing a single task may have a visuospatial processing advantage that allows them to cope better when decision-making during movement. Low T8–Fz coherence during single task performance might, for example, reflect more efficient visuospatial processing of movement. General brain activation patterns, such as higher alpha power (Cooke et al., 2014; Crews & Landers, 1993; Haufler et al., 2000; Hillman et al., 2000), have been linked to efficient movement processing (i.e., psychomotor efficiency), as have measures of cortico-cortical coherence (Deeny et al., 2009; Hatfield & Hillman, 2001). Hatfield et al. (2004) suggested that neural efficiency is represented by an appropriate “fit” of neural resources to specific task demands and a consequent reduction in irrelevant processing, which explains why experts (who rely on less verbal-analytic processing for motor control) show reduced T7–Fz (i.e., verbal-motor) coherence compared to novices. Zhu, Poolton, Wilson, Hu, et al. (2011) also argued that low coherence between the verbal processing and the motor planning regions of the brain (T7–Fz) during performance of a surgical task represented neural efficiency. In far-aiming tasks, however, activity in visuospatial brain areas may be more indicative of error correction through visuomotor mapping, so lower coherence between the visuospatial and the motor planning areas (T8–Fz) in some novices may reflect relative neural efficiency in this task.

It is of interest that movement specific reinvestment did not appear to play a role in early motor performance in this study. Score on the Movement Specific Reinvestment Scale (MSRS) is considered to be a measure of conscious, verbal engagement in the process of moving, and previous work has revealed an association between score on the MSRS and verbal WM capacity (Buszard et al., 2013). However, given that visuospatial processing may be particularly important in the push-pass, score on the MSRS may be an inappropriate measure of the mental processes engaged during push-pass performance.

### **Limitations**

A difference between the methodology of this study and Buszard et al. (2016) lies in the electrode locations used for coherence analysis. A change in electrode location by a few centimeters can have a significant influence on the outcome, and therefore interpretation of measurements (Jasper, 1958). Buszard et al.’s study used a site slightly temporal to the premotor region (F3 and F4, respectively), while we used the primary motor cortex (Fz) for both coherence calculations. An effect of hemispheric asymmetry would influence the results of both studies differentially. Intercorrelations between T7–Fz and T8–Fz

coherence in this study ( $r = 0.734$ ) show how closely related these variables are, while no strong correlation between the two measurements was evident in the Buszard et al. (2016) study ( $r = -0.03$ ).

### **Conclusion**

Far-aiming tasks require visuomotor mapping. Capacity to process visuospatial information, rather than verbal information, may therefore be an important contributor to the ability to perform novel motor tasks that involve far aiming. When discerning measures of conscious brain processes associated with superior early motor performance, it appears that, in some cases at least, capacity trumps coactivation and character.

Now it is of interest to determine the relationship between variables of cognitive processing and performance when instructions are provided. In order to determine whether analogy instructions promote psychomotor efficiency, Chapter 4 tested participants' brain activity (EEG power and coherence at verbal, visual and motor processing sites) before and after practice using analogy instructions and compared them to uninstructed and explicitly instructed groups. Finding out whether analogy instructions increase the efficiency of verbal or visual processes during movement preparation is an important step in determining potential mechanisms that underlie analogy motor learning. A separate set of data collected during the experiment described in Chapter 3 was analysed in Chapter 4.

## Chapter 4

# Analogy Instructions Promote Efficiency of Cognitive Processes during Performance of a Push-pass in Field Hockey<sup>18</sup>

### Abstract

Analogy instructions may promote effective skill acquisition by providing movement specific information that can be processed as a single, meaningful unit, rather than as separate 'bits' of information (Liao & Masters, 2001; Masters, 2000). Behavioural evidence suggests that information processing associated with motor performance following learning by analogy is less effortful than following learning by explicit instructions, with reduced verbal-analytical involvement in movement control (Lam et al., 2009b). These attributes are presumably markers of psychomotor efficiency (Hatfield & Hillman, 2001), which is characterised in the brain by greater high-alpha power in the left hemisphere (Hillman et al., 2000) and reduced coactivation between the verbal processing (T7) and motor planning regions (Fz, Hatfield & Hillman, 2001) during motor performance.

This experiment was designed to test whether analogy instructions promote higher psychomotor efficiency. We expected to see greater changes in left-temporal high-alpha power and T7-Fz coherence following analogy instructions compared to explicit instructions or no instructions. Novices practiced a hockey push-pass task (n=128 repetitions), using an analogy instruction, explicit instructions or no instructions (control). Push-pass accuracy during a combined task (passing coupled with decision-making) was significantly better following the analogy instruction, which suggested that information processing was less effortful. Left-temporal EEG high-alpha power was significantly higher in the analogy condition, supporting the hypothesis that psychomotor efficiency would be promoted by an analogy instruction; but T7-Fz coactivation was not significantly different among the conditions.

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<sup>18</sup> Based on: van Duijn, T., Hoskens, M. C. J., Crocket, H., Masters, R. S. W. (under review). Analogy instructions promote efficiency of cognitive processes during performance of a push pass in field hockey. *Biological Psychology*.

It is possible that the analogy instruction influenced verbal aspects of information processing without impacting on efficiency of motor planning. Consequently, an analogy instruction may promote cognitive, rather than psychomotor, efficiency by encouraging a different mode of information processing than explicit or discovery learning.

## **Introduction**

Implicit motor learning research has shown that during early stages of learning it can be advantageous to accrue only a minimum of declarative information about the movement to be learned (Masters, 1992). Various forms of implicit motor learning have been developed, including error-reduced learning (Maxwell et al., 2001), dual-task learning (Maxwell et al., 2000) and analogy learning (e.g., Liao & Masters, 2001). Benefits have been reported during performance under pressure (Hardy et al., 1996; Koedijker et al., 2007; Lam et al., 2009a, 2009b; Liao & Masters, 2001; Masters, 1992), fatigue (Masters, Poolton, & Maxwell, 2008; Poolton et al., 2007a) and when decisions have to be made during performance (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006). Performance of implicitly learned tasks has also been shown to remain stable when a cognitively challenging second task is completed concurrently (Koedijker et al., 2011, 2007; Lam et al., 2009b; Masters, Lo, et al., 2008; Maxwell et al., 2001; Poolton et al., 2006).

Analogy learning is a form of motor learning in which an analogical instruction is presented instead of declarative rules about the movement. An analogy conveys information about a complex construct or task (in this case, a motor task) by way of comparison with a simple, familiar concept, often in the form of an image. Liao and Masters (2001) provided empirical evidence that analogy learning benefits performance similarly to other methods of implicit motor learning (e.g., errorless learning, secondary task learning). Table tennis novices were instructed that in order to learn a topspin forehand they should “strike the ball while bringing the bat up the hypotenuse of [a] triangle” (Liao & Masters, 2001, p. 310). No other information was provided. Performance of participants instructed by analogy was robust both in a dual task situation and under psychological stress, compared to participants instructed explicitly with rules for how to hit a topspin forehand. Other research has since confirmed that when a skill is learned by analogy instead of declarative rules, performance remains stable under pressure (e.g., in an adapted basketball task, Lam et al., 2009a), when high-complexity decisions have to be made concurrently (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006), and in dual task settings (Lam et al., 2009b).

The exact mechanism by which analogy instructions influence motor learning and performance remains ambiguous. Donnelly and McDaniel (1993) showed that analogy learning leads to accrual of less verbalisable (but more inferential) knowledge about scientific concepts, which is one of the defining characteristics of implicit learning (Berry & Broadbent, 1984; Hayes & Broadbent, 1988). Liao and Masters (2001) found that analogy learners accrued only a small amount of explicit knowledge about the motor task that they were learning. Similarly, Schücker, et al. (2010) showed that analogy learning was associated with less awareness of skill-related factors under pressure compared to explicit learning. Worry (under pressure) or a cognitive secondary task can disrupt motor planning and performance if the limited capacity of working memory (WM), the mental domain for short-term storage and information processing, is reduced by a cognitive load, however, experimental studies suggest that motor skills that are acquired implicitly do not rely on WM to the same extent as skills acquired explicitly; processing of these skills is more efficient and performance is less likely to be disrupted (e.g., Maxwell et al., 2003; Poolton et al., 2005). It has been argued that analogy learning promotes efficient information processing by packaging movement-specific information in a single, meaningful unit, which reduces reliance on WM (Liao & Masters, 2001; Masters, 2000; Masters & Liao, 2003). However, little evidence exists to support this claim.

Highly efficient cognitive processing is a trademark of expert performance. Hatfield and Hillman (2001) used the term psychomotor efficiency to describe refined allocation of neural resources, absence of effortful cognition (based on brain activity measures), and adaptive, efficient movements by experts. Psychomotor efficiency may reflect less reliance on explicit, verbal information during preparation or performance of a movement, as seen in experts compared to novices (Hatfield & Hillman, 2001), following practice (Landers et al., 1994) or between successful and unsuccessful executions (Hatfield & Hillman, 2001; for a review see Hatfield, et al., 2004). If analogies represent movement-specific information as a unit of information rather than as a collection of explicit rules, analogy instruction might reduce the amount of verbal-declarative information that is processed during motor preparation or performance and therefore increase psychomotor efficiency. Electroencephalography (EEG) provides an objective method by which to examine this possibility. EEG quantifies electrical signals on the scalp surface. The signals are measured at different wavelengths, which reflect functionally different cognitive processes (Janelle et al., 2000; Ray & Cole, 1985; see also Smith et al., 1999). Psychomotor processes involve medium-range communication between different



brain areas, which manifests in signals of alpha-band wavelength (8-12 Hz, Crews & Landers, 1993; Klimesch, 1999; Nunez & Srinivasan, 2006). Alpha-wave activity measured on the scalp displays different cognitive functions depending on the exact scalp locations at which the electrical signals are measured. Verbal-cognitive activity, for example, is associated with alpha activity in the left temporal lobe, which underlies the T7 region in the International 10-20 system of electrode placement. Visuospatial processes are associated with activity in the right temporal lobe (T8 region) and motor planning is commonly associated with activity in the primary motor cortex (Fz region, Kaufer & Lewis, 1999).

Alpha band activity is, in general, inversely related to cortical activation, meaning that increased alpha power reflects decreased cerebral activation. In various expert-novice comparison studies, expertise has been associated with higher alpha power, suggesting that experts are neurally more efficient than non-experts when programming and executing a task (Haufler et al., 2000). Studies have also found higher alpha power at frontal and central sites in successful compared to unsuccessful performance (e.g., Cooke et al., 2015; Crews & Landers, 1993; Hillman et al., 2000). Cooke et al. (2015) found less power in the high alpha band (10-12 Hz) during the pre-movement period in golf putting following errors (especially in experts), which they attributed to increased conscious activity associated with processing and correcting errors. For a review of recent research using psychophysiological measures in sport performance, see Cooke (2013). Neural coactivation between brain regions can provide further insight into psychomotor efficiency. Termed EEG coherence, this measure can tell us how much cross-communication occurs between two regions at a specified time. For example, coherence between signals measured at the T7 and Fz regions indicates involvement of verbal brain areas during motor planning, and potentially is a marker of psychomotor efficiency (Hatfield & Hillman, 2001).

If motor analogies convey complex motor skill information in the form of a simple concept or image, then an analogy instruction may lead to a reduced load on verbal information processing resources (WM). This increased psychomotor efficiency should be evident in reduced neural coactivation between T7 and Fz during movement execution (at least compared to explicit instructions or no instructions). Zhu and colleagues showed that implicit motor learning resulted in less neural coactivation between the T7 and Fz regions than explicit motor learning, which supports this conclusion (Zhu, Poolton, Wilson,

Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Additionally, increased left-temporal high-alpha power should reflect more general economy of cognitive processes brought about by analogy learning. To date, no research has been conducted involving EEG alpha power as a measure of psychomotor efficiency in an implicit learning scenario, nor has any research generalised EEG findings related to error-reduced (implicit) learning (Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011) to analogy learning.

We developed an analogy instruction for a push-pass in field hockey (“move the [hockey] stick as if you are sloshing a bucket of water over the floor”) and asked whether it promoted higher psychomotor efficiency than explicit instructions (provided by a qualified coach) or no instructions. Psychomotor efficiency was quantified by measuring left-temporal high-alpha power and T7-Fz coherence. Participants performed the push-pass as a single task and as a combined task (with concurrent decision-making), both before and after practice (24h delayed retention). Combined tasks reduce the capacity available for motor processing (e.g. Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001) and therefore may be more sensitive to changes in efficiency than regular (single-task) tests. EEG activity was assessed during a 4-s preparation period prior to performing the push-pass alone (single task). We expected to find a greater increase in high-alpha power in the left temporal lobe (T7) following analogy instruction and a greater decrease in T7-Fz coherence, reflecting higher psychomotor efficiency. Alpha power at the T8 and Fz regions and coherence between the T8 and Fz regions was also assessed, but no differences were expected. We did not expect to find differences in performance of the push-pass as a single task, but we expected greater psychomotor efficiency following analogy instruction to be reflected by better push-pass performance in the combined task compared to people who were instructed with explicit rules or no instructions.

## Method

### Participants

Forty-eight novice hockey players (Mean age = 22.21, SD = 6.16) with normal or corrected-to-normal vision and no movement impairments participated in the study. Participants were recruited from the University of Waikato student population, from classes and by word of mouth. Participants were incentivised to participate with cafeteria vouchers (value NZD10). Participants with more than 20 hours of experience were excluded from the study. Ethical permission for the study was received from the Faculty Ethical Committee of the institution. Participants all provided informed consent.

### Materials

Standard field hockey sticks (92.7 cm length) were used on an artificial grass surface. Standard Wilson® tennis balls replaced hockey balls. Passes were directed toward a red circle on the wall surrounded by 13 concentric circles at 10 cm intervals. The distance from the starting position to the target was 340 cm. A Texas Instruments DLP projector was used to project images onto the blank laboratory wall. Performance (accuracy) was measured as distance from the target centre and was obtained by manual analysis of video footage from a Sony RX10pi camera focused on the target.

### *Electroencephalography*

EEG equipment included a wireless EEG / tDCS transmitter, a set of 4 measuring and 2 reference electrodes, conducting gel and electrode contact stickers (Neuroelectrics Barcelona, SLU, ESP). The system was connected to a desktop computer and analysed using Neurosurfer software by Neuroelectrics. EEG activity was recorded from 6 silver/silver chloride (Ag/AgCl) electrodes on the scalp positioned using different sized neoprene caps with pre-defined holes. Two reference electrodes were placed at the earlobe using a clip. Where the earlobe was too small to hold the clip, two stickrodes were attached to the left mastoid. In accordance with the requirements of the system, same-side referencing was used – we acknowledge that this may have an effect on the results and lead to more data loss. Caps and electrodes were adjusted carefully in line with the 10-20 system (Chatrian et al., 1985) and checked by two technicians before the start of the experiment. Signals were amplified at a sampling rate of 500 Hz with 24-bit resolution and 0 to 125 Hz bandwidth. Measurement noise was <1 microvolt RMS.

Prior to commencing the task, an appropriate level of impedance (below 15 kOhm) was achieved by adjusting electrode positions, the participant's hair and the amount of electrolyte gel. Potential issues associated with using repeated measures on two different days were overcome by fully standardizing the procedures and by scheduling the two sessions exactly 24h apart (see Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015). The pre-session criteria required participants to (a) wash their hair on the evening/morning before testing, and (b) not consume caffeine in the 2 hours preceding testing. Baseline EEG data was collected on both days prior to commencing the experiment (120 seconds). This took place while the participant was seated and motionless. The first 60 seconds were recorded with the participant's eyes open (blinks were not suppressed), while the second 60 seconds required the eyes to be closed.

### **Procedure**

Participants were randomly allocated to an analogy instruction group (AG), an explicit instruction group (EG) or a no instruction group (NIG), using a random number generator. They were asked to attend the laboratory on two separate days at the same time. On both days, participants were fitted with a Neuroelectronics cap and EEG electrodes were attached at the T7, T8, Fz (experimental) and Pz (control) locations of the scalp. Participants performed a hockey push-pass task in a pretest and a retention test. In both tests, a single task was performed (20 trials), followed by a combined task (20 trials). The *single task* required participants to pass the ball as accurately as possible to the target. Prior to completing the task, participants were shown an animation that illustrated the requirements of the task, however, participants were not instructed how to move. For the *combined task*, 20 images of hockey players (n=3) standing in different positions were projected onto the opposing wall. Two players were wearing black shirts and one was wearing an orange shirt. Arrangements of the players varied, with one or two players in the foreground (85% of life size) and the others in the background (70% of life size). Participants were informed that they were a member of the black team and were to push-pass the ball as quickly and as accurately as possible towards the hockey stick of the player who was in the best position to receive the ball. Presentation of each image was preceded by a brief countdown on a blank background.

#### *Practice phase*

Between the pretest and retention test, participants were provided with the analogy instruction (AG), written instructions about how to execute a push-pass (EG), or no

instructions (NIG) (see Table 7 for the exact instructions). They then practiced the push-pass by performing 4 blocks of 32 trials each. For each trial, they were required to pass the ball to a virtual teammate (75% of life size) who moved from right to the left on the screen, and vice versa (random order). Participants were instructed that they should time the pass so that the ball would accurately hit the strike zone of their teammate's hockey stick. The strike zone was indicated by a yellow circle (11cm diam) bounded by a blue circle (18cm diam). An opponent/defender, played by one of the researchers, was positioned 1.3 m from the screen either directly in front of the participant or 90 cm to the right or left, respectively. The participant was instructed to pass the ball so that the opponent/defender could not intercept it. Before starting each block of trials, participants were asked to repeat the specific instructions that they had received, in order to ensure that they remembered them and used them consciously during the block. Performance was recorded and feedback was provided to participants at the end of each block in order to maintain motivation.

Previous research has shown that analogies need to be meaningful and linked to personal experience in order to be of benefit during learning (e.g., Gentner, 1983; Poolton et al., 2007b). Therefore, preceding the analogy instruction, participants in the AG performed a familiarization task designed to provide them with personal experience of the analogy concept. EG and NIG participants performed a control task of the same duration with the same materials. Participants in the AG were provided a bucket of water and were instructed to knock over as many cones as possible (lined up on the floor in a single file) by "sloshing" the water underneath a bar raised 15 cm from the ground. The task, which was repeated twice, was designed to familiarise participants with the concept represented by the analogy (move the stick as if you are sloshing a bucket of water over the floor). Discussions with an experienced hockey player and an international coach suggested that the analogy (and the familiarization task) appropriately captured the concept of a push-pass (see Figure 10).

The control task for the EG and NIG participants was to scoop water from a full bucket into an empty one using a cup. The EEG cap worn by each participant was protected from water by a shower cap and the tasks were performed in an outdoor area next to the laboratory. After the familiarization task, participants were provided with the analogy instruction (AG), written instructions about how to execute a push-pass (EG), or no instructions (NIG).

Table 7. Push-pass instructions for each group

Group	Instructions
Analogy	Move the [hockey] stick as if you are sloshing a bucket of water over the floor.
Explicit	Hold the stick with a wide grip The ball should be in front of the right foot Make a side step with the left foot Pull the ball past the left foot Keep contact with the ball while pushing Finish by pointing at the target with the stick
No-instruction	Try to push the ball to the target as exactly as possible.



Figure 10. Performance of the familiarization task (left) vs. performance of a hockey push-pass (right).

### Dependent variables and data analysis

#### *Dependent variables*

Measurements for both performance variables were made using video recordings collected at normal speed (30 fps) and played frame-by-frame in order to determine the time when the ball contacted the wall. Single task performance was represented by mean contact distance from the target during the single task test (20 trials). Combined task performance was represented by mean contact distance from the target chosen by the participant (20 trials). For both tasks, we were mostly interested in improvement due to the intervention; therefore we investigated performance change between the pretest and the retention test, calculated by subtracting mean distance at pretest from mean distance at retention<sup>19</sup>. A positive value represents worse performance, whereas a negative value represents improved performance.

<sup>19</sup> Differences at pretest are not reported in the text as the sample was randomized (see de Boer et al., 2015). A one-way ANOVA revealed no significant differences between groups at pretest during the single task ( $F(2,45) = 1.417, p = .253$ ) or the combined task ( $F(2,45) = 1.778, p = .181$ ).

### *Data Reduction*

EEG values were only recorded during the single task, as artefacts caused by head movements during the combined task were expected to make the data unusable. Raw EEG signals were first filtered at 1-30Hz and a notch filter was added to exclude 50 Hz line noise. Signals were then resampled at 256 Hz. Data from the pretest and retention test were processed as 4-s epochs prior to movement initiation and split into 0.25-s segments for artefact removal. Blinks and eye movements are characterised by high potentials (Boudet et al., 2006). Eye artefacts were excluded by an extreme measures approach. Trials containing signals above 60mV were discarded. An average of 174.39 (SD = 69.14) trials per participant in the pretest and 167.35 (SD = 67.14) trials per participant in the retention test were retained. A Fast Fourier Transform with a Hamming window taper, and 50% overlap with a resolution of 0.49 Hz, was applied. EEG high-alpha (10-12Hz) power was calculated over the 0.25-s segments (e.g., Deeny et al., 2003) and averaged for the 4 sec epoch preceding each trial.

The EEG analyses in this study focused on the high-alpha (10-12 Hz) band. Activity in this bandwidth indicates long- and medium-range cortico-cortical communication (Crews & Landers, 1993; Nunez & Srinivasan, 2006; Janelle et al. 2000; Nunez et al. 1999) and is representative of task-specific attention processes (Smith et al., 1999, for a review see Klimesch, 1999). Matlab scripts (MATLAB Release 2016b, The MathWorks, Inc., Natick, MA - US) were used to calculate EEG outputs. The processing and analysis steps described above were implemented with the EEGLAB toolbox (Delorme & Makeig, 2004).

### *Statistical analyses*

In order to test our a priori predictions concerning high-alpha power at T7, and T7-Fz coherence, as well as combined task performance, we conducted planned contrasts. The NIG was expected to learn by discovery and thus to show the same behaviour as the EG. Planned contrasts therefore compared the AG against the EG and NIG in the first instance, and the EGs against the NIG in the second instance. We did not make clear predictions regarding changes in T8-Fz coherence, T8 or Fz high-alpha power, or single task performance, so univariate ANOVAs were conducted for these variables. Statistical significance was set at  $p < .05$  for all primary analyses.

## Results

Baseline EEG high-alpha power was highly correlated between the first and second session ( $r = .65, p < .001$  at T7;  $r = .46, p < .005$  at T8; and  $r = .22, p < .05$  at Fz). Table 8 shows mean changes in performance and EEG power as well as coherence between the pretest and retention tests, for all groups collapsed and separately.

Table 8. Means and standard deviations of change (ret-pre) in power, coherence and performance across groups

		Change in high-alpha power [mV]			Change in coherence [decimal]		Change in performance (distance from target [cm])	
		T7	T8	Fz	T7-Fz	T8-Fz	Single	Combined
Overall	Mean	0.65	0.17	0.34	-0.00	0.03	-7.21	-4.09
	SD	1.49	1.65	1.16	0.16	0.14	9.82	8.03
Analogy	Mean	1.35	0.55	0.54	0.00	0.02	-11.12	-6.24
	SD	1.94	2.26	1.49	0.17	0.19	8.56	9.44
Explicit	Mean	0.15	0.07	0.37	-0.03	0.03	-6.99	-3.98
	SD	1.23	1.14	1.16	0.15	0.07	11.63	8.70
No Instr.	Mean	0.37	-0.12	0.10	0.02	0.03	-3.48	-2.01
	SD	0.86	1.27	0.74	0.16	0.14	8.31	5.42

### EEG power and coherence

EEG high-alpha power at T7, measured during the single task, was analysed using planned contrasts. Change in EEG high-alpha power at T7 was significantly different in the AG compared to the EG and NIG combined ( $t(21.49) = -2.13$ , contrast =  $-2.17, p = .045$ ). No difference was evident between EG and NIG ( $t(22.51) = .56, p = .580$ ). Figure 11 illustrates the mean change in high-alpha power for each group.

EEG coherence between the T7 and Fz regions, measured during the single task, was also analysed using planned contrasts. Change in EEG coherence was not significantly different in AG compared to the EG and NIG combined ( $t(45) = -.07, p = .942$ ), nor was there a difference between the EG and NIG ( $t(45) = .80, p = .431$ ).



The remaining variables were investigated using univariate ANOVA. No significant differences were evident between the groups with respect to change in T8-Fz coherence ( $F(2,45) = .02, p = .980, \text{partial } \eta^2 = .001$ ), change in high-alpha power at Fz ( $F(2,45) = .60, p = .556, \text{partial } \eta^2 = .03$ ) or change in high-alpha power at T8 ( $F(2,45) = .71, p = .497, \text{partial } \eta^2 = .03$ ).

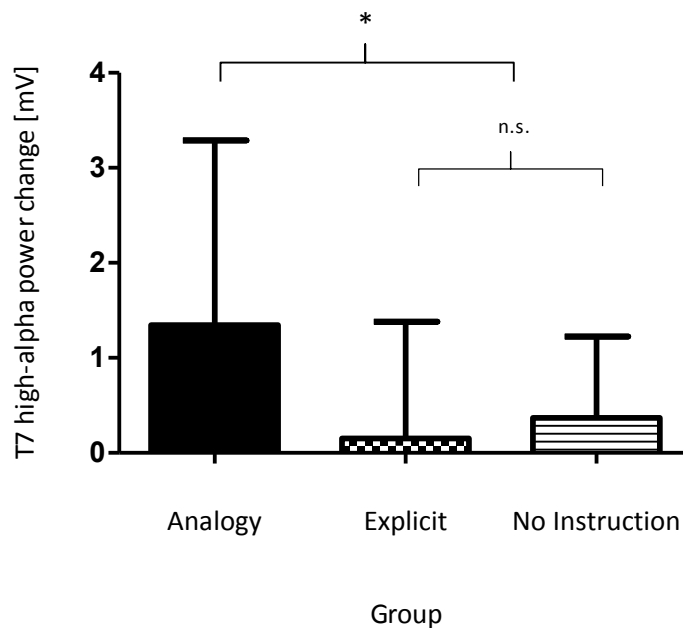


Figure 11. Change (mV) in high-alpha power at T7 between the pretest and retention test.

A higher value indicates increased power (but reduced activation). \* indicates a significant difference between groups.

### Performance

Change in single task performance (mean distance) between the pretest and retention test was investigated using a one-way ANOVA. No significant difference was found between groups ( $F(2,45) = 1.19, p = .314, \text{partial } \eta^2 = .05$ ). Change in combined task performance was analysed using planned contrasts. A significant difference was evident between the AG and the EG and NIG combined:  $t(45) = 2.06, \text{contrast} = 11.78, p = .045$  (equal variances assumed). The contrast between EG and NIG was not significant ( $t(45) = 1.03, p = .311$ ). Figure 12 shows combined task performance change for each group.

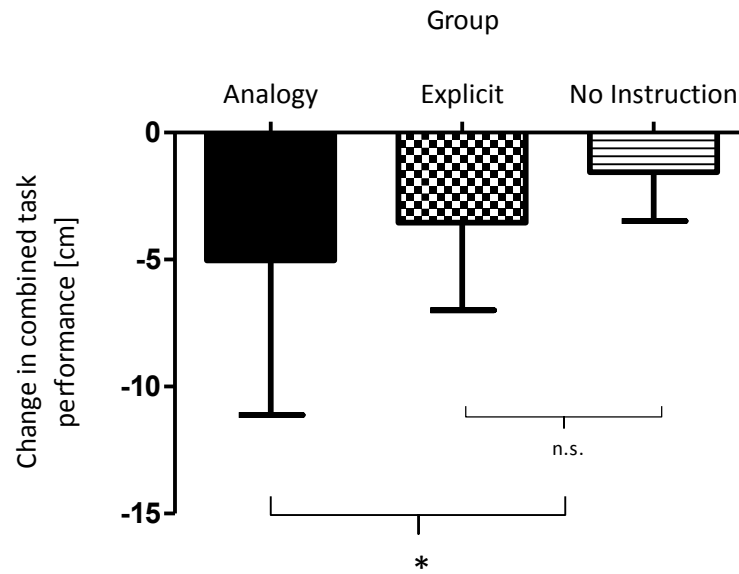


Figure 12. Change (cm) in combined task performance between the pretest and the retention test. A greater negative value indicates greater improvement.

\* indicates a significant difference between groups.

## Discussion

We investigated whether using an analogy instruction leads to increased psychomotor efficiency compared to explicit instructions or no instructions (discovery). While all participants improved in single task performance following practice, improvement did not differ between instruction groups. This meets expectations, considering that changes in efficiency due to analogy instructions were expected to happen on a cognitive rather than a motor level, and thus not to affect motor performance alone. The analogy group showed greater improvement in combined task performance compared to the explicit and no instruction groups. This finding is consistent with previous research on analogy learning and confirms the validity of the hockey push pass analogy developed for this study. The finding also provides support for our hypothesis that analogy instructions promote efficiency in verbal-cognitive processing.

With respect to our EEG measures, differences between the instruction groups were evident in verbal-cognitive brain regions (T7), but not in motor planning or visuospatial regions, with an increase in EEG high-alpha power evident in the left temporal lobe for the analogy group compared to the explicit and no instruction groups. This finding

corroborates our premise that cognitive efficiency is promoted by analogy instructions relative to explicit instructions or no instructions. EEG high-alpha power in the Fz and T8 regions did not differ between the groups, which is consistent with our expectations; activation in these areas was not expected to become more efficient due to the analogy instruction. High-alpha power at Fz represents efficiency in motor planning processes, which did not seem to be affected by analogy instructions. Since no differences were found in motor performance (single task), these results fit well with the neural data. Regular motor performance, as well as neural processes related to motor planning, did not improve due to the analogy instruction.

EEG coherence between the T7 and Fz brain regions did not show the expected difference between groups, thus the hypothesis that an analogy instruction would affect this measure of psychomotor efficiency was not supported. This finding may indicate that analogies affect efficiency of verbal- cognitive processes but not verbal-cognitive motor control. Since T7-Fz coherence reflects verbal-motor cross-communication, including motor planning processes (Deeny et al., 2003), the measure is likely linked to efficiency in motor planning and verbal processing combined rather than verbal processing alone. This notion is supported by work of Zhu, Poolton, Wilson, Maxwell, et al. (2011), who showed a connection between T7-Fz coherence and motor performance in a single task as well as dual task condition. In their experiment, participants in an implicit (error-reduced) treatment condition exhibited lower T7–Fz coherence compared to participants in an explicit (errorful) treatment condition. This decrease in T7-Fz coherence was not only connected to reduced mental load, reflected by superior dual task performance, but also to performance benefits at a purely motor level, as shown by improved single task performance. Therefore, coherence may not represent efficiency of verbal-cognitive processes alone but rather efficiency of psychomotor processes (see Hatfield & Hillman, 2001). Although learning by analogy has been linked to implicit motor learning, the mechanism that underpins analogy instruction may be different from error-reduced learning and may only affect efficiency of the verbal-cognitive aspect of information processing. The notion that learning by analogy affects cognitive but not motor processes finds some support from work by Lam et al. (2009b), which failed to find significant differences in kinematic outcomes between analogy and explicit learners in a basketball shooting task. The authors concluded that analogy learning may not cause qualitative differences in the way that a motor task is performed.

The fact that analogy instructions may result in more efficient verbal-cognitive processing explains why performance differences in dual task tests, but not single-task tests, have been found in previous analogy learning research (Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001). To date, there has been little evidence that dual task performance benefits can be attributed to increased efficiency. However, the present study provides objective neural evidence that this is the case. The mechanism by which analogy instructions render cognitive processes more efficient remains unclear, however.

A tentative mechanism underpinning the effects of analogy learning uses the concept of chunking (Masters, 2000; Masters & Liao, 2003), during which information becomes organised into higher order structures – many small ‘bits’ of information are collapsed into fewer larger chunks. Although fewer chunks are processed, they contain the relevant information, meaning that information can be processed with relatively less cognitive effort; processing becomes more efficient (Newell & Rosenbloom, 1980). This chunking process is a part of the learning process. Masters and Liao (2003) suggested that during motor learning, slow natural chunking processes can be accelerated by using analogy. The analogy has been described as an “all encompassing, biomechanical metaphor” (Koedijker et al., 2011; Liao & Masters, 2001; Masters, 2000). Since all necessary information for the fulfilment of the task is condensed into the analogy, it represents a higher level of organization among the rules for the movement rather than explaining the task step-by-step (Gentner, 1983). Analogy instructions may thus render information processing more efficient by chunking movement relevant information into a single unit or concept (Masters, 2000). However, this theory has not been backed by strong empirical support to date. Gathering sufficient evidence to either corroborate or discard such a chunking hypothesis of implicit motor learning is an important next research step to determine the mechanism of analogy learning.

### **Conclusion**

In this experiment, we observed that people who were instructed by analogy improved more distinctly at a combined task compared to people who practised using explicit instructions or no instructions. Increased EEG high-alpha power at verbal processing regions of the brain during performance suggested that analogy instructions may have resulted in more efficient verbal-cognitive processing compared to learning by explicit instructions. Brain regions related to purely motor aspects of the movement did not display increased efficiency. These findings lead us to contend that benefits of analogy

instructions may reflect improved efficiency in the processing of verbal-cognitive information, but not in motor planning.

As previous chapters showed, individual differences in information processing characteristics, such as reinvestment (Chapter 2) or working memory capacity (Chapter 3), may be related to motor performance. Personality traits may also influence how analogy instructions are applied in the motor learning process. In order to determine a mechanism that is responsible for the benefits of analogy instructions on performance, Chapter 5 investigated whether individual differences in brain activity at baseline (i.e., uninstructed movement) are related to performance changes when analogy or explicit instructions are used. Data were collected during the hockey study described in Chapters 3 and 4; however, a different hypothesis and different dependent variables were investigated.

## Chapter 5

# Individual Differences in Baseline EEG Coherence Predict Benefit from Analogy Instructions in Field Hockey<sup>20</sup>

### Abstract

Analogies are often used when teaching movement skills – the learner gains understanding of how to perform the skill via reference to a familiar concept with similar underlying properties. It is common for analogies to have a strong visual component, hence it is possible that their use is influenced by tendencies to process movement-specific information visually. We examined the associations between analogy learning and visuomotor processing by assessing neural communication between brain regions associated with motor planning and visual, or verbal, processing.

The study tested whether cortico-cortical communication measured via electroencephalography (EEG coherence) during baseline performance of a motor task predicted change in performance when an analogy or explicit instructions were used. Novices performed 20 hockey push-passes without instructions (baseline pretest), while their EEG activity was measured. Subsequently, they were taught to push-pass either by analogy or by explicit instructions and performed a second block of 20 passes (retention test) after 24 hours. Improvement after explicit instructions correlated significantly with verbal-motor coherence at pretest, whereas improvement after analogy instruction correlated significantly with visuomotor coherence (i.e., with the use of visuospatial processing regions during movement planning).

We suggest that analogy learning may be of greater benefit to people who tend to rely on visual processes during motor planning. Potential explanations for the effect of analogy learning are discussed.

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<sup>20</sup> Based on: van Duijn, T., Hoskens, M. C. J., Masters, R. S. W. (in preparation). Individual differences in baseline EEG coherence predict benefit from analogy instructions in field hockey.

## Introduction

Analogies are often used when teaching movement skills. Instead of a set of explicit rules, people are taught by way of one single analogical instruction, which compares the novel movement to a well-known situation or concept (e.g., Liao & Masters, 2001; Gentner, 1983). A consequence of this form of teaching is that the learner acquires minimal verbalisable knowledge about the skill, yet develops a correct mental representation of how to execute the movements (Liao & Masters, 2001). Analogy learning has been shown to result in performance that is similar to learning by explicit instructions, but more stable when the learner has to multitask or make decisions concurrently while performing the motor task. These are characteristics aligned with implicit methods of motor learning, which have been shown to result in a lower load on working memory during performance (Masters, 2000; Masters & Poolton, 2012; Poolton et al., 2007a). Working memory (WM) refers to an individual's mental capacity for short-term storage and manipulation of information, and has been likened to a mental desktop (Baddeley, 1981; Baddeley & Hitch, 1974). According to the most recent model of WM (adapted by Baddeley, 2000; see also Baddeley, 2012), WM consists of four components: the central executive, which fulfils control functions and directs attention through inhibition, shifting and updating of attention; an episodic buffer (a modelling space that acts as an interface between long term memory and the slave systems) and two subordinate "slave systems"; the visuospatial sketchpad for visual information processing and the phonological loop for speech-based information. If one subsystem of WM (e.g., the phonological loop) is loaded by performing a cognitively challenging task, the capacity remaining for the execution of other tasks within the same subsystem may be limited. This may lead to a reduction in performance, especially if performance depends on similar functions (e.g., verbal-cognitive functions) that are processed within the same subsystem.

Analogy learning may result in stable performance under dual task or decision-making loads by facilitating processing efficiency (Chapter 4), but the question of the underlying mechanism by which these benefits are achieved has only been addressed in a limited number of recent publications. Researchers have pointed out that analogies contain strongly visual components; they might be processed in the visuospatial sketchpad rather than in the phonological loop of WM, which leaves processing resources available for verbal tasks (Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008). Tse, Wong, et al. (2016) investigated whether the mode in which the analogy was presented had an

effect on the subsystem of WM in which analogy instructions were processed. Participants memorised visual or verbal stimuli before reading a text with maximum pitch variation. Ability to recall stimuli after reading was used as a measure of the visual or verbal load imposed on WM by the analogy. When a visual analogy was presented (a picture of a choppy sea, along with the instruction “read the paragraph like this picture”), recall of verbal stimuli was good, suggesting that there was reduced load on verbal WM. When the analogy was presented verbally (“read the paragraph like a choppy sea”), recall of verbal and visual stimuli was reduced, suggesting that use of the analogy loaded both visual and verbal components of WM. Explicit instructions loaded on verbal aspects of WM only. It appears from the findings of Tse, Wong, et al. (2016) that analogies can be processed either visually or verbally, which affects whether they engage more visuospatial or more verbal sub-systems of WM. In concept learning, it has been shown that presenting an analogy visually leads to better problem solving performance during physics tasks (Podolefsky & Finkelstein, 2006). Better learning (understanding of scientific devices, and general understanding in chemistry) was also documented when the analogy was referred to repeatedly with visuospatial cues and gestures, and when mental imagery and visualization were encouraged (Mayer & Gallini, 1990; Orgill & Bodner, 2004).

However, whether analogy instructions should be presented visually or verbally may depend on the learner. Although people can process the same information in different modalities, unless one modality is suppressed by specific task constraints (Irwin & Andrews, 1996; Palmer, 1990; Sperling, 1960; Vogel et al., 2001), they often have a preference for visual or verbal modalities when thinking or learning (e.g., Mayer & Massa, 2003). People with a verbal cognitive style tend to prefer instructions while people with a visual style prefer images (Riding & Watts, 1997). Visual vs. verbal instruction preference has furthermore been linked to visual or verbal ability. Kirby, Moore, & Schofield (1988; see also Alesandrini, 1981) found significant correlations between verbal preference with verbal ability and of visual preference with visualization ability.

Kirby et al. (1988) suggested that the reason why visualisers and verbalisers learn differently might lie in the different styles of information processing inherent to each modality. Drawing from their earlier definition of cognitive styles (Das, Cummins, Kirby, & Jarman, 1979; Kirby, 1984), they argued that a strongly visual style may rely on simultaneous processing of information, similarly to looking at a single picture, whereas a verbal style may be connected to successive processing, as in the processing of a



phonological chain of information. For people who prefer to process information in a simultaneous manner, an analogy might benefit motor learning by providing all necessary information in a single, holistic picture. For learners who prefer successive processing, step-by-step explicit instructions may be more suitable.

Cognitive style or instruction preference is usually evaluated with self-report questionnaires, such as the Individual Differences Questionnaire (Paivio & Harshman, 1983) or the Verbalizer-Visualizer Questionnaire (VVQ; Richardson, 1977). However, introspective self-report measures have inherent weaknesses, including difficulty reporting one's own behaviour accurately and objectively, unwillingness to make the necessary effort to respond accurately and bias due to social desirability (e.g., Riding, 1997). Additionally, a measure that applies to learning and instruction preferences in the sport context has yet to be developed (Fuelscher et al., 2012). Glass and Riding (1999; see also Riding et al., 1997) found that people with different cognitive styles exhibited divergent cortical activity in the alpha frequency band when solving cognitive tasks, which shows that they used verbal and visual brain areas to different extents. Classic "verbalisers" (based on Cognitive Styles Analysis; Riding & Cheema, 1991) exhibited a greater suppression over verbal processing areas (Broca's and Wernicke's area) during a verbal task, while "imagers" showed less alpha suppression over these regions. We have previously shown that analogy learning leads to higher alpha power at verbal regions, which indicates low verbal activity (see Chapter 4). When analysing EEG data, a more specific indicator of functional activation of resources is found in coherence measures. The coactivation of verbal and motor areas (e.g., T7 and Fz<sup>21</sup>) during motor preparation and initiation allows us (to some extent at least) to quantify the use of verbal (in the case of T7-Fz coherence) or visual (T8-Fz) information during motor planning (Zhu, Poolton, Wilson, Maxwell, et al., 2011).

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<sup>21</sup> All labelings in this chapter are reported in accordance with the nomenclature suggested in the American Electroencephalographic Society's "guidelines for standard electrode position nomenclature" (American Electroencephalographic Society, 1994). The terms T7 and T8 are used for left and right temporal lobes, while Fz is used for frontal lobe site.

EEG coherence has been investigated in several studies in the movement context. Experts display lower coherence between the T7 and Fz regions during movement execution compared to novices (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003), suggesting that skilled performance is associated with a decrease in explicit, verbal processing of movements. Zhu, Poolton, Wilson, Hu, et al. (2011) found that participants who learned a movement pattern on a laparoscopic trainer with conscious awareness of the movement pattern (explicit learning) displayed higher T7-Fz coherence compared to participants who learned the same movement implicitly (without awareness of the movement pattern, i.e., implicit motor learning). Zhu et al. (2011) concluded that EEG coherence between T7-Fz is a useful yardstick of (verbal) conscious control in motor performance. In another study, Zhu, Maxwell, Hu, et al. (2010) found that increased T8-Fz coherence accompanied performance improvements in a visuospatial aiming task. High coherence between these regions might represent more functional activation of visuospatial processing resources.

In this chapter, we hypothesise that T7-Fz coherence measured during an uninstructed pretest may be used to quantify a general tendency for processing movement-specific information verbally, and T8-Fz coherence may quantify a preference for visual processing of movement. Analogy may cause the benefits attributed to it merely by being processed in the visuospatial sketchpad of WM, which would leave verbal resources intact to deal with other cognitive tasks. If the benefits of analogy learning are indeed based on its visual quality, it should benefit people with a preference for visual instructions more than people who prefer verbal instructions. We suggest that analogy learning might advantage people who tend to plan their movements in a more visual manner (less deterioration at a combined task), while explicit instructions might bring a stronger benefit to people who prefer to plan their movements using verbal processes.

The Movement-Specific Reinvestment Scale (MSRS, Masters et al., 2005; Masters & Maxwell, 2008) is a different measure for a person's preference related to information processing during movement planning. The 10-Item questionnaire measures the propensity to consciously process movement-specific information and to be self-conscious about one's movement<sup>22</sup>. The application and use of verbal instructions

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<sup>22</sup> The MSRS contains two subscales which are often analysed separately: Conscious Motor Processing (CMP) and Movement Self-Consciousness (MSC). The present study did not analyse these two subscales separately.

requires conscious, verbal processes, which may be better developed in people who have a tendency to consciously process movement-related information, as measured by the MSRS (Malhotra et al., 2015). Findings in Chapter 2 suggested that reinvestment may portray a preference for processing of verbal information during movement preparation. The MSRS might reflect verbal preference and therefore help generate insight into the involvement of cognitive predispositions in analogy motor learning.

Visual WM capacity has been shown to have an impact on early motor performance (Chapter 3). When no instructions were given and no practice was involved, visuomotor coactivation (T8-Fz coherence) and visual WM capacity predicted performance in a hockey task when execution was combined with decision-making. Whether this relationship remains after practice with instructions, likely depends on the type of instruction given and on the modality the learner uses to process them.

This study assessed whether individual differences in visuomotor and verbal-motor cortico-cortical communication were related to performance changes in early stages of motor learning when analogy or explicit instructions were used. Two groups learned a hockey push pass either by analogy or by explicit instructions, and their learning progress in a realistic choice-task (combined task) was recorded. WM capacity, MSRS scores, EEG measurements at baseline, and performance variables were examined as predictors of performance. Performance effects were expected to be intensified in a combined task, where the capacity available for motor planning was impeded by the need to perform a cognitive choice task.

Analogy was hypothesised to be a visual instruction requiring processing in the visual domain, while it was expected that explicit instructions would be processed in verbal and phonological areas of WM. We expected that participants instructed by analogy would benefit most with respect to performance if they had high visuomotor (T8-Fz) coherence at pretest, but participants instructed by explicit rules would benefit most if they had high verbal-motor (T7-Fz) coherence at pretest. Alpha power at T7 (verbal association region) and T8 (visuospatial processing region) was also analysed. Previous research has shown that analogy learning was related to increased T7 alpha power, which indicates reduced activation in verbal areas of the brain (Chapter 4). We expected pretest alpha power at T7 to have a negative association with performance improvement in the explicit group, while T8 alpha power would have a positive association with performance improvement in the analogy group.

## Method

### Participants<sup>23</sup>

Forty-seven novice hockey players (mean age = 22.32 years, SD = 6.24) with normal or corrected-to-normal vision and no movement impairment participated in the study. Participants were recruited from the University of Waikato student population, from classes and by word of mouth. Participants were incentivised to participate with cafeteria vouchers (value NZD10). Participants with more than 20 hours of experience were excluded from the study. Ethical permission for the study was received from the Faculty Ethical Committee of the institution. Participants all provided informed consent. Participants were randomly allocated to three instruction groups: analogy, explicit instructions or no instructions.

### Materials

Standard field hockey sticks of 92.7 cm (36.5 in) length were used both by the participant and an adversary. Standard Wilson® tennis balls replaced hockey balls. The laboratory floor was covered with artificial golf turf. A line on the floor marked the starting position of the ball; a red circle on the wall with concentric circles at 10 cm intervals provided a target for the passes. The distance from the starting position to the target was 340 cm. For the practice task, an opposing player was positioned at three different locations 130cm from the wall. They were 90cm apart from each other. A Texas Instruments DLP projector was used to present video clips, stills and animations in the different tasks and during practice. Performance was measured as distance from the target center and was obtained by visual analysis of video footage from a Sony RX10pi camera focused on the target, using the concentric circles around the target as an indicator of distance.

### *Electroencephalography*

EEG equipment included a wireless EEG / tDCS transmitter, a set of 4 measuring and 2 reference electrodes, conducting gel and electrode contact stickers (Neuroelectrics Barcelona, SLU, ESP). The system was connected to a desktop computer and analysed using Neurosurfer software by Neuroelectrics. EEG activity was recorded from 6 silver/silver chloride (Ag/AgCl) electrodes on the scalp positioned using different sized neoprene caps with pre-defined holes. Two reference electrodes were placed at the

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<sup>23</sup> Separate sets of data based on the same experiment were analysed in Chapters 3 and 4.

earlobe using a clip. Where the earlobe was too small to hold the clip, two sticktrodes were attached to the left mastoid. Caps and electrodes were adjusted carefully in line with the 10-20 system (Chatrian et al., 1985) and checked by two technicians before the start of the experiment. Signals were amplified at a sampling rate of 500 Hz with 24-bit resolution and 0 to 125 Hz bandwidth. Measurement noise was under 1 microvolt RMS.

Prior to commencing the task, impedance needed to reach a satisfactory level (below 15 kOhm). This was achieved by adjusting electrode positions, the participant's hair and the amount of electrolyte gel. Based on a study by Ring et al., (2015), issues due to repeated measures on a different day were overcome by standardizing all procedures and by scheduling the two sessions exactly 24h apart. The pre-session criteria required participants to (a) wash their hair on the evening/morning before testing, and (b) not consume caffeine in the 2 hours preceding testing. Baseline EEG data was collected on both days prior to commencing the experiment. This took place while the participant was seated and not moving during 120 seconds. The first 60 seconds were recorded with the participant's eyes open (blinks were not suppressed), while the second 60 seconds required the eyes to be closed.

### **Procedure**

Participants were randomly allocated to an analogy group, an explicit instruction group, or a no- instruction group. On two separate days, participants visited the laboratory and were fitted with the Neuroelectrics cap and the EEG electrodes, which were attached to the T7, T8, Fz and Pz regions of the brain, according the 10-20 system.

On the first day, participants completed a demographics sheet plus the Movement Specific Reinvestment Scale (MSRS - Masters & Maxwell 2008; Masters et al. 2005). The MSRS assesses a person's propensity to consciously monitor and control their movements. The scale consists of 10 items and includes items such as "I am self-conscious about the way I look when I am moving" and "I am aware of the way my body works when I am carrying out a movement". Participants indicate to what extent each statement describes them, using a six-point Likert type scale ranging from 'strongly disagree' to 'strongly agree'. The Scale has been shown to have a high internal consistency and test-retest reliability (Masters et al., 2005).

After completing the questionnaire, participants were fitted with the Neuroelectrics cap and the EEG electrodes were attached. They then completed a computerised test of

WM capacity. The test was an adapted version of the rotation-span test (Oswald et al., 2015; Shah & Miyake, 1996). The to-be-remembered stimuli in this task were images of arrows that could be differentiated by (a) their length (long or short), or (b) their angle of rotation. Participants were required to remember and recall the specific arrows that were presented (i.e., the length and the angle of rotation) at the conclusion of each trial. After each arrow was presented, participants had to perform a distraction task during which they had to judge the orientation of a letter on the screen.

Afterwards, participants performed a hockey push pass single task test (20 trials) in which they passed the ball as accurately as possible to the target on the opposing wall. The ball was always placed on the same mark at a distance of 3.4m from the target. Prior to completing the task, participants were shown an animation that illustrated how the task was to be completed. After the single task, a combined task was performed (20 trials), in which 20 images of hockey players ( $n=3$ ) standing in different positions were projected onto the opposing wall. Two players were wearing black shirts and one was wearing an orange shirt. Arrangements of the players varied, with one or two players in the foreground (85% of life size) and the others in the background (70% of life size). Participants were informed that they were a member of the black team and were to push-pass the ball as quickly and as accurately as possible towards the hockey stick of the player who was in the best position to receive the ball. Presentation of each image was preceded by a brief countdown on a blank background. After pretesting the single and combined task, participants were provided with an analogy instruction (analogy group), instructions about how to execute a push-pass (explicit group), or no instructions (no-instruction group) (see Table 9 for the exact instructions). A delayed retention test was performed after 24 hours (day 2), which was identical to the pretest.

### **Instruction phase**

Previous research in analogy learning has shown that the analogy needs to be well-known and linked to personal experience in order to be useful (see Gentner, 1983). This is also true in motor learning (Poolton et al., 2007b). Therefore, preceding the analogy instruction, participants in the analogy group had to complete a preparation task designed to ensure that they concept underlying the analogy was meaningful/familiar to them. They were presented with a stick resting on two upturned cups, with 5 upturned cups lined up behind it. Participants were given a bucket of water and told to “slosh the bucket of water over the floor so it spills beneath the stick and wipes out all the cups” (see Figure

13). The movement was repeated twice. Participants in the explicit and no instructions groups completed a control task of the same duration with the same materials, in which they scooped water from a full bucket into an empty one using a cup. All participants' EEG caps were covered with a shower cap for protection against water and the tasks were performed outdoors. After the preparation task, they received group-specific instructions (see Table 1 for the exact instructions).

To practice the push pass, participants in all groups performed 4 blocks of 32 trials each. For each trial, they had to push-pass the ball to the hockey stick of a teammate (75% of life size) who moved from one side of the screen to the other. A yellow circle (diam. 11 cm) surrounded by a blue circle (diam. 18cm) identified the correct position on the teammate's stick. Additionally, an opponent, enacted by one of the researchers, was positioned between the participant and the screen at a distance of 1.3m from the screen in one of three different positions (either in the middle or 90 cm to the right or left, respectively). The participant was told to make sure the opponent could not intercept the ball. Before starting each block of trials, participants were asked to repeat the specific instructions that they had received for the push technique. Performance was recorded and reported back to the participant at the end of each block in order to keep motivation high.

Table 9. Instructions for each group

Group	Instructions
Analogy	Move the stick as if you are sloshing a bucket of water over the floor.
Explicit	Hold the stick with a wide grip The ball is in front of the right foot make a side step with the left foot pull the ball past the left foot keep contact with the ball while pushing finish by pointing at the target with the stick
No-instruction	Try to push the ball to the target as exactly as possible.



Figure 13. Performance of the preparation task (left) vs. performance of a hockey push-pass (right).

### Dependent variables and data analysis

#### *Dependent variables*

Measurements for both performance variables were made using video recordings collected at normal speed (30 fps) from a camera focused on the wall. Video clips were played frame-by-frame (Quicktime player, Apple Inc., Cupertino, CA.) in order to determine the time when the ball contacted the wall.

Single task accuracy was represented by mean contact distance from the target during the single task test (20 trials). Combined task accuracy was represented by mean contact distance from the target chosen by the participant. Inter-rater reliability for the video rating procedure, obtained for 540 trials, was high (single task:  $r = .96, p < .001$ ; combined task:  $r = .97, p < .001$ ). For both the single and the combined task, we were mostly interested in improvement due to practice; therefore, we investigated performance change between pretest and retention test, calculated by subtracting pretest error from



retention error averages<sup>24</sup>. This variable represents positive change in performance; a high value represents improvement, while a negative value represents deterioration.

WM capacity measures were calculated via the program 'R' using a software script provided by Stone and Towse (2015). The measure of WM capacity that we used reflected the maximum number of items a participant remembered correctly. Although other measures exist, this variable was considered prior to data collection to be the most informative for our study, as it represents the maximum capacity, rather than general WM ability (Stone & Towse, 2015). Score on the MSRS was calculated by summing the Likert Scale responses, leading to a cumulative range of 10 to 60 points.

#### *Data Reduction*

EEG values were only measured during the single task, as technical problems (i.e., head movements leading to electrode artefacts) made measurements during combined task problematic. Efficiency in verbal-cognitive areas during pure motor performance is representative of the motor skill's independence from WM.

Raw EEG signals were first filtered at 1-30Hz and a notch filter was added to exclude 50Hz line noise. Signals were then resampled at 256 Hz. Data in the pretest and retention test were cut to 4-s epochs before movement initiation. Epochs were split into 0.25-s trials for artefact removal. Blinks and eye movements are characterised by high potentials (Boudet et al., 2006). Eye artefacts were excluded by an extreme measures approach using the EEGLAB toolbox (Delorme & Makeig, 2004). Trials containing signals above 60mV were discarded. An average of 174.39 (SD = 69.14) trials per participant in the pretest and 167.35 (SD = 67.14) trials per participant in the retention test were retained. A Fast Fourier Transform was applied with a Hamming window taper, 50% overlap and a resolution of 0.49 Hz. EEG high-alpha (10-12Hz) power was calculated over the 0.25-s epochs (e.g., Deeny et al., 2003) and averaged for the 4-s epochs preceding each trial.

The EEG analyses focused on the high-alpha (10-12 Hz) band. Activity in this bandwidth indicates long- and medium-range cortico-cortical communication (Crews & Landers, 1993; Nunez & Srinivasan, 2006; Janelle et al. 2000; Nunez et al., 1999) and is

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<sup>24</sup> Differences at pretest are not reported in the text as the sample was randomized (see de Boer, Waterlander, Kuijper, Steenhuis, & Twisk, 2015). A one-way ANOVA showed no significant differences at pretest between groups in the single task, ( $F(2,45) = 1.42, p = .253$ ) or the combined task ( $F(2,45) = 1.78, p = .181$ ).

representative of task-specific attention processes (Smith et al., 1999; for a review see Klimesch, 1999). Matlab scripts (MATLAB Release 2016b, The MathWorks, Inc., Natick, MA - US) were used to calculate EEG outputs. The processing and analysis steps described above were implemented with the EEGLAB toolbox (Delorme & Makeig, 2004).

### *Statistical analyses*

Associations between WM capacity, movement specific reinvestment, EEG coherence and improvement in the combined task were investigated using Pearson's product-moment correlation coefficient. Regression analyses were conducted to predict improvement in the combined task, for both groups separately. The predictor variables included WM capacity, T7-Fz coherence, T8-Fz coherence and score on the Movement Specific Reinvestment Scale. A backward elimination approach was chosen for the regression analyses, with the aim of unpicking the relationships between different measures of conscious processes and performance. Moderated regression analysis was employed to investigate the joint influence of MSRS and T8-Fz as well as T7-Fz coherence on performance in the combined task for each instruction group separately. In each moderation analysis, variables were entered into the regression equation in a step-wise manner. In the first step, the predictor variable (T8-Fz coherence or T7-Fz coherence) and potential moderator variable (MSRS) were entered. In the second step, a product term created by multiplying the standardised predictor variable by the standardised MSRS was entered. For the second step, significant change in  $R^2$  for the product term indicates a significant moderator effect. Assumptions for regression analyses were tested and satisfied. Alpha value for statistical significance was set to .05.

## Results

### Correlation between EEG coherence, power and performance variables

Means, standard deviations and Pearson Product-Moment correlation coefficients for all variables are presented for all participants in Table 10, and for the two groups separately<sup>25</sup> in Table 11. T8-Fz coherence correlated significantly with combined task improvement when all participants were analysed together. The relationship was positive, suggesting that higher T8-Fz coherence was associated with better improvement. However, when the explicit and analogy groups were analysed separately, T7-Fz coherence showed an association with improvement in the explicit, but not in the analogy group. Therefore, regression analyses were run for both groups separately. WM capacity and MSRS scores were not significantly correlated with any variable. T7-Fz and T8-Fz coherence showed a significant correlation.

Table 10. Means and standard deviations for predictive and outcome variables

Variable	Overall		Explicit		Analogy	
	M	SD	M	SD	M	SD
1. Combined task improvement	7.68	8.75	5.16	8.21	12.13	8.06
2. WM capacity	2.11	1.49	2.43	1.33	1.53	1.63
3. MSRS	38.79	7.45	39.03	7.98	38.35	6.61
4. T7-Fz	0.47	0.13	0.48	0.13	0.45	0.12
5. T8-Fz	0.43	0.14	0.44	0.15	0.41	0.14
6. T7 power	3.76	1.77	3.63	1.14	4.00	2.60
7. T8 power	4.47	1.59	4.49	1.53	4.43	1.75

<sup>25</sup> Planned contrasts revealed a significant difference in movement-related knowledge (number of rules) between the analogy group and the explicit and no-instruction groups ( $t(45) = -2.55, p = .014$ ), but no significant difference between the explicit and the no-instruction group ( $t(45) = .88, p = .380$ ). This is consistent with previous research, which has shown that uninstructed discovery learning usually results in accumulation of similar knowledge to explicit instructions (e.g., Masters, 1992). Consequently, the explicit and no instruction control groups were collapsed into a single 'explicit' group for analysis (Explicit  $n = 30$ ; Analogy  $n = 17$ ).

Table 11. Pearson Product-Moment correlation coefficients for predictive and outcome variables for each group separately

Overall		1.	2.	3.	4.	5.	6.
1.	Combined task improvement	-					
2.	WM capacity	-.15	-				
3.	MSRS	.05	-.18	-			
4.	T7-Fz coherence	.25	-.17	-.04	-		
5.	T8-Fz coherence	.34*	-.01	-.10	.57*	-	
6.	T7 high-alpha power	.00	-.09	-.11	-.04	.11	-
7.	T8 high-alpha power	-.12	-.12	-.15	.08	-.10	.55*
Explicit		1.	2.	3.	4.	5.	6.
1.	Combined task improvement	-					
2.	WM capacity	-.09	-				
3.	MSRS	-.01	-.32	-			
4.	T7-Fz coherence	.40*	-.08	-.15	-		
5.	T8-Fz coherence	.36	-.03	-.14	.63**	-	
6.	T7 high-alpha power	.15	-.14	-.03	.18	.10	-
7.	T8 high-alpha power	-.02	-.14	-.13	.07	-.18	.50**
Analogy		1.	2.	3.	4.	5.	6.
1.	Combined task improvement	-					
2.	WM capacity	.05	-				
3.	MSRS	.24	.01	-			
4.	T7-Fz coherence	.16	-.45	.23	-		
5.	T8-Fz coherence	.51*	-.05	-.00	.42	-	
6.	T7 high-alpha power	-.22	-.01	-.21	-.23	.16	-
7.	T8 high-alpha power	-.30	-.13	-.20	.09	.03	.65**

Note: \*  $p < 0.05$ , \*\*  $p < 0.01$ .

## Role of coherence, WM capacity and reinvestment in predicting improvement

### Explicit learners

For the explicit group, a backward stepwise regression analysis was conducted to predict the change in performance using T8-Fz coherence, T7-Fz coherence, MSRS score and WM capacity. Results of the analysis are presented in Table 12. A first model, including all variables, was not significant ( $p = .368$ ). Consequently, MSRS, WM capacity, and T8-Fz coherence ( $p$ 's  $> .10$ ), respectively, were eliminated to yield a final model (Model 4) in which T7-Fz coherence was the only predictor, explaining 12.6% ( $R^2_{adj}$ ) of the variance in combined task improvement. Higher coherence during the movement only (i.e., single task) in the pretest was associated with better learning of the combined task (movement plus decision, Figures 14 and 15).

The potential interaction between MSRS and T8-Fz coherence was analysed for the explicit group using moderation analysis. In the first step, the predictor variable (T8-Fz coherence) and potential moderator variable (MSRS) were entered. In the second step, a product term created by multiplying standardised T8-Fz coherence by the standardised MSRS was entered. Results of the analysis are presented in Table 13. No significant interactions were found ( $B = -.34$ ,  $p = .871$ ), suggesting that T8-Fz coherence and MSRS were unique predictors of improvement in the explicit group.

Table 12. Regression analyses predicting combined task improvement in the explicit group

	Model 1		Model 2		Model 3		Model 4	
$R^2_{adj}$	.05		.09		.11		.13	
$p$	.268		.155		.074		.031	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
MSRS	.05	.819	-	-				
WM capacity	-.05	.790	-.07	.709	-	-		
T8-Fz coherence	.18	.436	.18	.434	.18	.433	-	-
T7-Fz coherence	.28	.241	.28	.239	.28	.219	.40	.031

Beta ( $\beta$ ) and  $p$ -values for predictor variables, and  $R^2_{adj}$  values and  $p$ -values for each model

Abbreviations: WM, working memory; MSRS, Movement Specific Reinvestment Scale score.

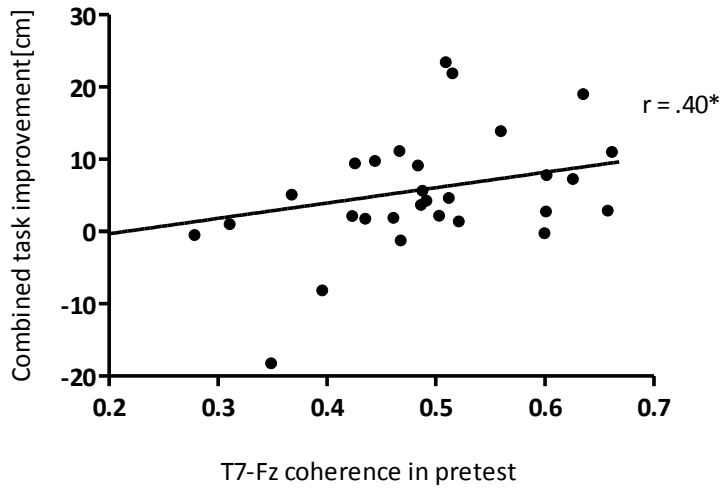


Figure 14. T7-Fz coherence and combined task improvement in the explicit group.

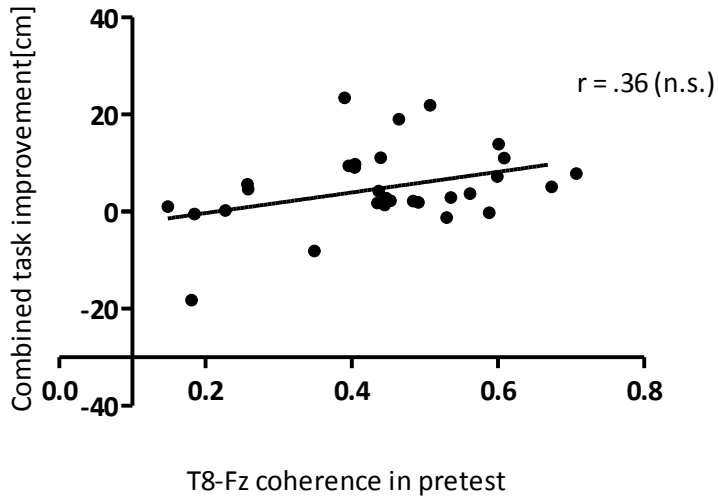


Figure 15. T8-Fz coherence and combined task improvement in the explicit group.

Table 13. Moderation analyses for interaction of MSRS with T8-Fz coherence or T7-Fz coherence in predicting combined task improvement in the explicit group

	<i>B</i>	<i>SE B</i>	$\beta$	<i>R<sup>2</sup> Change</i>
T8-Fz coherence				
Step 1				
MSRS	.41	1.47	.05	
T8-Fz coherence	3.00	1.51	.36	.13
Step 2				
MSRS x T8-Fz coherence	-.36	2.03	.07	.00
T7-Fz coherence				
Step 1				
MSRS	.41	1.41	.05	
T7-Fz coherence	3.67	1.43	.45	.20
Step 2				
MSRS x T7-Fz coherence	-.51	2.52	-.04	.00

Note: no interaction reached  $p < .05$ .

#### *Analogy learners*

Stepwise regression analysis was also conducted to predict combined task improvement in the analogy group using T8-Fz coherence, T7-Fz coherence, MSRS score and WM capacity. Results of the analysis are presented in Table 14. A first model, including all variables, was not significant ( $p = .266$ ). Consequently, WM capacity, T7-Fz coherence, and MSRS ( $p$ 's  $> .10$ ), respectively, were eliminated to yield a final model (Model 4) in which T8-Fz coherence was the only predictor, explaining 21.0% ( $R^2_{adj}$ ) of the variance in combined task improvement. Higher coherence during the movement only (i.e., single task) in the pretest was associated with greater improvement at the combined task (movement plus decision, Figures 16 and 17).

A potential interaction between MSRS and T8-Fz coherence was analysed using moderation analysis. In the first step, the predictor variable (T8-Fz coherence) and potential moderator variable (MSRS) were entered. In the second step, a product term created by multiplying standardised T8-Fz coherence by the standardised MSRS was entered. Results of the analysis are presented in Table 15. No significant interactions were found ( $B = -.36$ ,  $p = .888$ ). This indicates that T8-Fz coherence and MSRS variables were unique predictors of performance in the analogy group.

Table 14. Regression analyses predicting combined task improvement in the analogy group

	Model 1		Model 2		Model 3		Model 4	
$R^2_{adj}$	.11		.18		.22		.21	
$p$	.266		.143		.070		.037	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
WM capacity	.01	.972	-	-				
T7-Fz coherence	-.14	.659	-.15	.585	-	-		
MSRS	.27	.296	.27	.269	.24	.301	-	-
T8-Fz coherence	.57	.054	.57	.041	.51	.037	.51	.037

Beta ( $\beta$ ) and p-values for predictor variables, and  $R^2_{adj}$  values and p-values for each model.

Abbreviations: WM, working memory; MSRS, Movement Specific Reinvestment Scale score.

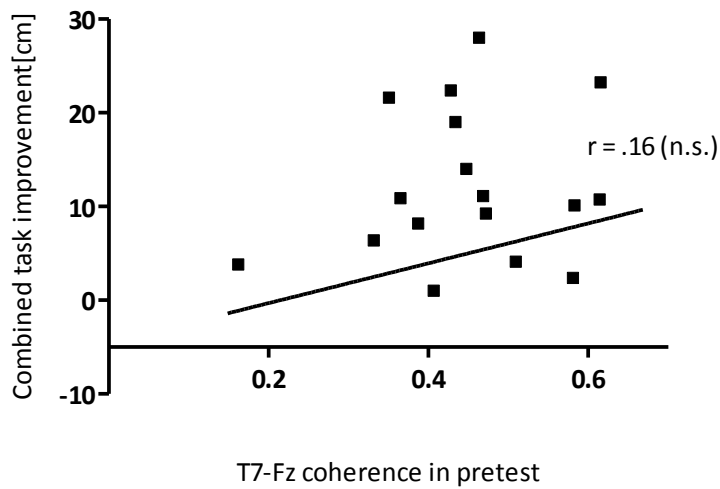


Figure 16. T7-Fz coherence and combined task improvement in the analogy group.



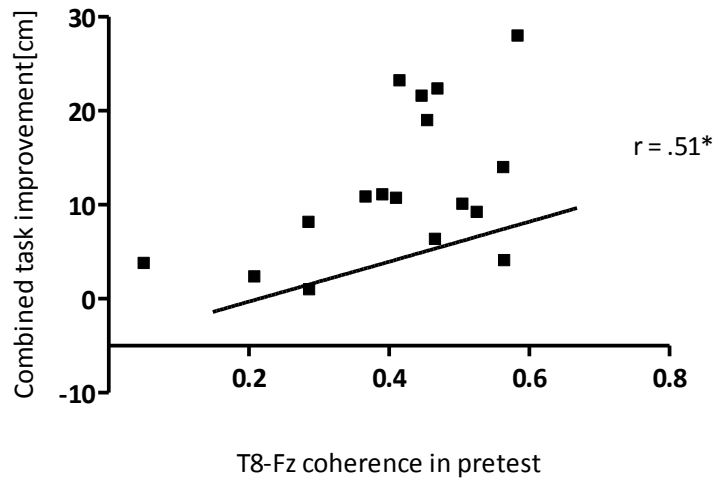


Figure 17. T8-Fz coherence and combined task improvement in the analogy group.

Table 15. Moderation analyses for interaction of MSRS with T8-Fz coherence or T7-Fz coherence in predicting combined task improvement in the analogy group

	<i>B</i>	<i>SE B</i>	$\beta$	<i>R<sup>2</sup> Change</i>
T8-Fz coherence				
Step 1				
MSRS	2.81	2.27	.29	
T8-Fz coherence	5.13	2.07	.58*	.40
Step 2				
MSRS x T8-Fz coherence	4.15	2.50	.37	.13
T7-Fz coherence				
Step 1				
MSRS	2.09	2.81	.22	
T7-Fz coherence	2.04	3.30	.18	.09
Step 2				
MSRS x T7-Fz coherence	-.07	6.71	-.00	.00

Note: no interaction reached  $p < .05$ .

## Role of alpha power in predicting learning

A backward stepwise regression analysis was also conducted to predict combined task performance using alpha power at T7 and T8 locations, along with MSRS and WM capacity. Results of the analysis are presented in Table 16. None of the four models was significant in either group, indicating that pretest alpha power did not predict learning by analogy or explicit instructions.

Table 16. Regression analyses predicting improvement in the analogy and explicit groups

<b>Explicit group</b>	Model 1		Model 2		Model 3		Model 4	
$R^2_{adj}$	-.11		-.07		-.04		-.01	
$p$	.885		.773		.624		.421	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
MSRS	-.05	.807	-	-				
WM capacity	-.10	.630	-.09	.666	-	-		
T8 alpha power	-.14	.550	-.13	.565	-.12	.583	-	-
T7 alpha power	.21	.370	.21	.363	.21	.338	.15	.421
<b>Analogy group</b>	Model 1		Model 2		Model 3		Model 4	
$R^2_{adj}$	-.19		-.09		-.02		.02	
$p$	.802		.634		.459		.266	
Variables	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
T7 alpha power	.00	.999	-	-				
WM capacity	-.13	.670	-.13	.654	-	-		
MSRS	.16	.603	.16	.584	.16	.552	-	-
T8 alpha power	-.28	.473	-.28	.330	-.26	.340	-.30	.266

Beta ( $\beta$ ) and p-values for predictor variables, and  $R^2_{adj}$  values and p-values for each model.

Abbreviations: WM, working memory; MSRS, Movement Specific Reinvestment Scale score.

## Discussion

This study assessed to what extent baseline T7-Fz and T8-Fz coherence, baseline T7 and T8 alpha power, MSRS and WM capacity predicted learning of a combined task in analogy and explicit learning conditions. Over all participants, T8-Fz coherence correlated positively with improvement in the task. In the analogy group alone, performance improvement positively correlated with T8-Fz coherence but not with T7-Fz coherence. In

the explicit group, performance improvement correlated with T7-Fz, but not with T8-Fz coherence. Since differences between groups were evident, groups were further analysed in two separate regression analyses. A backward regression analysis for the explicit group showed that T7-Fz coherence was the sole predictor for learning. In the analogy group, T8-Fz coherence was shown to be the sole predictor for learning. The same backward regressions were run with alpha power at T7 and T8 replacing the coherence values, yielding no significant models.

Based on Chapter 2, which showed that MSRS score in children was connected to improvement during analogy learning, movement specific reinvestment was hypothesised to have an effect on how well the analogy is used by adults. However, information processing in children might differ greatly from adults. The fact that no such effect was found in the present study leads us to speculate that the propensity for consciously processing and monitoring movements might not be related to the modality in which instructions are processed, but probably only to the extent, or amount, of conscious processing that a participant engages in. It is possible to be movement self-conscious with or without using verbal processes, and similarly, conscious motor processing may happen in the form of visualization as well as verbalization<sup>26</sup>. Reinvestment might therefore not reflect a purely verbal measure, but a more general measure of self-focus, which includes both verbal and visual processes. A study by Ellmers et al. (2016) investigating EEG coherence during uninstructed baseline performance at a postural sway task supports this hypothesis. The study found no difference in T7-Fz or T8-Fz coherence<sup>27</sup> between people who scored high and low on the conscious motor processing subscale of the MSRS. This indicated that high and low conscious processors did not differ in their extents of verbal-motor or visuomotor control<sup>28</sup>.

Although visual WM capacity seemingly plays an important role in determining initial performance without practice or instructions (Chapter 3), the variable did not correlate with improvement when instructions were given. Prolonged practice increases the

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<sup>26</sup> This refers to the two separate subscales of the MSRS, Conscious Motor Processing (CMP) and Movement Self-Consciousness (MSC).

<sup>27</sup> The study analysed T3-Fz and T4-Fz coherence, which are equivalent to T7-Fz and T8-Fz coherence according to the standard 10-10 nomenclature.

<sup>28</sup> A slightly contradictory finding by Buszard et al., (2013) found that movement self-consciousness was related to verbal working memory. The authors suggested that reinvestment might be associated with verbal rather than visual working memory.

efficiency of cognitive processes related to motor performance (e.g., Hatfield & Hillman, 2001) and may have therefore reduced the importance of having a large WM capacity in order to learn successfully.

No effects of baseline alpha power at T7 and T8 on performance improvement were found. Since high-alpha power represents a general measure of activation in a specific brain region, rather than functional communication between several regions, this result indicates that purely verbal (T7) or visual (T8) activity during baseline performance did not affect how well analogy or verbal instructions were adapted.

T8-Fz coherence indicates cross-communication between visual and motor areas, i.e., visuomotor processing during motor control (Zhu et al., 2010). Similarly, T7-Fz coherence indicates verbal-motor cross-communication or involvement of verbal processes during motor planning. Across all groups, T8-Fz coherence was positively associated with improvement at the combined task. During a push-pass, the performer attempts to strike a ball towards an often moving target, which can be many meters away. Error correction in this type of task relies on the integration of visuospatial information with effector movements (Vickers, 1996), which is likely to require visuospatial processes. This is consistent with previous research (Chapter 3) where visual processing aspects were shown to be central to early motor performance. However, in Chapter 3, initial dual task performance was negatively associated with T8-Fz coherence, whereas in the present study, improvement in dual task performance after practice was positively associated. It seems that the relationship between baseline T8-Fz coherence and performance may change with practice. Lower pretest T8-Fz coherence can be interpreted as greater efficiency of visuospatial cognitive processes, which may be beneficial to performance when there is no time for practice. However, high T8-Fz coherence may also be interpreted as functional activation of visual resources, which may benefit the learning process and lead to better improvement after practice (e.g., Deeny et al., 2003). We argue that when time for practice is allowed, an initial tendency to engage in visual motor planning may be beneficial for learning.

Based on differences between results in high-alpha power and coherence variables in Chapter 4, we argued that the two measures might not measure the same underlying process. While alpha power reflects activation of locally specified brain regions, which represent specific functions, coherence reflects communication between brain regions, supposedly as a more global sign of collaboration (Deeny et al., 2003). Based on results in

Chapter 4, we suggested that although local (verbal) processes may have been rendered more efficient by analogy instruction, efficiency of verbal-motor planning may not have been affected. Similarly, we found differing results for power and coherence variables in the present study. Here, we can extend the previous argument by stating that high coactivation of visuospatial and motor planning regions in the first instance (baseline) might be beneficial for later performance, independent of instruction mode, although visual or verbal processing alone did not seem to have an effect.

People who showed high coactivation of visual and motor brain regions during baseline motor control improved more when they were instructed by analogy. Contrastingly, in the explicit group, learning was predicted by T7-Fz coherence at baseline, which indicates that people who exhibited high involvement of verbal brain regions during baseline motor performance improved more when taught by explicit instructions or when learning by discovery (which often is also highly explicit) compared to people with low verbal engagement. These results support our hypothesis that analogy instructions lead to better learning by those who tend to process information visually, and that explicit instructions lead to better learning in people who tend to use verbal information processes. Riding et al. (2010) have shown that cognitive style is reflected in brain activity (alpha power in verbal association regions) during execution of tasks (Glass & Riding, 1999; McKay et al., 2002; Riding et al., 1997). We therefore assumed that pre-test EEG coherence, a specific measure of functional coactivation of two brain regions, might also be reflective of information processing preferences. EEG measures in the alpha frequency have been shown to reflect large, relatively stable interindividual differences, which are related to age and memory performance (Klimesch, 1999). EEG coherence specifically measures functional coactivation, therefore it is not likely that the measure is confounded by other verbal or visual processes that may have been ongoing during that time. It is feasible to assume that participants who exhibit high T7-Fz coherence during baseline motor control may be more likely to process a lot of verbal information about a movement during immediate motor preparation. Likewise, high T8-Fz coherence during preparation for uninstructed movements (baseline) may indicate a general tendency for visual processing during motor planning. If people with high verbal-motor coherence during baseline motor performance are indeed verbalisers (i.e., prefer verbal instructions for learning movements), EEG might extend the collection of measures for cognitive style and preference with an objective tool (Milz, Faber, et al., 2016; Riding et al., 1997) that may

even be applicable to the sports field (Fuelscher et al., 2012). However, further research that links the two measures is needed.

Self-focused conscious control may be a factor connected to individual differences in cognitive style and performance. Malhotra et al. (2015) showed that MSRS score was positively related to performance in early learning stages of a golf putting task. At these early stages, it may be beneficial to have a high propensity for conscious control of movements, because verbal-cognitive processes during motor acquisition may lead to the build-up of more movement-specific rules to better control or guide the movement (e.g., by hypothesis testing, (Berry & Broadbent, 1988; Masters, 1992; Maxwell et al., 2000). Malhotra and colleagues (2015) also showed that a higher propensity for conscious motor processing resulted in lower variability of movement kinematics. The low variability may be indicative of a “freezing” of degrees of freedom in the learning process (Greenwald, 1970; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001), which is functional for early motor learning (Cordier, France, Pailhous, & Bolon, 1994). The authors concluded that high reinvestors might be better at freezing degrees of freedom, which leads to superior performance early in the learning process. T7-Fz coherence during motor preparation may represent conscious, verbal control of movements, which has been shown to concur with a freezing of joint angles (Rosenbaum et al., 2001; van Ginneken et al., 2017). During learning, degrees of freedom are liberated step by step until, at an expert level, one can reach a movement goal in many different ways. Freezing of joint angles may be beneficial for people using stepwise verbal instructions to control their movements or at early stages of learning that are marked by conscious, step-wise movement control. However, freezing might not be as helpful at later stages in learning that are characterised by less consciously controlled movement or for people trying to apply a single, visual analogy instruction. The current study found that reliance on verbal information processes, as measured by pretest T7-Fz coherence, was positively related to improvement in an explicitly instructed group but not in a group instructed by analogy, which fits this argument. Van Ginneken et al. (2017) have recently conducted a study investigating degrees of freedom following motor learning with explicit and implicit (errorless) forms of instruction. They found that propensity for conscious control was positively associated with both freezing and performance in an error-strewn condition, while in an error-reduced condition, propensity for conscious control was not associated with freezing of mechanical degrees of freedom. This suggests that implicit learning may affect the impact of conscious control on movement kinematics such as freezing of degrees of freedom. While normal learning

progresses slowly from a stage of closely controlled, constrained movements towards a stage of more liberated degrees of freedom, analogy instruction may help to liberate degrees of freedom at an earlier stage in the learning process. In the absence of a measure of degrees of freedom in this study, this line of argument needs further examination and testing.

Liao and Masters (2001) argued that motor analogies are likely to be processed as an image in the visuospatial sketchpad of WM. Our results suggest that visuomotor processing during an uninstructed baseline predicted performance improvement after analogy instruction, which provides support for the claim by Liao and Masters (2001). We acknowledge, however, that baseline EEG coherence can only tentatively be used as a measure for visual or verbal instruction preference. In order to confirm whether analogies are processed in visuospatial domains of WM, a potential next study should include controlled manipulation of visuospatial resources available during analogy learning. A validated and reliable measure of visual or verbal preference should be included.

### **Conclusions**

When time for practice is allowed, an initial tendency to engage in visual motor planning may be beneficial to learning. Furthermore, analogy instructions may lead to better learning by those who tend to process information visually, while explicit instructions may benefit people who tend to rely on verbal information processes. The present results provide some support for a visual processing explanation of analogy motor learning.

A more direct personality measure related to verbal and visual processing is the preference for verbal or visual instructions. In the next chapter, we tested whether preference can predict whether a learner benefits from analogy instruction or not. Determining characteristics that are related to successful and unsuccessful learning by analogy instruction may help to guide the development of analogies that are adapted to specific learning groups (e.g., clinical patients) or to the individual learner.

## Chapter 6

# Effects of Instructional Preference on Performance and Cognitive Processes During Adaptation of a Motor Analogy<sup>29</sup>

### Abstract

During skill learning, analogy instructions impart knowledge about how to move by way of comparison with a similar, well-known concept. This reduces the number of verbal instructions or rules that need to be given to the learner. It has been argued that analogy reduces reliance on verbal information processes during motor planning (Masters 2000; Liao & Masters, 2001), which may be reflected by reduced verbal activity in the brain (measured by EEG alpha power at the temporal region, T7) as well as reduced verbal-motor cross-communication (EEG T7-Fz coherence) during the preparation phase of a movement.

Preference for using verbal or visual instructions is likely to influence the efficacy of analogy instructions. This study investigated whether preference for verbal instructions was related to changes in performance and neural activity related to information processing during performance (preparatory phase) of an adapted basketball task after instruction by analogy. While electro-cortical measurements at pre-test did not differ significantly, people with a preference for verbal instructions showed a decrease in activation of verbal regions when they used the analogy (high-alpha power). People with low verbal preference did not show a significant decrease in activation of verbal regions, and their performance deteriorated significantly after introduction of the analogy instruction, whereas people with high verbal preference remained stable. Results generally support our hypothesis that analogy reduces verbal processing demands. It is likely that both cognitive and performance changes after analogy instruction depend on personal aspects of information processing, such as verbal preference.

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<sup>29</sup> Based on: van Duijn, T., Masters, R. S. W. (in preparation). Effects of instructional preference on performance and cognitive processes during adaptation of a motor analogy.



## Introduction

Analogy learning means learning by mapping structural features from a familiar concept to a novel concept (Gentner, 1983; Gentner & Gentner, 1983). Its application to motor learning has been shown to be especially useful for novices. Motor learning by analogy is characterised by stable motor performance when a secondary, cognitive task is performed concurrently (Jie et al., 2016; Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, et al., 2016; Tse et al., 2017), stable performance under pressure (Lam et al., 2009a; Law et al., 2003; Liao & Masters, 2001; Vine et al., 2013), as well as stable performance under decision making conditions (Masters, Poolton, Maxwell, et al., 2008; Poolton et al., 2006). Effects have been demonstrated following 40 to 400 practice trials (but see contrasting results when a longer practice period was used, Koedijker et al., 2008, and in the learning of a dynamic balancing task, Orrell et al., 2006b).

Although Gentner (1983) devised a structure mapping model that convincingly explains the mechanism for concept learning, we cannot fully explain the benefits of analogy instructions over conventional explicit instructions in motor learning. It has been suggested that analogy learning may lead to reduced verbal-cognitive control of the movement (Liao & Masters, 2001), which makes information processing more effortless and efficient (Hatfield & Hillman, 2001; Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Working memory (WM), the mental domain for short term storage and processing of information, has a limited capacity (Baddeley & Hitch, 1974) and thus limits the amount of cognitive information that can be processed concurrently. A high reliance on verbal-analytic planning of the movement may lead to an increased load on WM, which is debilitating to performance when secondary, cognitive tasks have to be performed alongside the movement (Masters & Maxwell, 2004; Maxwell et al., 2001; Poolton et al., 2005; Schlapkohl et al., 2012). Reducing verbal control of movements (e.g., by analogy learning) may free up capacity for information processing for other tasks (Berry & Broadbent, 1984) and allow stable performance in dual task and pressure situations (Maxwell et al., 2003). Typically, learners receive explicit instructions or rules, which they consciously implement during practice. If left to their own devices, they may test hypotheses about how to move themselves, thus accumulating their own rules (e.g., Masters, 1992; Masters & Maxwell, 2004; Maxwell et al., 2000). In any case, novice performers are likely to come to rely on declarative, explicit (verbalisable)

knowledge when learning a movement and tend to consciously control their performance (Fitts & Posner, 1967; Fitts, 1964). Analogy learning may limit the amount of verbal information that novices access at an early stage of learning, leading to lower processing demands (Bobrownicki et al., 2015; Masters, 2000; Masters & Poolton, 2012), which may be responsible for the demonstrated advantages of analogy learning.

In most motor analogy experiments to date, fewer verbalisable rules were reported by the participants learning by analogy compared to explicit instructions or discovery learning (uninstructed) (Bobrownicki et al., 2015; Lam et al., 2009a, 2009b; Law et al., 2003; Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008; Orrell et al., 2006a; Poolton et al., 2006, 2007b; Schücker et al., 2013). The notion that analogy instructions may lead to reduced reliance on verbal-declarative knowledge to control a movement is further supported by evidence of reduced cognitive load (measured by a probe reaction time paradigm) after practice using analogy instruction (Lam et al., 2009a). In Chapter 4, we also found that analogy learning may lead to higher general economy of verbal-cognitive processes, as indicated by brain activity measurements.

#### **Preference for verbal instructions**

Collectively, research points towards a limitation in effortful, verbal-analytic information processing when analogy instructions are used to teach a movement skill. If verbal information processing is altered or improved by using an analogy, individual differences in information processing are likely to have an effect on these changes. In particular, a person's preference for visual or verbal instructions may play a key role. The visual-verbal preference dimension is a stable personality trait (Mayer & Massa, 2003) differentiating between verbalisers who tend to prefer verbal instructions, and visualisers who tend to prefer images (Riding & Watts, 1997).

Instruction preference may affect the modality in which movement-specific information is processed (Milz, Pascual-Marqui, Lehmann, & Faber, 2016). Research has shown that cognitive style<sup>30</sup> is reflected in specific brain activity during execution of tasks (Glass & Riding, 1999; McKay et al., 2002; Riding et al., 1997). Glass and Riding (1999) found that verbalisers exhibited higher activation of verbal processing areas during a verbal task compared to "imagers" as measured by EEG (electroencephalographic)

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<sup>30</sup> Cognitive style is a measure of preferred modality (visual or verbal) for information processes, based on Cognitive Styles Analysis by Riding and Cheema (1991).

analyses. Also fMRI studies have assessed visual-verbal preference in combination with BOLD<sup>31</sup> activity during different tasks. Visual preference measured by the Visualizer-Verbalizer Questionnaire (VVQ, modified by Kirby et al., 1988) was shown to be positively correlated with BOLD activity at cortical areas associated with visual WM, while verbal preference was related to activation of areas associated with verbal WM during a color knowledge retrieval task (Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill, 2011) and during visual and verbal tasks (Kraemer, Rosenberg, & Thompson-Schill, 2009).

High dependence on verbal processes during initial practice (reflected by activation of verbal brain regions) may lead to a larger pool of explicit, verbalisable knowledge available to the learner, which often incurs higher processing demands (Maxwell et al., 2003). This high amount of verbalisable and task-related knowledge acquired during early practice by high verbalisers may be efficiently reduced when an analogy is introduced subsequently, reducing the load on verbal WM, and rendering processing more efficient. Thus, the analogy may be especially useful for people with a verbal preference.

### **Measuring verbal-cognitive engagement in movement control**

Measuring and quantifying verbal-cognitive information processes connected to motor control is an important step in determining the mechanism behind analogy learning. Indirect measures of verbal processing during motor preparation or execution include verbal protocols, dual task paradigms and probe reaction time tasks (Baddeley, 1966; Berry & Dienes, 1993; Hayes & Broadbent, 1988; Lam et al., 2010; MacMahon & Masters, 2002). Performance decrement in a dual task has been suggested to be an indicator of conscious verbal involvement in motor control (MacMahon & Masters, 2002; Maxwell et al., 2000), with people with high involvement of verbal WM (e.g., using movement rules to guide the movement outcome, Berry & Broadbent, 1984) more susceptible to dual task decrements.

However, verbal-cognitive contributions to motor planning processes can be measured more objectively using electroencephalography (EEG), a measure that assesses electrical potentials produced by brain cells through electrodes placed on the scalp. From the detected voltages, cortical activity in different areas of the cerebral cortex can be analysed. For reviews on recent research using psycho-physiological measures during

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<sup>31</sup> BOLD is a form of functional brain mapping using blood oxygenation-level dependent contrast magnetic resonance imaging. It represents activity of the specified area at a high spatial resolution.

sport and motor performance, see Cooke (2013) or Hatfield et al. (2004). EEG power in the high-alpha power band (10-12Hz), is inversely related to cortical activation: an increase in alpha power reflects decreased cerebral activation and vice versa a decrease in alpha power represents a rise in activity (Hillman et al., 2000; see Klimesch, 1999, for a review).

Different brain areas are related to different functions of the brain, so activation of brain regions reflects specific cognitive processes during movement preparation or execution. The left temporal lobe (T7)<sup>32</sup> contains verbal-analytic brain regions such as Broca's area and Wernicke's area and has been shown to be involved in verbal-analytic processing (Kaufer & Lewis, 1999; Sperry, 1974; Springer & Deutsch, 1998). Lower alpha power in the left temporal region is associated with a high degree of conscious engagement in a motor task, and conversely high alpha power in these areas suggests that verbal-analytical processes may be suppressed during performance (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001).<sup>33</sup> Studies found higher alpha power and lower processing demands in successful compared to unsuccessful executions (e.g., Hillman et al., 2000, Crews & Landers, 1993; Babiloni et al., 2011; Cooke et al., 2015) as well as in experts compared to novices (e.g., Haufler et al., 2000; Wolf et al., 2015), indicating that involvement of conscious control mechanisms during performance is gradually reduced as motor tasks are refined (Babiloni et al., 2008, 2009, 2010, Del Percio et al., 2008, 2010; Zhu et al., 2010).

A direct indicator of verbal-cognitive contributions to motor planning is found in neural coactivation, or EEG coherence, a measure of functional communication between regions of the brain. EEG coherence between regions associated with motor planning (Fz, frontal midline) and verbal-analytic processing (T7) is thought to indicate the involvement of verbal processes in motor performance (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Lawton et al., 1998; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Recent studies have found that experts display lower coherence between the T7 and Fz regions

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<sup>32</sup> In this paper, all labelings are translated to the nomenclature suggested in the American Electroencephalographic Society's "guidelines for standard electrode position nomenclature" (American Electroencephalographic Society, 1994; Chatrian et al., 1985; Jurcak et al., 2007; Klem et al., 1999). The terms T7 and T8 are used for left and right temporal lobes, while Fz is used for the frontal lobe site. Odd numbers indicate left hemisphere, even numbers right hemisphere locations.

<sup>33</sup> Comparatively, the pre-motor area (Fz) is crucial in movement planning, while activity in the right temporal lobe (T4 or T8) has been shown to represent visuospatial mapping of movements (Wolf et al., 2015).

during movement execution compared to novices (Deeny et al., 2003; Gallicchio et al., 2016), and that T7-Fz coherence also increases in conditions of heightened anxiety (Chen et al., 2005) and psychological pressure (Hatfield et al., 2013, but see also Rietschel et al., 2011, for a contrary finding), which are situations known to be connected with increased verbal load due to self-monitoring. EEG high-alpha power and EEG coherence are therefore validated neural measures when investigating the effect analogy learning has on brain processes underlying performance.

### **The present study**

We investigated whether preference for verbal instructions was related to changes in performance and in information processing (EEG high-alpha power and coherence at verbal and visual sites) immediately after a task-specific analogy was instructed. Verbal preference was assessed using the verbal subscale of the VVQ (Verbalizer-Visualizer Questionnaire, developed by (Kirby et al., 1988)<sup>34</sup>.

Brain activity (EEG) was measured during two blocks of trials (10 trials each) before and after an analogy instruction was provided, to examine whether changes in verbal or visual information processing were related to scores on the verbal subscale on the VVQ.

Performance was expected to improve after introduction of the analogy, and more strongly so for people with a high verbal preference. Since the analogy has been shown to increase neural efficiency by increasing high-alpha power in the left temporal lobe, an increase in high-alpha power was expected to be stronger for the verbal preference group.

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<sup>34</sup> Although the adapted version of the Verbalizer-Visualizer Questionnaire (Richardson, 1977) has been validated (Kirby et al., 1988) and used in previous studies (Hsu et al., 2011; Kollöffel, 2012; Kraemer et al., 2009; Milz, Faber, et al., 2016), it is not a validated instrument to measure preference in the sport context. The importance of developing a validated tool applied to motor learning preferences has been mentioned before (Fuelscher et al., 2012). Visual preference was also investigated using the visual subscale of the VVQ (Kirby et al., 1988), however, the experiment population scored low on the scale and results were not used in the analysis.

## Method

### Participants

Initially, 74 participants (mean age = 19.35 years, SD = 2.76, 38 females and 36 males) with normal or corrected-to-normal vision and no movement impairment participated in the study. Participants were recruited from a sports undergraduate class. Ethical permission for the study was received from the faculty ethical committee of the institution. Participants all provided informed consent. Participants with over 200 hours of basketball experience ( $n = 12$ ) were excluded from the analysis. Only participants who used incorrect shooting technique at pre-test ( $n = 32$ ) were included, which reduced the sample by a further 16 participants. Correct or incorrect shooting technique at pre-test was judged by two independent raters using video footage (side-on perspective)<sup>35</sup>. Cases in which the raters differed (6.75 %) were discussed until an agreement was reached. Additionally, extreme outliers in T7 high-alpha power ( $n = 2$ ) and T8 high-alpha power ( $n = 2$ ) were excluded. Participants were allocated to low ( $n = 13$ ) and high ( $n = 15$ ) verbal preference groups using a median split approach. Five participants with scores on the median were excluded from the analysis. The final sample (7 male, 21 female participants) showed a mean age of 19.25 years (SD = 2.67).

### Materials

For the basketball shooting skill, a soft, slightly deflated beach volley ball (diameter = 23 cm) and a junior indoor basketball setup with backboard (height = 45cm, width = 71 cm) and hoop (diameter = 39cm) were used. Participants were seated on a chair (height = 45 cm) with horizontal distance from the rim equal to 315 cm. Height of the basket was adjusted to seated reaching height (at full arm extension) plus 30 cm. A laptop with speakers was used to generate two signal beeps 4s apart, to indicate the preparation and execution phase of each shot. Performance measures were obtained by manual analysis of video footage from a Sony RX10pi camera focused on the target.

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<sup>35</sup> Correct technique was defined as matching the movement described by the analogy instruction of “putting cookies into a cookie jar on a high shelf”, i.e., high elbow, wrist flick, and nondominant hand guiding the throw.

### *Electroencephalography*

EEG equipment included a wireless EEG / tDCS transmitter, a set of 8 measuring and 2 reference electrodes, conducting gel and electrode contact stickers (Neuroelectrics Barcelona, SLU, ESP). The system was connected to a desktop computer and analysed using Neurosurfer software by Neuroelectrics. EEG activity was recorded from 6 silver/silver chloride (Ag/AgCl) electrodes on the scalp positioned using different sized neoprene caps with pre-defined holes. Two reference electrodes were placed at the earlobe using a clip. Where the earlobe was too small to hold the clip, two stickrodes were attached to the left mastoid. Caps and electrodes were adjusted carefully in line with the 10-20 system (Chatrian et al., 1985) and checked by two technicians before the start of the experiment. Signals were amplified at a sampling rate of 500 Hz with 24-bit resolution and 0 - 125 Hz bandwidth. Measurement noise was under 1 microvolt RMS.

Prior to commencing the task, impedance needed to reach a satisfactory level (below 15 kOhm). This was achieved by adjusting electrode positions, the participant's hair and the amount of electrolyte gel. The pre-session criteria required participants to (a) wash their hair on the evening/morning before testing, and (b) not consume caffeine in the 2 hours preceding testing. Baseline EEG data was collected prior to commencing the experiment. This took place while the participant was seated and not moving during 120 seconds. The first 60 seconds were recorded with the participant's eyes open (blinks were not suppressed), while the second 60 seconds required the eyes to be closed.

### *Visual-verbal preference*

Verbal-visual preference was assessed using an adapted version of the VVQ (Verbalizer-visualizer Questionnaire, adapted by Kirby et al., 1988). The original measure, developed by Richardson (1977) asked 15 yes/no questions about preference for visual or verbal instructions and cognitive style. Based on issues with unidimensionality, Kirby et al. (1988) developed an extended version to include a separate visual and verbal dimension (treated as separate scales). Additionally, a dream vividness dimension was extracted from the original scale and treated as a separate dimension. The adapted VVQ contains 30 items, 10 each for visual preference, verbal preference, and dream vividness. The latter subscale was not used in the present study. Out of the remaining 20 items, half were reversed for each subscale (i.e., a 'yes' answer would indicate low preference for that type of instruction). The visual and verbal dimensions of the questionnaire have been tested for reliability and validity (Kirby et al., 1988).

## Procedure

Participants completed the VVQ questionnaire online before the experiment (as part of a class assignment); however, they were unaware of any connection with the experiment. They provided informed consent and completed the rest of the experiment in the laboratory. They were fitted with the Neuroelectrics cap and the EEG electrodes were attached at the T7, T8, Fz, F3, F4 (experimental) and Cz, Fp1, Fp2 (control) locations.

The motor task required participants to perform a modified, seated basketball-shooting task. This modified task was adopted to reduce the difficulty of the task and thus shorten the length of the adaptation process (shorter shooting distance and lower rim height compared with a regular free throw position and a different ball) and to allow collection of data in a controlled laboratory environment. Additionally, head movements were kept at a minimum by this adaptation of the task, which is a prerequisite for EEG measurement. Participants performed the task in a pre-test and a post-test of 20 repetitions each, during which EEG was collected. The task required participants to throw the ball as accurately as possible into the basket from where the chair was positioned. Participants were told to keep their back off the backrest of the chair in order to generate enough force. A signal consisting of two beeps, spaced 4s apart was used to indicate the start of preparation and shooting phase. Participants were required to prepare for each shot during the preparation phase (after hearing the first signal) and to shoot after they heard the second signal. They were also informed that they should not rush the execution of their shot after hearing the second signal.

### *Instruction*

For the pre-test, participants were told to shoot the ball into the hoop, and were informed about the scoring method (see below). No instructions were given about how the movement should be performed. After the pre-test, participants were instructed with a validated analogy for the seated basketball shooting task (Lam et al., 2009a, 2009b), which required them to “shoot as if you are trying to put cookies into a cookie jar on a high shelf”. No other instruction was provided.



## **Dependent variables and data analysis**

### *Dependent variables*

Performance was measured on-line during the experiment, using a 6-point scale developed by Hardy and Parfitt (1991), according to which a score of 5 was awarded for shots that went through the hoop without touching the rim or backboard, 4 for those which touched the rim, 3 for those which hit the backboard before dropping through the hoop, 2 for those that touched the rim but did not drop through the hoop, 1 for those that touched the backboard and missed the hoop, and 0 for a complete miss. Doubtful or unsure calls were reinvestigated using video recordings collected at normal speed (30 fps) from a camera focused on the backboard. Hardy and Parfitt (1991) reported that the test-retest reliability of this scoring system over a 3-day interval and at different levels of physical fatigue (induced by running) was moderate ( $r = .54$ ). Lam et al. (2009a, 2009b) used the same scoring method in a seated basketball task and reported high reliability (cr. alpha = .94). Mean shooting score in each block (i.e., maximum score 5 points) was calculated. Items for both subscales of the VVQ were reversed for negatively worded items. Item scores were summed up separately for each subscale, leading to cumulative score ranges of 0 – 10 for verbal preference and visual preference.

### *EEG Data Reduction / Processing*

Raw EEG signals were filtered at 1-30Hz and a notch filter was added to exclude 50Hz line noise. Signals were then resampled at 256 Hz. Data from the accuracy tests in pre and retention were cut to 4-s epochs before movement initiation. Epochs were split into 0.25-s trials for artefact removal. Blinks and eye movements are characterised by high potentials (Boudet et al., 2006). Based on previous studies in the field (Deeny et al., 2003; Haufner et al., 2000; Janelle et al., 2000; Kerick et al., 2001), eye artefacts were excluded by an extreme measures approach using the EEGLAB toolbox (Delorme & Makeig, 2004). Trials containing signals above 70mV were discarded. An average of 251.24 (SD = 68.43) trials per participant in the pre-test and 237.18 (SD = 77.19) trials per participant in the post-test were retained. A Fast Fourier Transform with Hamming window taper, 50% overlap with a resolution of 0.49 Hz, was applied. EEG high-alpha (10-12Hz) power was calculated over the 0.25-s epochs (e.g., Deeny et al., 2003) and averaged for the 4-s epochs preceding each trial.

### *Calculation of EEG power and coherence*

The EEG analyses in this study focused on the high-alpha (10-12 Hz) band. Activity in this bandwidth indicates long- and medium-range cortico-cortical communication (Crews & Landers, 1993; Nunez & Srinivasan, 2006; Janelle et al. 2000; Nunez et al. 1999) and is representative of task-specific attentional processes (Smith et al. 1999; for a review see Klimesch, 1999). Coherence was analysed for T7-Fz and T8-Fz regional combinations separately, as these areas represent verbal-analytic (T7), visuospatial (T8) and motor planning (Fz) regions (Kaufer & Lewis, 1999; Haufner et al. 2000; Kerick et al. 2001). Matlab scripts (MATLAB Release 2016b, The MathWorks, Inc., Natick, MA - US) were used to calculate EEG outputs.

### *Statistical analysis*

Performance scores, EEG high-alpha power and EEG coherence of high and low verbal preference groups were analysed using 2 (verbal preference: low, high) x 2 (test: pre-analogy, post-analogy) ANOVA's with repeated measures on the second factor. Follow-up t-tests were conducted to investigate changes within preference group if there was a significant interaction. Alpha value for statistical significance was set to .05.

## **Results**

### **EEG high-alpha power**

Two separate 2 (verbal preference: low, high) x 2 (test: pre-analogy, post-analogy) ANOVA's with repeated measures on the second factor were conducted to investigate differences in high-alpha power at T7 and at T8. The analysis of T7 alpha power revealed no significant main effect of test ( $F(1,26) = 2.44, p = .130$ , partial  $\eta^2 = .09$ , observed power = .33) or verbal preference ( $F(1) = .21, p = .654$ , partial  $\eta^2 = .01$ , observed power = .07). A significant verbal preference x test interaction was evident ( $F(1,26) = 5.15, p = .032$ , partial  $\eta^2 = .17$ , observed power = .17). Follow-up t-tests showed that T7 high-alpha power did not change significantly for the low verbal preference group ( $t(12) = 1.02, p = .326$ ), but increased significantly in the high verbal preference group ( $t(14) = -2.18, p = .047$ , see Figure 18). A t-test was also conducted to investigate differences between the groups at pre-test. No significant difference in high-alpha power at T7 was evident ( $t(17.951) = 1.50, p = .162$ , equal variances not assumed).

The ANOVA for high-alpha power at T8 revealed no significant main effect of test ( $F(1,26) = 3.73, p = .064, \text{partial } \eta^2 = .13, \text{observed power} = .46$ ) or of verbal preference ( $F(1,26) = .003, p = .959, \text{partial } \eta^2 = .00, \text{observed power} = .05$ ) and no significant verbal preference x test interaction ( $F(1,26) = 2.96, p = .097, \text{partial } \eta^2 = .10, \text{observed power} = .38$ , see Figure 19).

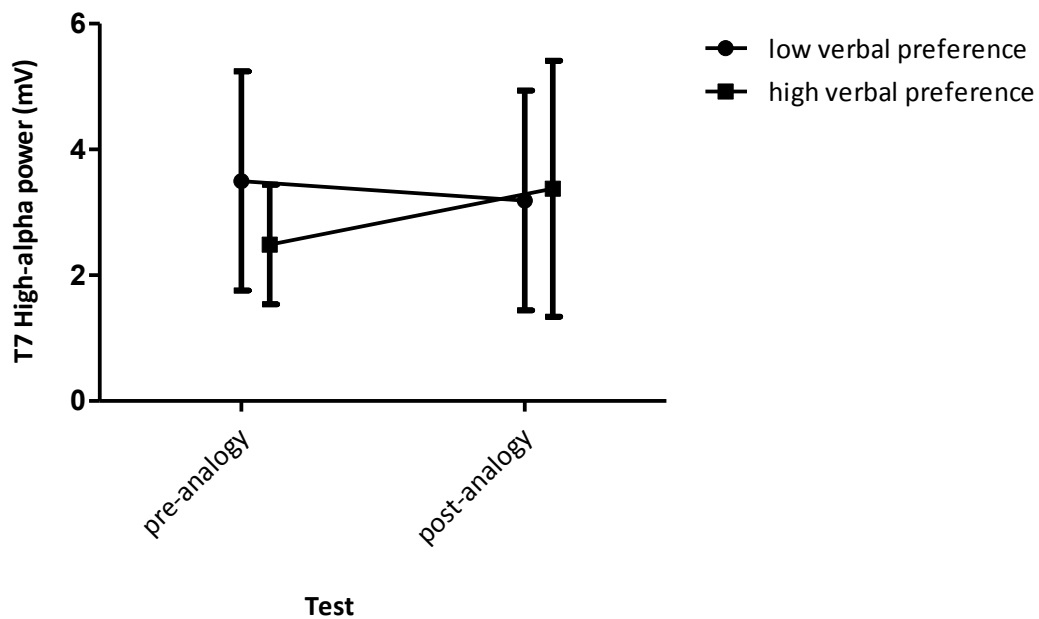


Figure 18. High-alpha power at T7 (verbal processing area) in low and high verbal preference groups during the pre-analogy and post-analogy performance test.

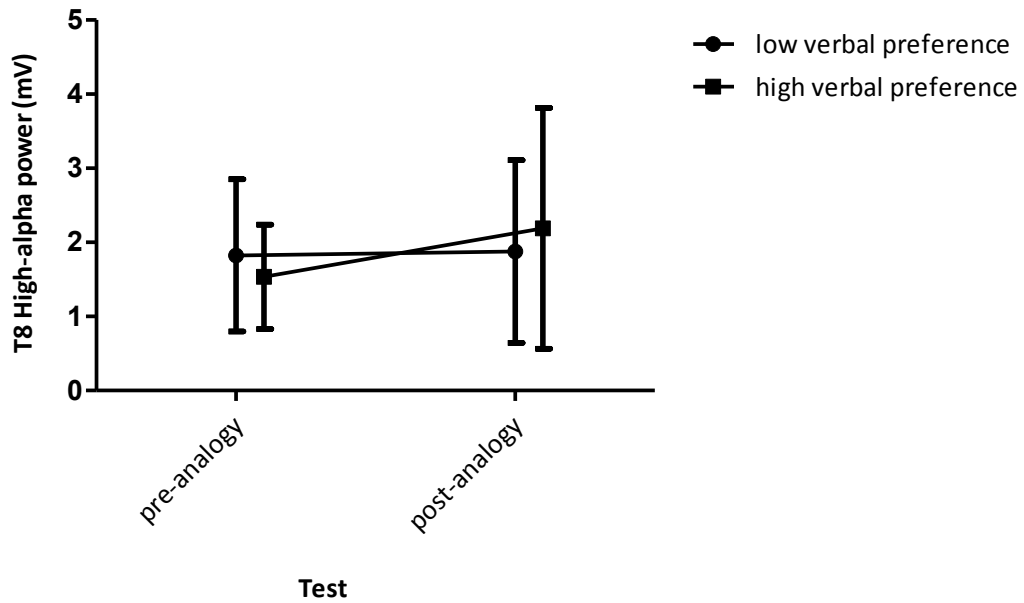


Figure 19. High-alpha power at T8 (visuospatial processing area) in low and high verbal preference groups during the pre-analogy and post-analogy performance test.

### EEG high-alpha coherence

Two separate 2 (verbal preference: low, high) x 2 (test: pre-analogy, post-analogy) ANOVA's with repeated measures on the second factor were conducted to investigate differences in T7-Fz and T8-Fz coherence. The analysis of T7-Fz coherence revealed no significant main effect of test ( $F(1,26) = 3.27, p = .082, \text{partial } \eta^2 = .11, \text{observed power} = .41$ ) or of verbal preference ( $F(1,26) = 1.74, p = .199, \text{partial } \eta^2 = .06, \text{observed power} = .25$ ) and no significant verbal preference x test interaction ( $F(1,26) = .94, p = .340, \text{partial } \eta^2 = .04, \text{observed power} = .16$ ).

The analysis of T8-Fz coherence revealed a significant main effect of test ( $F(1,26) = 4.71, p = .039, \text{partial } \eta^2 = .15, \text{observed power} = .55$ ), but no significant main effect of verbal preference ( $F(1,26) = 1.23, p = .278, \text{partial } \eta^2 = .05, \text{observed power} = .19$ ) and no significant verbal preference x test interaction ( $F(1,26) = 1.11, p = .301, \text{partial } \eta^2 = .04, \text{observed power} = .17$ ). Mean values and standard deviations of high-alpha coherence are shown for both groups in Table 17.

Table 17. Descriptive statistics for high-alpha coherence

		Pre-test		Post-test	
		Mean	SD	Mean	SD
T7 -Fz	Low verbal preference	0.35	0.08	0.37	0.12
	High verbal preference	0.38	0.12	0.43	0.09
T8-Fz	Low verbal preference	0.29	0.10	0.31	0.07
	High verbal preference	0.32	0.14	0.37	0.12

### Performance

Mean performance scores for participants with low and high verbal preference are presented in Figure 20. A 2 (verbal preference: low, high) x 2 (test: pre-analogy, post-analogy) ANOVA with repeated measures on the second factor was conducted to examine the performance scores. The analysis revealed no significant main effect of test ( $F(1,26) = 3.41, p = .076, \text{partial } \eta^2 = .12$ ) or of verbal preference ( $F(1) = 1.25, p = .275, \text{partial } \eta^2 = .05$ ). A significant verbal preference x test interaction was evident ( $F(1,26) = 7.65, p = .010, \text{partial } \eta^2 = .23, \text{observed power} = .76$ ). Follow-up t-tests showed that performance decreased significantly in the low verbal preference group ( $t(12) = 3.59, p = .004$ ), but no change was evident in the high preference group ( $t(14) = -0.62, p = .547$ ).

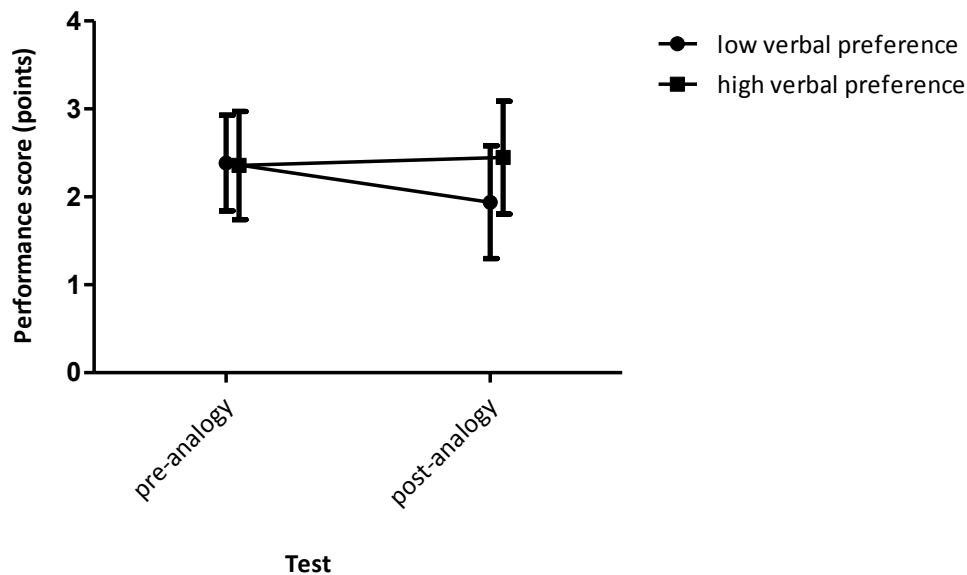


Figure 20. Performance scores for low (dots) and high (squares) verbal preference groups in the pre-analogy and post-analogy test.

## Discussion

Participants with a high preference for verbal instructions showed an increase in high-alpha power at T7 after they were instructed with an analogy, while participants with a low verbal preference did not show any changes in cortical activity. An increase in high-alpha power at T7 has been linked to a decrease in cortical activation, suggesting higher efficiency in those regions (Cooke, 2013; Hatfield et al., 1984), which is consistent with *psychomotor efficiency* (Hatfield & Hillman, 2001). Psychomotor efficiency refers to a decrease in cognitive effort required for performance of a movement, concurrent with an increase in performance during development of expertise and has been linked to electrocortical measurements such as higher alpha power (Cooke et al., 2014; Crews & Landers, 1993; Haufler et al., 2000; Hillman et al., 2000) or reduced cortico-cortical coherence (Deeny et al., 2009; Hatfield & Hillman, 2001; Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011). In this study, analogy instructions led to a reduction in activity in verbal-cognitive processing areas of the brain during motor control, which may indicate increased efficiency of verbal processes, but only in people who preferred verbal instructions. A potential explanation may lie in the creation of a larger pool of explicit, verbal knowledge during uninstructed practice by participants with a verbal preference, which often incurs higher processing demands (Maxwell et al., 2003). However, the amount of information that was acquired by participants was not analysed in this study.

Not just processing of movement, but also processing of instructions, is a cognitive process that is reflected in cortical activity. Higher left-temporal high-alpha power (i.e., lower activation) in the verbal preference group could therefore be related to more efficient processing of the analogy instruction or better ability to process the analogy. Verbal preference is potentially related to verbal ability (e.g., Kirby, et al., 1988; but also see Alesandrini, 1981 for a contradictory finding), so verbalisers may be better at making abstract connections between the source (i.e., cookie jar) and the target (i.e., movement), which is necessary for successful processing of analogies (Gentner, 1983; Sternberg, 1977). Better ability to process the analogy may thus explain why high verbalisers showed brain activity patterns related to more efficient verbal processing after analogy instruction.

No difference between verbal preference groups was found in T7-Fz coherence, which indicates that neither group's verbal-motor cross-communication became more efficient.

This is at odds with previous findings by Zhu and colleagues, which showed that implicit motor learning leads to a decrease in T7-Fz coherence (Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011). The only previous study of analogy learning that involves cortical activity measures found that high-alpha power at T7, but not T7-Fz coherence was affected by analogy (Chapter 4). We argued that using analogy may increase efficiency of verbal-cognitive processes, but verbal-motor cross-communication may remain the same. The mechanism responsible for the benefits connected to analogy in motor learning may be tied to verbal-cognitive processes, rather than verbal-motor cross-communication, and it might thus differ from the mechanism underlying other forms of implicit motor learning.

Previous experiments showed that learning by analogy progressed at the same rate as learning by explicit instructions or without instructions (Bobrownicki et al., 2015; Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001; Poolton et al., 2007b; Tse et al., 2017). Usually, the beneficial effect of analogy instructions on cognitive processes only becomes visible in dual task or pressure conditions, where an additional load on WM is present. The results of the current study are somewhat at odds with these results, since we found that high and low verbalisers showed differences in their performance in a single-task test after analogy instruction. However, this study differs from previous studies as we investigated immediate effects after introduction of analogy. The shortest periods of practice after introduction of the analogy in the existing literature consisted of 40 trials (Bobrownicki et al., 2015) or around 80 trials (Koedijker et al., 2011; Vine et al., 2013).<sup>36</sup> Since the present experiment did not include a control group that received a different set of instructions (either explicit instructions or no instructions), we cannot compare analogy learning to explicit learning results after 20 practice trials.

The fact that a deterioration, rather than an improvement, was found in performance measures also makes sense given the low number of practice trials in this study. Researchers have argued that processing of an analogy instruction may take some time, leading to a delay in benefits related to performance (Masters & Liao, 2003). The demands of processing new instructions have been shown to lead to an initial decrease in motor performance, presumably because they reduce the capacity available for the adjustment

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<sup>36</sup> In a walking study by Jie and colleagues (2016), as few as 8 practice trials were included, however, one trial of a 10m walk included around 10 repetitions of the step pattern, resulting in an estimated total of 80 practice trials of the step pattern. Furthermore, patients were asked to train at home additionally (Jie et al., 2016).

of movements during learning (Hodges & Lee, 1999; Wulf & Weigelt, 1997). When applying an analogy instruction, parallels have to be drawn between a known and a new concept in order for learning to be successful, which is a cognitive process that may be effortful (Gentner, 1983). The notion that processing of an analogy may require some time and cognitive effort is supported by a study by Masters and Liao (2003), which reported a decrease in performance immediately following instruction by analogy.

Performance results in this study indicate that deterioration after analogy instruction may be negatively related to verbal preference. A possible explanation is that the difference between high and low verbal preference participants may not be linked to analogy learning specifically, but to differences between them in learning. This is rather unlikely, since no practice repetitions after the analogy instruction were included. Another explanation could be related to the differing ability of verbalisers and non-verbalisers to process and apply verbal instructions. Although the analogy is a visually salient instruction that captures a complex concept within a simple comparison, it is instructed orally and is thus a verbal instruction (e.g., Poolton et al., 2006). Verbalisers may have simply benefited more from it as they were better able to use it. The deterioration in the low verbal preference group may also be due to misunderstanding. Misunderstanding has not been investigated in analogy motor learning; however, it is a very likely cause of performance deterioration after analogy instruction. The low verbal preference group in the present study may have experienced more instances of misunderstanding due to having accumulated less knowledge about the movement during practice, since low verbalisers might not be prone to (verbally) test hypotheses about how to move. Additionally, as mentioned earlier, high verbalisers who are used to processing large amounts of verbal information may have an advantage in processing an instruction.

When looking at cognitive and performance parameters in combination, differences between the groups in psychomotor efficiency are evident. High verbalisers did not show a change in performance but exhibited a decreased activation in the verbal brain region, which indicates increased efficiency of verbal-cognitive processes. Verbalisers thus became relatively more efficient in their verbal-cognitive processes. In contrast, the low verbalisers deteriorated in performance, without showing any change in brain activity, which equals a relative decrease in efficiency.



A potential explanation for this finding is at the same time an attempt to explain the mechanism underpinning analogy learning, which may be useful in improving and extending its application across motor learning fields: the chunking hypothesis of analogy learning (Masters & Liao, 2003). Chunking is a process of grouping a higher number of small chunks into a smaller number of larger chunks by organizing patterns during learning (Newell & Rosenbloom, 1980). Masters and Liao (2003) suggested that analogy learning may be a way to chunk information more effectively than in the long learning process, as it provides “pre-chunked” information that is already on a higher organizational level. The present finding of a relationship between verbal preference and changes in performance and cognitive measures of efficiency supports the chunking argument. As mentioned earlier, the high verbal preference group might accumulate more verbal knowledge about the movement and thus have a more in-depth understanding of the movement components. Since only items that are understood and that fit within a common higher-order structure can be chunked together (Baddeley et al., 1975), a more complete understanding of the movement may speed up chunking. Chunking may also lead to a more marked effect in the verbal preference group because a higher number of rules is reduced into a single chunk. The finding that verbalisers showed a greater increase in left-temporal high-alpha power, as well as less performance deterioration compared to low verbalisers, supports this proposition.

An alternative explanation for the benefits of analogy learning that has been proposed is a visual processing argument (Liao & Masters, 2001). Based on Baddeley and Hitch’s (1974) model of WM, Liao and Masters (2001) pointed out that analogies might be processed in the visuospatial sketchpad rather than in the phonological loop of WM, since they contain mainly visual components (Baddeley, 1981; Baddeley & Hitch, 1974). This would leave verbal processing resources to deal with other tasks, such as secondary cognitive tasks (Liao & Masters, 2001; Masters, Poolton, Maxwell, et al., 2008). However, if analogy learning does indeed rely on visuospatial information processing, people who tend to process movement-related information visually would be expected to benefit more from the analogy, whereas people who generally process information verbally would only be able to use the instruction with increased cognitive effort. The present study addressed this issue directly by assessing visual versus verbal preference. Results, however, are opposite to expectations based on the visual processing argument. That is, participants with a high verbal preference benefited most from being taught by analogy. An increase in efficiency of cognitive processes after analogy instruction may depend on

pre-existent verbal information, and thus be related to verbal, rather than visual instruction preference.

### **Conclusion**

The results of the present experiment indicate that performance changes as well as changes in cognitive efficiency after analogy instruction may be related to verbal preference. Analogy instruction may increase efficiency of verbal processes in high verbalisers, but not low verbalisers. This generally supports the hypothesis that analogy reduces verbal processing demands by reducing the amount of verbal information being processed, providing some support for a chunking hypothesis of analogy instruction. Changes in information processing may be responsible for relatively superior motor performance in high verbalisers.



# Chapter 7

## General Discussion

### Summary of main findings

The main aim of this PhD thesis was to investigate the potential underlying mechanisms that lead to benefits in motor performance after analogy instruction. For this, various variables connected to information processing (ability, capacity, propensity and personality) were assessed in the context of skill learning by analogy instruction. Chapter 2 showed that children who scored low on the Movement Specific Reinvestment Scale (MSRS) benefited more from the use of analogy compared to children who scored high. Learning a movement by analogy may be related to personal characteristics of information processing such as reinvestment. The results in Chapter 3 did not find reinvestment to be an important factor in general motor performance, but indicated that capacity for short-term storage and processing of visuo-spatial information (WM capacity) may be of central importance in early motor control. Chapter 4 showed an effect of analogy instructions on activation of verbal-processing brain regions, suggesting that analogy instructions may influence verbal aspects of information processing without directly impacting general motor planning processes. In sum, analogy instruction may promote efficiency of verbal-cognitive processes. In Chapter 5, results suggested that analogy learning may be of greater benefit to people who tend to rely on visual processes during motor planning. However, Chapter 6 showed that people with a high verbal preference benefited more from analogy. EEG results of Chapter 6 are in line with Chapter 3, suggesting that analogy reduces verbal processing demands.

### Potential mechanisms underlying the benefits of analogy instructions

Chunking has previously been suggested as a potential underlying mechanism that may lead to reduction of verbal components in motor planning (Masters & Liao, 2003). Chunking is a process of grouping a large number of small chunks into a small number of large chunks by organizing patterns during learning (Newell & Rosenbloom, 1980). Instead of chunking the information into a unified movement representation during learning, the necessary movement-related information contained within an analogy is already on a higher organizational level, or “pre-chunked”. The learner’s representation of the motor skill is thus improved without increased processing effort. Evidence of increased neural

efficiency in learners with a high preference for verbal instructions in Chapter 4 indirectly supports the chunking hypothesis.

The chunking explanation was not directly tested in this thesis. Although Masters and Liao (2003) made an attempt to test the hypothesis, this has not been backed up with more findings to date. In part, this is probably a consequence of difficulties in testing chunking of movement sequences. The approach used by Masters and Liao (2003) involved presentation of a sequential pattern of explicit instructions followed by an analogy. It has been shown that chunking only occurs when units of information are subjectively meaningful (Baddeley et al., 1975). Based on the premise that analogy should only chunk explicit rules that fit within its concept (meaningful units of information), manipulating “fit” of the explicit rules with the analogy would allow researchers to better examine chunking processes. The difficulty with this paradigm is to develop two equal sets of rules that both allow equal learning and improvement, yet differ significantly in their “fit” to the analogy.

Previous research on chunking of movement sequences was conducted on sequential movements, such as SRT or tracking tasks, which are compiled of defined subsequences. Reaction times and inter-sequence times allow a direct measurement of how subsequences are chunked into larger representations (Stöcker & Hoffmann, 2004). Complex motor skills are often non-repetitive, goal-directed movements that do not allow direct measurement of chunking mechanisms. Movement kinematic analyses have revealed that certain characteristics, such as fluency and variability of a movement (i.e., degrees of freedom), are representative of expertise and of less conscious control of the movement (Bernstein, 1967). Researchers have argued that an increase of degrees of freedom associated with execution of a movement might represent a more flexible, expert-like pattern that is controlled by fewer nodal points, which indicate control points or chunks in the representation of the movement (e.g., Hossner & Ehrlenspiel, 2010). Analysis of degrees of freedom, nodal points or fluency of a movement may, therefore, serve as an indirect measure of chunking. An alternative solution to the problem might lie in determining a more direct measure of chunking. For example, recent research has shown that representations of a movement within long term memory are a function of expertise, practice and instruction, but are relatively stable across repetitions (Frank et al., 2013; Schack & Mechsner, 2006; Seegelke & Schack, 2016).

An alternative explanation for the benefits of analogy learning, a visual processing explanation, was introduced in Chapter 1 (Liao & Masters, 2001; Poolton et al., 2006). An analogy is a visually salient instruction, so it may be processed within the visuo-spatial sketchpad of working memory, which is separate from the central executive and phonological loop (Baddeley, 2012). Thus, processing and use of an analogy might rely less on verbal processes than visual processes, and therefore be less likely to interfere with other verbal processes, such as dual-tasks or decisions. Although some findings in Chapter 5 suggest that people with higher visual-motor coherence improved more when using an analogy, the EEG findings of Chapters 4 and 6 do not support this premise. Verbal processing was reduced by using an analogy, but visual processing did not increase significantly. If analogy is indeed purely superior because of its visual characteristics, we would expect visualisers to benefit more from its use, since the instruction would be matching with their preference. Chapter 6 showed that people who tended to prefer verbal instructions over visual instructions showed a stronger change in their verbal-cognitive processing compared to people with low verbal preference, which indicates that verbal, rather than visual, preference is related to effects of analogy.

A more direct way of testing a visual argument could be based on a study in speech by Tse, Wong, et al. (2016), in which measurement of load on visual or verbal WM resources used separate visual and verbal secondary tasks after practice by analogy. Using this approach, Tse et al. (2016) showed that analogies loaded less on verbal modules, and that a visually instructed analogy loaded more on visual resources. However, their study concerned instruction of speech rather than complex movements and did not involve a learning phase.

Apart from chunking and visual explanations, there are various other mechanisms that may explain parts of the findings related to analogy motor learning. For example, a factor that has a well-documented effect on performance is the focus of attention that instructions promote in the performer. Wulf (2007) argued that a more external (outcome-oriented) focus of attention leads to a release of kinematic degrees of freedom and, thus, superior performance. It has been argued that analogy may simply promote a more external focus compared to explicit instructions. Koedijker, Oudejans, and Beek (2007) tested this assumption in an experiment including external, internal, analogy and explicit instruction conditions. Results suggested that the effect of analogy instructions was stronger than that of external focus of instructions; however, the focus manipulation

may not have been effective<sup>37</sup>. It is possible that differences in focus of attention have confounded previous findings related to analogy learning - comparison of an analogy instruction that encourages an external focus of attention with explicit rules that cause an internal focus of attention, or vice versa, should therefore be controlled in future studies.

A further possible explanation is that the analogy may simply capture the most important aspect of the movement and render any further instructions unnecessary. When devising analogies for use in experiments or teaching, a teacher or researcher would naturally choose one that summarises the central part of the movement. In addition to the fact that information processing demands are reduced by using one as opposed to several instructions, distraction from using additional, unnecessary instructions may affect explicit learners. This premise has not been tested as an alternative explanation as yet.

Rather than accepting or rejecting either of these explanations in favour of the other, it may be possible to unite them as separate and important aspects of an analogy instruction. It is very likely that both chunking and visual processing are factors that contribute to the benefits of analogy learning.

### **Efficiency of cognitive processes in analogy learning and errorless learning**

Previous research has shown an increase in high-alpha power over the left hemisphere (or less desynchronization in the seconds before movement initiation), especially in T7, as a result of practice (Babiloni et al., 2011; Crews & Landers, 1993; Hillman et al., 2000), or expertise (Cooke et al., 2014; Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Lawton et al., 1998). This was interpreted as a reduction in verbal-analytic processing in favour of visuo-spatial processing. Finding increased high-alpha power at T7 for analogy instructed subjects in this thesis (Chapters 4 and 6) suggests that analogy led to reduced verbal-analytic activity during motor preparation. Analogy instructions might reduce the need for verbal processing or make verbal processing more efficient.

Previous research has shown that errorless learning, a form of implicit motor learning, leads to increased psychomotor efficiency, as measured by reduced co-activation

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<sup>37</sup> Rule reports showed more internal than external rules in all conditions, indicating that the focus manipulation might not have been successful.

between the verbal processing (T7) and motor planning regions (Fz) during motor performance (Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, et al., 2011). This research did not report high-alpha power. In contrast, the present results (Chapter 4 and 6) only found an effect in the EEG high-alpha power variable with no effects evident for measures of co-activation. This discrepancy might reflect a functional difference between analogy and errorless learning methods. For example, there are clear differences between the instructions given in analogy versus errorless experimental protocols – analogies provide some movement-specific information, while most other forms of implicit learning prevent all instruction about the task execution. The two approaches may therefore not work in identical ways. The analogy instruction influenced verbal aspects of information processing without impacting on efficiency of motor planning aspects. An effect on verbal, but not motor planning, processes would also agree with different findings regarding performance. While performance at a regular task was not affected by using analogy instructions in the present experiments, single task performance of the errorless group was superior to an explicitly trained group (Zhu, Poolton, Wilson, Maxwell, et al., 2011). Effects of an errorless learning protocol may be effective on the motor execution level, while analogies impact movement on the conceptual level, that is, the representation of the movement rather than its execution.

### **Analogy and theories of movement automation**

Results in this thesis (Chapter 4) indicate that analogy instructions may lead to less verbal-declarative planning of a movement, indicating that control structures might be more procedural than declarative. Based on models of skill automation (Fitts & Posner, 1967), participants who rely on less verbal processes for motor control are potentially further advanced in their progression towards skill automation. Less verbal-declarative processing after analogy learning suggests that analogy instructions may allow an advancement to a more automated stage of learning, as control structures may become more expert-like. It has been argued that the automation process may be sped up by using analogy instructions (Koedijker et al., 2011).

A modular theory of automation and motor control by Keele, Jennings, Jones, Caulton, and Cohen (1995) suggests that during learning, the sequence structure or representation of a movement is automated first, followed by a system of effector dynamics which is developed more slowly. The sequence structure, or sequence representation, of a movement is the cumulative information about the mechanics of the movement (Park &



Shea, 2002). It describes the trajectory of a limb, the relative speed, forces and timing of different sub-movements, and the relative positions of all body parts involved during the movement – for example, in walking the ratio of timing of a single step remains the same whether the subject is walking or running (Shapiro, Zernicke, Gregor, & Diestel, 1981). Similarly, the progression of each limb in the course of a throw remains constant over different throwing distances.

In contrast, the system of effector dynamics indicates the absolute force, speed and timing that has to be applied to the movement in order to reach a specific movement outcome or goal. For example, it describes how much effort has to be put into a throw in order for the ball to land at a certain distance. The system of effector dynamics is developed over a longer period of time and practice. Different theoretical perspectives (Keele, Cohen, & Ivry, 1990; Keele et al., 1995; Klapp, 1995; S. Sternberg, Knoll, & Turock, 1990) state that the processing, programming, and production of response sequences is independent of scaling of elements that constitute the sequence. Park and Shea (2002) found that movement structure was independent of the effector (the executing limb), while rules specifying absolute force were effector dependent. This is consistent with classic models of motor control, such as Schmidt's Schema theory (Schmidt, 1975; Schmidt & Lee, 1999), which suggests that after a general motor program (GMP) has been adapted the task invariant characteristics inherent to it are scaled and parameterised to fit specific task demands in each situation. Whiting (1984) suggested an idea of separate adaptation and attunement processes of a movement. Adaptation reflects changes in the motor pattern when trying to achieve a movement outcome (i.e., general motor program or sequence structure), and attunement reflects the fine-tuning of the new motor pattern to the task or environmental constraints (i.e., effector dynamics or parametrization). These theories also correspond with Bernstein's ideas of automation (1996, translated by Latash & Latash, 1994), which suggest that a movement is first automated and then fine-tuned towards a consistent and flexible behaviour by increasing standardization (i.e., the development of repeatability) and stabilization (i.e., resistance to disruptive influences).

Support for these theories has been found in sequential movements, such as moving a lever (Park & Shea, 2002) or serial reaction time tasks (Curran & Keele, 1993; Keele & Jennings, 1992). However, recent research has involved more complex tasks and attempted to measure the cognitive representation of a movement within a person's long-term memory (Schack, 2011; Schack & Mechsner, 2006; Seegelke & Schack, 2016).

For example, Bläsing, Tenenbaum, and Schack (2009) investigated the representation of dance movements by use of a hierarchical sorting task that involved participants sorting so-called Basic Action Concepts (BACs) underlying the movements according to their functional relevance for the movement execution. Results pointed toward a unique mental representation as a function of skill-level, indicating that sequence representation depends on expertise.

Analogies are intended to provide the learner with a mental image or representation of functional aspects of a movement, which corresponds with the initial adaptation of a sequence structure. This representation is flexible and can be adapted to constraints of different environments by adjusting effector dynamics. Errorless learning, however, involves withholding of movement-specific information and withholding of erroneous outcome feedback by reducing errors that typically occur. By preventing errors, the likelihood of error-based hypothesis testing regarding effector dynamics or parametrization is reduced; in theory, however, a learner is still be able to test hypotheses about the movement sequence. In sum, while analogy instructions might affect the first stage of automation by rendering the acquisition of a sequence structure more implicit and fitting it into a single concept (see chunking, Chapter 1), errorless learning paradigms potentially improve the system of effector dynamics by rendering it more implicit. Findings of effects of analogies on the cognitive level have not always been paired with effects in performance outcome, and similarly, neural efficiency is not always reflected by improved performance (Sayala, Sala, & Courtney, 2006; Zhu, Poolton, Wilson, Hu, et al., 2011). This indirectly supports the notion that although the sequence structure or representation of a movement may be automated, leading to more ease of processing, the system of effector dynamics may still be developing (Keele, Jennings, Jones, Caulton, & Cohen, 1995). More direct support for this premise in analogy learning is found in an experiment by Koedijker et al. (2011), which indicated that an analogy instruction circumvented the declarative stage of learning, but still disrupted performance in a speeded condition, suggesting that participants had not stabilised the skill enough to cope with the increased disruptive effect of temporal demands (Koedijker et al., 2011).

Results of analogy learning in hockey (Chapter 4) showed a significant difference in electrocortical measures and combined task performance, which is an indicator of psychomotor efficiency, but no effect was evident for performance of the motor task alone. Often, efficiency of cognitive processes may be improved earlier in the automation

process before an effect is visible on the performance level. Gentile (1998) argued that building up a sequence representation involves explicit processes, while the effector dynamics are organised implicitly. Improved verbal-cognitive efficiency after analogy learning may be due to the movement sequence representation becoming more implicit, although the effector dynamics are still in the process of developing. Reduced T7-Fz coherence, which was found in experts compared to novices, may be related to more implicit processing of the sequence representation as well as the effector dynamics.

To date, errorless learning has only been used in tasks where the sequence structure is simple or already known, where errors in the movement pattern are not likely to occur and thus no hypotheses regarding the movement structure are tested. The development of effector dynamics may have been sped up or made more implicit by errorless learning, but the sequence representation may not have been affected. It seems evident that the two approaches may involve a separate part of the automation process. If automaticity can indeed be sped up by increasing procedural contributions during the development of both the sequence structure and the effector dynamics the best learning result might be achieved by a combination of the two approaches. By combining analogy instruction to provide implicit guidance towards an efficient movement pattern, with an errorless approach to develop an ideal force, speed, and timing pattern, control of a movement may come to rely largely on implicit processes, which are more durable and stable to influence from pressure and cognitive load.

As the representation of the sequence structure of a movement has been shown to be effector-independent, effector independence may be a measurement criterion to tell the two automation processes apart. Keele et al. (1995) tested effector independence by transferring a movement from one limb to a different, ipsilateral or contralateral limb, or by transitioning from a static to a dynamic task. Interestingly, a measure of the structure of the response sequence (relative error) remained the same through these transfers, indicating that the movement sequence did not change even if the effector did. An experiment to test which aspect of the automation process is affected during analogy learning of a complex motor task might include similar measures, potentially by using kinematic aspects.

## **Adapting analogy instructions to the learner's personality, ability, and preference**

Although Chapter 4 supports previous research showing that analogy instructions lead to performance that is immune to dual-task demands (Koedijker et al., 2011; Lam et al., 2009b; Liao & Masters, 2001; Tse et al., 2017), experiments in Chapter 2 showed that a dual-task did not effectively reduce performance after explicit learning in children. We may face some challenges if we try to apply frameworks from adult learners directly to children. Previous work has shown that analogies may be a fruitful means of teaching concepts or grammar to children (Gentner et al., 2011; Gentner & Toupin, 1986; Glynn & Takahashi, 1998; White, 2005). Although only one study to date has been conducted on children's learning of movements (Tse, Fong, et al., 2016)<sup>38</sup>, the use of visual instructions in general, and motor metaphors specifically, seems promising.

However, the results in Chapter 2 stress the importance of using relevant, individual analogies. The analogy used in Chapter 2 may simply not have been appropriate for most children, or it may not have been applied to the movement correctly. Gentner and Toupin (1986) have shown that young children tend to be distracted by surface similarities and may not see structural similarities when mapping by analogy. Similarly, in the movement context, children may focus on an aspect of the analogy that is not relevant to the movement. Poolton et al. (2007b) reported that Chinese learners, who have a different cultural background that affects their use of instructions, struggled to use an abstract geometric analogy, but profited when the analogy was changed to a more visually salient mountain analogy. Therefore, it seems logical that analogies might have to be tailored to the learning and/or instructional style preferred by the learner. Since children are known to rely more on visual processes, it is important that analogies are presented visually or at least allow vivid imagination. Furthermore, the complexity of the concept should not be too high, since conscious processing of movement-related information is limited and a high processing load may affect performance negatively. Another issue is that the experiment described in Chapter 2 made use of an airplane landing analogy, which required the child to imagine an airplane landing and apply it to the movement of their golf club. This meant that the child's perspective had to change from first to third person.

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<sup>38</sup> This study included several analogies and added explicit instructions rather than the single, standalone analogy suggested by Masters (2000).

Applying the analogy should be as straightforward as possible. In sum, it might be best to develop appropriate analogies in direct collaboration with the group of learners that it is aimed at. Kleynen et al. (2014) and Jie et al. (2016) successfully used this approach in Parkinson's disease (PD) and stroke patients. In a pilot study, an analogy was devised with each learner individually, which was then used by the learner during a practice period.

Individual differences in preference, ability, and cognitive styles may have a large influence on how analogy is used and whether it is effective in reducing verbal-cognitive processing. Based on Reber (1993) and Stanovich (2009), previous implicit learning research argued that individual differences in implicit learning are minimal relative to individual differences in explicit learning (Masters & Maxwell, 2004). In general, implicit learning has been shown to be more weakly related to psychometric intelligence than explicit learning, and unrelated to working memory (e.g., Unsworth & Engle, 2005). Any individual differences that were found in implicit learning were thus either ignored or considered to be noise. However, implicit learning differences may be related to factors of complex cognition (Kaufman et al., 2010). Kaufman and colleagues found that verbal analogical reasoning, processing speed, and factors of personality such as intuition, impulsivity and lack of deliberation were related to differences in implicit learning. Kaufman et al. (2010) suggested that people who tend to deliberate less may generally focus on a wider variety of stimuli (i.e., less selective attention) and thus be more open to new associations during implicit learning. Findings related to movement specific reinvestment in Chapter 2 are consistent with this view and may indicate that reinvestment is associated with the tendency to deliberate. Our findings related to verbal preference (Chapter 6) may also relate to Kaufman et al.'s findings, as verbal analogical reasoning may be related to a verbal preference. However, it is presently unclear whether preference and ability in the visual-verbal dimension are related (Alesandrini, 1981; Kollöffel, 2012; Mayer & Massa, 2003). In order to test which dimensions of personality, preference, ability and cognitive style are related to learning a movement by analogy, we first need to establish which measures of these traits are applicable to the sports domain. For example, measures of visual-verbal preference have not been reliably assessed in the motor learning context (Fuelscher et al., 2012). After establishing measures for each trait, style and preference, they may be included in a large study of analogy learning.

If the relevance and applicability of analogies can be increased by adapting the instruction to a learner's needs, the fields of potential application for analogy instructions

are almost unlimited. Cognitive as well as motoric difficulties, personality, cognitive ability and preferences regarding instruction type or modality may be catered to individually in this way.

### **The use of EEG for investigating brain dynamics in the movement context**

Electroencephalographic (EEG) signals provide a wealth of information about brain dynamics. Most of the research in this thesis made use of EEG measures in order to deduce cognitive processes during motor preparation at different stages of adaptation or learning. However, using surface electrodes reduces the inferences that can be made regarding the underlying neural generators of the signals (Haufler et al., 2000). Brain structures in the cortex directly underlying the electrode locations, and other deeper structures, may contribute to signals measured on the surface. In order to improve depth of measurement, the use of functional near infrared spectroscopy (fNIRS) may be a solution. Similar to EEG, fNIRS is a portable system that allows real time recording of cortical activity. As a blood flow method that measures hemodynamic responses, fNIRS can show more precisely which neural networks are activated, without the costs and difficulties that lie in the use of an fMRI machine (Irani, Platek, Bunce, Ruocco, & Chute, 2007; Leff et al., 2008, 2011). Combining EEG with fNIRS might improve our understanding of the cortical activation patterns in motor learning using analogy or other forms of instruction (Aghajani, Garbey, & Omurtag, 2017). Furthermore, EEG measures in this thesis were limited to eight electrodes, which led to a relatively low spatial resolution. We focused on measuring activity of the frontal midline (Fz) and left and right temporal regions (T7 and T8), as these regions have been shown to reflect verbal-analytical processing during movement preparation (Deeny et al., 2003; Hatfield et al., 1984; Haufler et al., 2000). This limitation in spatial resolution also limited the data processing measures that were possible. Performing an Independent Components Analysis (ICA) for the specific localization of the source of each signal, requires a minimum of 35 electrodes (Lau, Gwin, & Ferris, 2012). Future studies should include a higher spatial resolution by using more electrodes, and perform ICA analyses prior to data analyses. A further limitation in this thesis is the use same-side referencing, which may allow instances of hemispheric asymmetry to affect the results and lead to more data loss.

When using EEG analyses in the sports context, further issues have to be taken into consideration. Thompson, Steffert, Ros, Leach, and Gruzelier (2008) described how common sources of contamination of real cerebral (EEG) data are exacerbated when the

analyses are conducted in the sport or movement context. Artefacts caused by muscle activity, skin conductance and sweating, as well as electrode movement, eye movement, ECG and respiration artefacts, among others, are affected by performing even low-intensity movements. The experiments in this thesis tried to overcome these challenges by using a system that amplifies the signal at the source (to minimise wire artefacts), by standardizing the preparation procedure, measuring EEG during the pre-movement phase rather than during the movement, and by choosing tasks that involved minimal head and neck movement during the preparation phase. Furthermore, within-subject changes were generally analysed in favour of inter-subject differences (with exception of Chapter 5), which reduced the risk of extreme inter-individual differences affecting outcomes. Eye and muscle artefacts were removed computationally using a validated procedure (Deeny et al., 2003; Haufler et al., 2000; Janelle et al., 2000). Measurements in the alpha frequencies are least affected by low frequency (movement, blinks and sweat) and high frequency (muscle and electrical noise) artefacts (Thompson et al., 2008), so we expected confounding of our results to be acceptably minimal.

### **Alpha power and coherence**

Analyses in this thesis have focused on high-alpha power (10-12 Hz). When interested in general attention processes, low-alpha power (8-10 Hz) may provide more insight, as increased low-alpha power has been connected with attentional processes (Klimesch, 1999; Pfurtscheller & Lopes da Silva, 1999). Power analyses in the theta band (4-8 Hz) have been shown to be related to working memory (Doppelmayr, Finkenzeller, & Sauseng, 2008; Klimesch, 1999; Pfurtscheller & Lopes da Silva, 1999). For example, Onton, Delorme, and Makeig (2005) found that theta power at the frontal midline (Fz) corresponded with performance during working memory tasks, and Grunwald, Weiss, and Krause (2001) found the same in a haptic object recognition task. Future studies that are interested in the contribution of working memory to motor control should include analyses of power in the theta band. When investigating emotional aspects of performance (e.g., emotional situations related to winning and losing in competition), measurements of beta power may provide better insight (Ray & Cole, 1985).

In general, alpha is not defined by a frequency range but a specific waveform pattern. The frequency band that includes alpha waves differs between participants, averaging around 8-12 Hz. As age and cognitive impairments have a large effect on individual alpha frequency, it has been suggested that the alpha band should be defined individually for

each person using their peak frequency (Klimesch, 1999; Nunez, Wingeier, & Silberstein, 2001). Future studies should take this into consideration, especially if people of different age and cognitive impairments are tested (for an example, see Gallicchio, Cooke, & Ring, 2017).

Although analyses of coherence seem to be established measures of neural co-activation and psychomotor efficiency, the variables show some inherent weaknesses. Coherence measures can be affected by variations or individual differences in EEG power, which has been a potential confounder in previous studies (Cohen, 2014). Recent research has reported substantial inter-subject variability in absolute values of pre-movement alpha power (Babiloni et al., 2008; Cooke et al., 2014). To address this issue, a recent study by Gallicchio, Cooke, and Ring (2017) computed connectivity by inter-site phase clustering (Cohen, 2014; Lachaux, Rodriguez, Martinerie, & Varela, 1999). Furthermore, to provide a stronger test of causality than a mere comparison between experts and novices, they suggested conducting mediation analyses (see also Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011). They found that similar to other studies investigating psychomotor efficiency, improvements in performance were connected to reduced cross-regional alpha connectivity.

As a further means of determining causalities, Cooke (2013) suggested that neurofeedback studies should be conducted that train the participant to achieve brain activation patterns that are associated with successful performance. Neurofeedback studies that have been conducted in complex motor tasks to date are few and show ambivalent results (Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2007; Kavussanu, Crews, & Gill, 1998; Landers et al., 1991; Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015; for a brief review of neurofeedback studies in sport, see Thompson, Steffert, Ros, Leach, & Gruzelier, 2008).

In order to get a more global picture of psychomotor efficiency, a number of complexity measures from information theory, chaos theory, and random fractal theory have recently been applied to the analysis of EEG data. For example, Hung, Haufler, Lo, Mayer-Kress, and Hatfield (2008) calculated a “correlation dimension D2” as a measure of complexity. In a rifle-shooting task, they found that complexity of neural activity was associated with visuomotor expertise - experts had lower complexity than novices. This shows that refinement and efficiency of cortical processes is related to superior performance.



## **Suggested further research**

This discussion section introduced topics to investigate in future studies. First, to understand the mechanism(s) underlying analogy learning, a chunking explanation could be tested in a direct way, potentially using EEG (or fNIRS) and direct measures of movement representation (e.g., Seegelke & Schack, 2016). It would also be interesting to follow up the visual argument by specifically testing visual and verbal cognitive load after instruction by analogy. Brain imaging measures provide a great source of additional information; however, based on limitations related to application in sports movement, they should be combined with other, established measures of cognitive load, such as dual-tasks or probe reaction time tasks. Second, research might investigate whether the development of a sequence representation (GMP or movement concept) and of a system of effector dynamics (parametrization or attunement) are affected differentially by analogy and errorless learning paradigms. Third, future research in analogy learning should explore the use in populations with special constraints on their motor learning, such as children, elderly people, and patients with stroke, PD, Alzheimer's disease or other cognitive deficiencies. For this, it is important that cognitive ability and preference and personality are considered well before developing the analogy to be used. Ideally, analogies would be developed in collaboration with individuals to best leverage the advantages that they offer when acquiring a motor skill.

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## Appendices

### Appendix 1 Information letter to the principal (Chapter 2)

TINA VAN DUIJN, PHD STUDENT  
tinavanduijn@gmx.ch

INFORMATION LETTER TO THE SCHOOL PRINCIPAL  
[DATE LETTER SENT]

*RE: Important information about a research project being conducted at St Peter's school  
University of Waikato Faculty of Education Ethics Approval # [INSERT NUMBER HERE]*

Dear (name of principal),

My name is Tina van Duijn and I am a researcher in the Department of Sport and Leisure Studies at Waikato University. I am currently working on a research project looking at motor learning with different instructions. The study is being supervised by Professor Rich Masters who is a renowned psychologist who specialises in the psychology of skill learning and performance.

Simon Thomas (St. Peter's Golf Academy) and I would like St Peter's School to participate in the project.

We are interested in how teenagers learn a new movement and how their learning depends on different instructions that they receive from teachers. The results of our study could lead to better knowledge of how movement-related knowledge is processed during learning, and how we can influence performance by adapting our instructions. Students who participate will be asked to visit the golf grounds at St. Peter's school for about 1 hour during their PE lessons. In this time, they will complete a short questionnaire, learn and practice a novel motor task and perform this new task in different situations (e.g., when performing a secondary task while doing the main task). All students' answers and scores are highly confidential and anonymous. We will, of course, ask your students' parents for permission, and we will ask the students themselves whether they assent to participating before beginning. If they do not agree, they will just continue normal school activities.

Our research has been reviewed by the University's Ethical Review committee ([http://www.waikato.ac.nz/research/ro/ethics/human\\_ethics.shtml](http://www.waikato.ac.nz/research/ro/ethics/human_ethics.shtml)) to ensure that it meets ethical guidelines and poses minimal risk to participants. Studies involving children are subject to the fullest review by the committee. We will coordinate with PE teachers to ensure minimal disruption within the classroom or gym. My colleagues and I generally find that the students really do enjoy taking part.

**If you are happy for your some of your students to take part please return a signed copy of the attached consent slip to Tina van Duijn or Simon Thomas.**

The study will begin on [DATE] so please confirm your permission before then. If you have any further questions please do not hesitate to contact me on my email or phone: 027 356 8242. Thanks you for your co-operation.

Sincerely,

Tina van Duijn

Consent form:

The above study has been fully explained to me and I have had the opportunity to ask questions.

Initials

I understand that parents/guardians of each child participating in this study will be fully informed about the nature of the research by letter sent home to them.

Signatures:

Name of Principal  
(block capitals)

Date

Signature

Researcher (block capitals)

Date

Signature

If you would like a copy of this consent slip to keep, please ask the researcher. If you have any complaints or concerns about this research, you can direct these to the researcher, Tina van Duijn, by e-mail ([tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz)) or mobile phone (027 356 8242).

## Appendix 2 Parent information letter (Chapter 2)

TINA VAN DUIJN, PHD STUDENT  
tinavanduijn@gmx.ch

Dear Parents / Carers,

My name is Tina van Duijn and I am a researcher in the Department of Sport and Leisure Studies at Waikato University. I am currently working on a research project looking at motor learning with different instructions. The study is being supervised by Professor Rich Masters who is a renowned psychologist who specialises in the psychology of skill learning and performance.

[HEADTEACHERS NAME] would like St. Peter's School to participate in the project. I would be most grateful if you would allow your child to take part.

We are interested in how teenagers learn a new movement and how their learning depends on different instructions that they receive from teachers. The results of our study could lead to better knowledge of how movement-related knowledge is processed during learning, and how we can influence performance by adapting our instructions. Students who participate will be asked to visit the golf grounds at St. Peter's school for about 1 hour. In this time, they will complete a short questionnaire, learn and practise a novel motor task and perform this new task in different situations (e.g., when performing a secondary task while doing the main task). All students' answers and scores are highly confidential and anonymous. We will, of course, ask your child whether they assent to participating before beginning. If they do not agree, they will just continue normal school activities.

Our research has been reviewed by the University's Ethical Review committee ([http://www.waikato.ac.nz/research/ro/ethics/human\\_ethics.shtml](http://www.waikato.ac.nz/research/ro/ethics/human_ethics.shtml)) to ensure that it meets ethical guidelines and poses minimal risk to participants. Studies involving children are subject to the fullest review by the committee. We have also obtained permission from the school's head teacher before beginning the study and we will coordinate with teachers to ensure minimal disruption within the classroom. My colleagues and I generally find that the students really do enjoy taking part.

Although [HEADTEACHERS NAME] has allowed me access to the school, I do require individual permission from parents to allow children to participate. If you are happy for your child to take part please return a signed copy of the parent consent form that comes with this letter.

The study will begin on [DATE] so please confirm your permission before then. Otherwise your child will not be included. If you would like to withdraw your child's participation, you can do so at any time by contacting me. Should you decide after the study that you no longer want your child's data included, you can do so up until the point of analysis. If you have any further questions please do not hesitate to contact me on my email or phone: 027 356 8242. Thanks you for your co-operation.

Sincerely,

Tina van Duijn

### Appendix 3 Parental consent form (Chapter 2)

<b>Title of Project:</b>	Chunking mechanisms in motor learning	<b>Ethics Approval Number:</b>	
<b>Investigator(s):</b>	Tina van Duijn	<b>Researcher Email:</b>	tinavanduijn@gmx.ch

Please read the following statements and, if you agree, initial the corresponding box to confirm agreement:

	Initials
The above study has been fully explained to me in an information letter.	<input type="text"/>
I have been informed that I can withdraw my child from the study at any point, and that I can withdraw their data up to the point of analysis.	<input type="text"/>
I understand that neither participation nor the results of this study will influence any aspect of their schooling. The study is absolutely independent.	<input type="text"/>
I understand that all data are anonymous and will be treated with the utmost care.	<input type="text"/>
I give permission for my child to participate in Tina van Duijn's project.	

Name of participant \_\_\_\_\_

Name of parent / caregiver \_\_\_\_\_

Date: \_\_\_\_\_ Signature \_\_\_\_\_

If you would like a copy of this consent form to keep, please ask the researcher. If you have any complaints or concerns about this research, you can direct these to the researcher, Tina van Duijn, by e-mail ([tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz)) or mobile phone (027 356 8242).

## Appendix 4 Informed consent form for students (Chapter 2)

### Dear participant

My name is Tina van Duijn and I am a researcher in the department of sport and leisure studies at Waikato University. I am currently working on a research project looking at motor learning with different instructions. If you read this, your parents have already consented by writing to allow you to take part in this study. Still, I would like to have your personal consent that you agree to all of the conditions of this study. Please read the following information carefully before signing at the bottom.

### The Experiment

You will be asked to visit the golf grounds at St. Peter's school for about 1 hour. In this time, you fill in a short questionnaire, learn and practise a golf task and perform this movement in a few different situations.

### Risks

There is a (very low) possibility that you can get sore muscles on the following day, or that you could hurt yourself during the movement. The risk is not greater than normal everyday risks. Tina van Duijn is a trained emergency first responder and the school has medical assistance ready.

### Confidentiality

Your answers and scores are highly confidential and anonymous and your name will not be used in connection with the results in any way. The information obtained in this study will be used for research purposes only.

### Withdrawal from the study

Your participation is voluntary: you can choose to withdraw yourself from the study at any time. You can withdraw or your data from the analysis up until the point of analysis. There will be no consequences for you if you choose to do so and you do not have to give a reason for doing so.

### Other issues, questions or concerns

If you have any questions or concerns about the research, please feel free to contact: Tina van Duijn (email: [tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz), telephone 027 356 8242).

My colleagues and I generally find that the students really do enjoy taking part. After taking part in the study, you will be given a letter to take home outlining in more detail the purpose of the study.

I give consent to participate in Tina van Duijn's project.

Name of participant ..... Date .....

Signature .....

## **Appendix 5 Participant information sheet (Chapters 3-5)**

### **Investigation: Neuroscience of Skill Acquisition**

#### **Project name: EEG and motor learning in hockey**

*UoW Human Research Ethics Approval #7 (Health)*

Dear Participant,

We would like to invite you to participate in this research project conducted by researchers at the School of Sport and Leisure Studies, University of Waikato. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

#### **Research Aims**

We are interested in better understanding: a) how brain activity changes when we learn a new motor movement; and b) how the activity in brain changes depending on different instructions.

#### **Who Must We Exclude?**

The only exclusion criteria for this study is having too much Hockey experience. If you have played Ice-hockey, Floorball / Unihockey or Hockey more than 10 times or have had any lessons in it, we won't be able to use your data.

#### **What Will You Be Asked to Do?**

You will be asked to come into the lab on two separate days. On both occasions, we would like you to abstain from drinking coffee or any other drinks containing caffeine (Coke, energy drinks etc.) for at least 6 hours before the experiment. Also, it is necessary that you wash your hair the evening before the experiment for both days. Please make sure your hair is dry when you come in.

After administering a cap with sensors for your brain activity, you will complete a short questionnaire and a memory task, learn and practice a novel motor task (the hockey push) and perform this new task in a few different situations, e.g. when performing a secondary task while playing. Part of the study includes a simple game which helps you practice the hockey movement. We, the researchers, will tell you each time when you have to perform different tasks. During these tasks your brain activity will be measured through you wearing a special cap that includes sensors that will rest on your scalp. Finally, at the end of the second session you will be asked to answer some questions related to the practice.

### **Where Will the Study Take Place?**

The study will take place at the motor learning lab of the School of Sport and Leisure Studies, University of Waikato (see the map at the end of this form).

### **How Long Will the Study Last?**

The experiment consists of two sessions, the first of which will take about 2 hours and the second 1 hour to complete. The sessions are on consecutive days at the same time.

### **Why Are We Measuring your Brain Activity?**

It is important to measure brain activity as doing so will allow us to objectively demonstrate how the brain changes during learning and when instructed with different information. This is important as it could allow us to develop more effective training methods, such as “brain training” protocols, which could help us to speed up learning and to achieve personal best performances.

### **Are There Any Risks Involved in Participating?**

The risks involved in participating are minimal. The surface electrodes used to monitor your brain activity can cause short-lasting minor skin irritation to participants with sensitive skin. However, this eventuality is unlikely.

### **Are There Any Benefits Involved in Participating?**

The results of the study will give us important information about mechanisms related to motor skill acquisition. If you are interested in the outcome of the study, you will be given the opportunity to leave your e-mail address to the researchers and they will send you the results of the study after the analyses are finished. Additionally, we will reward your efforts with two 5 \$ cafeteria vouchers and you go in the draw to win a sailing trip on a date of your own choosing.

### **What If I Have Questions about the Project?**

If you have any question regarding this research please feel free to contact us. Thank you in advance for your participation, it is greatly appreciated.

It is up to you to decide whether to take part or not. If you decide to take part you are still free to withdraw at any time and without giving a reason. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

Yours Sincerely,

Tina van Duijn, [tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz)

Merel Hoskens, [m.c.j.hoskens@student.vu.nl](mailto:m.c.j.hoskens@student.vu.nl)

Prof. Dr. Rich Masters, [rmasters@waikato.ac.nz](mailto:rmasters@waikato.ac.nz)

### **Location**

The experiment will take place in the TT building, marked with a black circle on the map below. A researcher will meet you at the entrance of the building.

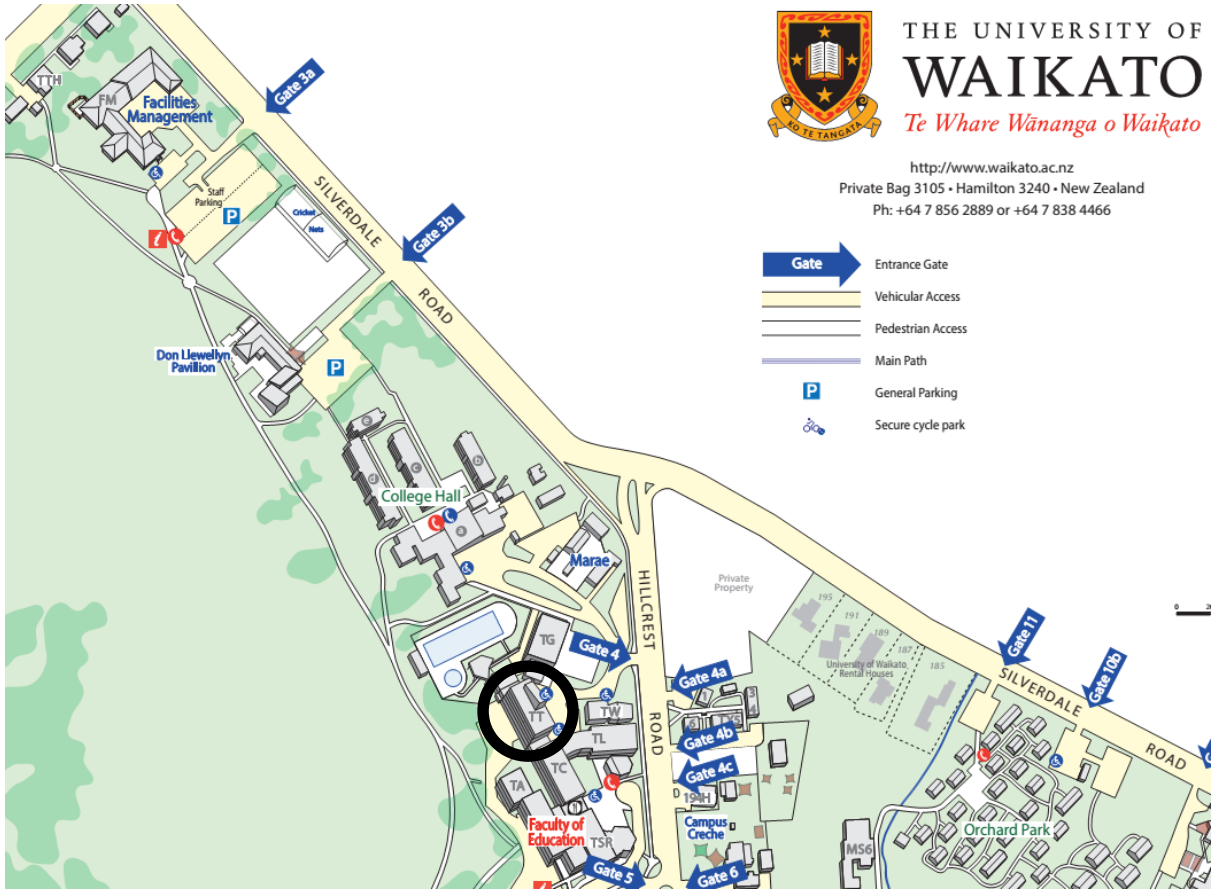




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- Gate Entrance Gate
- Vehicular Access
- Pedestrian Access
- Main Path
- General Parking
- Secure cycle park



## Appendix 6 Informed consent form (Chapters 3-5)

Project name: EEG and motor learning in hockey

Investigators: Tina van Duijn (PhD student), Merel Hoskens, Prof R. Masters

### Purpose of the study

We are interested in how people learn a new movement in a team-sport setting. It is important to measure brain activity as doing so will allow us to objectively demonstrate how the brain changes during learning and when instructed with different information. This is important as it could allow us to develop more effective training methods, such as “brain training” protocols, which could help us to speed up learning and to achieve personal best performances.

### Procedures

You will be asked to visit the motor learning laboratory at Waikato University Faculty of Education (TT0.10) for about one and a half hours, spread over two days’ time. In this time, you complete a few short questionnaires, learn and practice a novel motor task as well as a decision task and perform both tasks in a few retention tests.

### Potential risks or discomfort

The risks involved in participating are minimal. For a part of the experiment, you will be wearing a neoprene cap with sensors on it. These are completely harmless but may feel a bit uncomfortable to you. The surface electrodes used to monitor your brain activity can cause short-lasting minor skin irritation to participants with sensitive skin. However, this eventuality is unlikely. You will have a little bit of gel on some spots on your head after your experiment. There is a (very low) possibility that the new movement may cause sore muscles on the following day, or that you could hurt yourself during the movement. The risk is not deemed greater than normal everyday risks. Tina van Duijn is a trained emergency first responder and the school has medical assistance ready.

### Confidentiality

Your answers and scores are highly confidential and anonymous and your name will not be used in connection with the results in any way. The information obtained in this study will be used for research purposes only.

### Withdrawal from the study

Your participation is voluntary: you can choose to withdraw yourself from the study at any time. You can withdraw or your data from the analysis up until the point of analysis. There will be no consequences for you if you choose to do so and you do not have to give a reason for doing so.

### Other issues, questions or concerns

If you have any questions or concerns about the research, please feel free to contact: Tina van Duijn (email: [tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz), telephone 027 356 8242), or professor Rich Masters (email: [rmasters@waikato.ac.nz](mailto:rmasters@waikato.ac.nz), telephone 838 45 00 or ext. 6206).

I give consent to participate in Tina van Duijn’s and Merel Hoskens’s project.

Name of participant ..... / Date .....

Signature .....

## Appendix 7 Cover letter (Chapter 6)

School of Human Development & Movement Studies  
University of Waikato, Hamilton

### Cover letter

Project name: Analogy learning in motor acquisition  
Investigators: Tina van Duijn (PhD), Prof Rich Masters

Dear participant,

My name is Tina van Duijn and I am a researcher in the School of Human Development and Movement Studies at the University of Waikato. I am currently working on a research project examining the role of instructions during motor learning. The study is being supervised by Rich Masters who is a professor at the university. I would be very happy to have you as a participant in this study, so please read the following information carefully before signing your consent.

#### Purpose of the study

We are interested in how instructions by teachers influence motor learning. The results of our study could lead to better knowledge of how to influence performance using instructions.

#### Procedures

You will be asked to visit the motor learning laboratory for about 2 hours. During this time, you will complete a short questionnaire, a computer-based task, learn and practise a novel motor task and perform the movement in different situations (e.g. when performing a secondary task during the movement). Your movements will be filmed for kinematic and qualitative analysis, and the experimenters will fit a neoprene cap with sensors to your head in order to measure your brain activity (electroencephalography - EEG) throughout the study. EEG is non-intrusive with no harmful side effects.

#### Potential risks or discomfort

There is a (very low) possibility that the new movement may cause sore muscles on the following day, or that you could hurt yourself during the movement. The risk is not deemed greater than normal everyday risks. Wearing the EEG cap might be a bit uncomfortable as you might get sweaty, but there are no harmful side effects to the measurements. Tina van Duijn is a trained Emergency first responder and the school has medical assistance ready.

#### Confidentiality

Your answers and scores are highly confidential and anonymous and your name will not be used in connection with the results in any way. The information obtained in this study will be used for research purposes only.

#### Withdrawal from the study

Your participation is voluntary: you can choose to withdraw yourself and / or your data from the study at any time of your choosing. There will be no consequences for you if you choose to do so and you do not have to give a reason for doing so. Before starting the experiment, you will have to sign a consent form stating that you have read this letter and agree to participate.

#### Other issues, questions or concerns

If you have any questions or concerns about the research, please feel free to contact: Professor Rich Masters (email: [rmasters@waikato.ac.nz](mailto:rmasters@waikato.ac.nz), telephone 838 45 00 or ext. 6206) or Tina van Duijn (email: [tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz), telephone 027 356 8242)

Our research has been reviewed by the University's Ethical Review committee ([http://www.waikato.ac.nz/research/ro/ethics/human\\_ethics.shtml](http://www.waikato.ac.nz/research/ro/ethics/human_ethics.shtml)) to ensure that it meets ethical guidelines and poses minimal risk to participants.

My colleagues and I generally find that the students really do enjoy taking part. After taking part in the study, you will be given a letter to take home outlining in more detail the purpose of the study. Thank you for participating!

Sincerely,

Tina van Duijn

## Appendix 8 Consent form (Chapter 6)

### Consent form

**Project Title:** Analogy learning during motor acquisition

Researchers: Tina van Duijn, Rich Masters

I \_\_\_\_\_ agree to participate as a volunteer in a scientific investigation, which is as an approved part of a research program at the University of Waikato under the supervision of \_\_\_\_\_.

The investigation and my part in the investigation have been defined and fully explained to me by \_\_\_\_\_ and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts have been provided to me and discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all questions have been answered to my satisfaction.
- I understand that the data collected in this research project may be reported in scientific publications, presentations, teaching, and student theses.
- I understand that I am free to withdraw from the project, and ask for my data to be destroyed within a 3-week period after the research activities, without disadvantage to myself.
- I understand that my data will be anonymised through a coding system, to protect my identity in the research reporting.
- I am participating in this project of my own volition and I have not been coerced in any way to participate.

Signature of Participant: \_\_\_\_\_

Date: \_\_\_\_/\_\_\_\_/\_\_\_\_

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: \_\_\_\_\_

Date: \_\_\_\_/\_\_\_\_/\_\_\_\_

#### **Contact Details for Researchers:**

Professor Rich Masters (email: [rmasters@waikato.ac.nz](mailto:rmasters@waikato.ac.nz), telephone 838 45 00 or ext. 6206) Tina van Duijn (email: [tv24@students.waikato.ac.nz](mailto:tv24@students.waikato.ac.nz), telephone 027 356 8242)

## Appendix 9 Movement Specific Reinvestment Scale (MSRS)

### THE MOVEMENT SPECIFIC REINVESTMENT SCALE

© Masters, Eves & Maxwell (2005)

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Age: \_\_\_\_\_ Hand: L / R

DIRECTIONS: Below are a number of statements about your movements in general. Circle the answer that best describes how you feel for each question.

**1 I remember the times when my movements have failed me.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**2 If I see my reflection in a shop window, I will examine my movements.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**3 I reflect about my movement a lot.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**4 I try to think about my movements when I carry them out.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**5 I am self conscious about the way I look when I am moving.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**6 I sometimes have the feeling that I am watching myself move.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**7 I am aware of the way my body works when I am carrying out a movement.**

strongly moderately weakly weakly moderately strongly  
disagree disagree disagree agree agree agree

**8 I am concerned about my style of moving.**

strongly   moderately   weakly   weakly   moderately   strongly  
disagree   disagree   disagree   agree   agree   agree

**9 I try to figure out why my actions failed.**

strongly   moderately   weakly   weakly   moderately   strongly  
disagree   disagree   disagree   agree   agree   agree

**10 I am concerned about what people think about me when I am moving.**

strongly   moderately   weakly   weakly   moderately   strongly  
disagree   disagree   disagree   agree   agree   agree

## Appendix 10 Co-authorship forms for Chapters 3 and 4



### Co-Authorship Form

Postgraduate Studies Office  
Student and Academic Services Division  
Wahanga Ratonga Matauranga Akonga  
The University of Waikato  
Private Bag 3105  
Hamilton 3240, New Zealand  
Phone +64 7 838 4439  
Website: <http://www.waikato.ac.nz/sasd/postgraduate/>

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in your appendices for all the copies of your thesis submitted for examination and library deposit (including digital deposit).

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter in thesis:

Title: Discerning measures of conscious brain processes associated with superior early motor performance: Capacity, coactivation, and character

Nature of contribution by PhD candidate	Main investigator: conception, design, data collection, data processing, analysis, interpretation, drafting, revision
Extent of contribution by PhD candidate (%)	60%

#### CO-AUTHORS

Name	Nature of Contribution
Rich Masters	Supervisor: contribution to conception, design, and critical revision of the article
Tim Buszard	Critical inputs to interpretation of results, contribution to drafting of the article
Merel Hoskens	Co-investigator, contributions to design, data collection, data processing

#### Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
R.S.W. MASTERS		26-OCT-17
M.C.J. HOSKENS		26-OCT-17
Tim Buszard		30-OCT-17







## Co-Authorship Form

Postgraduate Studies Office  
 Student and Academic Services Division  
 Wahanga Rāroanga Mātauranga Akonga  
 The University of Waikato  
 Private Bag 3105  
 Hamilton 3240, New Zealand  
 Phone +64 7 838 4439  
 Website: <http://www.waikato.ac.nz/sasdi/postgraduate/>

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in your appendices for all the copies of your thesis submitted for examination and library deposit (including digital deposit).

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Analogy instructions promote efficiency of cognitive processes during performance of a push-pass in field hockey

Nature of contribution by PhD candidate	Principal investigator: planning, design, data collection, data processing, analysis, write-up
Extent of contribution by PhD candidate (%)	70%

### CO-AUTHORS

Name	Nature of Contribution
Rich Masters	Supervision of all stages (planning, design, data collection, data processing, analysis, write-up)
Merel Hoskens	Planning, design, data collection, data processing
Hamish Crocket	Comments

### Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Rich Masters		20. 11. 2017
Merel Hoskens		20. 11. 2017
Hamish Crocket		23/11/2017

July 2015