THE EFFECTS OF DELAY-TO-REINFORCEMENT, RESPONSE REQUIREMENT AND SCHEDULE DURATION ON PERFORMANCE UNDER FIXED-RATIO SCHEDULES

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ABSTRACT

Experiment 1 examined the effects of delay-to-reinforcement on between-ratio pausing in multiple fixed-ratio 5 fixed-ratio 5 schedules. In one component the reinforcer was delivered immediately on completion of the ratio, and in the other there was a delay before reinforcement. The longest between-ratio pauses always preceded the ratio in which the delay was signalled, and these pauses increased as the delay increased. Experiment 2 examined the effects of varying delay-to-reinforcement on behaviour under fixed-ratio schedules that were increased each session, keeping the time available for responding constant. At each ratio requirement, with increased delay, total consumption and response rates decreased and between-ratio pause durations increased, although this effect was small. Functions were fitted to the relation between the natural logarithms of the consumption and fixed-ratio size using Hursh, Raslear, Shurtleff, Bauman and Simmonds's (1988) nonlinear and Hursh and Silberberg's (2008) exponential equations. Both fitted the data well, but in neither case did any of the parameters vary systematically with delay. The only consistent finding was that initial consumption was largest when there was no delay and smallest in the condition with the largest delay. This suggests a decreasing effect of delay-to-reinforcement with increases in the response requirement. Experiment 3 used conjunctive fixed-ratio fixed-interval schedules to separate the effects of schedule duration and ratio requirement in increasing fixed-ratio schedules. The schedule-initiation immediacies (the inverse of the pause following reinforcement) decreased in conditions in which the ratio was fixed and duration increased, and remained relatively constant in conditions in which the ratio was increased and duration fixed. It is suggested that the schedule-initiation immediacy is a useful measure as it eliminates some of the confounds of measures such as total consumption or consumption rate. These experiments show that with some procedures delay-to-reinforcement affects behaviour under fixed-ratio schedules in a way similar to reduced reinforcer magnitude and an increased force requirement. However, with other procedures, delay-to-reinforcement has different effects from reinforcer magnitude and quality. Also, overall, these three experiments show that increased time to reinforcement (whether as part of schedule requirements or at the end of the response requirement) has a larger effect on behaviour than the number of responses it takes to complete the ratio.

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DEDICATION

This thesis is dedicated to my parents Austin and Carin Harris. Thank you for your unwavering belief in me, your endless patience, and your emotional and financial support. It has been a long time coming, but thanks to you both this dream is now reality!

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In fixed-ratio (FR) schedules a reinforcer follows a predetermined number of responses counted from the previous reinforcer (Ferster & Skinner, 1957). FR schedules are seemingly simple schedules of reinforcement (Mackintosh, 1974), under which the pattern of responding is often said to be characterised by a high constant rate, following a pause after the delivery of a reinforcer (cf., Mazur, 1983). FR schedules were described in 1957 by Ferster and Skinner, who provided detailed descriptions of the behaviour of many pigeons under many FR conditions. These conditions were not limited to, but included the transition from continuous reinforcement to small FR values, large changes in the FR value, extinction after FR, and the effect of drugs on FR performance. Ferster and Skinner (1957) typically exposed the pigeons to one particular schedule until performance was judged stable. They illustrated instances of FR performance with cumulative records and described behaviour in terms of local rates of responding.

Almost 20 years later, Skinner (1976) lamented the change in experimental practice with the decreasing reliance on cumulative records. Modern practice has resulted in a move towards the systematic manipulation of FR schedules in shorter sessions and an increasing reliance on describing performance in terms of the averages of total session data over a fixed time. FR performance has been examined and measured using the overall response rates (the responses per minute, excluding reinforcement time), running response rates (number of responses per minute, excluding both reinforcement and duration of the pause following reinforcement), and the length of the pause following reinforcement (time from reinforcement to first response), all of which are typically averaged (using means) across a session (Mazur, 1983).

Research detailing the relation between running response rate and ratio requirement has produced mixed results (Crossman, Bonem & Phelps, 1987), but generally increases in FR are said to decrease the average running response rate (e.g., Felton & Lyon, 1966; Foster, Blackman & Temple, 1997; Mazur, 1983). Findings from research investigating overall response rates in FR schedules are also mixed. Overall response rates are reported by some to be bitonic, initially increasing across small FRs, then decreasing as the FR increases further (e.g., Barofsky & Hurwitz, 1968; Crossman et al., 1987; Mazur, 1983). Foster et al. (1997) found, in conditions with long sessions in which the subjects obtained all of their food, that overall response rates steadily increased with increasing FR over the range of FR values studied. It has been suggested that the overall response rates and the way they change with the FR schedule may be influenced by whether or not supplementary food is available to the subject outside of the experimental session (Hursh, 1980) and by the length of the session (Foster et al., 1997).

Even though there has been much research investigating behaviour under FR schedules, there are still many aspects of FR performance that require further investigation. As noted by Schlinger, Derenne and Baron (2008), recent studies have cast doubt upon long held assumptions about pausing under FR schedules, in particular, the pause following reinforcement. Understanding the pause following reinforcement is important because increases in the length of the pause following the delivery of a reinforcer will decrease the overall response rate and prolong the time to the next reinforcer (Schlinger et al., 2008).

The pause characteristic of FR schedule performance was first described by Ferster and Skinner (1957) as ‘the pause after reinforcement’, and soon became known as the ‘post-reinforcement pause’ (PRP; Griffiths & Thompson, 1973). Although this term may be descriptive, some researchers believe that it suggests an erroneous relation between the pause and the previously completed ratio (Griffiths & Thompson, 1973). Many researchers suggest that the pause following reinforcement may actually be a function of the upcoming ratio, or may be a function of the combination of the preceding and upcoming ratios (e.g., Baron & Herpolsheimer, 1999; Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz, Mourer & Gofseyeff, 1967; Perone & Courtney, 1992; Wade-Galuska, Perone & Wirth, 2005).

The pause following reinforcement has been found to increase with an increase in ratio size (e.g., Felton & Lyon, 1966), with a decrease in reinforcer magnitude (e.g., Powell, 1969), and with an increase in delay-to-reinforcement (e.g., Morgan, 1972). However, most studies of FR schedules do not help clarify whether the pause following reinforcement is influenced by the parameters of the preceding or upcoming schedule, because the same schedule is normally used throughout a session (e.g., Stewart, Wang, Bass & Meisch, 2002). Several researchers have used multiple FR FR schedules to investigate the effects on pause duration of manipulating the ratios (e.g., Baron & Herpolsheimer, 1999;

Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz et al., 1967). In multiple FR FR schedules, two (or more) ratios are alternated or randomised, and each is associated with a stimulus (e.g., different coloured key lights) which signals the upcoming ratio (Ferster & Skinner, 1957).

In other studies using multiple FR FR schedules, researchers have manipulated the reinforcer magnitude (Perone & Courtney, 1992) and the force requirement (Wade-Galuska et al., 2005) as alternative ways of changing one of the schedule parameters. In all of these studies, the upcoming schedule was found to have more effect on behaviour than the previous schedule, in that the pause following reinforcement increased when the upcoming schedule was numerically larger, required more force, or the reinforcer was small. In most cases, the longest pauses occurred when the previous schedule had been a smaller ratio, required less force, or the reinforcer was large. All of these schedule manipulations (increasing the ratio size and force requirement, and decreasing the reinforcer magnitude) could be regarded as producing more ‘unfavourable’ schedule parameters (cf., Wade-Galuska et al., 2005). One possibility is that it is the signalled arrival of the less favourable schedule that causes the increased pause following reinforcement.

Another way to lower the favourableness of a schedule is to impose a delay between responding and reinforcement. Investigations of the effects of delay-to-reinforcement (also known as immediacy of reinforcement) on behaviour have been conducted using a variety of different procedures (Sizemore & Lattal, 1978). The delay may be unsignalled, or may be signalled to the subject, with, for example, a blackout (e.g., Chung & Herrnstein, 1967) occurring for the duration of the delay. Typically responding during the delay has no effect, however a resetting delay may also be used, in which responding during the delay acts to extend the delay period (e.g., Azzi, Fix, Keller & Rocha e Silva, 1964).

The effects of delay-to-reinforcement on behaviour have been studied under a range of schedules of reinforcement. Generally, unsignalled non-resetting delays of reinforcement are said to decrease rates of responding even at very small delays (e.g., 3-s delays; Williams, 1976). It has been reported that response rates decrease further as the delay increases in duration (Dews, 1960; Shahan & Lattal, 2005; Sizemore & Lattal, 1978). Unsignalled resetting delays are reported to reduce response rates to a greater extent than unsignalled non-resetting delays of the same duration (Dews, 1960). A signalled delay is also reported to reduce response rates compared to those obtained with immediate reinforcement, and the response rate has been reported to decrease further as the duration of the delay increases (Schaal, Schuh & Branch, 1992). However, a signalled delay is thought to result in a more stable pattern of responding, and to reduce the response rate less than an equivalent unsignalled delay (Azzi et al., 1964; Cardinal, Robbins & Everitt, 2000; Lattal, 1984; Reilly & Lattal, 2004; Richards, 1981; Williams, 1976).

There is limited research investigating the effects of delay-to-reinforcement on FR performance. In one relevant study Morgan (1972) used FR 9 schedules of reinforcement that were followed by a signalled delay. Morgan (1972) reported that as the delay following the completion of the schedule requirement increased, so did the length of the pause following reinforcement. This finding was confirmed by Topping, Johnson and McGlynn (1973) who examined the effects of delay on the pause following reinforcement by systematically manipulating the delay duration for rats responding under one of three FR values (10, 75 and 150). Azzi et al. (1964) found similarly using continuous reinforcement (FR 1) and increasing unsignalled resetting delays. Azzi et al. (1964) reported a decrease in the overall response rate as delay increased when the delay was unsignalled, but in a second condition found that responding was faster and more regular when a 20-s or a 30-s delay was signalled compared to when it was not signalled. Morgan (1972) and Topping et al. (1973) found no consistent effects of delay on rates of responding. The different results are likely to have been found because it appears that Azzi et al. (1964) included the delay in their calculation of the overall response rate. They also used resetting delays, which, as mentioned above, have been found to have more effect on response rates than non-resetting delays, such as used by Morgan (1972) and Topping et al. (1973). Also, in each study, different delay durations and FR values were used.

Overall, the existing data suggest that the addition of a delay-to-reinforcement to FR schedules is likely to increase durations of the pause following reinforcement compared to no delay, more so as the delay is increased. The effect of a delay-to-reinforcement on rates of responding is unclear in the FR research (Azzi et al., 1964; Morgan, 1972; Topping et al., 1973). Based on these studies, it may be expected that the use of a signalled non-resetting delay would have no effect on response rates. However, if research on the effects of delay-to-reinforcement on performance under other schedules of reinforcement is considered, it is generally found that when a reinforcer is delayed, it becomes less effective at maintaining behaviour, resulting in an inverse relation between the length of the delay and response rate (e.g., Gentry & Marr, 1980; McDevitt & Williams, 2001; Neuringer, 1969; Sizemore & Lattal, 1978).

There is research investigating the effects of delay-to-reinforcement on choice behaviour in concurrent chain schedules. In concurrent schedules, two or more schedules are operating simultaneously, resulting in a choice situation. In chained schedules, responding in the presence of one stimulus is reinforced by the arrival of another. Responding in the presence of the second stimulus is, in turn, reinforced with a primary reinforcer (Ferster & Skinner, 1957). According to Mazur (2003), the most common concurrent chain procedure involves the initial choice between two identical variable-interval (VI) schedules. Under a VI schedule, the first response following an average specified period of time results in a reinforcer becoming available (Ferster & Skinner, 1957). The VI schedules are known as the initial-links. Completion of either initial-link schedule leads to the corresponding terminal-link, and responding on this schedule is reinforced with food. In concurrent chain schedules, subjects will typically respond more in the initial-link towards the alternative with a shorter delay (or no delay) in the terminal-link (e.g., Davison, 1983; Dunn & Fantino, 1982; Mazur, 2003; McDevitt & Williams, 2001; Squires & Fantino, 1971).

More evidence that an increasing delay-to-reinforcement reduces the favourableness of a schedule comes from delay models (e.g., the delay reduction hypothesis; Fantino, 1969), which attempt to explain choice behaviour and predict responding in concurrent situations. Such models are often based on the premise that when a reinforcer is delayed the scheduled consequence will decrease in value as delay increases, as would be expected with reinforcers of reduced quality or magnitude. Furthermore, Davison and Baum (2007) investigated the effect of delay-to-reinforcement on local choice (the short period of increased responding towards an alternative where a reinforcer was just delivered). They found that the local rate of responding increased as the delay decreased. This was similar to their previous findings with increasing reinforcer rate and reinforcer magnitude.

They argued that increases in delay have effects similar to decreases in reinforcer magnitude.

Delaying reinforcement has been found, in research with other schedules, to have effects similar to changes in other parameters of reinforcement. For example, Nevin (1974; Experiment 4) arranged two-component multiple schedules with VI 60-s schedules in each component. He placed either a short delay (e.g., 1 s) or a long delay (e.g., 9 s) between the first response after reinforcement became available and the delivery of the reinforcer. During one condition, food was delivered aperiodically throughout the session independently of the schedule of reinforcement. It was observed that as the frequency of free food increased, response rates decreased to a greater extent in the component with the longer delay than the shorter delay. In another condition, the subjects experienced several sessions of extinction, in which responding had no consequence and no reinforcement was delivered. Across extinction sessions, responding decreased, again more so in the component associated with the longer delay. Nevin (1974) concluded that, like large magnitudes and high rates of reinforcement, behaviour under short delays-to-reinforcement was less affected by free food and extinction, suggesting that delay-to-reinforcement, rate of reinforcement and reinforcer magnitude are functionally equivalent. Given the limited research on the effects of delay-to-reinforcement on performance in FR schedules, Experiment 1 of this thesis used delay-to-reinforcement in one component of multiple FR FR schedules and examined the effects of this on responding and pausing.

One way the effect on FR performance of variables such as reinforcer magnitude and force has been investigated is methods used in behavioural economics and the assessment of demand. Behavioural economics involves the investigation of animals' needs using methods derived from consumer demand theory (Dawkins, 1983). Demand refers to the way in which a consumers' consumption of a commodity changes with increases in price. In behavioural economics the subject is the consumer and the effort required to gain access to the commodity (reinforcer) is the price (Lea, 1978). To investigate demand, the effort required is changed and consumption monitored. One of the most common schedules used in such behavioural economic research is an FR schedule, although other manipulations of increasing price such as force and type of response have also been used (Sumpter, Temple & Foster, 1999).

One published (Foster, Sumpter, Temple, Flevill & Poling, 2009) and several unpublished (e.g., Bruce, 2007; Grant, 2005) studies known to this author have been conducted examining how demand, when measured using behaviour under FR schedules, changes when differing magnitudes or qualities of food are assessed. The relative values of the foods were also assessed using concurrent schedules. Foster et al. (2009) and Bruce (2007) both found, paradoxically, that in fixed-length sessions, the numbers of reinforcers obtained at small FR values were greater for the food of lower value (puffed wheat) than the food of higher value (wheat). At these small FR values, the hens paused following reinforcement for shorter durations and responded faster for puffed wheat than wheat. Grant (2005) had found similarly when different reinforcer magnitudes were used to provide different reinforcer values. A greater number of shorter duration (2 s) reinforcers than larger duration (12 s) reinforcers were obtained at small FR values, and the hens responded faster for the small amounts of food than for the larger amounts of food.

The results of previous research investigating the effects of differing reinforcer magnitude are mixed. In some studies it has been reported that across most or all ratio values the larger reinforcer was associated with lower response rates and longer pauses following reinforcement (e.g., Bizo, Kettle & Killeen, 2001; Leslie, Boyle & Shaw, 2000). In other studies, larger reinforcers have also been associated with longer pausing and therefore lower overall response rates, but particularly at small to moderate FR values. For example, Lowe, Davey and Harzem (1974) reported that when rats worked under FR 30 schedules, the pauses following reinforcement increased and overall response rates decreased as the concentration of the condensed milk reinforcer was increased. Hursh, Raslear, Shurtleff, Bauman and Simmonds (1988) found that across small to medium FR values, rats performed a larger number of FR completions for 1 pellet than for 2 pellets. They reported that consumption of the single pellet decreased faster than consumption of 2 pellets as the FR increased. Collier, Johnson and Morgan (1992) found that rats working in closed economic conditions responded fastest for smaller food pellets under FR 10 and FR 40 schedules. The same effect was found in open economies under FR 10 schedules, but not under the FR 40 schedules. Foltin (1994) reported that when baboons worked for pellets under FR schedules, initial demand was lower for 5 pellets than for 1 pellet, suggesting faster response rates for the smaller reinforcer at small FR values. The 10 pellet data, however, were similar to the 5 pellet data. Stewart et al. (2002) found the response rates of rhesus monkeys at the smallest FR value tested to be highest for the lowest concentration of ethanol, and lowest for the highest concentration of ethanol. As the FR increased, responding at the lowest concentration was most affected, while responding at the highest concentration was least affected. Thus the finding that the more unfavourable consequence leads to higher response rates at smaller FR values is not uncommon.

It is possible that findings such as these may be similar to the ‘magnitude-of-reinforcement effect’. When the larger reinforcer and smaller reinforcer were presented concurrently, Grant (2005) found the hens showed a bias toward the larger reinforcer, that is, the hens responded more for the larger reinforcer than the smaller reinforcer. Using similar procedures, Foster et al. (2009) and Bruce (2007) both found the hens to show a bias toward wheat compared to puffed wheat. Wheat grains are smaller and heavier than puffed wheat, and it is likely that in each 3-s reinforcer access, a larger amount and more calories were obtained when the reinforcer was wheat. Therefore, 3-s access to wheat might be a reinforcer of greater magnitude than 3-s access to puffed wheat. Using this analogy, the seemingly paradoxical findings of longer durations of the pause following reinforcement and lower rates of responding across small FR values for the foods in which the hens were found to show biases towards, may be similar to the ‘magnitude-of-reinforcement’ effect. Unfortunately, simply noting this similarity does not provide any robust explanation for the effect.

However, some researchers investigating reinforcer magnitude have found larger reinforcers to be associated with shorter pauses following reinforcement (e.g., Meunier & Starratt, 1979; Powell, 1969). Thus, is it unclear whether the findings of Foster et al. (2009), Grant (2005) and Bruce (2007) may or may not be similar to the ‘magnitude-of-reinforcement effect’. Investigating the effect of delay-to-reinforcement on FR performance and the assessment of demand may help to clarify these findings. Delay can devalue a reinforcer without changing the actual reinforcer and adding any possible confounding effects of reinforcer magnitude. Experiment 2 extended research investigating the effect of various parameters of reinforcement on FR performance and the assessment of demand by adding a delay-to-reinforcement to increasing FR schedules.

When the price analogue in behavioural economics is an FR schedule, there is a problem because increasing the response requirement means the subjects may take more time to complete it. As the time to complete the response requirement increases, so too does the inter-reinforcement interval, resulting in a decreasing rate of consumption and usually also total consumption. For example, increasing an FR 10 schedule to an FR 20 schedule approximately doubles the time to complete the ratio, whereas, for a consumer, spending $20 takes no more time than spending $10. Foster et al. (1997) argued that this is particularly a problem in sessions of fixed duration. As the FR is increased, so too is the time it takes to complete the ratio, and responding then takes up an increasing proportion of the total session time (Foster et al., 1997). Foster et al. (1997) found total consumption remained relatively constant as the FR increased in their long (24-hr) sessions in which the hens were required to obtain their entire dietary requirements (termed closed-economy sessions). However, consumption was found to decrease with increasing FR in short (40-min) closed-economy sessions, as well as in short sessions in which supplementary food was given (termed open-economy sessions). This makes fixed session durations, particularly short sessions, confounding when using FR schedules to assess demand. It means that using FR schedules to assess animals’ demand is not perfectly analogous to price in consumer demand theory. Experiment 3 attempted to explore the confound of increasing schedule duration, aiming to determine whether it is the increasing response requirement or the increasing schedule duration that has more effect on behaviour in FR schedules.

In summary, in Experiment 1 various delays were added (between the terminal response and reinforcement) to one component in multiple FR FR schedules. This was to determine whether increasing the delay before reinforcement in the upcoming ratio, like an increase in the ratio or force requirement or a decrease in reinforcer magnitude, would result in increased durations of the pause following reinforcement. Experiment 2 examined the more general effect of delay-to-reinforcement on FR performance and on the assessment of demand, extending similar research investigating the effects of other parameters of reinforcement. Finally, increasing the response requirement in FR schedules necessitates an increase in the time required by the subject to complete the schedule. Experiment 3 separated the confounding effects of response requirement and schedule duration in FR schedules by using conjunctive schedules in which either the duration of the schedule or the response number could be varied independently.

EXPERIMENT 1

As previously mentioned, multiple schedules have been used to determine whether the duration of the pause following reinforcement is influenced by the outcome of the preceding or upcoming schedule (e.g., Baron & Herpolsheimer, 1999; Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz et al., 1967; Perone & Courtney, 1992; Wade-Galuska et al., 2005). Typically, a large and a small ratio are presented (Baron & Herpolsheimer, 1999; Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz et al., 1967) according to a quasi-random sequence (Baron & Herpolsheimer, 1999; Griffiths & Thompson, 1973; Perone & Courtney, 1992; and Wade-Galuska et al., 2005). This means that there can be four different transitions between ratios; small-small, small-large, large-large and large-small.

Other ways in which the outcomes of the schedules have been varied include the manipulation of reinforcer magnitude (Inman & Cheney, 1974; and Perone & Courtney, 1992), and the force requirement (Wade-Galuska et al., 2005). Again, it is common to present the schedules quasi-randomly (Baron & Herpolsheimer, 1999; Griffiths & Thompson, 1973; Perone & Courtney, 1992; and Wade-Galuska et al., 2005), however some have simply alternated the schedules (Crossman, 1968; Inman & Cheney, 1974; Mintz et al., 1967).

Crossman (1968) reported that pauses preceding the initiation of a large ratio were longer than those preceding a small ratio. Inman and Cheney (1974) manipulated the size of the larger ratio and reported that durations of pausing preceding this ratio increased as the ratio increased. However, because the schedules were simply alternated in these studies (excepting the final six sessions of Inman and Cheney’s experiment), the subjects were exposed to only large-small and small-large schedule transitions. This means that the effect of the preceding schedule requirement was unclear in Crossman’s (1968) research, while Inman and Cheney (1974) reported that the preceding ratio had no effect on pausing.

Mintz et al. (1967) alternated pairs of schedules (large-large-small-small), and thus the subjects were exposed to all four transition types. Mintz et al. (1967) reported that the pauses following reinforcement were shortest during small-small and large-small transitions, longest during small-large transitions and next longest during large-large transitions. This finding suggests that the pause following reinforcement is influenced by both the upcoming and preceding schedules. The authors noted that these results are the opposite of those expected if the pause following reinforcement were a result of fatigue due to the effort required. If pause duration were a result of fatigue, pausing would be longer following the large ratio.

The same finding, that pausing following reinforcement in multiple FR FR schedules is largely influenced by the upcoming schedule, but also somewhat by the previous schedule, (i.e., longer in small-large transitions than large-large transitions) has also been reported when the schedules have been presented using quasi-random sequencing (Baron & Herpolsheimer, 1999; Griffiths & Thompson, 1973; Perone & Courtney, 1992; Wade-Galuska et al., 2005). Similar results have also been found when other parameters of the multiple FR FR schedules have been varied. In a second experiment, Inman and Cheney (1974) held reinforcement following the small ratio constant, and systematically increased the reinforcer magnitude following the large ratio. They reported that pausing preceding large ratios decreased with increasing reinforcer magnitude until the relation found in the previous experiment was reversed (i.e., pausing preceding the large ratios was significantly shorter than pausing preceding small ratios). Similarly, Perone and Courtney (1992) found that pauses following reinforcement were shorter before the large reinforcers than before the small reinforcers. They also found pauses were longer after the large reinforcers than after the small reinforcers, suggesting that the pause following reinforcement was a function of both the previous reinforcer size and the stimulus signalling the upcoming reinforcer.

More recently, Wade-Galuska et al. (2005) manipulated the force required to press levers in multiple FR 30 FR 30 schedules using quasi-random sequencing. They found that pauses following reinforcement were longer when the upcoming schedule signalled a large force, and longer still when the previous force had been small. They conceptualised the increase in force as conditions having become ‘more unfavourable’.

Baron and Herpolsheimer (1999) noted that means have been used to describe much of the previous data examining FR responding and pausing, and pointed out that averaging data may change the individual results. When they analysed the results of their multiple FR FR schedules study using means, the outcomes were similar to those found in previous research; the mean pause following reinforcement increased with an increase in the number of responses required, and the duration of the pause was more influenced by the upcoming requirement than the preceding one. However, they also found that the distributions of pauses following reinforcement were positively skewed and became more so as the FR increased, and suggested that the increases in pausing found in mean data may be more attributable to the increase in skew, rather than a change in the entire distribution. They concluded that when data are summarised using means, the presentation of individual distribution data may be necessary. This is to justify that the mean is representative of the distribution and that reported changes in the mean are not due to changes in the skewness of the distribution. Their findings highlight the importance of examining pause distributions, and suggest that it may be more suitable to use medians in the analysis of such data rather than means as they are less sensitive to skewed distributions and outliers that will have a large influence on the mean (Baron & Herpolsheimer, 1999).

Accordingly, most of the above researchers have avoided the use of means to describe durations of the pause following reinforcement in multiple FR FR schedules except for Crossman (1968) and Inman and Cheney (1974). Mintz et al. (1967) and Wade-Galuska et al. (2005) analysed their data using medians. Baron and Herpolsheimer (1999) favoured the use of frequency distributions to describe their data. Griffiths and Thompson (1973) used cumulative records as well as frequency distributions. Perone and Courtney (1992) also used frequency distributions, as well as medians and interquartile ranges. Therefore medians will be used in the present experiment to summarise the pause distributions.

Delay-to-reinforcement, like an increase in the ratio requirement, and a decrease in reinforcer magnitude, has previously been found to increase the duration of the pause following reinforcement in FR schedules (e.g., Morgan, 1972). All of these manipulations could be regarded as producing ‘more unfavourable’ schedule parameters (cf., Wade-Galuska et al., 2005). In this first experiment, delays of differing durations were added to one of the components in multiple FR FR schedules to investigate whether pausing would be affected in the same way it has been shown to be with the manipulation of other reinforcement parameters. Based on previous multiple FR FR research, it was expected that pausing would be longer before ratios in which a delay was signalled and longest when the previous ratio had resulted in an immediate reinforcer. Additionally, based on previous delay-to-reinforcement research, it was expected that the median pause durations would increase with increasing delay. Further, it was expected that response rates would decrease during the ratio in which a delay was signalled compared to a ratio in which immediate reinforcement was signalled.

Method

Subjects

The six subjects, numbered 61 through 66, were Shaver-Starcross domestic hens. At the beginning of the experiment, the hens were two years old, and had had some experience on simple schedules of reinforcement. The hens were housed individually in home cages (500-mm long × 510-mm wide × 420-mm high), in a ventilated room on a 12-hr light: 12-hr dark cycle. They had free access to water, and grit and vitamins were provided weekly. Throughout the experiment all hens had red fleshy combs suggesting good health. Each hen was weighed every day experimental sessions took place (approximately six days per week) and they were maintained at 80% (+/-5%) of their free-feeding body weights through feeding of commercial layer pellets.

Apparatus

The apparatus was a particleboard experimental chamber (640-mm long × 450-mm wide × 580-mm high), located in a room with several other experimental chambers. The chamber floor was covered with a thick metal grid (30 mm × 30 mm) enclosed in a steel tray. A food magazine was located on the right-hand wall of the chamber behind an opening (115-mm high × 70-mm wide) that was centred 105 mm above the floor. When operational, the magazine was lit and raised to allow 3-s access to wheat. Above the magazine opening (390 mm from the floor) was a frosted transparent plastic response key (30 mm in diameter), which could be lit red and green with a 28-V multi-chip LED (light-emitting diode) bulb, and that required a force of approximately 0.2 N, resulting in an audible beep.

All experimental events were recorded and the experiment was controlled by a Dell PC computer (1.6GHz, P4, 256MB, Windows XP Service Pack 2) running Med-PC® IV software. Total session data were also manually recorded into a data book at the end of each session.

Procedure

Multiple schedules. The response key could be lit red or green, each colour being associated with an FR schedule of reinforcement. Each component terminated after one reinforcer had been obtained on that schedule. During the delivery of the reinforcer, the key light was extinguished and the food magazine was lit and raised for 3 s. Immediately following reinforcement, the key was relit and the next component started. There were four different transitions that could occur within a session, red-red (RR), red-green (RG), green-green (GG), and green-red (GR). A quasi-random sequence based on the Gellerman (1933) sequence was used to determine the order in which these lights were presented (including the initial key colour at the start of a session). This sequence ensured that each transition was presented an approximately equal number of times within a session and that the same schedule (and key colour) was not presented more than three times sequentially. Sessions ended (and the key light was extinguished) when 40 reinforcers had been delivered, or after 40-min total time. Data were discarded if fewer than 30 reinforcers had been obtained or if an egg had been laid during the session.

Conditions were changed when pausing durations (the time from the end of reinforcement to the first response on the next schedule) were considered to be stable over the most recent 10 sessions using a criterion similar to those used by Perone and Courtney (1992) and Baron and Herpolsheimer (1999). For each session, the median pause lengths were calculated for each of the four transitions. First, a plot of the medians over sessions had to show that there were no visual increasing or decreasing trends across the last 10 sessions. In addition, the medians of the first five and of the second five sessions were calculated and were required to differ from the overall median of the last 10 sessions by no more than 15%.

Training. Hens 61, 62, 64, 65 and 66 required only one session of training in which a reinforcer was manually delivered after every one or two responses for the first 10 to 20 reinforcers. When the hens were responding to the lighted response key consistently, they completed a session that ended after 40 reinforcers were delivered according to multiple FR 5 FR 5 schedules. For Hen 63, an additional day of training was required, in which she was trained to peck the response key using the method of reinforcement of successive approximations.

Experimental Conditions. In all conditions the FR schedules in effect were always multiple FR 5 FR 5 schedules. The first condition was an equal schedule condition. In subsequent conditions, a delay-to-reinforcement (signalled by the darkening of the key light) was added to one of the FR schedules, between the final response requirement and the raising and lighting of the magazine. Table 1.1

presents a list of conditions, the delays, and the number of days each condition was in effect.

Data that were collected and manually recorded in the data book at the end of each session included the numbers of responses to each of the schedules in effect, the numbers of reinforcers delivered, mean run time (time from first FR response to terminal FR response), mean eating time (time head was in magazine during reinforcer access), and total session time. Also recorded were the mean pause durations for each of the aforementioned light transitions; RR, RG, GG and GR. Computer files were generated which contained all experimental events and their time of occurrence.

Table 1.1.

The order of experimental conditions, together with the delay and the number of days each condition was in effect.

Condition	Red delay	Green delay	Days condition in effect
1	0 s	0 s	40
2	4 s	0 s	28
3	8 s	0 s	32
4	0 s	8 s	57
5	16 s	0 s	44
6	32 s	0 s	47
7	0 s	32 s	36

Results

Raw data from all conditions in Experiment 1 are presented in Appendix 1. The data from only the last 10 series of each condition have been analysed and presented here.

Between-Ratio Pause Histograms

Figure 1.1 presents histograms of the between-ratio pause durations (frequency of particular pause durations, y axis, plotted against the duration of pausing in 1-s bins, x axis) from the last 10 sessions of each condition (excluding reversals). Data from all hens were analysed, and the distributions and trends were similar, so data from Hen 61 are presented as representative. Data from Hens 62 through 66 are presented in Appendix 1. Four panels are presented for each condition, one for each of the key light transitions. In the 0-s delay condition, the key light transitions were RR, RG, GG, and GR. In the other conditions, the transitions were delay-delay (DD or RR), delay-immediate (DI or RG), immediate-immediate (II or GG), and immediate-delay (ID or GR). For reasons of clarity, the frequency axis is limited to 40 and the between-ratio pause duration axis is limited to 100 s. Pause durations of 100 s or longer are presented collectively at 100 s.

When there were no delays (0-s delay condition), pausing did not differ consistently across transitions. There were a large number of short pause durations, and a few slightly longer pauses, resulting in distributions with a small positive skew. The distributions in transitions where the upcoming reinforcer was immediate (DI and II; central two panels) remained similar to those in the 0-s delay condition as the delay was increased. In transitions in which the upcoming reinforcer was delayed (DD and ID), the data were still skewed, however the frequency of short pause durations decreased, increasingly so as the delay increased, and the distributions became more spread out with an increasing frequency of longer pause durations.

Median Pause Durations

Figure 1.2 presents the median pause durations and the interquartile ranges for each transition over the last 10 sessions of each condition for all hens. In some cases the interquartile ranges are too small to appear outside the data markers. The pause durations are plotted for each transition type and for each delay condition (filled circles) and the reversal conditions (open circles). The

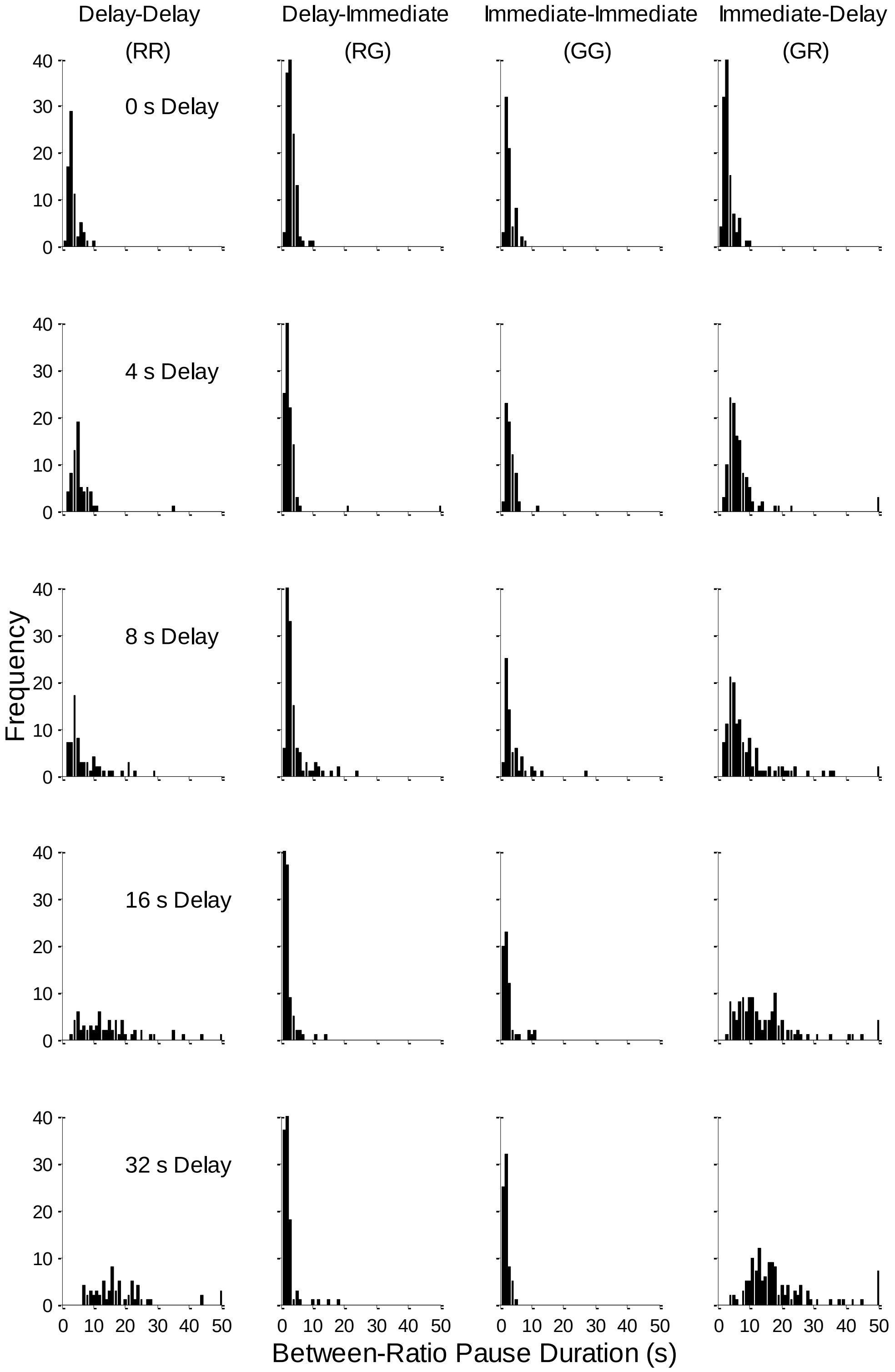

Figure 1.1. Histograms of the between-ratio pause durations for all transition types [Delay-Delay or Red-Red (RR); Delay-Immediate or Red-Green (RG); Immediate-Immediate or Green-Green (GG); Immediate-Delay or Green-Red (GR)], in the last 10 sessions of all conditions (0 s, 4 s, 8 s, 16 s and 32 s) for Hen 61.

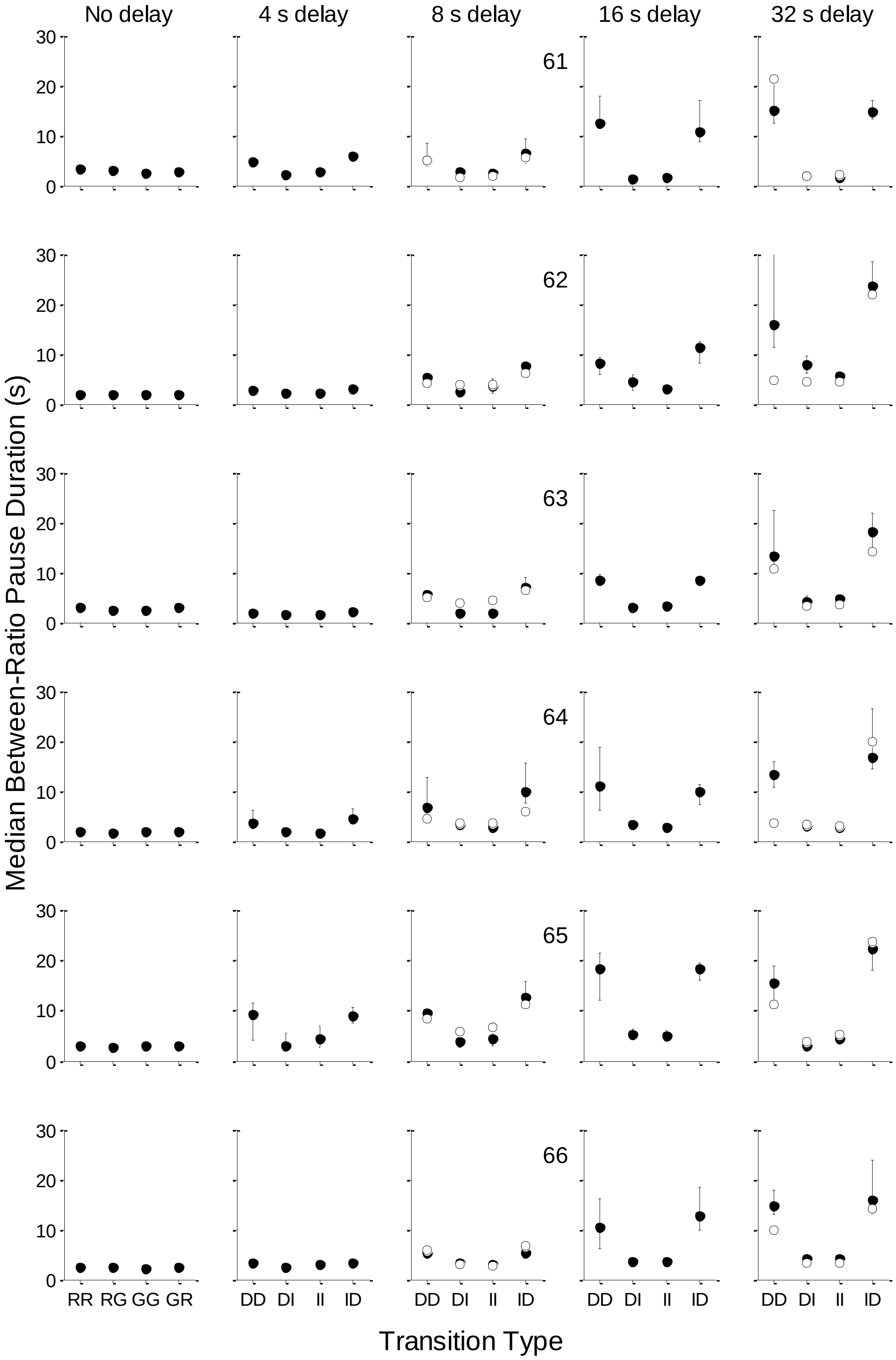

Figure 1.2. The median between-ratio pause durations (in s) plotted for each transition type [Red-Red (RR) or Delay-Delay (DD); Red-Green (RG) or Delay-Immediate (DI); Green-Green (GG) or Immediate-Immediate (II); and Green-Red (GR) or Immediate-Delay (ID)], for all hens and delay values (0 s, 4 s, 8 s, 16 s, 32 s). Data from the reversal conditions are presented as open circles.

extreme left panels show that there were no consistent differences across transitions when there were no delays. The pauses were generally quite similar and short in duration (2-3 s long). The remaining panels (4-s, 8-s, 16-s and 32-s delay) show that pauses tended to be longer before the ratio in which a delay-to-reinforcement was signalled (DD and ID transitions) than when the upcoming reinforcer was signalled to be immediate (DI and II transitions), resulting in u-shaped functions. This u-shape became more pronounced as the delay increased, meaning that durations of pausing before the ratio with a signalled delay increased as the delay increased. In most cases (29 of 36 instances including reversals) the pauses were longest before the delay when the previous ratio had resulted in an immediate reinforcer (ID transitions). Data from reversal conditions did not differ consistently from data in the original 8-s and 32-s delay conditions. One data point for Hen 61 from the 32-s reversal condition (33.9 s) is outside the graph axes.

Figure 1.3 re-presents the same median pause durations and the interquartile ranges for each transition over the last 10 sessions of each condition for all hens. The pause durations are plotted for each delay condition (excluding reversals) and for each transition type. The extreme left and right panels show that following DD and ID transitions (i.e., when there was a delay following the upcoming ratio), the median pause increased as the delay increased. The two centre panels show that following DI and II transitions (i.e., when there was no delay following the upcoming ratio), there was no consistent effect of delay duration on the median pause length across hens.

In sum, Figure 1.2 shows that when a delay was signalled to be upcoming, pause durations increased compared to when immediate reinforcement was signalled. Figure 1.3 shows that longer delays resulted in longer pauses when the delay was upcoming.

Median Running Response Rates

Figure 1.4 presents the median running response rates and the interquartile ranges for each ratio type (between a previous delayed reinforcer and an upcoming delayed reinforcer, DD; between a previous delayed reinforcer and an upcoming immediate reinforcer, DI; between a previous immediate reinforcer and an upcoming immediate reinforcer, II; and between a previous immediate reinforcer and an upcoming delayed reinforcer, ID), taken over the last 10

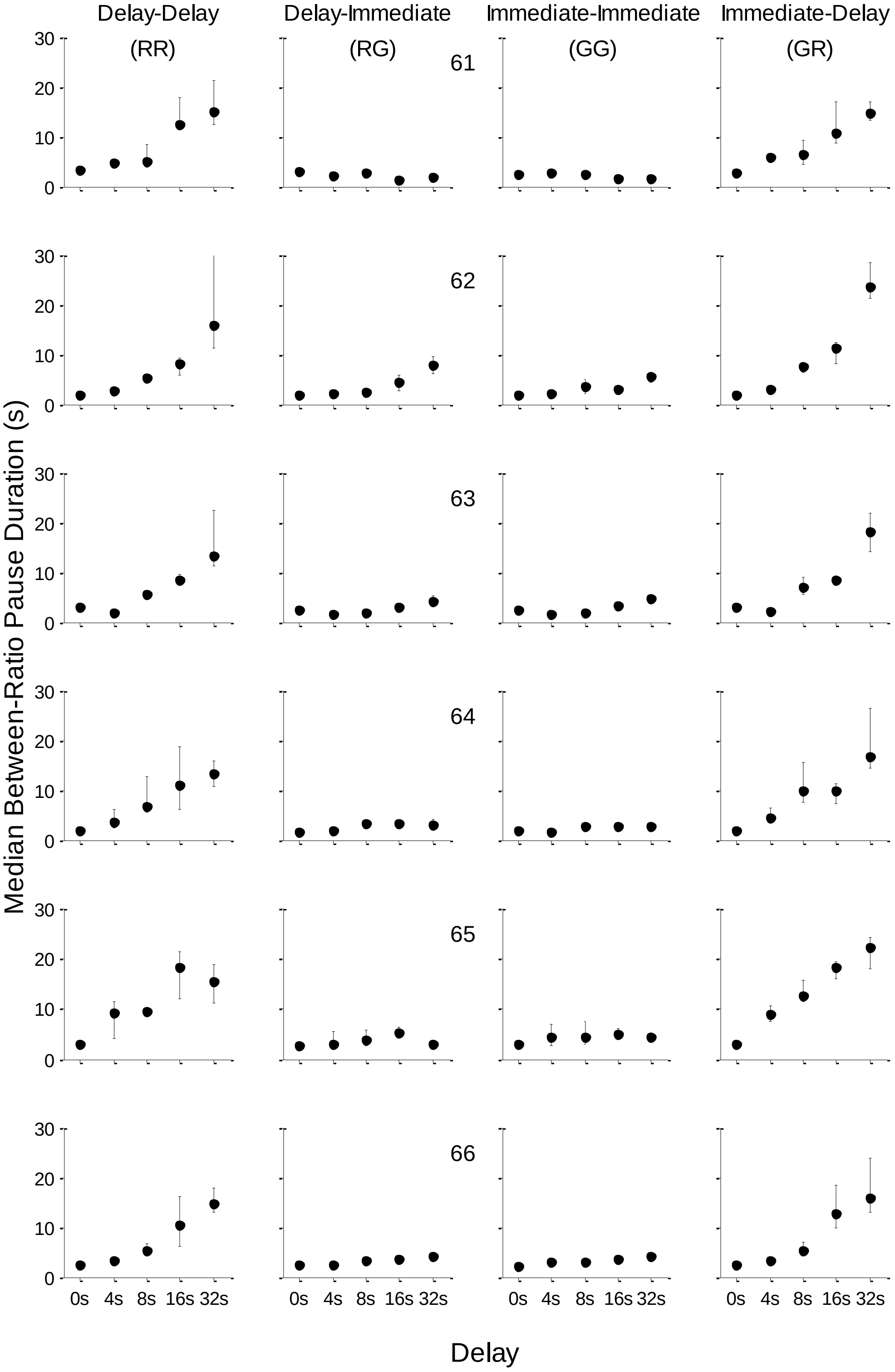

Figure 1.3. The median between-ratio pause durations (in s) plotted for each delay value (0 s, 4 s, 8 s, 16 s and 32 s), for all hens and transition types [Delay-Delay or Red-Red (RR); Delay-Immediate or Red-Green (RG); Immediate-Immediate or Green-Green (GG); and Immediate-Delay or Green-Red (GR)].

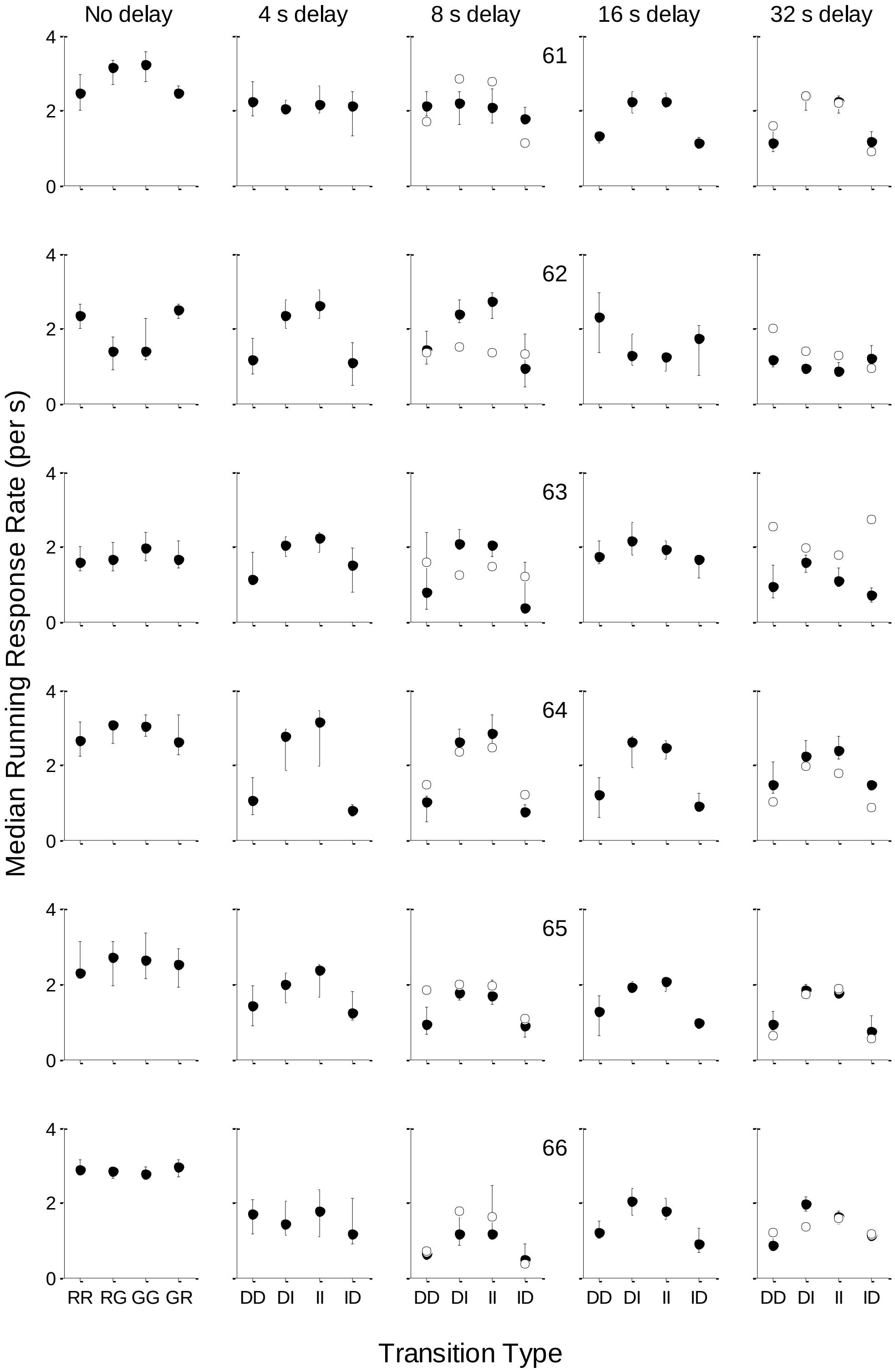

Figure 1.4. The median running response rates (per s) plotted for each ratio type [Red-Red (RR) or Delay-Delay (DD); Red-Green (RG) or Delay-Immediate (DI); Green-Green (GG) or Immediate-Immediate (II); and Green-Red (GR) or Immediate-Delay (ID)], for all hens and delay values (0 s, 4 s, 8 s, 16 s and 32 s). Data from the reversal conditions are presented as open circles.

sessions of each condition for all hens. The running response rates are plotted for each ratio type and for each delay condition (filled circles) as well as the reversal conditions (open circles). The extreme left panels show that when there were no delays, there were no systematic differences across ratio types. The remaining panels (4-s, 8-s, 16-s and 32-s delay) show that running response rates tended to be lower in the ratio leading to a delayed reinforcer (DD and ID ratios), than in the ratio leading to an immediate reinforcer (DI and II ratios) resulting in inverted u-shaped functions. In most cases (30 of 36 instances including reversals) the running response rates were slowest during the ratio leading to delay when the previous ratio had resulted in an immediate reinforcer (ID ratios). Data from reversal conditions did not differ consistently from data in the original 8-s and 32-s delay conditions.

Figure 1.5 re-presents the same median running response rates and interquartile ranges over the last 10 sessions of each condition for all hens. The running response rates are plotted for each delay condition (excluding reversals) and for each ratio type. During DD and ID ratios (the extreme left and right panels), the only consistent pattern was that the running response rates tended to be slower when there was an upcoming delay compared to no upcoming delay (0 s). The running response rates decreased monotonically with increases in delay duration for only Hens 61 and 65. The two centre panels show that, in most cases, following DI and II ratios the running response rates remained similar to those in the 0 s delay condition, showing no systematic pattern across hens.

In sum, Figure 1.4 shows that when a delay was signalled to be upcoming, the running response rates were lower compared to when immediate reinforcement was signalled. Figure 1.5 shows that any delay duration reduced the running response rate compared to immediate reinforcement, that is, the running response rates did not decrease monotonically with longer delays.

Median Overall Response Rates

Figure 1.6 presents the median overall response rates and the interquartile ranges for each ratio type (between a previous delayed reinforcer and an upcoming delayed reinforcer, DD; between a previous delayed reinforcer and an upcoming immediate reinforcer, DI; between a previous immediate reinforcer and an upcoming immediate reinforcer, II; and between a previous immediate reinforcer and an upcoming delayed reinforcer, ID), taken over the last 10

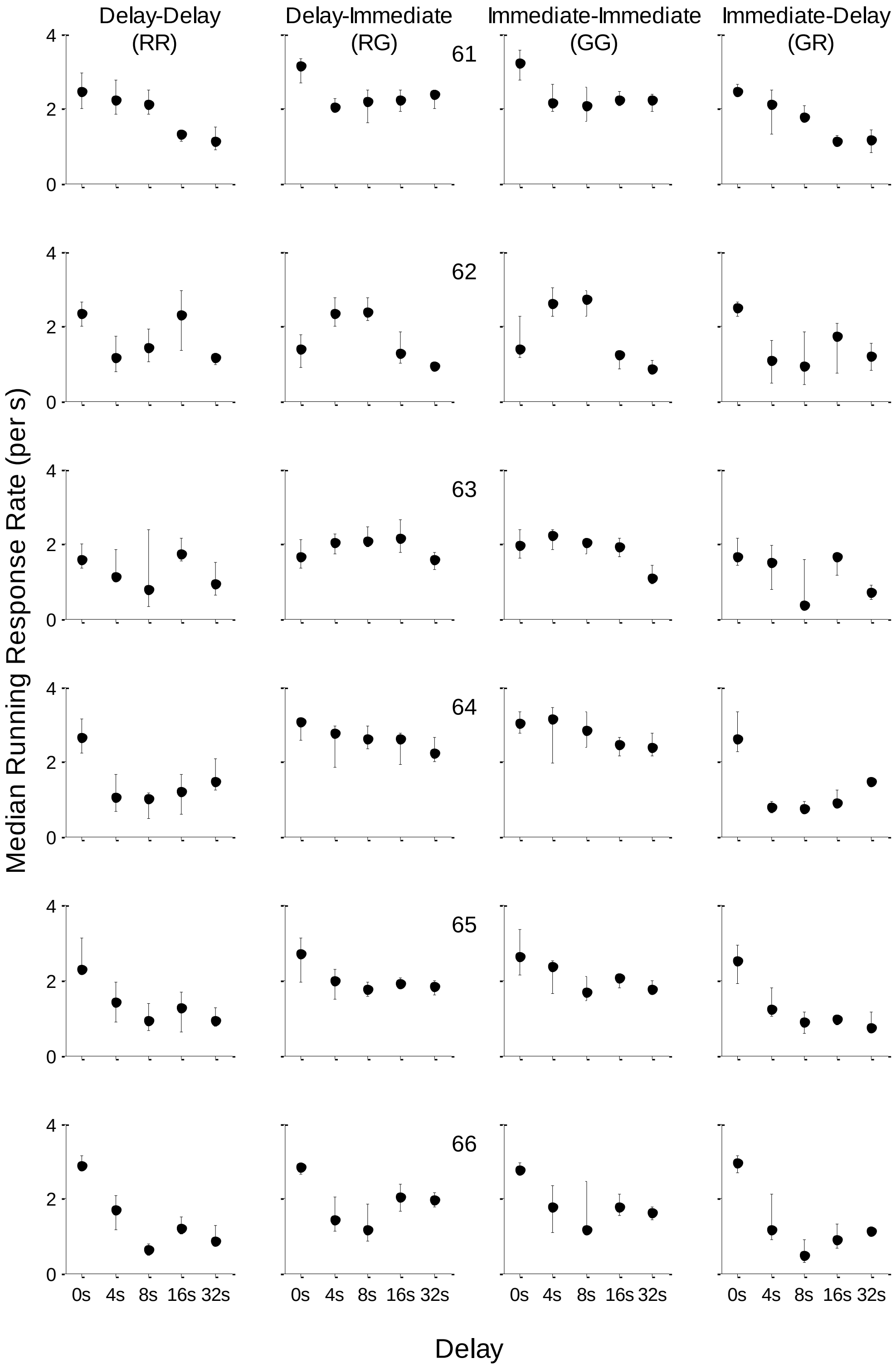

Figure 1.5. The median running response rates (per s) plotted for each delay value (0 s, 4 s, 8 s, 16 s and 32 s), for all hens and ratio types [Delay-Delay or Red-Red (RR); Delay-Immediate or Red-Green (RG); Immediate-Immediate or Green-Green (GG); and Immediate-Delay or Green-Red (GR)].

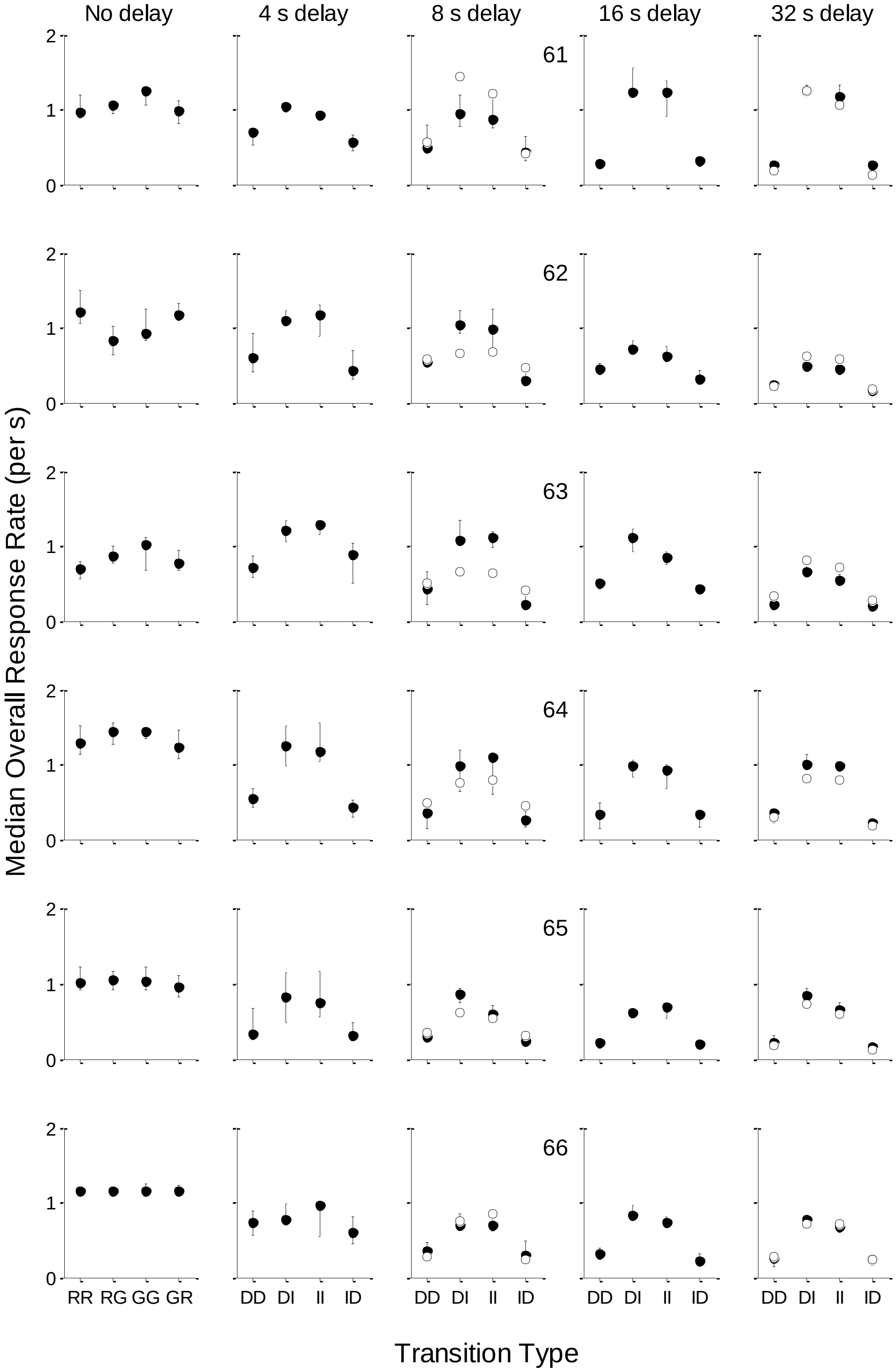

Figure 1.6. The median overall response rates (per s) plotted for each ratio type [Red-Red (RR) or Delay-Delay (DD); Red-Green (RG) or Delay-Immediate (DI); Green-Green (GG) or Immediate-Immediate (II); and Green-Red (GR) or Immediate-Delay (ID)], for all hens and delay values (0 s, 4 s, 8 s, 16 s and 32 s). Data from the reversal conditions are presented as open circles.

sessions of each condition for all hens. The overall response rates are plotted for each ratio type and for each delay condition (filled circles) as well as the reversal conditions (open circles). The extreme left panels show that when there were no delays, there were no systematic differences across ratio types. The remaining panels (4-s, 8-s, 16-s and 32-s delay) show that overall response rates tended to be lower in the ratio leading to a delayed reinforcer (DD and ID ratios), than in the ratio leading to an immediate reinforcer (DI and II ratios) resulting in inverted u-shaped functions. In 21 of 36 instances (including reversals) the overall response rates were slowest during the ratio leading to delay when the previous ratio had resulted in an immediate reinforcer (ID ratios). Data from reversal conditions did not differ consistently from data in the original 8-s and 32-s delay conditions.

Figure 1.7 re-presents the same median overall response rates and interquartile ranges over the last 10 sessions of each condition for all hens. The overall response rates are plotted for each delay condition (excluding reversals) and for each ratio type. The two centre panels show that, in most cases, during DI and II ratios the overall response rates remained similar to those in the 0-s delay condition, and in some cases decreased with increasing delay. This was not to the same extent as during DD and ID ratios (the extreme left and right panels). In the ratio leading to a delayed reinforcer, the overall response rates decreased as the delay increased.

In sum, Figure 1.6 shows that the overall response rates were lower when a delay was signalled to be upcoming compared to when immediate reinforcement was signalled. Figure 1.7 shows that longer delays resulted in lower overall response rates when the delay was upcoming.

Blackout Pecks

Although details are not presented here (they are presented in Appendix 1), examination of the rates of blackout pecking showed that throughout all experimental conditions, rates of blackout pecking were very low (below one peck per reinforcer). The rate of blackout pecking did tend to increase as the delay increased.

Duration from Reinforcement to Ratio Completion

Although details are not presented here (they are presented in Appendix 1), examination of the durations from reinforcement to ratio completion showed that when no delay was upcoming, this duration remained constant across all delay

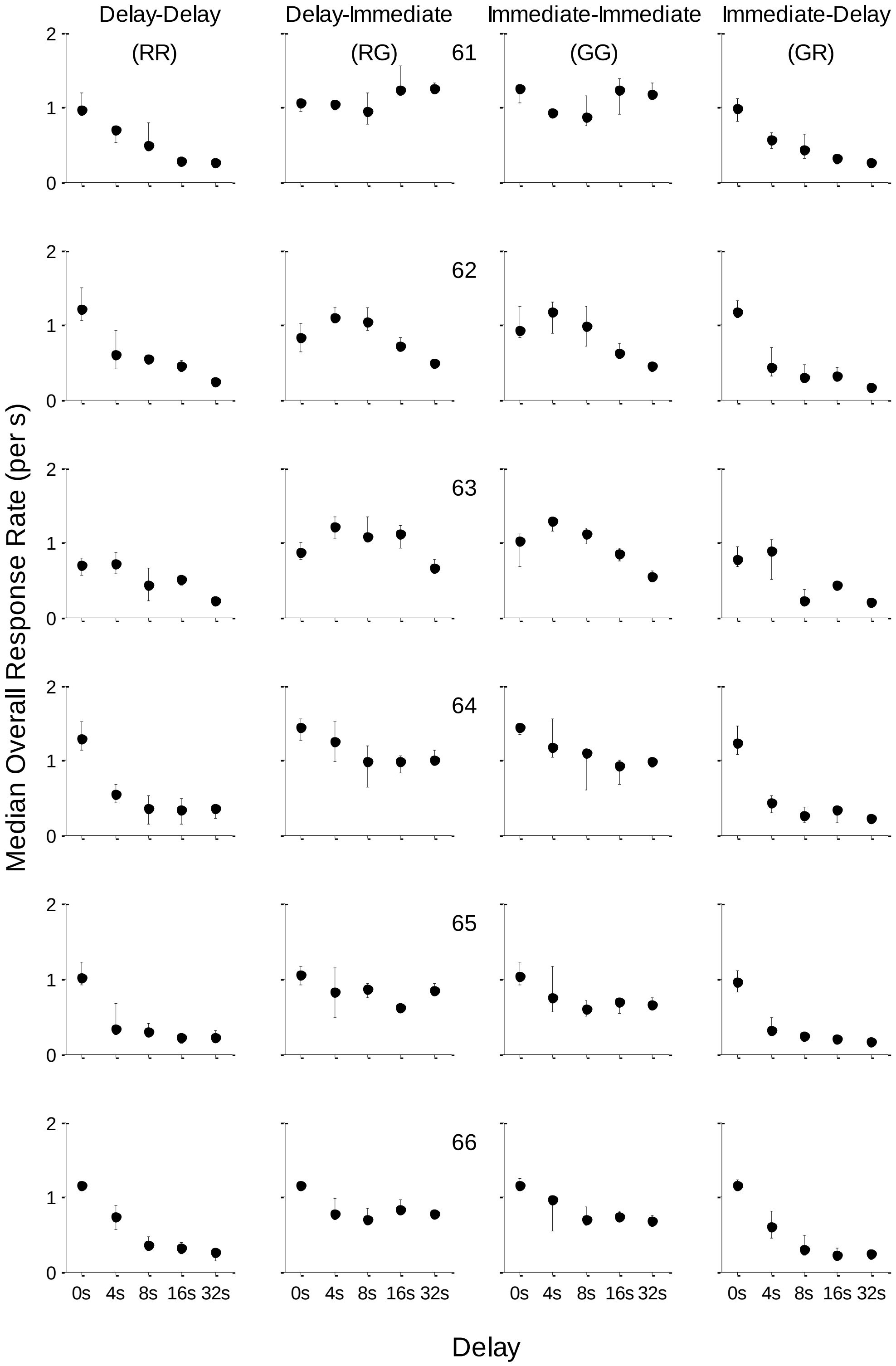

Figure 1.7. The median overall response rates (per s) plotted for each delay value (0 s, 4 s, 8 s, 16 s and 32 s), for all hens and ratio types [Delay-Delay or Red-Red (RR); Delay-Immediate or Red-Green (RG); Immediate-Immediate or Green-Green (GG); and Immediate-Delay or Green-Red (GR)].

conditions. When a delay was upcoming, this duration increased as the delay increased.

Discussion

The aim of the present experiment was to investigate the effects of varying delay-to-reinforcement in one FR component of multiple FR 5 FR 5 schedules on performance in that schedule. It was found that when the upcoming ratio had a delay-to-reinforcement signalled, the initial pause on that schedule was always longer than when the upcoming ratio had no delay. This adds to the evidence that pausing following reinforcement in FR schedules is more a function of signalled upcoming events than of recently completed events. This is in contrast to the older assumption that pausing in FR schedules is due to fatigue from the effort of completing the previous schedule (cf., Mintz et al., 1967).

Obviously the upcoming delay is a future event and cannot itself cause behaviour. The altered behaviour is a result of the history of reinforcement experienced by the subjects in the presence of each of the discriminative stimuli (Baum, 1994). For example, during Condition 1, reinforcers were delivered immediately in the presence of the both the red and green key lights. In Condition 2, reinforcers continued to be delivered immediately in the presence of the green key light, however, they were delayed by 4 s in the presence of the red key light. At the beginning of Condition 2, responding did not immediately become slower and pausing longer in the presence of the red key light. Behaviour changed in the presence of the different stimuli as the subjects gained more experience of the different contingencies. Therefore the pause length, although seeming to be a function of the upcoming delay, was actually a function of the subjects' history of responding in the presence of the stimulus signalling the delay.

As well as being more influenced by the upcoming ratio, the present experiment found that the durations of pausing following reinforcement became longer as the delay-to-reinforcement increased (Figure 1.3). This is in agreement with previous research investigating delay-to-reinforcement in FR schedules (Azzi et al., 1964; Morgan, 1972; Topping et al., 1973). The findings add to these data, in that they show that it is the upcoming delay and not the previous delay that is responsible for the increased pause duration.

In the present experiment, the response requirement was held constant at FR 5 in both components of the multiple schedules. Pauses preceding the first response in the component with the signalled delay increased as the delay duration became an increasing proportion of the total time to reinforcement. One possible prediction is that delay-to-reinforcement might have a lesser effect on behaviour at large FR values than at small FR values. This would be because the duration of the delay at, for example, FR 100 is a lesser proportion of the time it takes to complete the ratio than it would be at FR 1. It could be expected that if larger FR schedules were used in the multiple schedule, pausing following reinforcement may be less influenced by the delay durations that were used in this experiment. Further research is required to investigate whether or not this is so.

Previous research has found that the manipulation of ratio size, reinforcement magnitude, and the force requirement all have similar effects on pausing durations in multiple FR FR schedules of reinforcement (Baron & Herpolsheimer, 1999; Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz et al., 1967; Perone & Courtney 1992; Wade-Galuska et al., 2005). Durations of pausing increased when the upcoming reinforcer was of lesser magnitude, required greater force, or was delayed due to an increased ratio size. The present experiment has added delay-to-reinforcement as another parameter which affects pausing in multiple FR FR schedules. It would be interesting to extend this research using reinforcers of differing quality, a parameter of reinforcement that has also been found to influence behaviour under FR schedules (e.g., Foster et al., 2009). If the ‘unfavourable conditions’ analogue (cf., Wade-Galuska et al., 2005) holds, then pausing should be longer prior to an FR schedule delivering a less valued reinforcer. However, this prediction is in contrast to Foster et al.’s (2009) findings that the mean pauses following reinforcement were shorter for the less valued reinforcer across all FR values when single FR schedules were used.

Some previous multiple FR FR research (Baron & Herpolsheimer, 1999; Griffiths & Thompson, 1973; Mintz et al., 1967; Perone & Courtney, 1992, Wade-Galuska et al., 2005) has found that pausing may also be influenced, to a lesser extent, by the preceding ratio. The present experiment also found that pausing before the ratio with the delay-to-reinforcement tended to be longest (in 29 of 36 instances) when the preceding ratio had resulted in an immediate reinforcer (i.e., during an immediate-delay transition), although this effect was only small.

Overall, pausing durations in the multiple FR FR schedules here suggest that, although pausing is most influenced by events signalled to be upcoming, the preceding ratio also has some effect on pausing. Hence, the term ‘between-ratio pause’, suggested by Griffiths and Thompson (1973), may be the most descriptively accurate term.

Response rates in the present experiment were affected by the delay-to-reinforcement. Overall response rates decreased during ratios in which a delay was upcoming, and did so monotonically with increasing delay (Figures 1.6 and 1.7). Figure 1.4 shows that, in most cases, the running response rates during the ratio in which a delay was upcoming were lower than during those ratios in which there was no delay. Figure 1.5, however, shows that the presence of any delay lowered the running response rate, but that there did not appear to be any consistent effect of increasing delay. Running response rates decreased systematically with increasing delay for Hens 61 and 65 only. Similarly, Wade-Galuska et al. (2005) reported median running response rates that were lower when the ratio required a large force compared to when the ratio required a small force. Perone and Courtney (1992) reported median running response rates that were consistent with this finding for only one subject, being lower before the small reinforcer and higher before the large one. Response (overall and running) rates in most other multiple FR FR studies (Baron & Herpolsheimer, 1999; Crossman, 1968; Griffiths & Thompson, 1973; Inman & Cheney, 1974; Mintz et al., 1967) have not been reported.

Findings concerning changes in overall and running response rates from previous research investigating the effects of delay-to-reinforcement on performance in FR schedules are also mixed. With results similar to those of the present experiment, Azzi et al. (1964) found reduced overall rates of responding with increases in the delay when they used unsignalled resetting delays. Even though their results are similar to those of the present experiment, there are many methodological differences. It appears that Azzi et al. (1964) included the delay in their calculation of the overall response rates, meaning that even if the running response rates remained the same at each delay, the overall response rates would still decrease. Azzi et al. (1964) used unsignalled resetting delays, whereas the present experiment and other researchers used signalled non-resetting delays when investigating the effects of delay-to-reinforcement on behaviour in FR schedules. In contrast with the results of Azzi et al. (1964) and the present experiment, Morgan (1972) and Topping et al. (1973) reported no effect of signalled non-resetting delay on rates of responding. A number of factors may have given rise to the different results in the present experiment. Firstly, in each study, different delay durations and FR values were used. Morgan (1972) examined behaviour under three different delay values, and did not compare behaviour in these conditions to behaviour when there was no delay. Finally, Topping et al. (1973) provided no response rate data, they simply stated that response rates did not consistently vary with the duration of the delay. The running response rates in the present experiment did not change consistently with delay duration, but these rates were lower when there was any delay at all than when there was no delay. Similar conclusions may have been drawn had the data been reported by Morgan (1972) and Topping et al. (1973).

In the present experiment, reversal conditions were conducted after the 8-s and 32-s delay conditions. In these reversal conditions, the key colour signalling the upcoming component with a delay-to-reinforcement was changed from red to green. The reversal conditions were conducted because the red key had been associated with the delay-to-reinforcement increasing over conditions. Thus, the increase in pausing found with increasing delay could have been an order effect. However, when the delay signal was reversed, no consistent differences in pause durations were found when compared to the original conditions (Figure 1.2). Therefore, it is fair to conclude that the durations of pausing in the present experiment were a product of the delay and not a result of the effect of the simple order of conditions.

One problem found with the present experiment was that the stability criterion originally selected was very strict. The criterion was adapted from similar experiments conducted by Perone and Courtney (1992) and Baron and Herpolsheimer (1999). The criterion required visual stability over 10 days for all four pause length medians (one for each transition type) and for all six subjects. Statistical stability required 24 median pairs from the first and last five days to be within 15% of the overall medians of the 10. In most cases, although the subjects' pauses were close to statistical stability, visual stability was relied upon to change conditions. Typically, conditions were changed when the data were judged visually stable and approximately 20 (of 24) pairs of medians were statistically stable. In future experiments, the statistical stability criterion should be softened, or a rule adopted, such as that of Perone and Courtney (1992), where conditions were changed after a maximum of 50 sessions if stability had not been previously reached.

In their multiple FR FR experiment, Baron and Herpolsheimer (1999) called attention to the problem, elucidated by Sidman (1960), that averaging data may suggest regularities not present in the individual results. Except for Crossman (1968) and Inman and Cheney (1974), who did use means, the remaining researchers investigating multiple FR FR schedules (Baron & Herpolsheimer, 1999; Griffiths & Thompson, 1973; Perone & Courtney, 1992; Mintz et al., 1967; and Wade-Galuska et al., 2005) have described their data using a combination of cumulative records, cumulative frequency distributions, medians and interquartile ranges. Analysis of pausing distributions in the present experiment showed that the distributions were positively skewed with outliers (Figure 1.1). Therefore medians were used throughout the present experiment to summarise the pause durations and response rates. Medians were found to be a useful method of data analysis, which clearly showed trends, and were representative of the data.

In most previous studies investigating the between-ratio pause in multiple FR FR schedules, there are only a few subjects and data points. In three of the studies only two subjects were used (Crossman, 1968; Inman & Cheney, 1974 and Mintz et al., 1967), Baron and Herpolsheimer (1999) used three subjects, and Perone and Courtney (1992) and Wade-Galuska et al. (2005) each used four subjects. While Inman and Cheney (1974) and Wade-Galuska et al. (2005) both parametrically manipulated their respective parameters of reinforcement (FR and magnitude, and force), the remaining researchers did not parametrically manipulate the reinforcement parameter of interest. The present experiment prided a more extensive data set as it used six subjects, and parametrically varied the delay-to-reinforcement. Similarly to the present study, research that manipulated a parameter of reinforcement other than the ratio (Inman & Cheney, 1974; Perone & Courtney, 1992; and Wade-Galuska et al., 2005) used only one FR value (or in the case of Inman and Cheney only one set of multiple FR values) in which to do so. Therefore, although these findings hold for the FR value studied, they may not be representative of behaviour under all FR values. More research is needed in this area using more subjects and parametrically manipulating the reinforcement parameters of interest.

In sum, the present experiment found that the addition of a delay-to-reinforcement in one component of multiple FR 5 FR 5 schedules resulted in increased durations of pausing before the ratio in which the delay was signalled. Pause durations were found to increase monotonically with increases in the length of the delay-to-reinforcement. A small effect of the preceding ratio was also found, which suggests that although the upcoming ratio has a far larger effect, both ratios influence pausing in FR schedules. Thus, the term ‘between-ratio pause’ may be a better descriptor of pausing in FR schedules than the commonly used term ‘post-reinforcement pause’.

EXPERIMENT 2

As previously mentioned, in behavioural economic studies ‘price’ may be increased by increasing the FR requirement (Lea, 1978). The required ratio is changed, and the numbers of reinforcers obtained at each price (consumption) are graphed logarithmically as a function of the log schedule size to give the demand function (Lea, 1978). These procedures typically show a decrease in consumption as price (ratio) increases (Hursh, Raslear, Bauman & Black, 1989). It has been suggested that the slope of the demand function may be used to determine the importance of different reinforcers (Hursh, 1980). The slope reflects the elasticity of demand. A demand function with a slope less steep than negative 1.0 is said to show inelastic demand (Hursh, 1980). To maintain a relatively steady level of consumption and show inelastic demand, subjects would have to increase their rate of responding along with increases in price (Hursh, 1980; Hursh & Winger, 1995). Demand functions are said to be elastic when the slope is steeper than negative 1.0, and in such cases, the rate of responding declines rapidly with increases in price (Hursh, 1980).

The elasticity of a demand function for a commodity may not always remain the same across all prices. That is, the slope of a demand function may change from inelastic to elastic with increases in price (Hursh, 1984). This is termed mixed elasticity and results in curvilinear demand functions on log-log coordinates. Hursh (1984) pointed out that curvilinear demand functions or functions of mixed demand are common in animal experiments. Such data can be described by the following equation, as proposed by Hursh et al. (1988);

$$\ln Q = \ln L + b\,(\ln P) - a\,P \qquad (2.1)$$

where Q reflects total consumption (e.g., reinforcers obtained) per session, L estimates consumption at the minimal price (e.g., FR 1), b is the initial elasticity at the minimal price, P represents the price (with FR this is the response requirement), and a is a measure of the rate of change in elasticity across price increases (Hursh et al., 1988). In these functions, the FR value where demand changes from inelastic to elastic is termed P_{max} (Hursh et al., 1989). This may be determined from the equation;

$$P_{max} = (1 + b) / a \qquad (2.2)$$

where a and b are as defined in Equation 2.1. P_{max} reflects the FR value at which maximal responding occurs, and is a measure that is often used in the comparison of the value of different commodities. Inelastic demand to higher FR sizes will result in a larger value of P_{max} than elastic demand (e.g., Foster et al., 2009).

It has been argued that elasticity of demand may vary according the economic system used (Hursh, 1980). An economic system may be open or closed (Hursh, 1980). Within a closed economy, subjects have access to the commodity during experimental sessions only. If the commodity is food, then the subjects must obtain their entire daily food intake during the experimental session. Conversely, within an open economy, the subject may be given access to the commodity outside the experimental session (e.g., supplementary food to maintain body weight). Based on the results of a number of experiments using both open and closed economic conditions, Hursh (1980) argued that, for some commodities in closed economies, subjects may increase their rate of responding along with increases in the ratio in order to minimise changes in consumption, resulting in inelastic demand functions. He argued that for all commodities in open economies, subjects do not increase their rate of responding to maintain a relatively constant rate of consumption, resulting in elastic demand functions.

It has been argued, however, that such findings may be a consequence of other factors. Foster et al. (1997) pointed out that closed-economy experimental sessions are typically long, ensuring the subject is able to obtain all of the food it requires, while open-economy sessions are often short, resulting in the subject requiring supplementary food. Foster et al. (1997) examined demand for food in hens in open and closed economies. The hens were maintained at 80% of their free-feeding body weights through supplementary food during open economies. In closed-economy sessions, the hens obtained their entire daily food intake within both long and short experimental sessions. In concurrence with previous findings, demand was elastic during open-economy sessions and inelastic during long (24-hr) closed-economy sessions. However, demand was elastic during short (40-min) closed-economy sessions, leading to Foster et al.'s (1997) suggestion that session length may be more influential on demand than economy type.

When comparing differences between the analysis of their own data and that of Barofsky and Hurwitz (1968), Foster et al. (1997) pointed out one potential source of difference between results found. Traditionally, when food is delivered to an animal, like a pellet to a rat or the operation of a magazine, the time spent consuming the food is included in the session time. This eating time can reduce the time available for responding in the session. If the sessions are short and the FR value is small this may be a large proportion of the session. As the FR increases, the proportion of the session in which the magazine is operating decreases, and time available for responding increases. This means that the session time available for responding varies with the ratio requirement. To ensure that response time is constant across all values of FR, some researchers have a fixed total time across all experimental conditions that excludes magazine operation time (e.g., Foster et al., 2009; Green, Kagel & Battalio, 1987; McSweeney & Swindell, 1999). Such an arrangement eliminates one possible confound in experiments in which FR schedules are varied in short sessions.

Dawkins (1988) proposed that by measuring how hard an animal will work for access to a commodity (demand), it may be possible to determine the importance of that commodity to the animal. The assessment of demand may be a way in which to determine the relative importance of different commodities (Dawkins, 1983). Demand for commodities such as food can be expected to show inelastic demand which suggests the commodity is a ‘necessity’. Demand that is more elastic may indicate that the commodity is a ‘luxury’. For example, Matthews and Ladewig (1994) investigated environmental requirements of pigs, and found demand was highly inelastic for food, but not as inelastic for social contact. This suggests that food may be relatively more important than social contact.

Dawkins (1983) suggested that a behavioural investigation of an animal’s welfare should include the assessment of the animal’s ‘needs’ using demand, and also the assessment of the animal’s likes and dislikes, using a choice situation (preference). Some recent research has been aimed at determining whether an animal’s preference for a commodity influences the shape of the demand function. It would be expected that animals would work harder for commodities that are preferred (chosen more in a choice situation) as opposed to commodities that are less preferred (chosen less in a choice situation).

As previously mentioned, several studies have investigated how demand and responding under FR schedules changes when hens are presented with reinforcers of differing magnitudes or qualities (e.g., Bruce, 2007; Foster et al., 2009; Grant, 2005). In these studies, the hens showed response biases under concurrent schedules away from the foods of lesser qualitative value (Bruce, 2007; Foster et al., 2009) and smaller reinforcer duration (Grant, 2005), indicating that these foods were less preferred. While it might have been expected that preferred reinforcers would result in higher levels of consumption at all FR values tested, this was not the case. Paradoxically, it was found that the numbers of reinforcers obtained at small FR values were greater for foods of lesser qualitative value (Bruce, 2007; Foster et al., 2009) and smaller reinforcer duration (Grant, 2005). Demand functions were fitted to the data using Hursh et al.'s (1988) nonlinear equation. In contrast with the findings at small FRs, the foods of lesser quality and magnitude were found show to more elastic initial demand, larger rates of change of elasticity, and smaller P_{max} values, all indicating more elastic demand. Foster et al. (2009) suggested that these seemingly opposing findings highlight a problem when comparing the demand functions of different commodities.

In one attempt to address problems when comparing the demand functions of different commodities, Hursh and Winger (1995) suggested a normalisation process to allow the direct comparison of the demand functions for different drugs. The authors defined a reference consumption level as the numbers of reinforcers obtained at the lowest price. This reference level "is 'defended' under the challenge of increasing prices or effort" (Hursh & Winger, 1995 p. 377). Consumption at all other FR values was then normalised in terms of this. They then compared their method of normalisation to a unit price analysis, which is a cost-benefit ratio that presents the cost of a commodity as the effort required for a particular amount of each reinforcer. The resulting demand functions were similar for both the normalisation and unit price approaches. However, Hursh and Winger (1995) suggested that their normalisation approach may be better than the unit price technique because, rather than being decided by the experimenter, it is based on comparison with total consumption as obtained by the subject.

Whether the demand functions of different commodities are standardised using a unit price analysis or Hursh and Winger's (1995) normalisation technique, it still may be difficult to assess which commodity is more highly 'valued' by the subject. When, as found by Foster et al. (2009), the various parameters ($\ln L$, a, b and P_{max}) of the functions of each commodity are conflicting, it is difficult to determine which of the parameters are more important or influential in determining 'value'. More recently than Hursh and Winger (1995), with the aim of ordering the values of different commodities, Hursh and Silberberg (2008) suggested an alternate equation to the Hursh et al. (1988) equation to describe demand functions;

$$\ln Q = \ln Q_0 + k\,(e^{-\alpha P} - 1) \qquad (2.3)$$

Expressed in natural logarithms, in this exponential equation, the parameter Q_0 is comparable to the L parameter in Equation 2.1, estimating the highest level of consumption at the minimal price, while P and Q are as in Equation 2.1. The parameter k specifies the range of consumption, and α, the rate constant, denotes how consumption changes as the price increases. According to Hursh and Silberberg (2008) the parameter k is simply a scaling parameter and when set to the same constant across comparisons, changes in elasticity may be determined by changes in the parameter α. An increase in α reflects increasing elasticity, and a decrease in 'value' to the subject. Hursh and Silberberg (2008) refer to α as indicating the 'essential value' of a commodity. In an electronic tool referenced in the paper, Hursh suggests two ways of obtaining the value of k that may then be used for fitting all of the functions in a data set, allowing for comparison of the functions and of the parameter α. The first is by selecting the maximum range of consumption that occurred in any of the data sets to be compared, while the second is to select the mean range of consumption. Unfortunately, no clear indication is given as to how one would select one or the other method. It is desirable, however, to have a singular parameter to reflect the 'value' of a commodity as this will reduce difficulties of conflicting parameters in interpreting the 'value' of the commodity tested.

Hursh and Silberberg (2008) argued that their exponential equation is superior to the Hursh et al. (1988) nonlinear equation, in that it is similarly descriptively adequate and has the advantage of only one single measure reflecting value. The authors reported good and logically sensible fits to their exponential equation when they reanalysed previous data (Giordano, Bickel, Shahan & Badger, 2001; Jacobs & Bickel, 1999; Peden & Timberlake, 1984). Hursh and Silberberg (2008) concluded that the parameter α represents the 'essential value' of a reinforcer and is the best way in which the compare the 'value' of different reinforcers. Other studies have since reported that the exponential model suitably described their own data, and reflected the 'values' of different reinforcers (e.g., Christensen, Kohut, Handler, Silberberg & Riley, 2009; Christensen, Silberberg, Hursh, Huntsberry & Riley, 2008).

Foster et al. (2009) analysed their results using Hursh and Silberberg's (2008) equation, and found that α was smaller for puffed wheat than wheat for all subjects. This indicates that puffed wheat, the food of lowest qualitative value, was the food of highest essential value, and contrasts with the concurrent data in which wheat was found to be more highly preferred than puffed wheat. Again, these results seem to contain a paradox in that essential value (measured through α) was highest for the least preferred food. As previously mentioned, investigating the effect of delay-to-reinforcement on FR performance and the assessment of demand may help to clarify these findings.

Given that a delay-to-reinforcement is a way of changing the value of the schedule outcome, it might be expected that an increase in delay-to-reinforcement would also result in an increase in α and thus a decrease in essential value. Because the food delivered was the same at all delay values, the only difference was the duration between the final FR response and the delivery of this food. Adding a delay-to-reinforcement as a means of devaluing the reinforcer eliminates any possible confounding effects of differing reinforcer magnitudes.

Experiment 1 used a small FR schedule (FR 5) in multiple schedules, and found that response rates were faster and that pauses were shorter before reinforcers that were signalled to be delivered immediately, compared to before reinforcers that were signalled to be delayed. The data from Experiment 1 most likely to be predictive of findings if a delay were added to a single FR schedule (and the FR varied) come from consideration of same schedule transitions (immediate-immediate and delay-delay transitions). Response rates were faster and pauses shorter during II transitions than DD transitions. Therefore, it could be expected that with small FR values response rates would be faster and pauses shorter (and the thus total consumption higher) if there was no delay than if there was a delay. If a reinforcer that is delayed is analogous to a reinforcer of smaller magnitude or lesser quality, this prediction is in clear contrast to the findings of Bruce (2007), Foster et al. (2009) and Grant (2005).

The findings from Perone and Courtney's (1992) study examining the effects of differing reinforcement magnitudes on responding and pausing under FR 80 schedules are parallel to those from Experiment 1 if the same analogy holds. However, their findings are somewhat similar to those of Bruce (2007), Foster et al. (2009) and Grant (2005) when the FR value investigated is considered. The latter authors reported that initial levels of consumption were larger (and response rates faster) for the reinforcer of smaller magnitude or lesser quality only across small FR values. Examples of cumulative records from Foster et al. (2009) demonstrate that while responding across small FRs was faster for the reinforcer of lesser quality, at FR 64 this finding reversed and responding was faster for the reinforcer of greater quality (analogous to Perone and Courtney's finding).

However, there is still a discrepancy between the findings of Perone and Courtney (1992) and Foster et al. (2009), in that Foster et al. (2009) found pausing to be consistently longer for the reinforcer of greater quality across all FR values. Grant's (2005) data also show that pauses were longer across most FR values for the reinforcer of greater magnitude. Overall it remains unclear as to the effect delay-to-reinforcement would be expected to have on behaviour under increasing FR schedules.

The aim of the present study was to investigate the effect of delay-to-reinforcement on FR performance and hens' demand for food and, thus, extend research previously conducted with other parameters of reinforcement. As previously mentioned, research indicates that the manipulation of food magnitude and quality have similar paradoxical effects on both initial demand and overall elasticity of demand (Bruce, 2007; Foster et al., 2009; Grant, 2005). Some researchers have suggested that varying delays-to-reinforcement might affect behaviour in the same way as varying magnitude and quality (e.g., Davison & Baum, 2007). Further, in Experiment 1, increasing delay was found to have similar effects on behaviour as increasing ratio requirement and decreasing reinforcer magnitude.

Based on previous data two different outcomes are possible. First, by analogy with the demand experiments that found a higher rate of consumption for reinforcers of lower value (Foster et al., 2009, Grant 2005, and Bruce, 2007), it might be expected that consumption of more delayed reinforcers should be greater at small FR values than consumption of reinforcers that are not delayed or are less delayed. It might also be expected that consumption would fall sooner, that is, the demand functions would be more elastic, and that P_{max} would be smaller for reinforcers with a larger delay. However, based on the previous research on delayed reinforcers, such results would not be expected. Previous research has found increasing delay-to-reinforcement to increase the between-ratio pause durations and reduce response rates in FR schedules (Azzi et al., 1964; Experiment 1 in this thesis). Therefore, the second possible outcome is based on these findings. These findings suggest that for a reinforcer with a delay, consumption might be reduced across all FR values, including the smallest, compared with consumption of one with no delay. Also, the larger the delay the larger this effect would be. Additionally, if the increasing delay reduces the value of the outcome, then Hursh and Silberberg's (2008) equation should give larger values of α and, thus, indicate lower essential value for reinforcers with larger delays.

Method

Subjects

Six Shaver-Starcross domestic hens (Gallus domesticus), numbered 11 through 16, served as subjects. At the start of the experiment, all hens were one year old, and had previous experience on simple schedules of reinforcement. The hens were individually housed in home cages (500-mm long × 510-mm wide × 420-mm high), in a ventilated room that was lit on a 12 hr light: 12 hr dark cycle. The hens had free access to water, and were provided with grit and vitamins weekly. Throughout the experiment all hens had red fleshy combs suggesting good health. Each hen was weighed every day or every second day (days when experimental sessions took place), and they were maintained at 80% (+/–5%) of their free-feeding body weights through the supplementary feeding of commercial layer pellets.

Apparatus

The apparatus was a particleboard experimental chamber (640-mm long × 450-mm wide × 540-mm high), located in a room with several other operant chambers. The floor of the chamber was covered with a Leisuregrass (artificial grass by Astroturf) mat. A food magazine was located on the right-hand wall of the chamber behind an opening (120-mm high × 85-mm wide) that was centred 85 mm above the floor. When in operation, the magazine was lit and raised to allow 3-s access to wheat. The magazine was resting on a BH-3000 High Precision Balance scale (manufactured by Excell Precision Co ltd.). A frosted transparent plastic response key (30 mm in diameter) was lit white when operational, with a 28-V single chip LED bulb. The response key was 120 mm above the magazine opening, 365 mm from the floor of the chamber and required a minimum response force of approximately 0.2 N, resulting in an audible beep.

All experimental events were recorded and the experiment was controlled by a Dell PC computer (1.6GHz, P4, 256MB, Windows XP Service Pack 2) running Med-PC® IV software. At the end of each session, total session data were also manually recorded into a data book.

Procedure

In a series of conditions, the hens responded to gain 3-s access to wheat following a range of delay values (0 s, 4 s, 8 s, 16 s and 32 s) under increasing FR schedules. The first FR value in any series was FR 1 and the ratio requirement was doubled each session until no reinforcers were received. This FR value was re-presented in a second session, and if no reinforcers were obtained, the series was deemed to have ended. Preceding each series the hens responded on an FR 20 schedule of reinforcement and the delay relevant to that condition for at least three sessions (e.g., between each series of FR increases in the 0-s delay conditions, each hen was exposed to three sessions of FR 20 with no delay-to-reinforcement).

Training. As all hens had previous experience on simple schedules of reinforcement approximately six-months prior to the start of the present experiment, only one short (approximately 20 min) session of training was required during which the hens responded on an FR 20 schedule of reinforcement.

Experimental Conditions. In the experiment proper, sessions lasted for a total of 40-min key time (total session time less reinforcer time and delay time), ensuring that the available period of time in which the hens could respond was the same regardless of the duration of the delay. For each hen, experimental sessions were conducted every day, every second day, or every third day. At small FR values sessions were conducted every second day because the large numbers of reinforcers obtained at these FR values increased session length. In the 0-s delay conditions, experimental sessions were conducted every second day until the mean numbers of reinforcers obtained across all hens were less than 100. Once the numbers of reinforcers obtained were fewer than 100, experimental sessions took place daily. During the 4-s delay conditions, the mean numbers of reinforcers obtained were reduced to 80, as the delay durations further extended session lengths. Throughout the 8-s and 16-s delay conditions, sessions occurred every second day because the long delay durations increased session lengths substantially. During the 32-s delay condition, sessions occurred every third day until the mean numbers of reinforcers obtained were fewer than 70, and then occurred every second day. Table 2.1 presents the sequence of conditions and the break points (highest FR value at which at least one reinforcer was obtained) from each series for each hen.

On occasion, eggs were laid in the chamber during experimental sessions, resulting in variable data. This is because egg laying can occupy a considerable portion of the experimental session, resulting in less responding and atypical data. Data from sessions in which eggs were laid were removed.

Table 2.1.

The order of experimental conditions, together with the highest FR schedule completed in each series of each condition for each hen. A highest FR value of 128 indicates eight sessions (256 indicates nine, 512 indicates 10 and 1024 indicates 11) in which a minimum of one reinforcer was obtained and at least two more in which no reinforcers were obtained.

Order of			Hen					
Conditions	Delay	Series	11	12	13	14	15	16
Condition 1	0-s	1	512	512	512	256	256	256
		2	512	512	512	256	512	512
		3	512	512	1024	512	256	512
		4	1024	512	512	512	512	512
Condition 2	4-s	1	512	1024	512	512	512	256
		2	512	1024	1024	512	1024	1024
		3	512	512	1024	512	1024	1024
Condition 3	8-s	1	512	1024	1024	256	1024	1024
		2	1024	1024	1024	512	1024	1024
		3	512	1024	1024	1024	1024	1024
Condition 4	0-s	1	512	1024	1024	512	1024	1024
		2	1024	1024	1024	512	1024	512
Condition 5	16-s	1	512	1024	512	512	1024	512
		2	512	512	512	512	1024	512
		3	512	512	512	256	1024	512
Condition 6	0-s	1	512	512	256	256	512	512
		2	512	512	512	256	1024	256
Condition 7	4-s	1	512	512	256	512	1024	1024
		2	512	512	256	256	512	512
Condition 8	32-s	1	512	1024	128	256	1024	512
		2	512	1024	256	256	1024	512

Data collected and recorded in the data book for each session included the FR size, delay length, time to first response, total numbers of responses and numbers of reinforcers obtained. Also recorded was the between-ratio pause time, run time, key time, total session time, mean eating time (time head was in magazine during reinforcer access), the amount of wheat consumed and the amount of post feed (if required, based on the numbers of reinforcers received). Computer files were generated which contained all experimental events and their time of occurrence.

Results

Data from all series and conditions were analysed and are presented in Appendix 2 along with the raw data. No systematic differences were found between series or replications of the various conditions and therefore two series in each condition were averaged using the mean to present all of the following: demand functions, overall response rates, running response rates and between-ratio pause durations. In Condition 1, data from the third series contained many days in which eggs were laid in the chamber, and so were discarded. With this proviso, the data from the last two series in each condition were averaged. When there were replications of conditions (0-s and 4-s), these means were further averaged. In each case the breakpoint (largest FR value reached) was taken as the smallest reached in each condition. In all figures, delay time was excluded from the analysis of behaviour, in order to determine the effect of differing delays on behaviour during response time.

Hursh et al. (1988) Nonlinear Demand Functions

Presented in Figure 2.1 are the natural logarithms of the consumption data (the numbers of reinforcers obtained at each FR value in each session of 40-min key time) for each hen and for each condition. The lines were fitted to the data using Hursh et al.'s (1988) nonlinear equation (Equation 2.1), nonlinear regression, and the method of least squares. The parameters of these lines are displayed in Table 2.2, together with the variances accounted for by the lines (*%VAC*), the standard errors of the line estimates (*se*) and the FR value at which maximal responding is predicted (P_{max}, as calculated by Equation 2.2). The lines fitted to the consumption data accounted for over 90% of the variance in all 30 cases, and the *se* measures ranged from 0.12 to 0.40. In all cases, consumption decreased as the FR increased and the functions showed that demand was curvilinear.

For all hens, the largest initial demand (ln L values) occurred in the 0-s delay condition and the smallest always occurred in the 32-s delay condition. There were no other consistent patterns across all six hens. For only Hen 12 did ln L values decrease systematically with increasing delay. For three of six hens the ln L values in the 8-s delay condition were the largest after those in the 0-s delay condition. Apart from three hens having the smallest initial slopes (b values) and largest values of P_{max} in the 8-s delay condition, there were no other

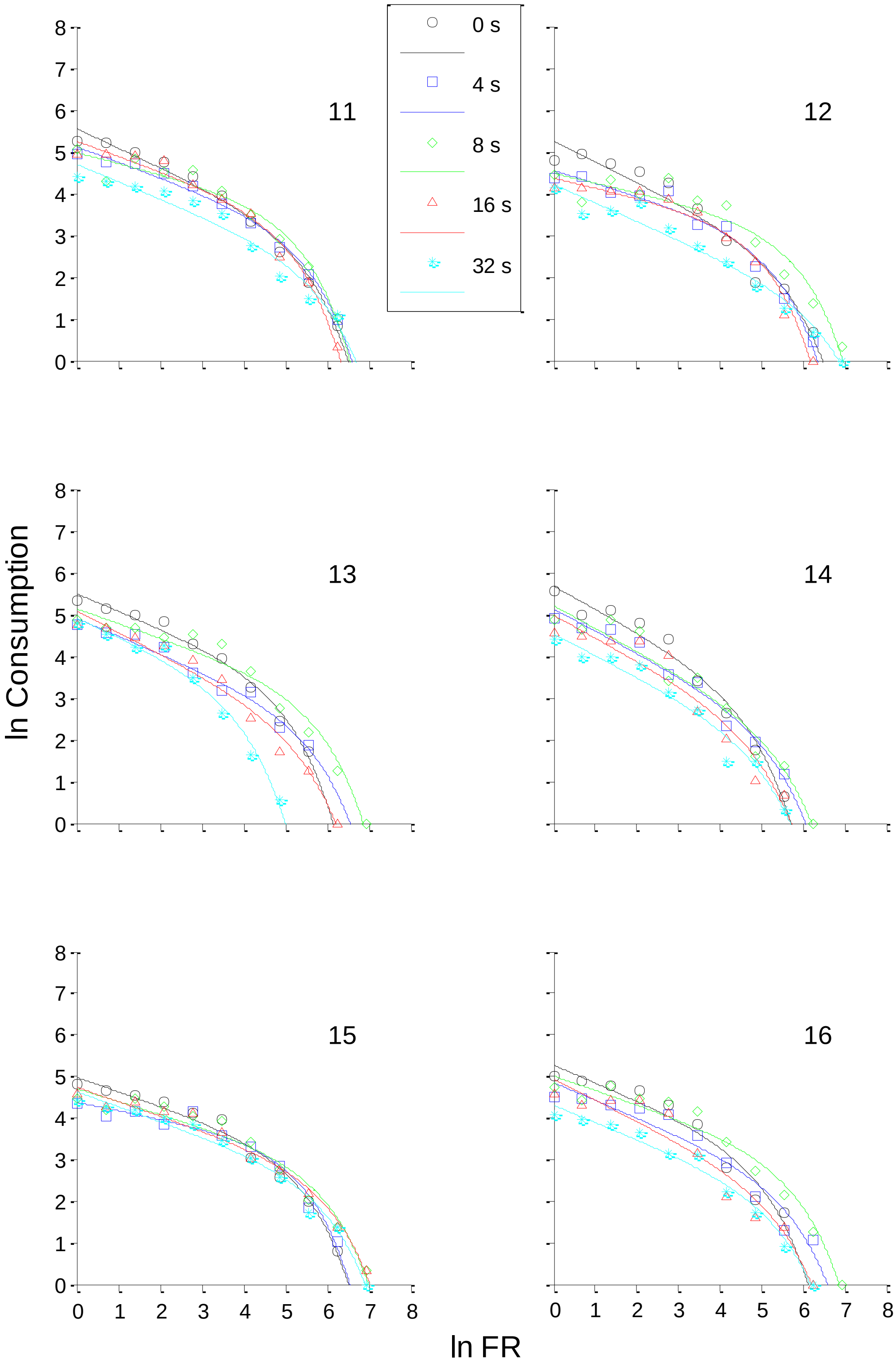

Figure 2.1. The natural logarithms of the consumption data, plotted against the natural logarithms of the FR size for each delay condition and each hen. The data are means of the series of each delay condition. The lines were fitted using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

Table 2.2.

The parameters a, b and ln L for Hursh et al.'s (1988) nonlinear equation (Equation 2.1) fitted to the natural logarithms of the mean consumption data from all delay conditions. Also shown are the standard errors of the estimates (se), the percentages of variance accounted for by the lines (%VAC) and the FR values at which maximal responding is predicted (P_{max}).

Hen	Delay	ln *L*	*b*	*a*	*se*	*%VAC*	P_{max}
11	0 s	5.57	-0.46	0.003904	0.16	98.75	139
11	4 s	5.14	-0.37	0.003759	0.12	99.14	169
11	8 s	5.00	-0.26	0.004808	0.23	96.38	155
11	16 s	5.27	-0.35	0.005476	0.19	98.38	118
11	32 s	4.71	-0.41	0.002482	0.25	95.42	237
12	0 s	5.29	-0.49	0.003268	0.30	95.74	155
12	4 s	4.57	-0.30	0.004706	0.21	97.40	149
12	8 s	4.51	-0.23	0.002758	0.34	93.43	279
12	16 s	4.39	-0.23	0.006232	0.21	97.60	124
12	32 s	4.24	-0.44	0.001275	0.22	97.12	438
13	0 s	5.51	-0.41	0.006495	0.14	98.65	91
13	4 s	4.92	-0.42	0.003105	0.16	97.42	187
13	8 s	5.15	-0.35	0.002886	0.27	97.04	226
13	16 s	5.10	-0.51	0.003969	0.23	97.77	124
13	32 s	4.94	-0.44	0.018620	0.19	98.15	30
14	0 s	5.71	-0.54	0.008679	0.24	97.80	53
14	4 s	5.16	-0.52	0.004647	0.21	97.36	103
14	8 s	5.24	-0.54	0.003780	0.32	96.01	121
14	16 s	5.01	-0.54	0.006477	0.40	92.74	71
14	32 s	4.56	-0.51	0.005624	0.26	96.22	87
15	0 s	4.97	-0.34	0.004124	0.17	98.27	160
15	4 s	4.37	-0.19	0.004495	0.18	97.01	179
15	8 s	4.70	-0.30	0.002392	0.25	96.54	292
15	16 s	4.73	-0.34	0.002080	0.18	98.14	317
15	32 s	4.62	-0.35	0.002175	0.17	98.51	297
16	0 s	5.28	-0.42	0.005960	0.28	94.66	98
16	4 s	4.86	-0.42	0.002903	0.30	94.19	200
16	8 s	5.02	-0.34	0.002768	0.27	96.77	238
16	16 s	4.94	-0.50	0.003744	0.37	94.29	135
16	32 s	4.31	-0.41	0.003754	0.18	98.09	158

consistent patterns across increasing delays in the *b* values, rate of change of elasticity (*a* values) or P_{max} values.

Hursh and Silberberg (k set as mean consumption data)

Re-presented in Figure 2.2 are the consumption data from Figure 2.1, however, this time the lines shown were fitted using Hursh and Silberberg's (2008) exponential equation (Equation 2.3). The *k* value was obtained (as suggested by Hursh in the electronic tool referenced in the 2008 paper) by averaging the sums of all of the consumption data, and adding 0.2 to this figure, resulting in a *k* value of 3.48. The parameters of these lines, ln Q_0 (initial consumption) and α (essential value), are presented in Table 2.3, together with *%VAC, se,* and P_{max}. The lines fitted to the consumption data accounted for over 90% of the variance in all 30 cases, and *se* ranged from 0.04 to 0.46. The *k* value used is smaller than the range of the consumption found for many of the data sets. This means that the bottom asymptotes are too high and results in the functions not describing the data well at the larger FR values. This also means the functions predict constant consumption with further FR increases.

For all six hens, ln Q_0 was largest in the 0-s delay condition, and for five of six hens, smallest in the 32-s delay condition. For two hens (Hens 12 and 16), ln Q_0 decreased systematically with increasing delay. For five hens, α was smallest in the 8-s delay condition, and second smallest for the remaining hen. For five hens, α was largest in the 32-s delay condition, and second largest for the remaining hen. This indicates that the 32-s delay condition and 8-s delay condition produced the lowest and highest essential demand, respectively. For all six hens P_{max} was largest in the 8-s delay condition and for four hens P_{max} was smallest in the 0-s delay condition.

Hursh and Silberberg (k set as largest consumption data)

Re-presented again in Figure 2.3 are the consumption data from Figures 2.1 and 2.2. Again, the lines have been fitted using Hursh and Silberberg's (2008) exponential equation (Equation 2.3), however, in this case the *k* value was obtained (again, as suggested by Hursh in the electronic tool referenced in the 2008 paper) by taking the largest consumption data value, and adding 0.5 to this figure, resulting in a *k* value of 6.08. The parameters of these lines, ln Q_0 and α, are presented in Table 2.4, together with *%VAC, se,* and P_{max}. The lines fitted to the consumption data accounted for over 90% of the variance in 22 of 30 cases,

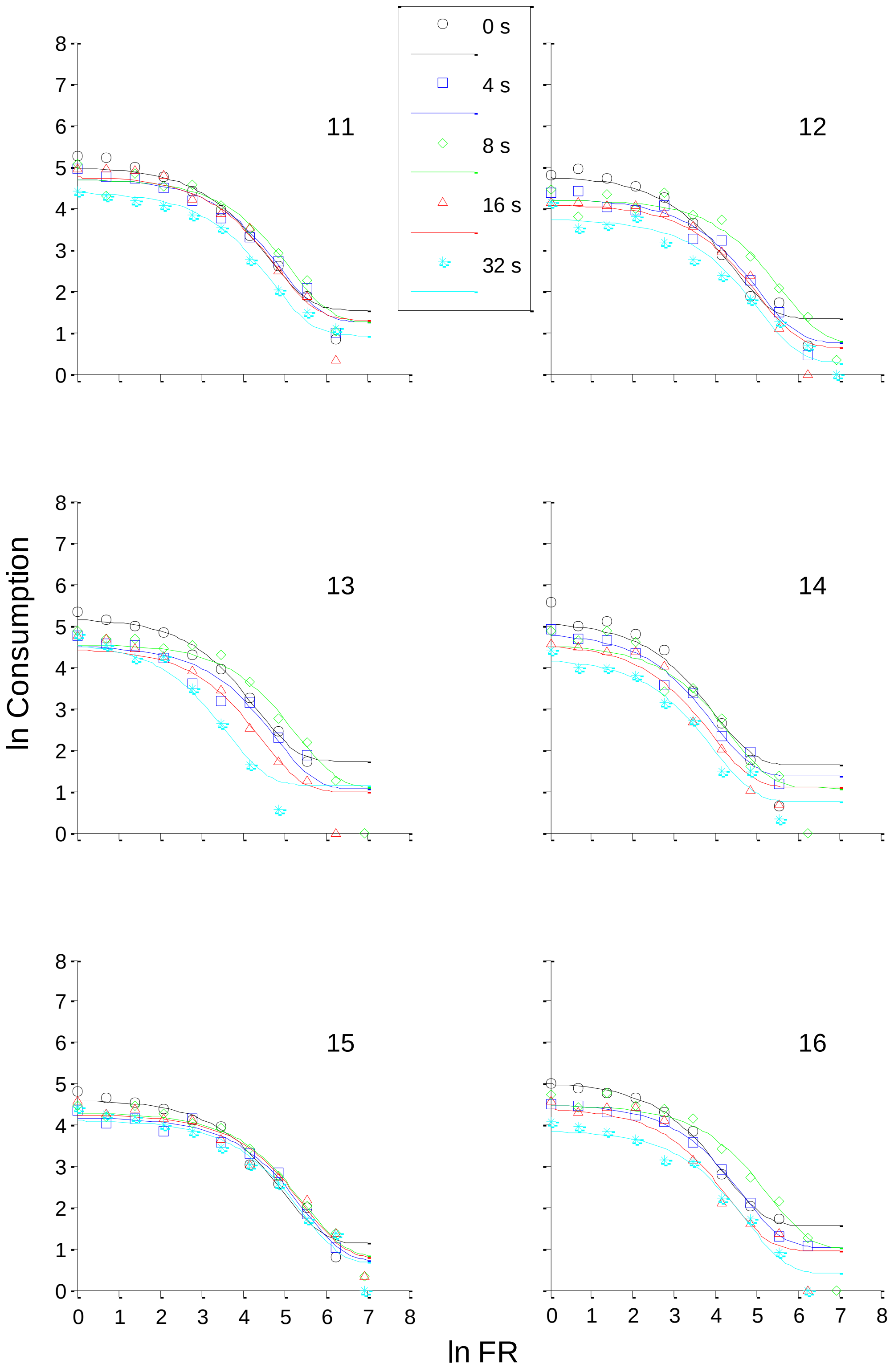

Figure 2.2. The natural logarithms of the consumption data, plotted against the natural logarithms of the FR size for each delay condition and each hen. The data are means of the series of each delay condition. The lines were fitted using Hursh and Silberberg's (2008) exponential equation (Equation 2.3) with a *k* value of 3.48.

Table 2.3.

The parameters ln Q_0 and α for Hursh and Silberberg's (2008) exponential equation (Equation 2.3) using a k value of 3.48, fitted to the natural logarithms of the mean consumption data from all delay conditions. Also shown are the standard errors of the estimates (se), the percentages of variance accounted for by the lines (%VAC) and the FR values at which maximal responding is predicted (P_{max}).

Hen	Delay	ln Q_0	α	*se*	*%VAC*	P_{max}
11	0 s	5.02	0.000066	0.28	96.42	15
11	4 s	4.73	0.000064	0.20	97.49	20
11	8 s	4.72	0.000052	0.24	96.23	26
11	16 s	4.78	0.000068	0.36	94.07	18
11	32 s	4.41	0.000111	0.11	99.17	16
12	0 s	4.80	0.000101	0.24	97.23	12
12	4 s	4.23	0.000096	0.21	97.23	23
12	8 s	4.22	0.000054	0.25	96.30	41
12	16 s	4.11	0.000107	0.27	96.12	23
12	32 s	3.75	0.000150	0.25	96.33	23
13	0 s	5.21	0.000074	0.12	99.07	11
13	4 s	4.53	0.000093	0.30	90.81	17
13	8 s	4.57	0.000051	0.38	94.05	30
13	16 s	4.47	0.000136	0.36	94.83	13
13	32 s	4.62	0.000267	0.30	95.65	6
14	0 s	5.11	0.000115	0.41	93.46	8
14	4 s	4.84	0.000151	0.18	97.91	8
14	8 s	4.56	0.000132	0.46	92.03	12
14	16 s	4.58	0.000207	0.26	96.79	7
14	32 s	4.22	0.000280	0.25	96.39	8
15	0 s	4.60	0.000072	0.21	97.31	21
15	4 s	4.17	0.000066	0.14	98.35	35
15	8 s	4.29	0.000058	0.19	97.96	35
15	16 s	4.25	0.000060	0.25	96.44	35
15	32 s	4.11	0.000075	0.27	95.98	33
16	0 s	5.04	0.000097	0.07	99.70	10
16	4 s	4.51	0.000105	0.04	99.88	16
16	8 s	4.47	0.000056	0.36	94.55	30
16	16 s	4.42	0.000158	0.37	94.20	11
16	32 s	3.87	0.000180	0.21	97.54	17

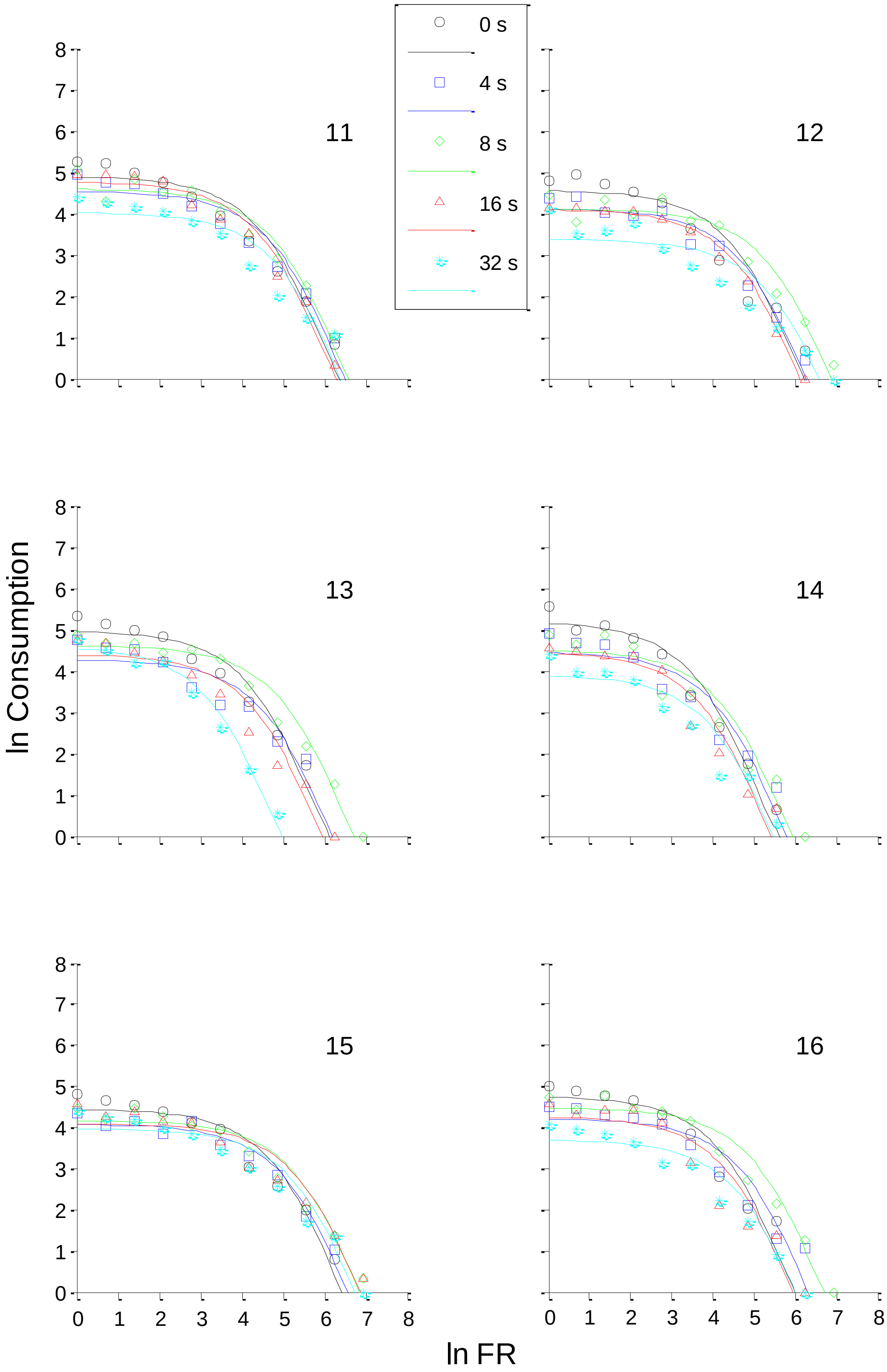

Figure 2.3. The natural logarithms of the consumption data, plotted against the natural logarithms of the FR size for each delay condition and each hen. The data are means of the series of each delay condition. The lines were fitted using Hursh and Silberberg's (2008) exponential equation (Equation 2.3) with a *k* value of 6.08.

Table 2.4.

The parameters ln Q_0 and α for Hursh and Silberberg's (2008) exponential equation (Equation 2.3) using a k value of 6.08, fitted to the natural logarithms of the mean consumption data from all delay conditions. Also shown are the standard errors of the estimates (se), the percentages of variance accounted for by the lines (%VAC) and the FR values at which maximal responding is predicted (P_{max}).

Hen	Delay	ln Q_0	α	*se*	*%VAC*	P_{max}
11	0 s	4.91	0.000021	0.37	93.41	36
11	4 s	4.55	0.000022	0.33	93.16	49
11	8 s	4.62	0.000019	0.28	94.76	52
11	16 s	4.79	0.000024	0.27	96.73	35
11	32 s	4.04	0.000032	0.44	86.26	56
12	0 s	4.59	0.000029	0.47	89.33	36
12	4 s	4.13	0.000035	0.27	95.49	47
12	8 s	4.14	0.000019	0.31	94.30	87
12	16 s	4.12	0.000041	0.14	98.99	41
12	32 s	3.38	0.000038	0.52	84.05	91
13	0 s	4.99	0.000026	0.31	93.38	27
13	4 s	4.29	0.000035	0.40	83.69	40
13	8 s	4.63	0.000017	0.29	96.56	59
13	16 s	4.43	0.000041	0.42	93.02	30
13	32 s	4.62	0.000099	0.21	97.79	10
14	0 s	5.21	0.000039	0.32	96.01	15
14	4 s	4.48	0.000046	0.44	88.07	25
14	8 s	4.53	0.000039	0.50	90.39	28
14	16 s	4.48	0.000066	0.45	90.65	17
14	32 s	3.92	0.000087	0.45	88.81	23
15	0 s	4.44	0.000025	0.31	93.85	49
15	4 s	4.08	0.000027	0.21	96.17	65
15	8 s	4.17	0.000019	0.32	94.30	83
15	16 s	4.10	0.000020	0.37	92.20	88
15	32 s	3.97	0.000024	0.37	92.64	82
16	0 s	4.76	0.000032	0.37	90.45	27
16	4 s	4.21	0.000032	0.44	88.01	48
16	8 s	4.48	0.000019	0.32	95.64	63
16	16 s	4.26	0.000045	0.51	89.13	32
16	32 s	3.70	0.000059	0.36	92.65	44

and *se* ranged from 0.14 to 0.51. Here, the value of k is larger than the previous analysis and results in the lower asymptote occurring off the graph. Thus the functions better describe the larger FR data, but also consistently miss at the smaller FR values.

The only consistent pattern was that for all six hens, ln Q_0 was largest in the 0-s delay conditions, and for five of six hens, smallest in the 32-s delay condition. For four hens, α was smallest in the 8-s delay condition, and second smallest for a fifth hen. For five hens, α was largest in the 32-s delay condition, and second largest for the remaining hen. Again, this indicates that the 32-s delay condition and 8-s delay condition produced the lowest and highest essential demand, respectively. For three of six hens P_{max} was largest in the 8-s delay condition and for four hens P_{max} was smallest in the 0-s delay condition.

Overall, all three figures appear to present lines that fit reasonably well. All three equations predicted that initial demand was largest in the 0-s delay condition, and smallest (in all but two cases) in the 32-s delay condition. None of the equations found initial demand or any other parameter (a, b, α, or P_{max}) to change systematically across subjects or with increases in the delay. The Hursh and Silberberg (2008) equation, with both values of k indicate that in most cases α was largest in the 32-s delay condition and smallest in the 8-s delay condition, indicating that the two conditions respectfully produced the smallest and largest essential demand. P_{max} was largest in the 8-s delay condition for all six hens when k was set at 3.48, and for three hens when k was set at 6.08. Similarly, the Hursh et al. (1988) equation found that 3 hens had the smallest initial slopes (b values) and largest values of P_{max} in the 8-s delay condition, indicating that this condition produced the most inelastic demand. For all hens and delay values, P_{max} values were largest using the Hursh et al. (1988) equation. The Hursh and Silberberg (2008) equation with the k value of 3.48 gave the smallest P_{max} values for all hens and delays, and also larger values of α than when k was set at 6.08.

To compare the fits of the equations, each fit was analysed using the Akaike Information Criterion (AIC; Davison & McCarthy, 1987). The AIC assesses the goodness of fit of estimated statistical models and can be used as a tool for model selection. The AIC takes into account the number of free parameters of the models, which is why it was selected to compare the Hursh et al. (1988) equation which has three free parameters with the Hursh and Silberberg's (2008) equation, which has two free parameters. The AIC indicated that the worst fits were produced by Equation 2.3 with a *k* value of 6.08. No consistent differences were found between the fits of Equation 2.1 or Equation 2.3 with a *k* value of 3.48, and therefore the two fits were equally good.

Consumption Data versus Delay

Figure 2.4 shows the consumption data at each FR value plotted for each hen and for each delay. In five of six cases, there is a slight decreasing trend in consumption as the delay increases which is most evident at small FR values. In some cases, across mid FR values, consumption increased from the 4-s delay to the 8-s delay. For Hen 15, the exception, consumption tended to decrease from 0-s delay to 4-s delay, but remained relatively constant across further increases in delay.

Mean Overall Response Rates

Presented in Figure 2.5 are the mean overall response rates (per s) for each hen and for each delay. The overall response rates were calculated by dividing the total numbers of responses at each FR by the key time (which excludes reinforcement time and delay time), and are plotted for each delay. Generally, as the delay increased the overall response rates decreased slightly. For Hens 11, 12, 13 and 16, the overall response rates peaked at mid FR values in the 8-s delay condition, in accordance with the demand data in which some hens were found to have the largest values of P_{max} and α in the 8-s delay condition. For Hen 15, the overall response rates remained relatively constant across increases in delay. Across all hens and conditions, the overall response rates tended to increase across small to mid FR values, and then remain constant or decrease across large FRs.

Mean Running Response Rates

Figure 2.6 presents the mean running response rates (per s) for each hen and for each delay. The running response rates at each FR were calculated by dividing the total numbers of responses by the run time (which excludes reinforcement time, between-ratio pause time and delay time), and are plotted for each delay. It is not possible to calculate running response rates at FR 1. Generally, as the delay increased, the running response rates tended to decrease, although in some cases, there was an increase from the 4-s delay to the 8-s delay (Hens 12, 13 and 16). In most cases the running response rates tended to decrease as the FR increased.

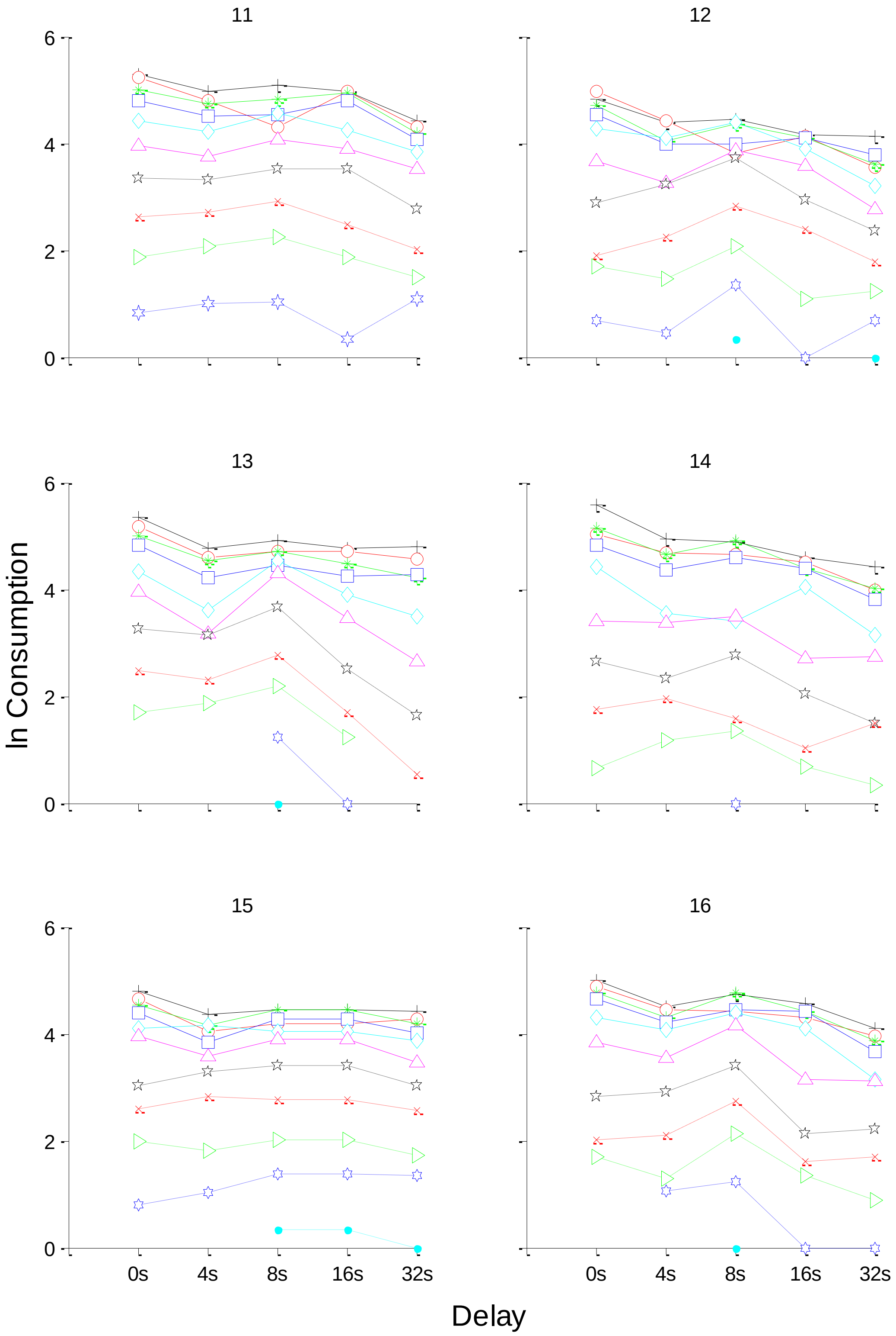

Figure 2.4. The natural logarithms of the consumption data, plotted for each delay size for each hen and each FR (FR 1 black cross; FR 2 red circle; FR 4 green asterisk; FR 8 blue square; FR 16 aqua diamond; FR 32 pink triangle; FR 64 black pentagon; FR 128 red x; FR 256 green triangle; FR 512 blue star; FR 1024 aqua dot). The data are means of the series of each delay condition.

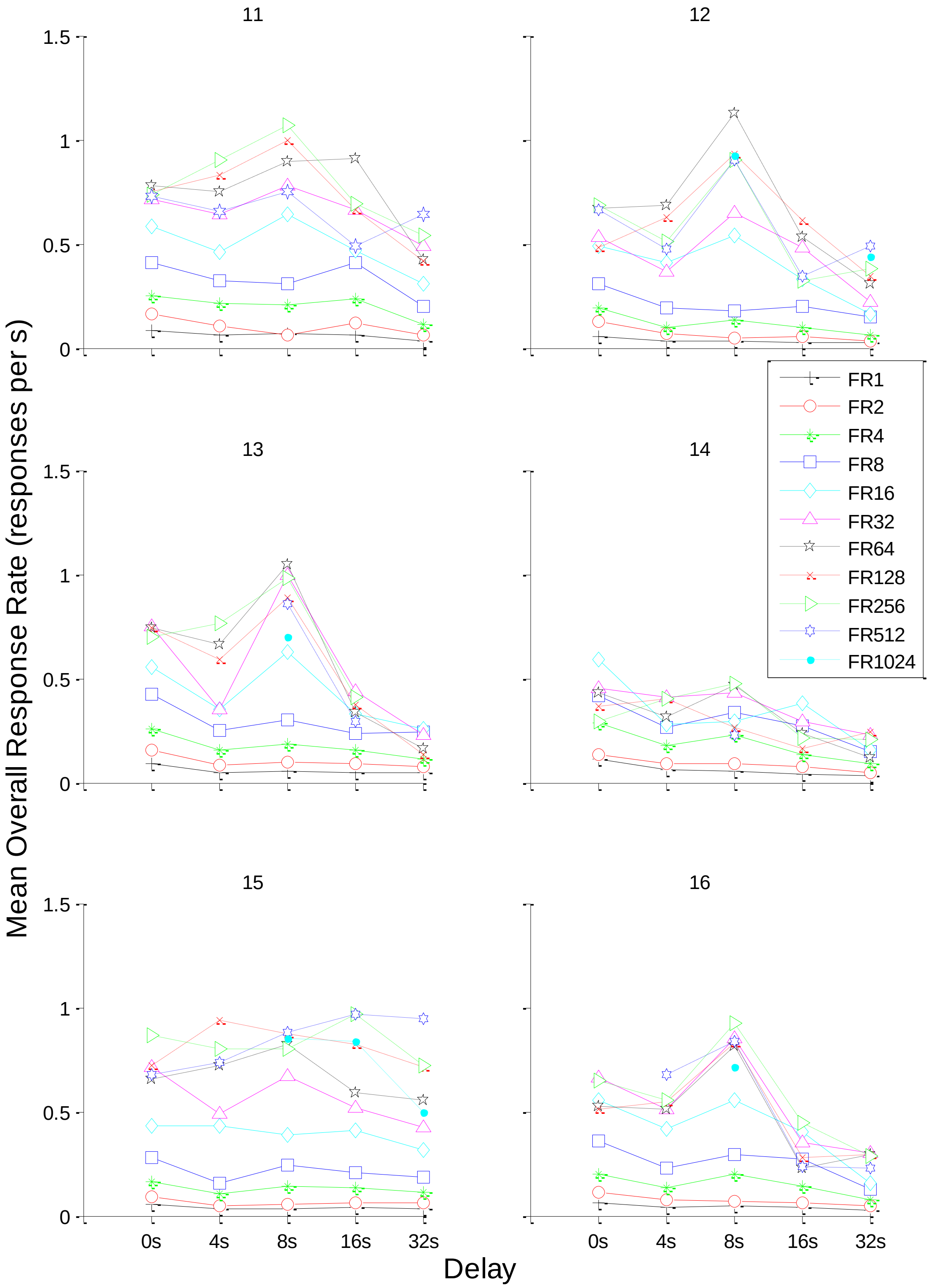

Figure 2.5. The overall response rates (per s), plotted for each delay size for each hen. The data are means of the series of each delay condition.

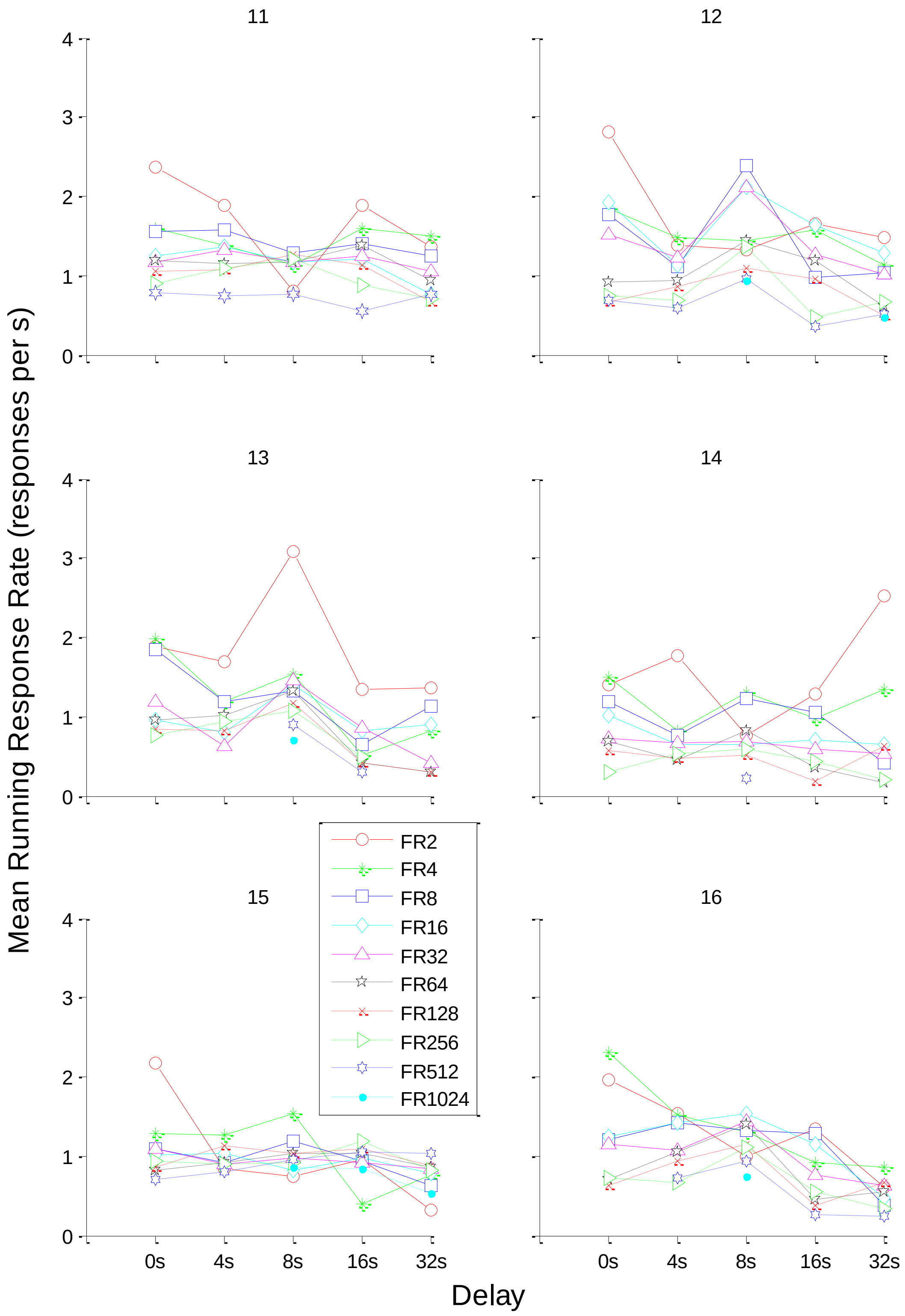

Figure 2.6. The running response rates (per s), plotted for each delay size for each hen. The data are means of the series of each delay condition.

Cumulative Records examples

Figure 2.7 shows examples of the cumulative response records at each FR value for Hen 13, plotted against key time (excluding delay time), for each of the delay conditions. Data from the other hens are presented in Appendix 2. Hen 13 was selected as she had no missing data and her data were representative of the other hens. The examples presented are from the most recently completed series in each condition. Because these data are examples from individual series not means across series, although there were no systematic differences, there may be some individual variation compared with the previously presented mean data. Within each condition, for Hen 13 and the other subjects, responding tended to become faster and more consistent across the session as the FR increased from small to mid FR values. This is seen as steeper response curves with fewer horizontal periods of non-responding. As the ratio increased further, responding became more inconsistent across the session, and both within session and between-ratio pausing increased.

Comparing delay conditions, with larger delays, responding at small to mid FR values tended to become slower, for all hens, although the effect was not large for Hens 15 and 16. For all hens, at mid to large FR values, the differences in the 0-s, 4-s and 8-s delay conditions lessened compared with differences at small FRs, and the rates of responding were similar. For Hens 11, 12, and 13, the rate of responding across mid to large FR values increased as the delay increased from 4 s to 8 s, resulting in similar rates of responding for the 0-s and 8-s delay conditions. Hens 14 and 16 showed similar patterns of responding in the 0-s and 8-s delay conditions across mid FRs only. At large FR values for Hens 11, 12, 13 and 14 there was more within session pausing in the 16-s and 32-s delay conditions than the conditions with shorter delays. For Hen 15, there was not much within session pausing at any delay and responding was not consistently different at large FR values in any condition. For Hen 16 at large FR values, within session pausing was common in all conditions except for in the 8-s delay condition.

Response Rate Data from 5-min Segments

To examine within-session changes in responding, each 40-min session (excluding the total durations of the various delays) was divided into segments of 5 min, and the mean response rates in each 5-min segment were calculated.

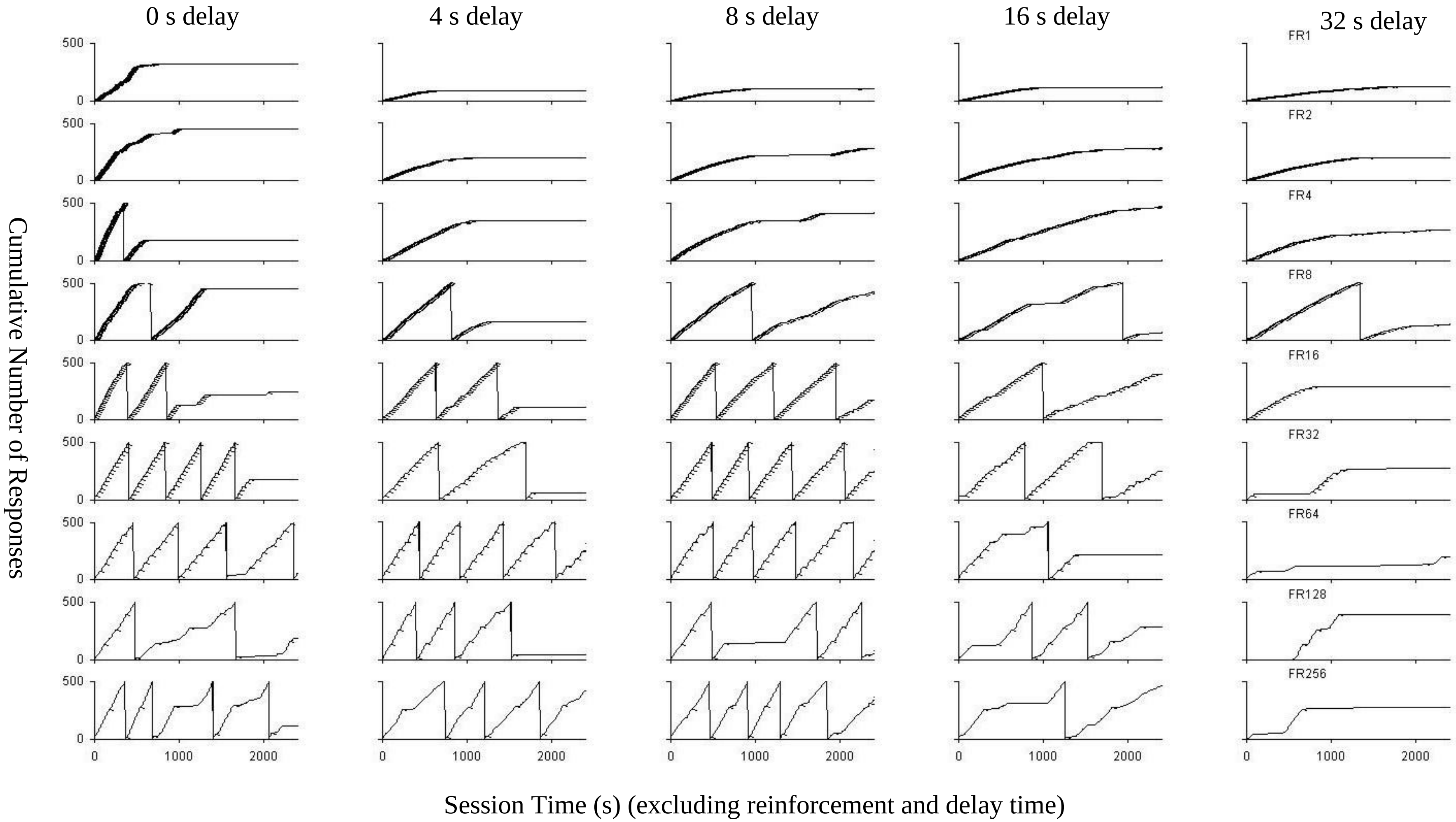

Figure 2.7. Examples of cumulative records from Hen 13 responding at each FR in the last series of each delay condition.

Figure 2.8 shows the whole session responding (in 5-min bins) for all hens across sessions and delay conditions for a selection of FR values (FR 1, 4, 16, 64 and 256). Within each condition, responding increased and tended to become more consistent across the session as the FR increased; that is, at FR 1, responding was slow during the first 10-15 min of the session, and then decreased over the rest of the session. As the FR increased, responding was faster at the start of the session and this rate was maintained throughout the entire session.

In most cases, as the delay increased, a relatively high rate of responding was maintained from the 0-s delay condition through the 8-s delay condition. The rate of responding in the 8-s delay condition was comparable to responding in the 0-s delay condition; in most cases, responding in the 8-s delay condition was the most consistent across the entire session at all FR values. Compared to shorter delays, in the 16-s and 32-s delay conditions responding became slower and more inconsistent across the session. The one exception is Hen 15, whose rate of responding at each FR value remained relatively consistent across increases in delay.

Mean Between-Ratio Pause Durations

Figure 2.9 presents the mean between-ratio pause durations (in s) for each hen and for each delay. The mean between-ratio pause durations were calculated by dividing the total cumulative between-ratio pause durations (time taken to respond following a reinforcer) at each FR, minus the time to the first response at the start of the session, by the total numbers of reinforcers obtained. This is plotted for each delay. Several data points lie beyond the graph axes; these between-ratio pauses typically occurred at large FR values where few reinforcers were obtained. Analysis of the cumulative session data suggests that in these cases, the hen either stopped responding mid way through the session after receiving a reinforcer, or paused after a reinforcer for an uncharacteristically long duration before responding again. Therefore these between-ratio pauses are not representative of normal between-ratio pause durations. These values are displayed numerically alongside the relevant graphs.

Generally, the mean between-ratio pause durations at large delays were longer than those at small delays, however in several cases (Hens 11, 13 and 16), the mean between-ratio pause durations decreased from the 4 s delay condition to the 8 s delay condition. Additionally, for all hens excluding Hen 15, the mean

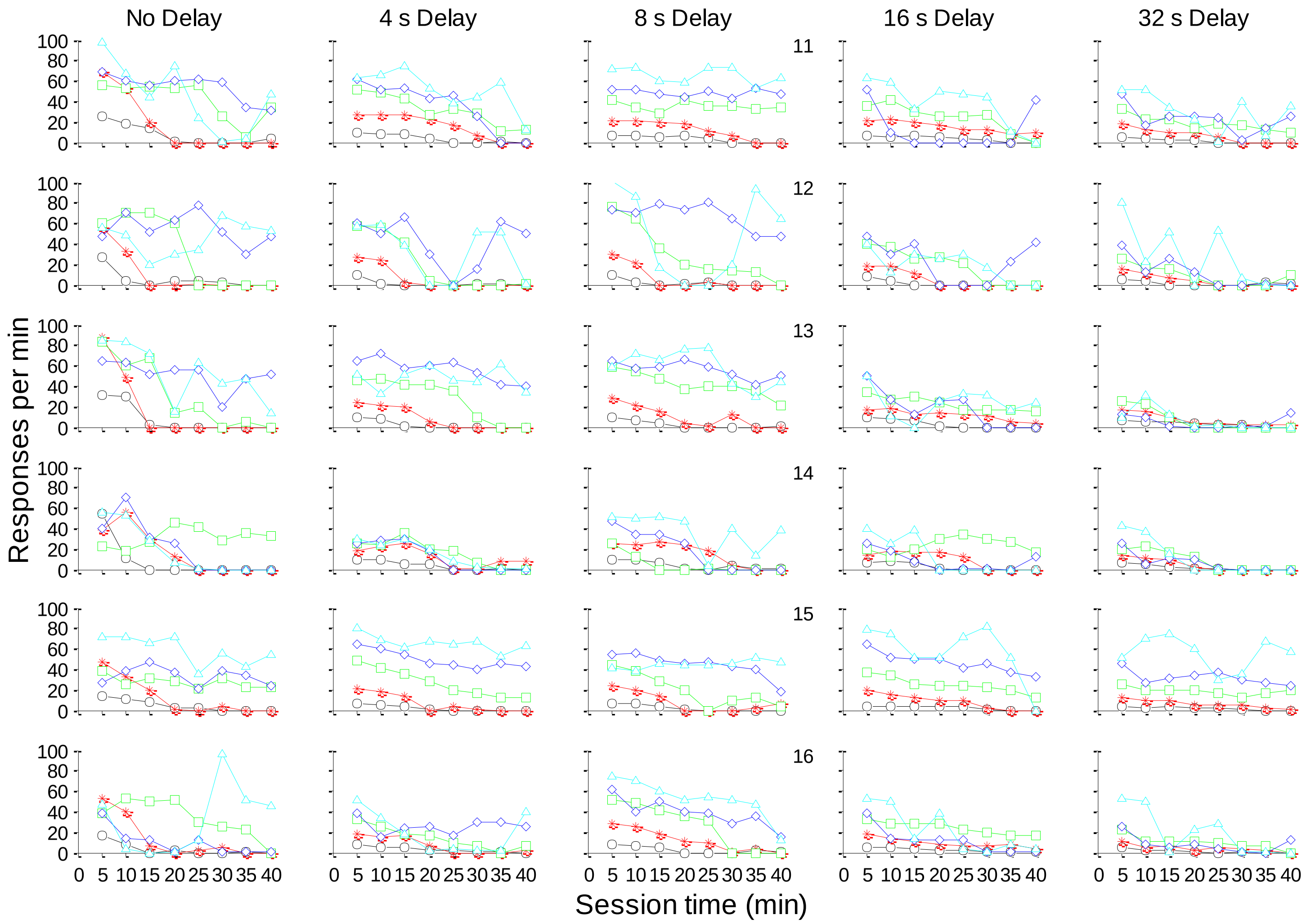

Figure 2.8. Responding in each 5-min segment of the session for all hens under FR 1 (black circles), FR 4 (red asterisks), FR 16 (green squares), FR 64 (blue diamonds) and FR 256 (aqua triangles) schedules in the last series of each delay condition.

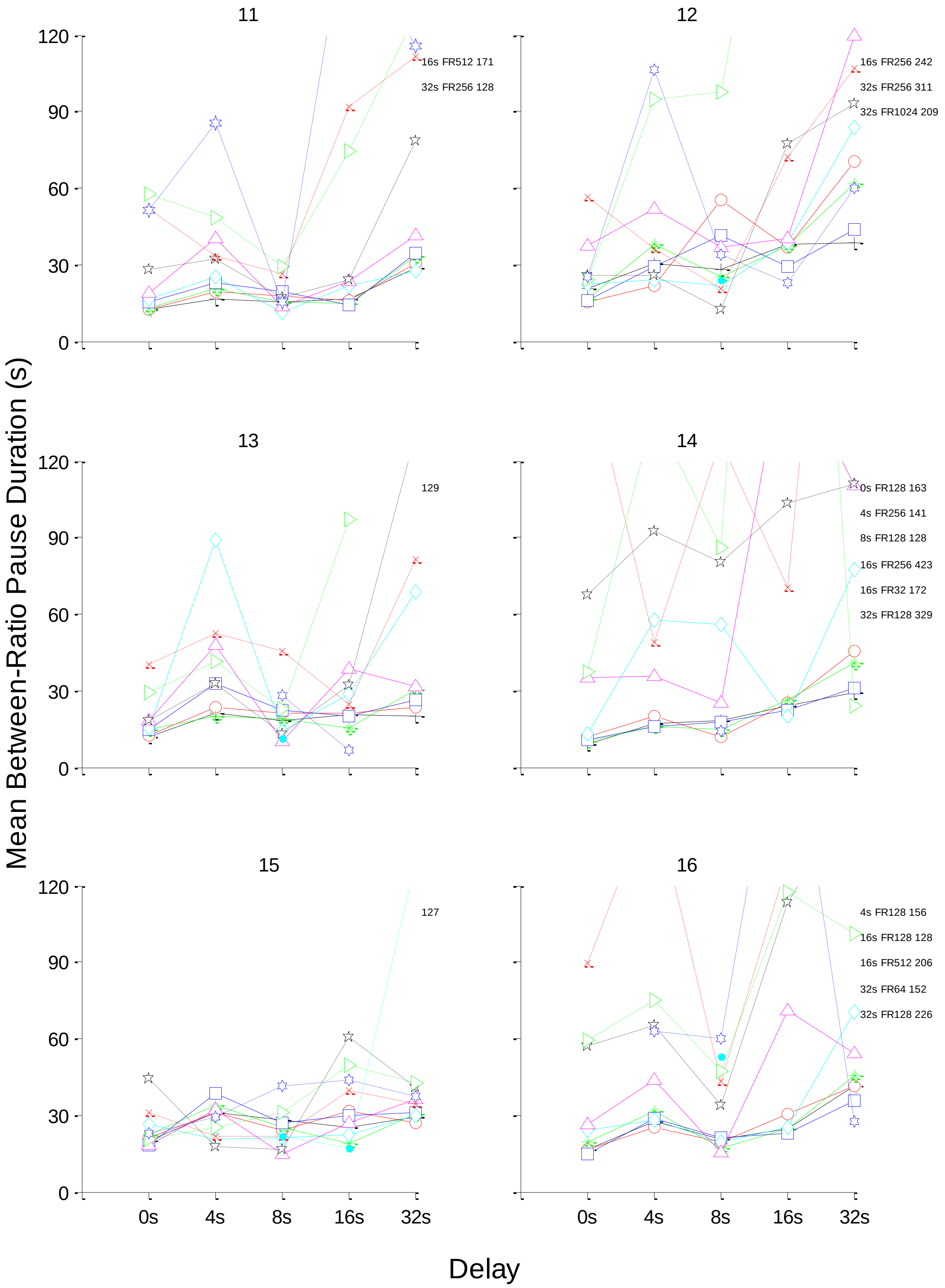

Figure 2.9. The mean between-ratio pause durations (in s), plotted for each delay for each hen and each FR (FR 1 black cross; FR 2 red circle; FR 4 green asterisk; FR 8 blue square; FR 16 aqua diamond; FR 32 pink triangle; FR 64 black pentagon; FR 128 red x; FR 256 green triangle; FR 512 blue star; FR 1024 aqua dot). The data are means of the series of each delay condition. Data points that lie beyond the axes are displayed numerically (delay, FR, pause duration) alongside the relevant graphs.

between-ratio pause durations tended to increase as the FR increased. The mean between-ratio pause durations for Hen 15 tended to remain constant or increase only slightly as the FR increased.

Between-Ratio Pause Histogram Examples

Figure 2.10 presents histograms of the between-ratio pause durations (frequency of pausing, y axis, plotted against the duration of pausing, x axis) at each FR value in the most recently completed series of the 0-s, 8-s and 32-s delay conditions. Data from all hens were analysed, and the distributions and trends were similar, so data from Hen 12 are presented as representative. Data from Hens 11 and 13 through 16 are presented in Appendix 2. Hen 12 was selected as she had no missing data and her data had not previously been used as an example. Note that the limit of the frequency axis is 20 to enable the smaller frequencies to be visible. Also for reasons of clarity, the between-ratio pause duration axis is limited to 30 s. Fewer than 7.4% of total pauses are outside the axes due to this. At small FR values, most of the pauses were short, and there were few long pauses, resulting in a positive skew. The skew lessened as both the FR and delay increased. The graph shows that there were fewer short pauses, a larger frequency of longer pauses, and the distribution of pauses was more spread out across a range of pause lengths.

Median Between-Ratio Pause Durations

Figure 2.11 presents the 25th, 50th and 75th percentile pauses at FRs 1 through 256, plotted for each delay condition for Hen 12 (taken from the histograms presented in Figure 2.10). At small to mid FR values, the durations of pausing increased as the delay increased. However, occasionally the pauses in the 8-s condition were smaller than in the 4-s condition. At large FR values, the data become untidy, and patterns of pausing with increasing delay are less clear.

Figure 2.12 re-presents the 25th, 50th and 75th percentile pauses for Hen 12, however, here the pauses at each delay are plotted against the FR value. Across all delay values, pausing increased as the FR increased. Figures 2.11 and 2.12 are representative of data from all hens.

Amount Eaten

Figure 2.13 presents the mean amounts of wheat eaten (in g) by each hen at each FR value in the most recently completed series of each condition. The total amounts eaten in each session were divided by the total numbers of reinforcers

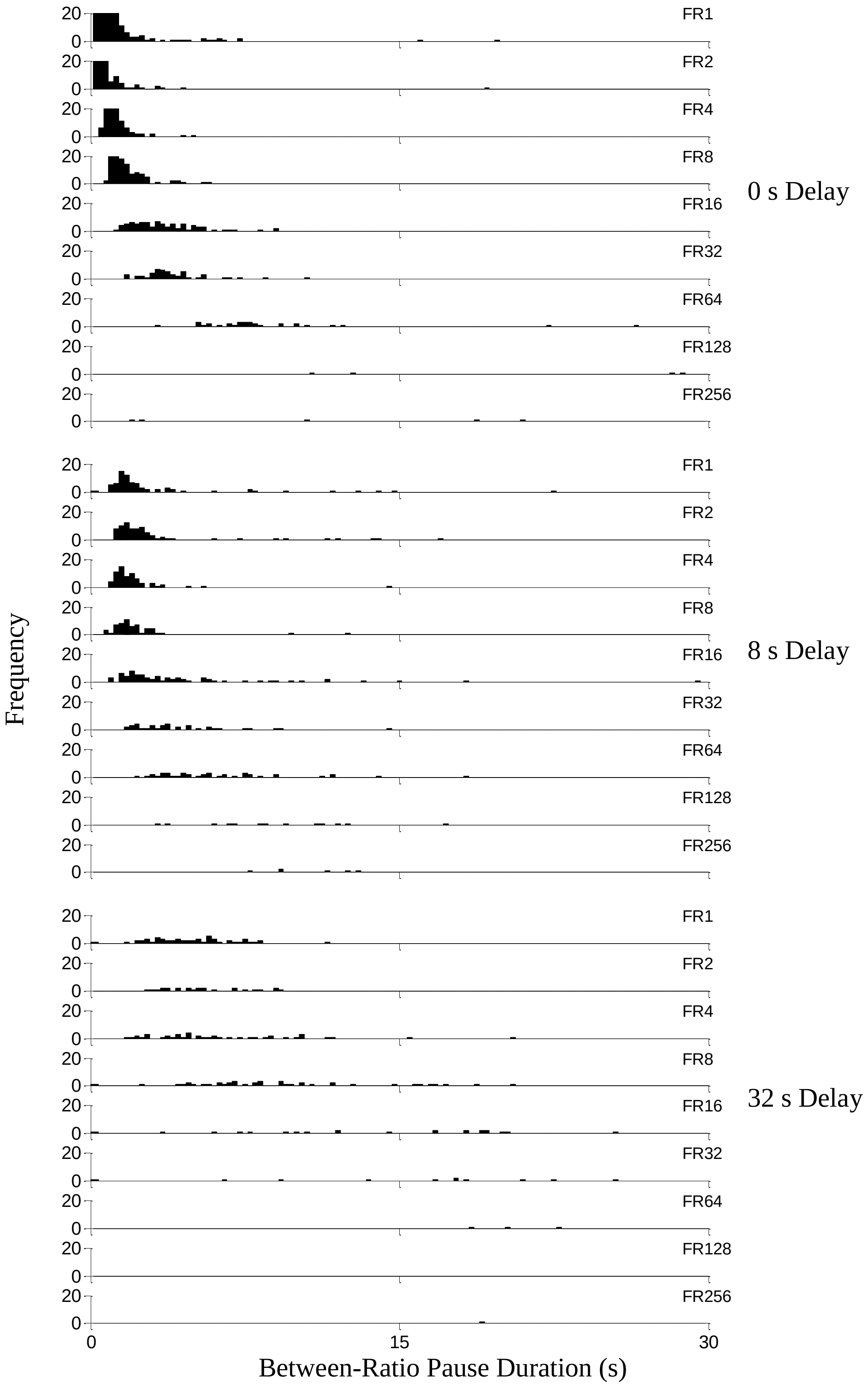

Figure 2.10. Examples of histograms of the between-ratio pause durations from Hen 12, at each FR in the last series of the 0-s, 8-s and 32-s delay conditions. For visibility, the frequency axis is cut off at 20.

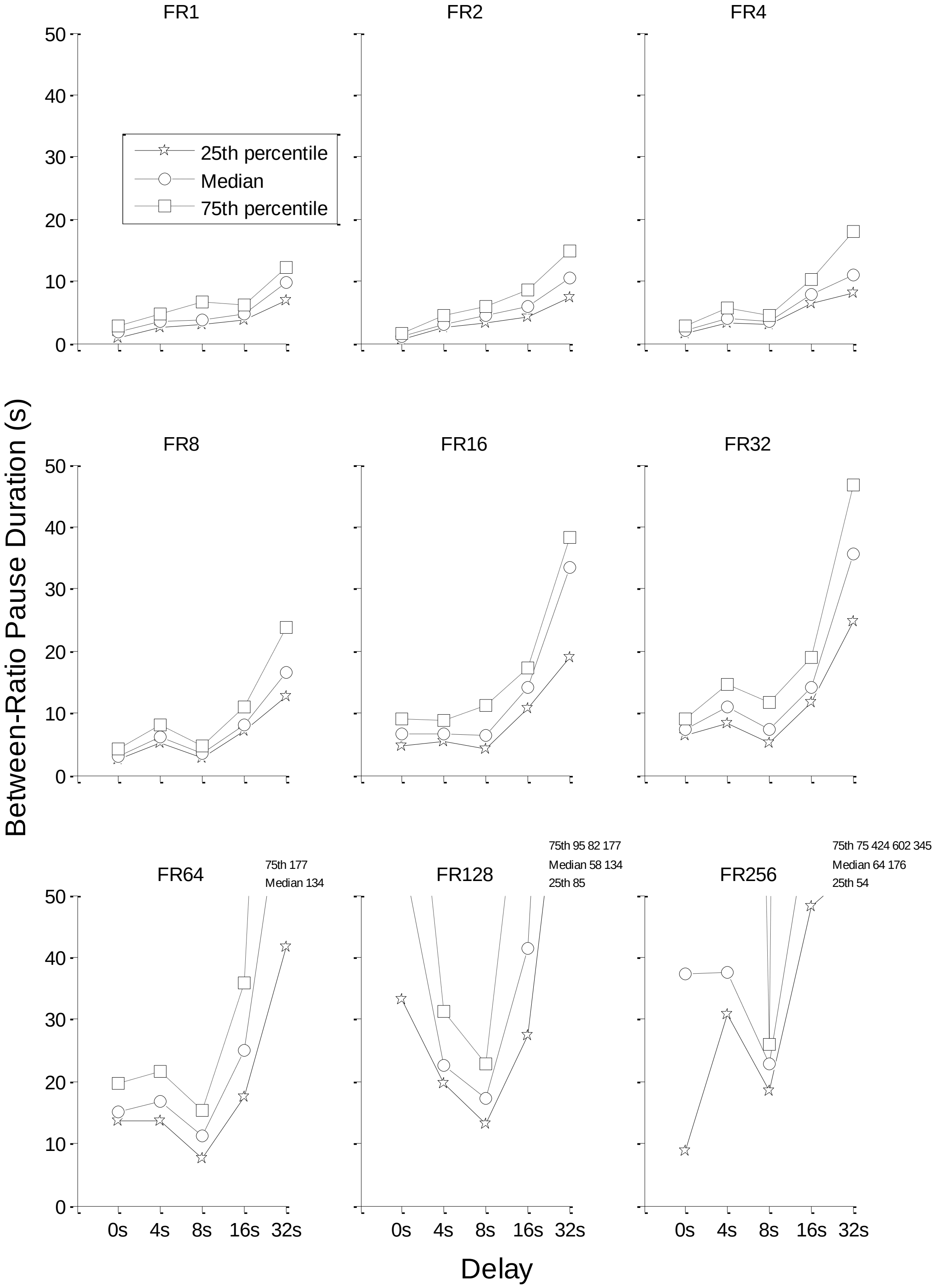

Figure 2.11. Examples of the median between-ratio pause durations plotted for each delay from Hen 12 at FR values up to 256. Data points that lie beyond the axes are displayed numerically (percentile, pause duration from smallest to largest delay) alongside the relevant graphs.

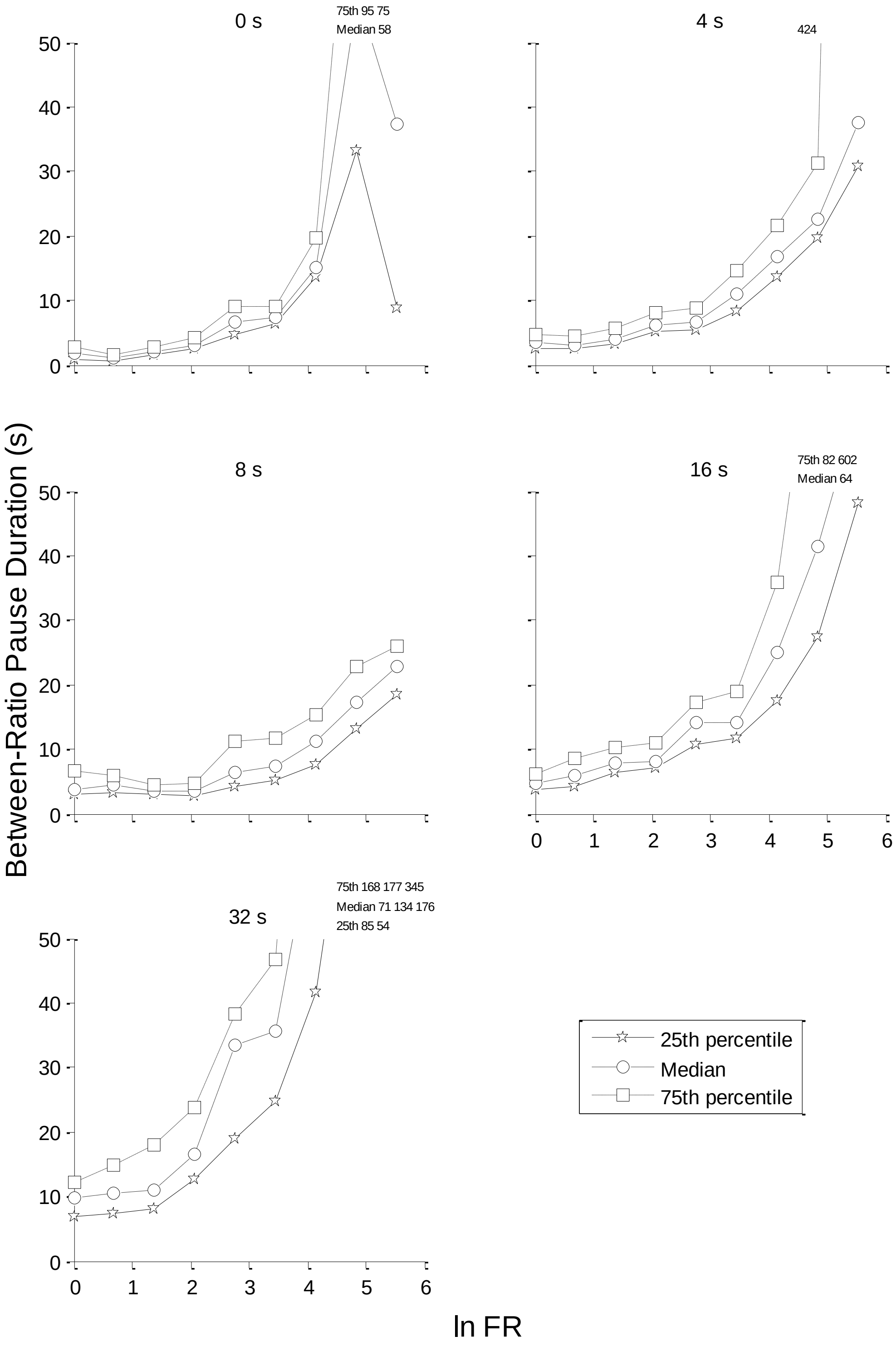

Figure 2.12. Examples of the median between-ratio pause durations plotted against the natural logarithms of the FR size (up to 256) from Hen 12 in each delay condition. Data points that lie beyond the axes are displayed numerically (percentile, pause duration from smallest to largest delay) alongside the relevant graphs.

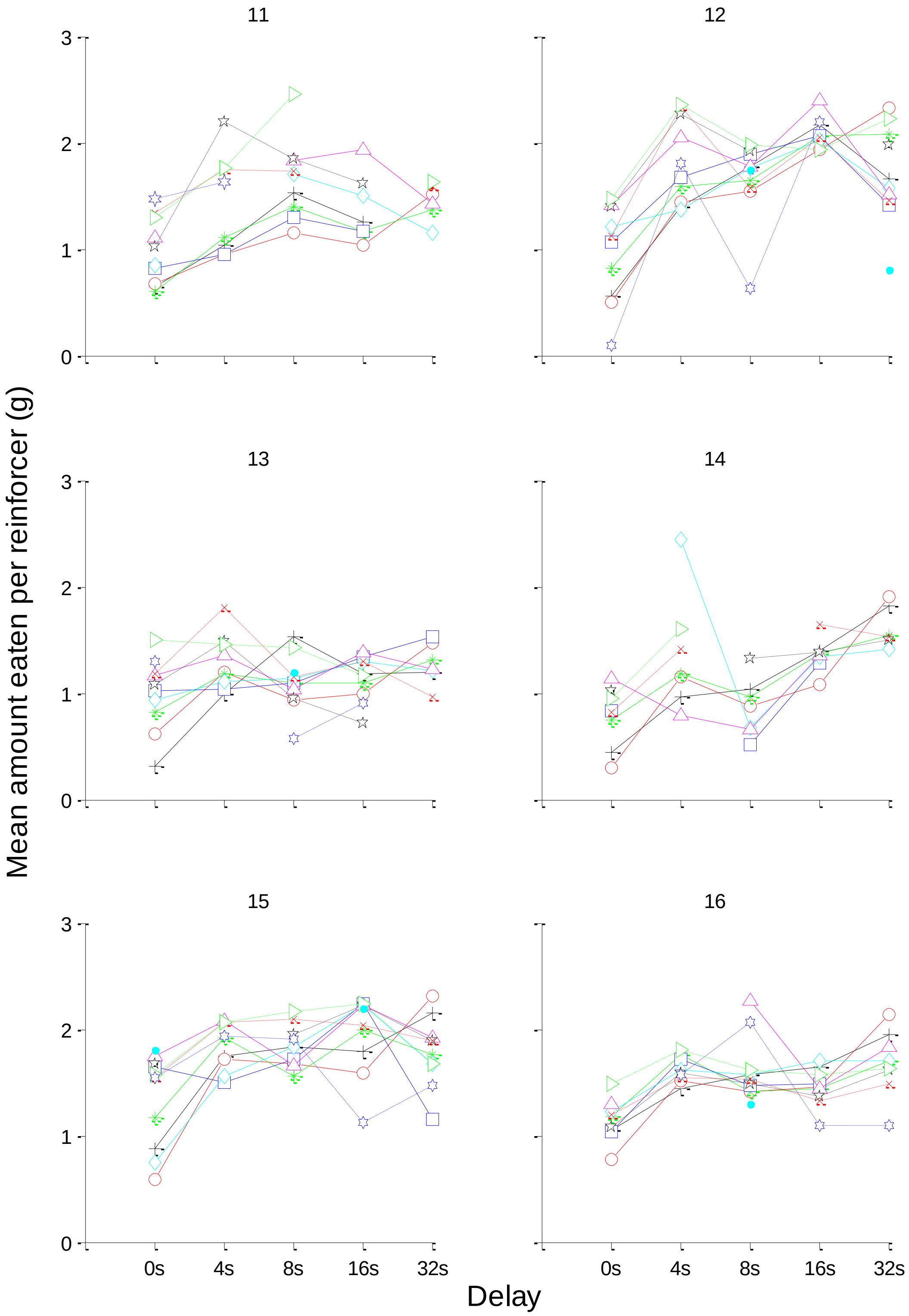

Figure 2.13. Mean amount eaten (in g) at each FR value plotted for each delay and for each hen in the most recently completed series of each condition (FR 1 black cross; FR 2 red circle; FR 4 green asterisk; FR 8 blue square; FR 16 aqua diamond; FR 32 pink triangle; FR 64 black pentagon; FR 128 red x; FR 256 green triangle; FR 512 blue star; FR 1024 aqua dot).

obtained. Some data have been removed due to the occurrence of faulty readings of the scales by the computer programme (negative values were removed, and any mean over 2.5 g).

For most hens, the amount eaten per reinforcer was the smallest across most FR values in the 0-s delay condition. As the delay increased from 4 s to 32 s there were no consistent patterns in the amount eaten per reinforcer. Furthermore, there were no consistent patterns in the amount eaten per reinforcer as the FR increased (increasing in 16 cases and decreasing or remaining constant in the other 14 cases).

Head in Magazine while Magazine Raised

Figure 2.14 presents the mean eating time (in s) for each hen at each FR value in the most recently completed series of each condition. The total duration that each hen's head was in the magazine when raised was divided by the number of reinforcers obtained. For five of six hens, the mean head in magazine time was shortest across all FR values in the 0-s delay condition, however, for Hen 15, there was no difference between conditions. For four of six hens in the 0-s delay condition, the mean head in magazine time increased as the FR increased. However, there were no other consistent patterns across FR or delay increases.

Blackout Pecks

Although details are not presented here (they are presented in Appendix 2), examination of the rates of blackout pecking showed that throughout all experimental conditions (across all delays and FR values), rates of blackout pecking were very low (in most cases fewer than one peck per reinforcer).

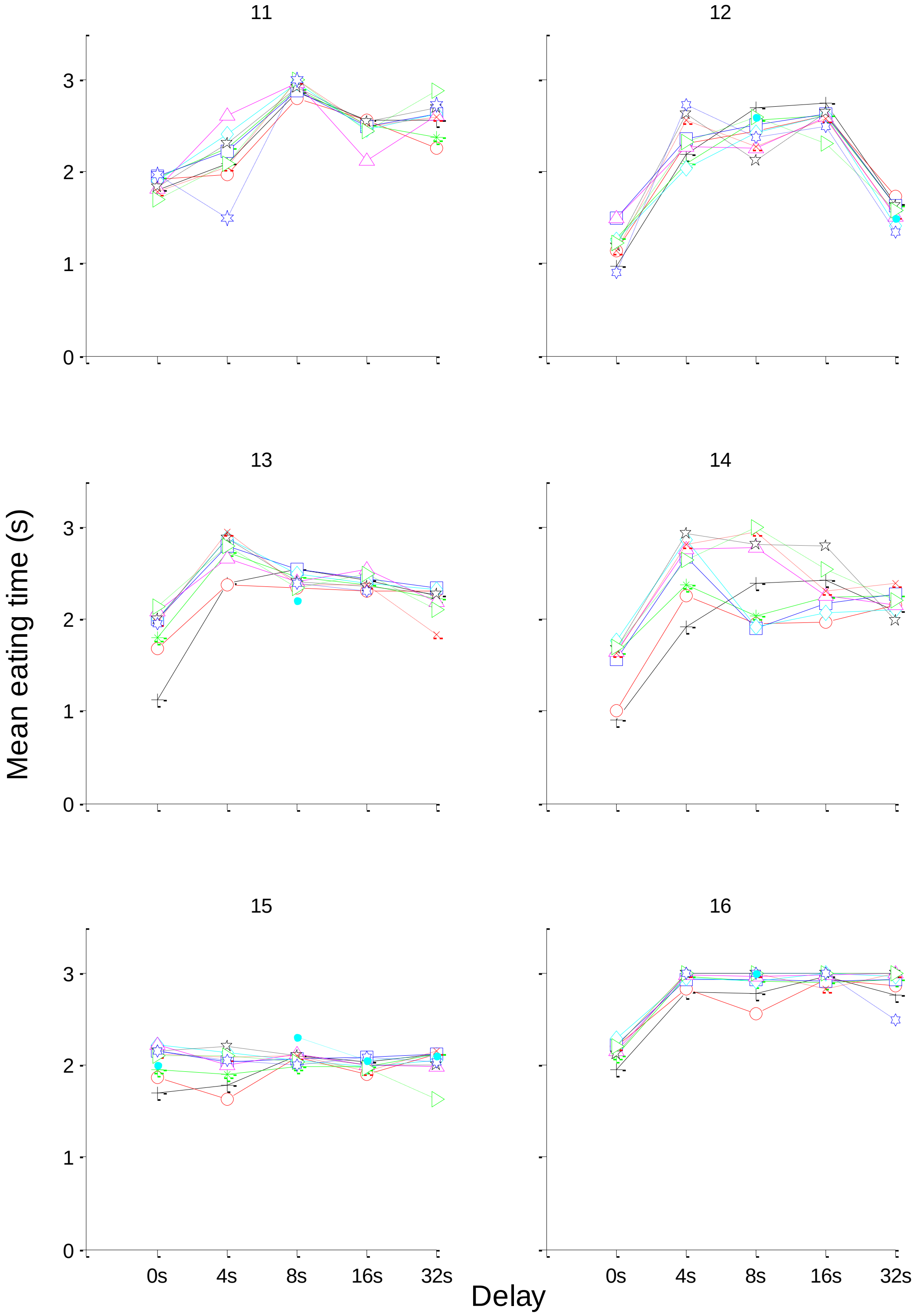

Figure 2.14. Mean eating time (in s) at each FR value plotted for each delay and for each hen in the most recently completed series of each condition (FR 1 black cross; FR 2 red circle; FR 4 green asterisk; FR 8 blue square; FR 16 aqua diamond; FR 32 pink triangle; FR 64 black pentagon; FR 128 red x; FR 256 green triangle; FR 512 blue star; FR 1024 aqua dot).

Discussion

The aim of the present experiment was to examine the effects of delay-to-reinforcement on hens' performance under increasing FR schedules and demand for food. The only clear effect of differing delays to reinforcement on hens' demand for food was that demand was highest when there was no delay across the smallest FR values, and was lowest at the largest delay value (32 s). Two different demand equations were fitted to the data; Hursh et al.'s (1988) nonlinear equation (Figure 2.1) and Hursh and Silberberg's (2008) exponential equation (Figures 2.2 and 2.3; using two different values of the constant *k*, as suggested by the electronic tool referenced in the paper). In all three instances, there were no consistencies other than those in the initial levels of demand across subjects, delays or parameters (*a*, *b* and α) of the fitted functions. One finding that was common, but did not hold for all subjects and both equations, was that the 8-s delay condition often yielded levels of initial demand that were second largest, the largest values of P_{max} (the FR associated with maximal responding) and the smallest values of α, Hursh and Silberberg's (2008) measure of essential value.

Another aim was to determine whether delay-to-reinforcement affects hens' demand for food in a manner similar to magnitude and quality. As previously mentioned, when investigating hens' demand for foods of differing quality, Foster et al. (2009) and Bruce (2007) both found, somewhat paradoxically, that initial demand was always larger for puffed wheat, the food that was both of lesser quality and was found to be less preferred than wheat. However, demand for this less valued reinforcer fell more steeply with increases in FR than did demand for wheat, resulting in more inelastic demand functions for wheat with larger values of P_{max}. Grant (2005) extended this research using reinforcer magnitude, finding that the largest reinforcer magnitude again yielded smaller initial demand and larger values of P_{max}, but more inelastic overall demand. As reinforcer magnitude was decreased, initial demand increased monotonically, and overall demand became increasingly elastic. These results can be compared to those found with delay here.

Chung and Herrnstein (1967) found that shorter delays-to-reinforcement are preferred to longer delays. If this holds in the present experiment, based on the findings of Foster et al. (2009), Bruce (2007) and Grant (2005) where the outcome which the animals preferred was found to yield smaller initial consumption levels, it would be expected that shorter delays would produce smaller levels of initial consumption than larger delays. This was not found in the present experiment. The only consistent effects found here were that initial consumption was largest in the 0-s delay condition and smallest in the 32-s delay condition. The present findings suggest that delay-to-reinforcement does not affect hens' demand for food in the same way as reinforcer quality and magnitude.

There is a possible confound in the present experiment when comparing the data from the 0-s delay conditions with that from the other conditions. Figures 2.13 and 2.14 show that for most hens, during the 0-s delay condition the duration of eating, and thus the amount of wheat eaten, was less than during the other delay conditions. This may be because the magazine was raised immediately following the final FR response during the 0-s delay condition. The distance from the key to the magazine was 120 mm, and it took the subjects approximately 1 s to move from the key to the magazine, restricting the actual eating time in the 0-s delay condition to approximately 2 s. During all delay conditions the magazine was raised at the end of the delay. This means that the subjects could locate their heads close to or inside the magazine during the delay, allowing them to eat more, coming close to the full 3 s. Therefore, during the 0-s delay condition, the subjects received a smaller magnitude of reinforcement. The larger initial demand for all hens in the 0-s delay condition could then be seen as similar to Grant's (2005) finding of larger initial demand in the 2-s access condition compared to the 12-s access condition.

However, it is unlikely that the discrepancy between the present findings and previous demand research is due to the reinforcer magnitude. Figure 2.4 shows that, although there was only a small effect, the numbers of obtained reinforcers at each FR tended to decrease with increasing delay. The effect is still present if the 0-s delay data are disregarded. This suggests that had the eating time been the same in the 0-s delay condition, the number of obtained reinforcers would still have been higher than in the delay conditions. One way that eating time could have been made identical would have been to time the 3 s of eating time from the moment the subject's head entered the magazine, thus ensuring consistency in reinforcer magnitude across all conditions and delays.

The only consistent effect of delay-to-reinforcement on performance on FR schedules occurred over the small FR values in the present experiment. As the FR increased the delay became a lesser and lesser proportion of the time it took to complete one FR requirement. At FR 1, a delay of 32 s would be large compared to no delay, however, at FR 512, the 32 s delay would be a lesser proportion. Assuming 1 s per response, the FR 512 requirement would take approximately 8.5 min to complete, and a 32-s delay adds only 1/16th of that duration to the ratio requirement. However, at FR 1, compared to no delay, the schedule with a 32-s delay would take 32 times as long to complete as it would with no delay. So in context of the FR 1 schedule, the 32-s delay represents a large portion of the inter-reinforcement interval and hence may affect the value of the reinforcer. In context of the FR 512 schedule it represents only a small proportion of the inter-reinforcement interval, and thus is unlikely to affect the value of the reinforcer to the same extent. This may help account for the effects of increased delay being seen only at small FR values.

The results of the present experiment, where the delay-to-reinforcement was increased from 4 s through to 32 s, suggest that delay-to-reinforcement does not have a large effect on hens' demand for wheat. Interestingly, Grant (2005) found only a small preference for 8-s access to wheat compared to 2-s access to wheat. She added a 12-s duration to the study in order to obtain larger biases towards the larger reinforcer. Thus, it seems that neither delay nor magnitude have large effects on hens' responding for wheat.

It is surprising that longer delays to reinforcement had such a small effect and did not reduce the number of reinforcers obtained to a greater extent. It should be noted that the delay time was always excluded from the key time (the time available for responding), and the key time was always held constant. Therefore, increasing the delay-to-reinforcement did not restrict the time in the session available for responding, and the subjects had the same opportunity at each FR to maintain the level of consumption they had obtained in the 0-s delay condition, regardless of the particular delay in effect. Obviously, if the measure of performance in the present experiment was consumption rate (reinforcers obtained per unit of time) and the time included delay, consumption rate would decrease with increasing delay, regardless of the subjects' behaviour. By restricting the analysis to only the time available for responding, it is possible to see changes that result from changes in the behaviour of the subjects and not from changes in the delay.

Foster et al. (2009), Grant (2005) and Bruce (2007) all found that the overall and running response rates were faster across small FR values for the least valued reinforcer. This was not the case in the present experiment in that the overall and running response rates tended to decrease with increasing delay (Figures 2.5 and 2.6). This further confirms the finding that delay-to-reinforcement does not seem to affect hens' demand for food in the same way as reinforcement quality and magnitude.

The finding of reduced response rates (overall and running) with increased delay duration is supported by the majority of previous delay-to-reinforcement research (e.g., Gentry & Marr, 1980; McDevitt & Williams, 2001; Neuringer, 1969; Sizemore & Lattal, 1978). Experiment 1 in this thesis also found that overall response rates decreased monotonically with increasing delays and that running response rates were slower when there was a delay-to-reinforcement compared to no delay.

As mentioned previously, when using FR schedules and varying delay-to-reinforcement, overall response rates have been found to decrease with increasing unsignalled resetting delays (Azzi et al., 1964), similarly to the present experiment. However, Morgan (1972) and Topping et al. (1973) reported that increasing a signalled non-resetting delay produced no consistent effect on responding, even though their delay procedures were more similar to the present experiment than those of Azzi et al. (1964). There are several possible methodological explanations for these discrepancies. As mentioned in Experiment 1, while non-resetting delays were used in the present experiment, Azzi et al. (1964) used resetting delays, which reportedly have more effect on behaviour than non-resetting delays. Azzi et al. (1964) appeared to include the delay in their calculation of the overall response rate, while the delay was excluded from such calculations in the present experiment and those of Morgan (1972) and Topping et al. (1973). Morgan (1972) did not examine behaviour under FR schedules when there was no delay. Topping et al. (1973) provided no response rate data, merely stating that the response rate did not consistently vary with the duration of the delay. Finally, in each of these experiments (and also in Experiment 1), the effects of delay-to-reinforcement on the behaviour of each subject were examined under only one FR value. In an attempt to produce more parametric data than were previously available, the present experiment examined the effects of delay-to-reinforcement on behaviour over a range of FR values and found that the effects varied depending on the FR size.

The reduction in response rate with increasing delay is shown in Figure 2.7. These examples of cumulative responding within each delay condition show that total responding tended to increase across small to mid FR values, with a decrease in responding at the largest values of FR. When behaviour under each FR value is compared across delays, an overall decrease in responding is apparent, along with an increase in within-session pausing. The effect on responding of the increasing ratio is larger than the effect of increasing delay.

Figure 2.7 also may help to account for the seemingly small effect of increasing delay on response rates. At small FR values (FRs 1 through 8) and delays (0 s and 4 s), responding took up only a small proportion of the session. Even though the response rates were fast over that initial part of the session, when they were calculated across the entire session, the response rate was reduced by the inclusion of the long period of non-responding at the end of the session in the time base. Therefore the response rates at small FRs and delays were similar to response rates at larger delays where local rates of responding were lower but where these rates persisted throughout the entire session.

An unexpected finding that is evident in Figures 2.5 through 2.8 is that the response rates were often the fastest or amongst the fastest in the 8-s delay condition across medium to large FR values. Figure 2.7 shows that for Hen 13, for FRs 32 through 512, responding in the 8-s delay condition was comparable to that in the 0-s delay condition, and similar to or faster than that in the 4-s delay condition. Response rates that are fastest for the 8-s delay condition may be partially accounted for by consideration of Figure 2.8. In the 8-s delay condition the response rates are the most consistent across the entire session. However, if the response rates over the first half of each session in the 0-s delay condition are compared visually with those of the 8-s delay condition, in most cases the response rates at each FR are very similar. The response rates fell sharply during the second half of the session during the 0-s delay condition yet tended to persist across the entire session in the 8-s delay condition. This persistence over the session gave rise to the faster response rates in the 8-s delay condition in Figure 2.5.

The comparison of the response rates calculated over the whole session with those seen in the cumulative records in the present study highlight the problem of averaging data. Perhaps a way to resolve this would be to redefine the point at which the session is said to end, and then calculate the response rate over the portion of the session in which responding actually occurred. However, this point would be difficult to define and calculate especially if responding ceased mid-session only to continue later in the session. Also, if the time available for responding differed over sessions, food would not be equally available in each session. The cumulative response data allows for comprehensive examination of responding in each session, although this type of analysis, in which each individual session must be graphed and interpreted, can be very time consuming. It is suggested that the data presented in Figure 2.8, which shows the response rates in each five-minute segment of the session, may be a useful compromise between micro- and macro-analyses.

Previous studies investigating the effect of delay-to-reinforcement on performance under FR schedules (Morgan, 1972; Topping et al., 1973; Experiment 1 in this thesis) and CRF (Azzi et al., 1964) have found that the length of the between-ratio pause tends to increase along with the delay. This was also found in the present experiment (Figure 2.9). However, this finding contrasts with the findings of Foster et al. (2009), Grant (2005) and Bruce (2007), where the less valued reinforcer yielded shorter between-ratio pause durations. Thus the between-ratio pause data in the present experiment are consistent with previous research investigating the effects of delay-to-reinforcement on performance in FR schedules, but are inconsistent with previous research investigating the effects of reinforcer magnitude and quality on behaviour under increasing FR schedules.

The mean between-ratio pause durations in Figure 2.9 are often variable, possibly due to the subject stopping responding mid-session (but after a reinforcer). These extremely long pauses (outliers) influence the mean and so present a problem when using the mean between-ratio pause durations to reflect pause length. As previously mentioned, in their study investigating between-ratio pausing in multiple FR FR schedules, Baron and Herpolsheimer (1999) called attention to the problem that mean data may suggest regularities not present in individual results. Therefore, in the present study, a selection of within-session between-ratio pause durations were presented for Hen 12 (Figure 2.10), along with the medians taken from these histograms (Figures 2.11 and 2.12). These between-ratio pause histograms show that between-ratio pausing distributions were positively skewed with a number of outliers, but, in contrast with Baron and Herpolsheimer's (1999) distributions, the skew lessened as both the FR and delay increased and the outliers were not so extreme. Similarly to the mean between-ratio pause data presented in Figure 2.9, the median between-ratio pause durations presented in Figure 2.11 show that between-ratio pausing increased with delay, however, the median data are more orderly than the mean data (up to FR 64). This suggests that the reduced effect of outliers helps in representing the pause durations more clearly. Overall, the median shows the same general effect as the mean, however the data are tidier and trends more easily visible, providing support for the use of medians in the analysis of such data. It is also possible that the use of medians may be a suitable way for comparing overall response rate data.

A finding similar to the faster response rates that were sometimes found in the 8-s delay condition is also shown in the between-ratio pause data. In Figure 2.11, the median between-ratio pause durations are often shorter in the 8-s delay condition than in the 4-s delay condition, and are of similar length to those in the 0-s delay condition. This finding is also shown in Figure 2.12, in which between-ratio pausing is shortest across medium to large FR values in the 8-s delay condition.

Two different equations were fitted to the data in ln-ln plots of consumption versus FR; Hursh et al.'s (1988) nonlinear equation (Figure 2.1) and Hursh and Silberberg's (2008) exponential equation (Figures 2.2 and 2.3). As previously mentioned, Hursh and Silberberg (2008) offered their exponential equation as an alternative to the commonly used nonlinear equation. They argued that the exponential equation with its one parameter, α, or essential value, is the best way to assess the value of a commodity. However, in order to compare essential value across conditions, the scaling parameter, k, must be set to a constant. The spreadsheet referenced in the paper suggests setting k as either the largest range of consumption found or as the mean value of consumption across the sets of data to be compared. Both methods were used here and the results are presented in Figures 2.3 and 2.2. All three figures present lines that seem to fit reasonably well. The fits of the Hursh and Silberberg (2008) equation using the largest value of the range of consumption as *k* (6.08) were the worst when assessed using the AIC. The Hursh and Silberberg (2008) exponential equation, using the mean value of the range of consumption as *k* (3.48), resulted in a function with an asymptote within the data range. The latter part of the figure is anomalous, suggesting that consumption is unchanging across large FR values.

As previously mentioned, in all three functions, the predicted level of consumption at the smallest price was always largest in the 0-s delay condition, and smallest (in most cases) in the 32-s delay condition. No other consistent findings (in *a*, *b*, α, or initial demand) across all subjects were found as the delay increased using either of the equations or values of *k*. The unexpected finding using the Hursh et al. (1988) nonlinear equation of larger P_{max} values and the most inelastic initial demand for some hens in the 8-s delay condition was also reflected in α values for Hursh and Silberberg’s (2008) exponential equation. With both *k* values α was smallest in the 8-s delay condition in 9 of 12 cases. It was also largest in the 32-s delay condition in 10 of 12 cases. This means that these conditions produced the greatest and smallest levels of essential value, respectively. Further, when the *k* value of 3.48 was used, P_{max} was largest for all six hens in the 8-s delay condition.

The values of P_{max} were larger for Hursh and Silberberg's (2008) equation using a *k* value of 6.08 than when using a *k* value of 3.48. The larger *k* value also resulted in smaller values of α than the smaller *k* value. Foster et al. (2009) fitted the Hursh and Silberberg (2008) equation to their data using a range of *k* values and reported that the larger the *k* value used the larger P_{max} and the smaller α. This appears to be the case for the present data set also. The P_{max} values were largest for all hens and delay values when based on the Hursh et al. (1988) equation. P_{max} is supposed to reflect the price that gives rise to the maximum response output. Inspection of the overall response rate graphs (Figure 2.5) shows that the FR corresponding to the highest overall response rate did not vary systematically with delay. For some hens and delays the overall response rates increased over all of the FR values and were still increasing at the largest FR tested. In these (seven of 30) cases the true maximum overall response rate should probably be at an FR larger than the largest FR value shown. In the remaining cases the relation is bitonic, and the overall response rates initially increased over small FR values, peaked at moderate FR values, then decreased over the larger FR values. In these (23 of 30) cases the FR value associated with the highest overall response rates might be expected to relate to P_{max}. When these FR values are examined for each hen and delay value they are closer to the Hursh et al. (1988) P_{max} values than they are to those from Hursh and Silberberg's (2008) equation in 14 of the 23 cases. While the P_{max} values from Hursh and Silberberg's (2008) equation tend to be smaller than the peak value in most cases (in all cases for the smaller k value, and in 20 of 23 cases for the larger), those from the larger value of k are closer to the peak value in nine of the 23 cases. Thus both equations result in P_{max} values close to the FR values corresponding to maximum response rate in some cases, but both also give P_{max} values that are very different from these in others.

Overall, the assessment of demand in the present experiment resulted in very similar findings with both equations tested. The new Hursh and Silberberg (2008) exponential equation did not seem to add any new information or clarify the findings of the present experiment when compared to the Hursh et al. (1988) nonlinear equation. In addition, the functions presented in Figure 2.2, based on the mean value of consumption with an asymptote within the data set, seem unsuitable. A problem with Hursh and Silberberg's (2008) exponential equation is that it is not clear which k value should be used. However, all three line fits were reasonably good and it is not really appropriate to argue that any one of the fits is theoretically superior. The data do not provide unequivocal support for any one model.

The reason for the unusual findings from the 8-s delay condition, that for some hens (namely Hens 11, 12, 13 and 16), response rates were fastest, between-ratio pause durations were shortest, P_{max} values were largest, and demand was most inelastic or had the greatest essential value, is not clear. It seems possible that this is the result of more persistent responding during the sessions with this delay value for these hens. The data in Appendix 2 show that it was replicated in the various series conducted with this delay so was not simply the result of some short period of aberrant responding. The question remains as to why these hens persisted in these sessions with this delay.

One way of viewing the findings from the 8-s delay condition lies in consideration of the amount of session time spent responding and pausing and how this was affected by both FR and delay. There were three sorts of pauses that occurred during the session. The first was pausing due to cessation of responding mid-session (within-session pausing). This type of pausing was most common at small FR values and decreased with increases in the FR value, although it often became more frequent at the very largest FR sizes (e.g., Figure 2.7). The second type of pausing was influenced by the ratio size and occurred following a reinforcer (between-ratio pause). This type of pausing tended to increase as the FR increased (e.g., Figure 2.12). Added together, these two types of pausing also helped to give rise to bitonic rates of overall responding and curvilinear demand functions with values of P_{max} at midrange FR values. At small FR values, even though between-ratio pausing was short, overall response rates were low, because within-session pausing occurred most frequently. At the largest FR values, overall response rates were also low because between-ratio pauses were long, and within-session pausing also occurred. Response rates typically peaked across moderate FR values because responding filled the session and no within-session pausing occurred. Between-ratio pausing was the only type of pausing that influenced the response rate at moderate FR values. Hence, the bitonic rates of overall responding common in behaviour under increasing FR schedules.

Between-ratio pausing in the present experiment was further influenced by the length of the delay, and increased as the delay increased (e.g., Figure 2.11). As the delay increased, between-ratio pause durations increased across all FR values, and within-session pausing occurred more frequently at large FR values. At small FR values and small delays, responding did not fill the session. Because of longer between-ratio pause durations at larger delays, responding was slower, but still did not fill the session. Therefore in all delay conditions, as the ratio increased to moderate FR sizes, rates of responding increased when calculated including the total key time. When the session was filled with responding at moderate FR values, overall response rates became lower with increased delay as more of the session was filled with longer durations of between-ratio pausing than at small delays. At the largest FR values, at large delays, between-ratio pause durations were large and within-session pausing occurred more frequently than at small delays, resulting in lower overall response rates. However, this consideration of the proportion of the session in which responding occurred does not fully clarify the unusual findings of some hens in the 8-s delay condition. Thus, it is not clear why behaviour persisted over the session in the 8-s delay condition for some hens and so resulted in summary measures (overall response rates and between-ratio pauses) that were similar to those in the 0-s delay condition.

Increasing the delay appears similar to increasing the FR response requirement, in that both increase the overall duration of the schedule. The relation between FR requirement and overall response rate tends to be bitonic. As the FR increases, the overall response rate increases over small FRs and then this peaks at moderate FR values. It may be that the function relating overall response rate to delay is also bitonic in some cases with the highest rates, for some hens, being at the moderate delay value of 8 s.

In sum, the present experiment found that delay-to-reinforcement did not influence demand in a manner similar to previous experiments which manipulated reinforcer quality and magnitude. Initial demand was not higher for the devalued reinforcer, and the effects of increasing delay were small. Total consumption and overall and running response rates decreased, and between-ratio pausing increased with increasing delay, congruent with previous delay-to-reinforcement research and the findings of Experiment 1. Alternatives to averaging the whole session data for presenting overall response rates and between-ratio pause durations have been discussed. The exploration of a new demand equation yielded no better fit to the data, nor provided further clarification of the present findings.

EXPERIMENT 3

As mentioned previously, when investigating demand across a range of prices, the length of the session, especially in short-session conditions, can influence consumption as the FR increases. Bauman (1991) outlined and attempted to separate two possible explanations as to why consumption decreases with increases in the FR requirement. He described the first as effort-based, and suggested that as the FR increases, the subject simply does not keep responding at rates sufficient to maintain the level of reinforcement obtained at the smallest ratio. He said the second time-based explanation depends on the increasing time between reinforcers that necessarily comes with an increase in the FR. Bauman (1991) pointed out that this increasing interval between reinforcers represents an increasing delay to reinforcement from the first response of the ratio. In Experiments 1 and 2 of this thesis, an increasing delay-to-reinforcement was found to reduce response rates, and increase durations of between-ratio pausing when compared to no delay.

Using 24-hr closed economic conditions, Bauman (1991) exposed rats to increasing FR schedules and their time-equivalent, response-initiated fixed-interval (FI) schedules to compare the time-based and effort-based explanations. In the response-initiated FI schedules the interval began with the subject's first response following reinforcement, whereas in traditional FI schedules the interval begins at the end of the reinforcement period. In the FR condition, as the FR increased, response rates increased, however, consumption decreased, and time to reinforcement increased. In the time-equivalent FI schedules, even though only two responses were required (one to start the schedule and one to produce reinforcement), consumption decreased similarly with increases in the schedule size. Bauman (1991) argued that this provides support for the time-based explanation that consumption decreases with increases in FR because of the increased time it takes to complete the schedule, rather than because of the increased response requirement. Perhaps increasing the responses required without increasing the duration of the schedule may not result in reduced response rates and increased between-ratio pause durations.

Partial support for Bauman's suggestion that time is a critical factor in decreasing consumption came from a similar study by Tsunematsu (2000). This study also compared performance on FR schedules with that on their time-equivalent response-initiated FI schedules. In a related study, Neuringer and Schneider (1968) manipulated inter-reinforcement time by following each unreinforced response with a blackout in FR and FI schedules. Both studies suggest that responding is controlled by the inter-reinforcement time rather than the number of responses made between reinforcers.

Neuringer and Schneider (1968) argued that they were able to manipulate the time to reinforcement and control responding in the FR conditions with the added blackouts. However, in both Bauman's (1991) and Tsunematsu's (2000) studies the number of responses were allowed to vary freely during the interval conditions. Bauman (1991) found that responses increased during the FI conditions, although generally not to the same degree as in the equivalent FR conditions, while Tsunematsu (2000) did not report these data. That the number of responses increased under the FI schedules means these data do not provide conclusive support for the suggestion that it is the increasing duration of the schedule alone that results in decreasing consumption when the FR is increased. To examine this further, it is necessary to extend this research with a schedule of reinforcement that controls both the time and response parameters of the price analogue. Such a schedule, allowing one of these parameters to be held constant while parametrically manipulating the other, would provide clarification as to whether it is the duration or response requirement that has more effect on behaviour. One schedule that allows responses and time to be varied independently is a conjunctive FR FI schedule of reinforcement.

Morse (1966) described conjunctive schedules as compound schedules, which consist of both a time and a response contingency. Barrett (1974) explained that under conjunctive schedules, both the time and response requirements must be met for a reinforcer to be delivered. For example, under a conjunctive FR 250 FI 5-min schedule, both the 5-min passage of time and the 250 required responses must be made to receive a reinforcer.

The earliest published study investigating conjunctive schedules was conducted by Herrnstein and Morse (1958) who initially trained two pigeons for several weeks on an FI 15-min schedule, with a 5-min blackout period following reinforcement. Following training, a range of FR requirements (FR 10, 40 120 and 240 for one subject; FR 40, 120 and 240 for the other) were added to the FI 15-min component. In order to receive a reinforcer while working under the conjunctive FR 40 FI 15-min schedule, the subjects had to complete both the 40 required responses and FI 15-min schedule. Herrnstein and Morse (1958) reported that the overall response rate was highest under the FI 15-min schedule. The addition of the smallest FR value, although much smaller than the number of responses typically completed under the FI 15-min schedule, reduced the overall response rate, which monotonically decreased with further increases in the FR requirement. This is because the variation in responding under the FI schedule was so great that occasionally the FR requirement was not completed within the FI. The authors reported that at the highest FR values, the rate of responding was so low that most of the reinforcers were obtained through the FR component of the schedule.

Much conjunctive schedule research since Herrnstein and Morse (1958), particularly those studies using conjunctive FR FT schedules, has been aimed at comparing behaviour on these schedules with behaviour on FI or similar schedules. Most have used only one value for each of the schedule components (e.g., Leander, Milan & Jasper, 1972; Morgan, 1970; Shull, 1970, 1971; Staddon & Frank, 1975). There are only some experiments in which either one of the schedule components of the conjunctive schedule has been manipulated systematically (e.g., Barrett, 1976; Herrnstein & Morse, 1958; Hitzing & Kaye, 1969; Katz & Barrett, 1979; Powers, 1968; Zieler, 1976; Zieler & Buchman, 1979). Furthermore, in both of these sets of studies, at times, various methodological details are often are unclear. For example, only one author (Zieler, 1976) specifically mentions at what point the interval component of the schedule began (immediately following reinforcement). It is not clear if this was also the case for the other studies mentioned above.

Sealey, Sumpter, Temple and Foster (2005) attempted to investigate the effects of time and effort independently in concurrent second-order schedules. Based on Foster, Temple, Mackenzie, DeMello and Poling (1995), Sealey et al. (2005) defined an operant unit (in concurrent schedules) as the completion of an FR requirement within a period specified by an FI schedule, followed by an additional response to fulfil the FI component. Hence, both the duration and the response requirement could be controlled and varied. The authors concluded that these contingencies controlled both the numbers of responses and durations allowed.

The Sealey et al. (2005) study suggests that conjunctive FR FI schedules of reinforcement may provide a means of varying time-cost and response-cost factors separately when evaluating demand. The present experiment used such a schedule to define an operant unit in a similar way to Sealey et al. (2005). This would allow determination of whether it is the duration of the schedule or the response requirement that has the most effect on behaviour in FR schedules. Thus an adaptation of Sealey et al.'s (2005) methodology was used. A recycling conjunctive FR FI schedule in which the ratio was increased across sessions but the FI schedule held constant allowed for the assessment of the effects of increasing the ratio requirement with a fixed interval-schedule duration (increasing FR conditions). In other conditions the FI schedule duration increased across sessions with the ratio requirement fixed (increasing FI conditions).

The recycling aspect means that if either of the schedule requirements was not completed, a reinforcer was not presented, and the interval began again (cf., Staddon & Frank, 1975). Like Sealy et al. (2005), the first response to the single lighted key started both the FR requirement and the FI schedule. This means that the FI schedule was response-initiated, resembling the methodologies of Bauman (1991) and Tsunematsu (2000), but dissimilar to most previous conjunctive schedule procedures in which the FI (or FT) schedules appear to have started at the end of the previous reinforcement time. In the present study, for the schedule requirements to be met and the operant unit completed, the FR requirement had to be completed within the FI duration and a further single response made within a brief time after the FI terminated.

If the FR requirement was not completed within the FI schedule, or the terminal response not made within 5 s of the end of the FI schedule, a reinforcer was not obtained, and the responses made did not 'carry over' to the next 'trial'. Instead, both schedule requirements recommenced from the next response following a 3-s blackout. Hence double or longer inter-reinforcement intervals were possible. Some researchers using traditional non-recycling conjunctive schedules have reported an increase in the inter-reinforcement interval along with increases in FR (Herrnstein & Morse, 1958; Zieler & Buchman, 1979). Resetting both the FR and FI requirements (recycling) in the present procedure, along with the response-dependent FI schedule, ensured that the time available for the subject to respond remained constant as the ratio requirement increased.

In the present study, once the FR was completed within the FI schedule, the response key was darkened, and a light below the response key lit. When a reinforcer was available according to the FI schedule, the light below the response key was extinguished, and the response key was re-lit for 5 s to allow the subject to perform the terminal response. Given that the response requirements of both schedules were met, the subject was given 3-s access to wheat. The first response following reinforcement restarted both schedule requirements.

In Experiment 2 of this thesis, total consumption was used as the measure for comparing conditions as the time available for responding was held constant in each condition. In the present experiment sessions lengths were expected to differ as they were to end either on a set number of reinforcers, or total session time, whichever occurred first. This means that consumption would not be a suitable way to compare the data in the present experiment. Consumption rate (reinforcers obtained divided by the session time) has been argued to be a better measure for comparing demand than total consumption when the time available for responding differs between sessions or experiments (Sumpter, Temple & Foster, 2004). One way in which the data in the present experiment may be analysed is using consumption rate.

However, consumption rate as a measure of performance for the present procedure using conjunctive schedules is confounded. In Experiment 1 where the total time to reinforcement increased with increases in the delay duration and with the FR held constant, response rates decreased and pausing increased, lowering the rate of reinforcement. In the present experiment, when the duration of the schedule was increased due to increasing the FI (increasing FI conditions), consumption rate would necessarily decrease, assuming that the subjects respond throughout the entire session. In the increasing FR conditions of the present experiment, in which the FI duration was held constant, the consumption rate could potentially remain constant across all FR values tested. In all conditions, the duration of any particular operant unit, once started, was fixed. This means that the only aspect of a subject’s behaviour free to vary was the pause prior to starting the operant unit (between-operant unit pause; equivalent to the between-ratio pause in Experiments 1 and 2). The maximum possible consumption rate in each set of conditions would be obtained if the hen started each operant unit immediately after the key was lit following reinforcement. Any pausing that delayed the initiation of the operant unit would lower the consumption rate. However, consumption rate would vary differently in the fixed-FI (increasing FR) and the fixed-FR (increasing FI) conditions. In conditions in which the FI is fixed the duration of the operant unit remains constant, and pausing between operant units is the only way that the consumption rate will differ from the maximum rate. In conditions in which the FR is fixed the consumption rate is jointly dependent on the length of the FI and the pausing. Hence, another possible measure of the rate of performance, independent of the duration of the operant unit, is the schedule-initiation immediacy, calculated as the inverse of the latency to respond (inverse of the between-operant unit pause duration). This measure would change similarly to the consumption rate if the time taken to complete the response requirement was disregarded. Additionally, the schedule-initiation immediacy, which varies with the pause duration alone, is independent of the duration of the operant unit and so can be compared over conditions where the operant unit differs in duration.

The aim of the current experiment was to separate the two parameters of FR schedule performance; that is to control both the number of responses made and the duration of the schedule independently. A response-initiated, recycling conjunctive FR FI schedule of reinforcement was used. Both the FR and FI were controlled by the experimenter, allowing the response requirement to be varied and the duration to be held constant, or the response requirement to be held constant and the duration to be varied. To complete the schedule, the subjects had to complete the FR within the FI, and to make a final terminal response to complete the FI requirement. In Experiments 1 and 2 of this thesis, increased schedule duration with the addition of various delays to reinforcement both reduced response rates (overall and running) and increased between-ratio pausing compared to when there was no delay. Based on these findings and the results of Bauman (1991), Neuringer and Schneider (1968), and Tsunematsu (2000), it could be expected that duration of the schedule would have a greater effect on behaviour than the number of responses required. It was expected that in conditions in which duration was increased (increasing FI), both the rates of consumption and the schedule-initiation immediacies would decrease (between-operant unit pauses would increase) along with increases in the FI. In conditions in which duration was constant (increasing FR), it was expected that both the rates of consumption and the schedule-initiation immediacies would remain relatively constant.

Method

Subjects

Six Shaver-Starcross domestic hens, numbered 71 through 76, served. They were two years old at the start of the experiment, and had had experience on simple schedules of reinforcement. They were given free access to water, with grit and vitamins provided weekly. All hens had red fleshy combs, suggesting good health. Each hen was weighed every day experimental sessions took place (approximately six days per week), and they were maintained at 80% (+/–5%) of their free-feeding body weights through feeding of commercial layer pellets.

Over the duration of these experimental conditions, approximately two and a half years, Hens 74 and 76 died of causes unrelated to the experiment. They were not replaced and therefore there are complete data sets for only four hens.

Apparatus

The particleboard experimental chamber (610-mm long × 450-mm wide × 570-mm high), was located in a room with several others. On the right-hand wall of the chamber, a food magazine was located behind an opening (100-mm high × 70-mm wide) centred 120 mm above the floor. When operational, the magazine was lit and raised to allow 3-s access to wheat.

Above the magazine opening (360-mm from the floor) was a frosted transparent plastic response key (30-mm in diameter), which was lit red with a 28-V multi-chip LED bulb. A response force of approximately 0.2 N resulted in an audible beep when operational. Centred between the magazine opening and response key (300 mm from the floor) was a signal light (14 mm in diameter), which, when operational, was lit green with a 28-V multi-chip LED bulb.

The experiment was controlled and all experimental events were recorded by a Dell PC computer (398MHz, P4, 192MB, Windows XP Service Pak 1) operating Med-PC® IV software. Total session data were also manually recorded into a data book at the end of each session.

Procedure

In the experiment proper, a single response to the lighted key initiated both components of the conjunctive FR FI schedule; it was counted as the first response of the FR schedule and started the timer of the FI schedule. When the FR component was complete, the key light was extinguished and the signal light was lit. Responses to the unlit key had no effect until the final 5 s of the FI schedule. In the final 5 s, if any non-FR responses (to the darkened key; blackout pecks) were made, the FI was automatically extended by 5 s. The ‘extension’ was restarted with each additional blackout peck. However, there was no penalty for FR responding that continued into the final 5 s of the FI schedule. At the completion of the FI duration, the signal light was extinguished and the key light was re-lit for 5 s to allow for the completion of the terminal FI response. If the terminal FI response was made, the key light was extinguished and the magazine was raised for 3 s. If the terminal response was not made in time, or the FR was not completed within the FI, the trial was aborted, signalled by a 3-s blackout. Immediately following the 3-s reinforcement or blackout, the key light was re-lit.

Training. The hens were initially exposed to two series of increasing FR schedules of reinforcement. The first FR value in a series was FR 1, and then the ratio was doubled each session until no reinforcers were received for two consecutive sessions. The series was deemed to have ended at this ratio. Initially, and between series, the hens were exposed to FR 20 for at least three sessions. The key light was lit at the start of the experimental session, which lasted until the key time (total session time less reinforcer time) reached 40-min, when the key light was extinguished. For each hen, experimental sessions were conducted every day or every other day (when FR values were below 16).

The hens were then exposed to a conjunctive FR 1 FI *x*-s schedule. During all training conditions responses to the darkened key in the final 5 s of the FI did not extend the FI duration. The FI was increased over sessions and the FR was always FR 1, therefore, two responses were needed to meet the schedule requirements. The first FI value in a series was FI 1 s, followed by FI 2 s and FI 5 s. The FI was then increased by 5 s until the final session in which the FI reached 30 s. Sessions ended after 50 reinforcers had been received or a total session time of 40 min had elapsed, whichever occurred first. This series was repeated six times. Experimental sessions were conducted for all six hens each day, approximately six days per week.

After this series, the conjunctive FR requirement was removed, and the hens were exposed to a limited-hold FI 60-s schedule for approximately 30 sessions. The FI timer began at the start of the session, and the key light remained on for the entire 60 s. If a response was made within the 5 s immediately following the completion of the FI 60-s schedule, the key was darkened and magazine raised for 3 s; otherwise the terminated trial was followed by a 3-s blackout. Immediately after the reinforcer or blackout, the key was re-lit and FI 60-s timer restarted. Experimental sessions were conducted every day and lasted for a total session time of 40 min.

In the final stage of training, a conjunctive FR *x* FI 60-s schedule of reinforcement was introduced. The FI was always 60 s in duration, while the FR increased each session (beginning with FR 1 and doubling each session until no reinforcers were obtained on two consecutive exposures to a single FR value). Sessions ended on the next reinforcer after 40 min. Three series of increasing FR schedules were conducted. Before and between each series all hens were exposed to a conjunctive FR 10 FI 60-s schedule for at least three days. This concluded the training. In total, training lasted 184 days.

Condition 1: Increasing FR (Conjunctive FR x FI 60-s schedule). The only difference between Condition 1 and the training conjunctive FR *x* FI 60-s schedule was that any non-FR responses made to the darkened key (blackout pecks) in the last 5 s of the FI resulted in a 5-s extension of the FI interval. Experimental sessions were conducted for each hen each day, approximately six days per week and sessions ended after a total session time of 40 min. Nine series of FR increases were conducted, and between each series the hens were exposed to a conjunctive FR 10 FI 60-s schedule for at least three sessions. The highest ratio requirement reached by each hen was either 64 or 128 in the last five series (indicating seven or eight sessions in which a minimum of one reinforcer was obtained and at least two in which no reinforcers were obtained).

Condition 2: Increasing FI (Conjunctive FR 1 FI x-s schedule). In Condition 2, the FR was always 1, and the FI schedule doubled each session, resulting in a series that started at FI 1 s, and ended at FI 512 s (a total of 10 sessions). Sessions ended after 40 min or 50 reinforcers, whichever occurred first, for ten series of FI increases. For the last two series of FI increases, the total number of reinforcers that could be obtained in a session was reduced to 40. This reduced the effects on a particular day’s data of a large number of reinforcers on the previous day. Experimental sessions were conducted daily for each hen.

Condition 3: Increasing FR (Conjunctive FR x FI 30-s schedule). Condition 3 was almost identical to Condition 1, except the FI was fixed at 30 s. Another alteration was that, like the last two series of Condition 2, sessions ended after 40 reinforcers or 40 min, whichever occurred first. Eight series of FR increases were conducted. The highest ratio requirement reached by each hen was either 32 or 64 in the last five series (indicating six or seven sessions in which at least one reinforcer was obtained).

Condition 4: Increasing FR (Conjunctive FR x FI 120-s schedule). Condition 4 was identical to Condition 3, except the FI schedule was fixed at 120 s. Seven series of FR increases were conducted. The highest ratio requirement reached by each hen was either 64 or 128 in the last five series (indicating seven or eight sessions in which at least one reinforcer was obtained).

Condition 5: Increasing FI (Conjunctive FR 8 FI x-s schedule). Condition 5 was identical to the two final series of Condition 2, except the ratio requirement was held constant at FR 8, and the series began with an FI 8 s schedule. Ten series (comprising of seven sessions) of FI increases were conducted.

Condition 6: Increasing FI (Conjunctive FR 16 FI x-s schedule). Condition 6 was identical to Condition 5, except the ratio requirement was held constant at FR 16, and the series began with an FI 16 s schedule. Ten series (comprising of 6 sessions) of FI increases were conducted.

Data that were collected and recorded manually in the data book at the end of each session included the FR size, FI duration, time to first response, total numbers of responses, and the numbers of reinforcers obtained. Also noted was the between-operant unit pause time, run time, key time, FI time (time from the final response of the FR schedule to end of FI time), mean eating time, the amount of post feed required, and total session time. The numbers of responses during the FI blackout period and the numbers of FI schedules that were extended due to blackout responses were also recorded. Computer files were generated which contained all experimental events and their time of occurrence.

Results

Raw data from all conditions in Experiment 3 are presented in Appendix 3. Only the data from the last five series of each condition have been used in the analysis and presented here.

Consumption Rates

Figures 3.1 and 3.2 present, for all hens, the consumption rate data for the increasing FR conditions (FR *x* FI 30 s, FR *x* FI 60 s, and FR *x* FI 120 s), and the increasing FI conditions (FR 1 FI *x* s, FR 8 FI *x* s, and FR 16 FI *x* s), respectively, plotted against the natural logs of the FR or FI values. The consumption rate (in reinforcers per min) data were calculated by dividing the numbers of reinforcers obtained at each FR value by the total session time and then multiplying this value by 60. The data from the five most recently completed series in each condition were plotted on a natural logarithmic axis. Lines were fitted to the medians of these data using Hursh et al.'s (1988) nonlinear equation (Equation 2.1), nonlinear regression, and the method of least squares. The parameters of these lines are displayed in Table 3.1, along with the variances accounted for by the lines (*%VAC*), and the standard errors of the line estimates (*se*). The lines fitted to the consumption rate data accounted for over 90% of the variance of the data in 25 of 28 cases, and the *se* measures ranged from 0.02 to 0.25. In four of 13 cases in Figure 3.2 the fits of the line resulted in *a* values that are negative, and u-shaped functions predicting an increase in the consumption rate as the FR value increases. Therefore the fitted lines for these *a* values are not good indicators of the rate of change of elasticity.

The left, middle and right panels of Figure 3.1 show that, for all hens (excepting Hen 71 in the FI 120-s condition), the consumption rate functions remained relatively stable (flat and inelastic) across most increasing FR values in each condition, with the functions curving downwards abruptly at the last data points. The exception to this is Hen 71, whose data from the FI 120-s condition show a smoothly decreasing function. The estimates of the initial consumption rate (ln *L*) as well as the actual initial consumption rate data tended to decrease (in all nine cases) with FI increases, and the *a* values (rate of change of elasticity) also decreased slightly (in seven of nine cases). In all but one instance (Hen 71 in the FI 120-s condition), the *b* values (initial slope) were positive, indicating initial inelasticity.

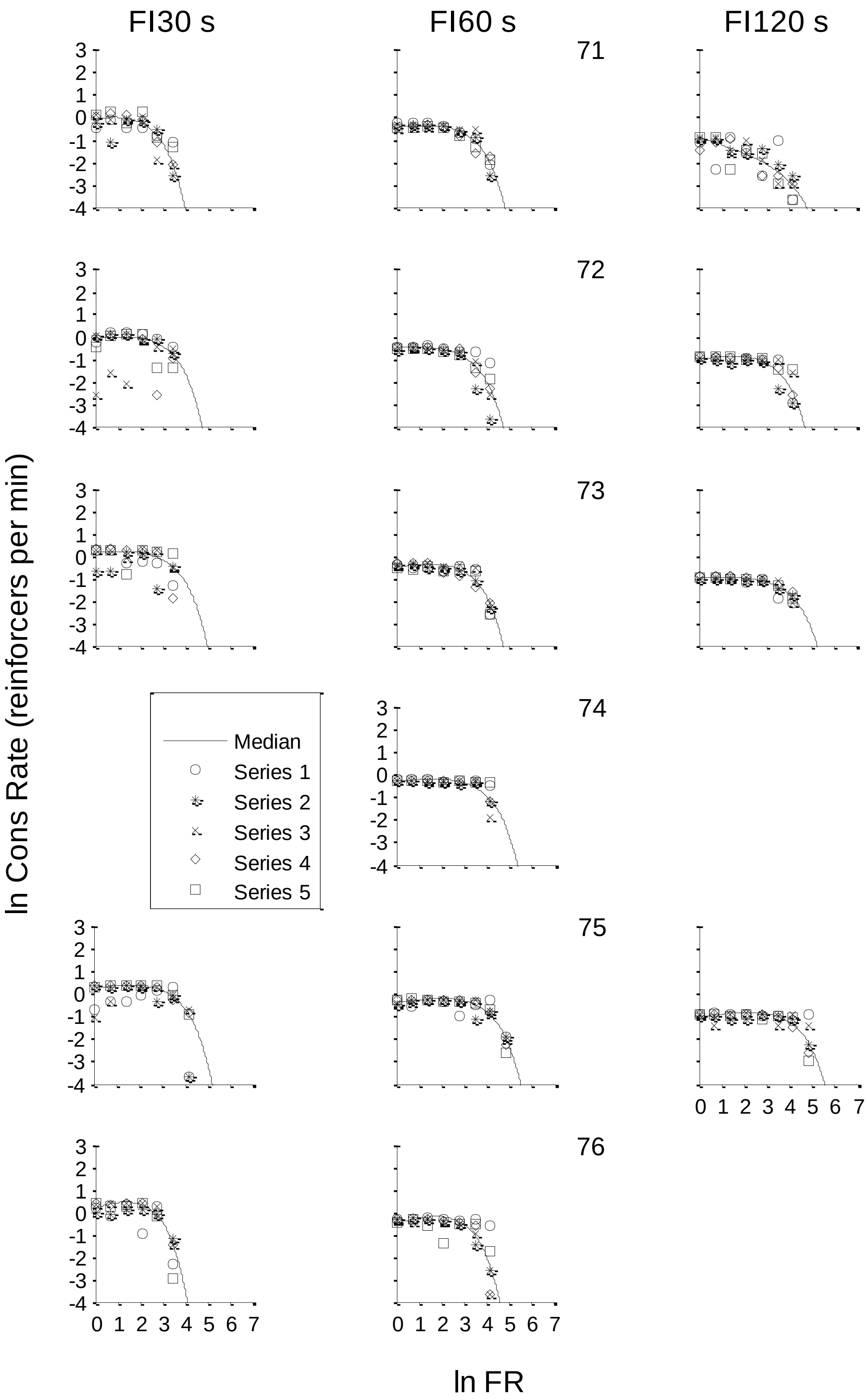

Figure 3.1. The natural logarithms of the consumption rate data, plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition (left panel), FR *x* FI 60-s condition (middle panel) and the FR *x* FI 120-s condition (right panel). All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

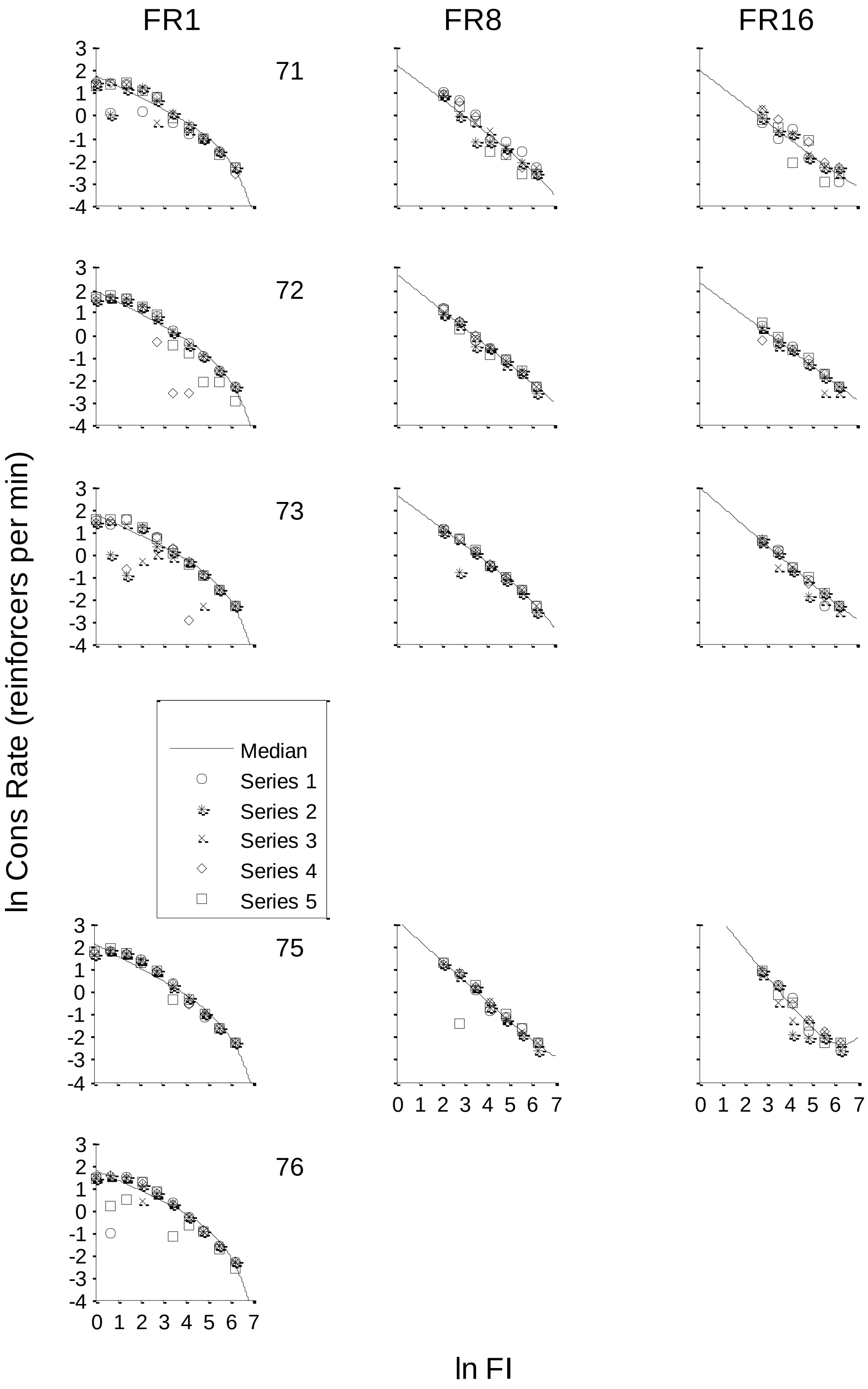

Figure 3.2. The natural logarithms of the consumption rate data, plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition (left panel), FR 8 FI *x*-s condition (middle panel) and the FR 16 FI *x*-s condition (right panel). All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

Table 3.1.

The parameters a, b and ln L for Hursh et al.'s (1988) nonlinear equation (Equation 1) fitted to the natural logarithms of the median consumption rate data from each increasing FR and increasing FI condition. Also shown are the standard errors of the estimates (se), the percentages of variance accounted for by the lines (%VAC) and the FR values at which maximal responding is predicted (P_{max}).

Hen	Condition	ln *L*	*b*	*a*	*se*	*%VAC*	P_{max}
71	FR *x* FI 30-s	0.04	0.21	0.08906	0.10	98.35	14
	FR *x* FI 60-s	-0.41	0.14	0.03462	0.03	99.65	33
	FR *x* FI 120-s	-0.88	-0.31	0.01409	0.12	96.96	49
	FR 1 FI *x*-s	1.82	-0.48	0.00243	0.25	96.32	213
	FR 8 FI *x*-s	2.95	-0.95	-0.00074	0.09	99.45	-72
	FR 16 FI *x*-s	0.63	-0.38	0.00207	0.25	77.92	301
72	FR *x* FI 30-s	-0.06	0.15	0.03936	0.11	86.27	29
	FR *x* FI 60-s	-0.45	0.08	0.03441	0.07	98.82	31
	FR *x* FI 120-s	-0.96	0.16	0.03482	0.08	97.96	33
	FR 1 FI *x*-s	2.00	-0.51	0.00247	0.23	97.09	199
	FR 8 FI *x*-s	2.72	-0.80	0.00011	0.02	99.97	1933
	FR 16 FI *x*-s	2.35	-0.74	0.00003	0.07	99.30	7692
73	FR *x* FI 30-s	0.20	0.09	0.03140	0.16	70.08	35
	FR *x* FI 60-s	-0.46	0.18	0.03820	0.18	91.58	31
	FR *x* FI 120-s	-0.98	0.05	0.01736	0.03	99.02	61
	FR 1 FI *x*-s	1.79	-0.46	0.00267	0.20	97.49	203
	FR 8 FI *x*-s	2.43	-0.67	0.00108	0.07	94.82	302
	FR 16 FI *x*-s	3.00	-0.86	-0.00016	0.04	99.82	-833
74	FR *x* FI 60-s	-0.29	0.11	0.02030	0.10	90.46	55
75	FR *x* FI 30-s	0.27	0.14	0.02764	0.04	99.19	41
	FR *x* FI 60-s	-0.37	0.14	0.01802	0.08	98.16	63
	FR *x* FI 120-s	-1.01	0.14	0.01464	0.11	93.67	78
	FR 1 FI *x*-s	2.12	-0.52	0.00257	0.25	96.88	186
	FR 8 FI *x*-s	3.20	-0.90	-0.00024	0.09	99.44	-417
	FR 16 FI *x*-s	4.43	-1.26	-0.00217	0.09	99.45	121
76	FR *x* FI 30-s	0.27	0.41	0.09760	0.10	97.67	15
	FR *x* FI 60-s	-0.44	0.30	0.05090	0.20	93.41	26
	FR 1 FI *x*-s	1.80	-0.44	0.00298	0.23	96.78	188

In Figure 3.2 the left, middle and right panels show that, for all hens, the consumption rate functions decreased across increasing FI values in each condition. In the left panels, the consumption rates in the FR 1 condition show curvilinear decreasing functions. In both the middle and right panels, the functions in the FR 8 and FR 16 conditions are almost linear (with very small a values), curving upwards beyond the last data point in four cases and downwards in the remaining four cases. While the actual individual consumption rate data points at the smallest FI values (FI 1, 8 and 16) decreased with increasing FR in all three panels, the estimates of $\ln L$ from the fitted lines tended to increase (in six of eight instances) with increasing FR values, while the b values became larger negative numbers (in six of eight instances), and the a values decreased in seven of eight cases.

In sum, Figure 3.1 shows that consumption rates remained stable across most FR increases in the increasing FR conditions. Figure 3.2 shows that consumption rates decreased with increasing FI in the increasing FI conditions.

Schedule-Initiation Immediacies

Figures 3.3 and 3.4 present, for all hens, the schedule-initiation immediacy data (using just the between-operant unit pause values) for the increasing FR conditions and the increasing FI conditions, respectively, plotted against the natural logs of the FR or FI values. The data were obtained by taking the median between-operant unit pause duration from each session. The schedule-initiation immediacies (per min) were calculated by dividing 60 by the median between-operant unit pause, and then plotted on natural logarithmic axes. Again, the lines were fitted to the medians of these data using Hursh et al.'s (1988) nonlinear equation (Equation 2.1), and the parameters of these lines are displayed in Table 3.2, along with the variances accounted for by the lines (*%VAC*), and the standard errors of the line estimates (*se*). The lines fitted to the schedule-initiation immediacy data accounted for between 30% and 99% of the variance of the data, and the *se* measures ranged from 0.05 to 0.29. In 17 of the 28 cases, the a values were negative, resulting in u-shaped functions, predicting an increase in the schedule-initiation immediacy as the FR value increases. Thus, the fitted lines for these a values are not a good indicator of the rate of change of elasticity.

Notwithstanding these negative a values, the left, middle and right panels of Figure 3.3 show that, for all hens (excepting Hen 71 in the FI 120-s condition),

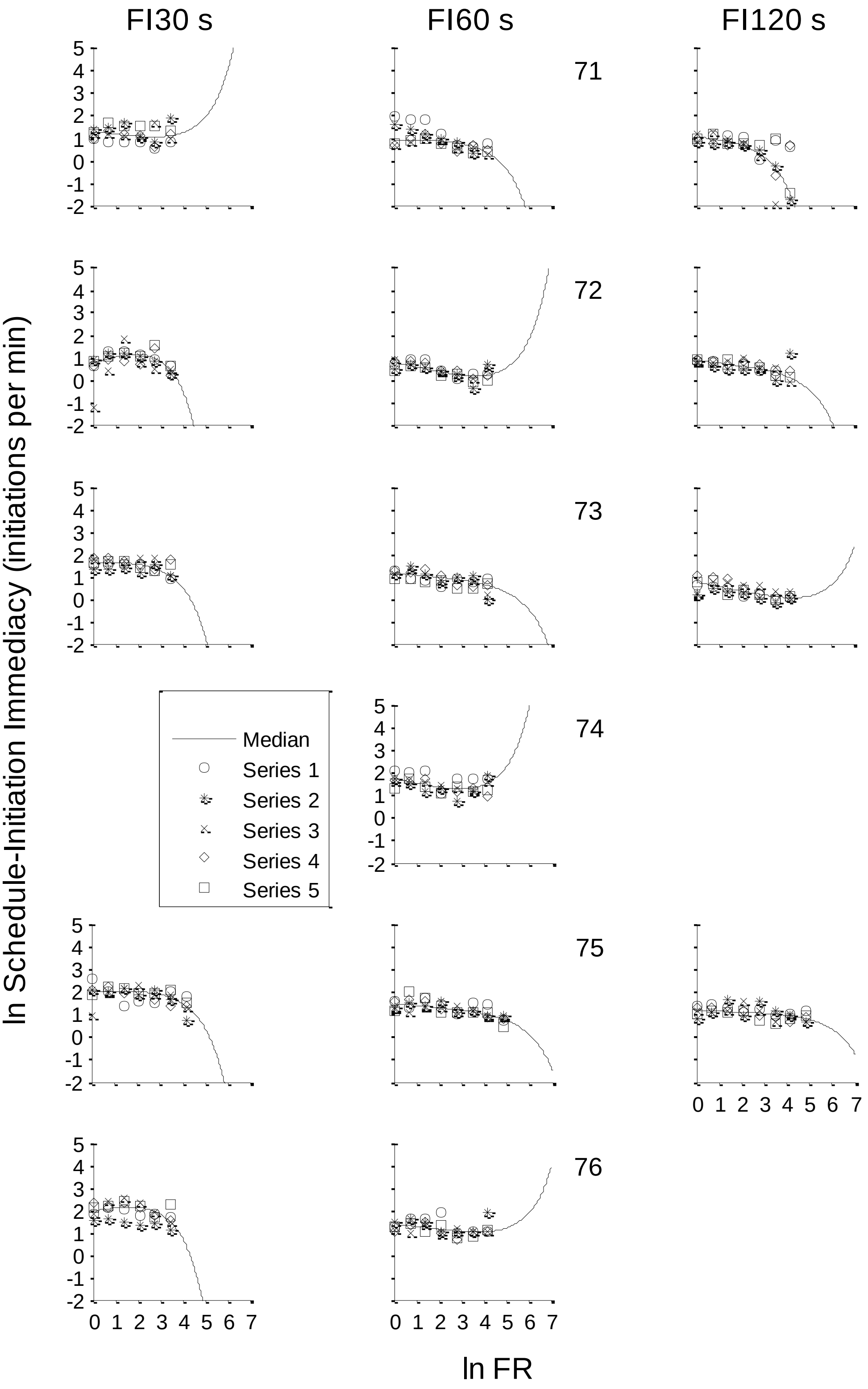

Figure 3.3. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

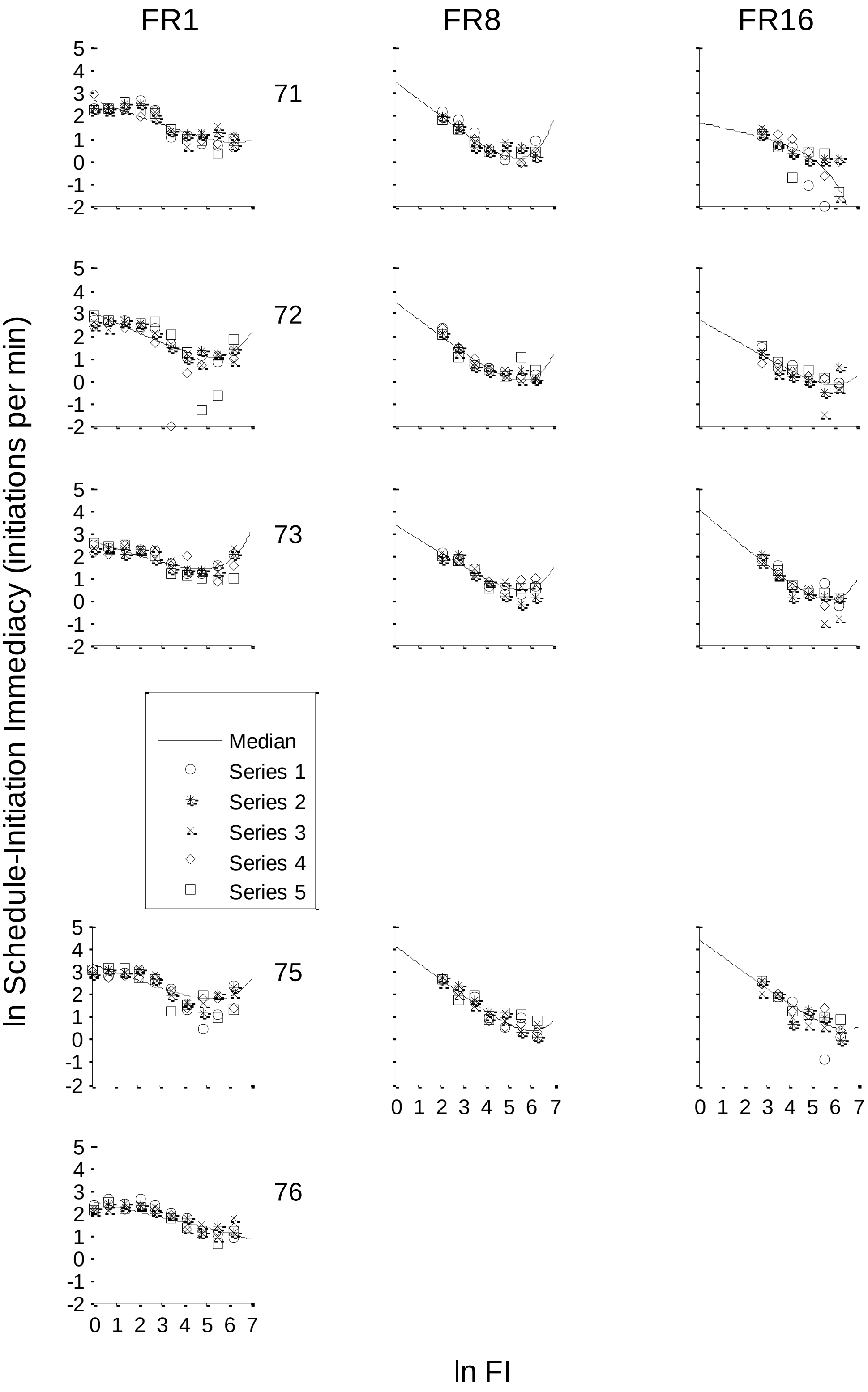

Figure 3.4. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.’s (1988) nonlinear equation (Equation 2.1).

Table 3.2.

The parameters a, b and ln L for Hursh et al.'s (1988) nonlinear equation (Equation 1) fitted to the natural logarithms of the median schedule-initiation immediacy data from each increasing FR and increasing FI condition. Also shown are the standard errors of the estimates (se) and the percentages of variance accounted for by the lines (%VAC).

Hen	Condition	ln *L*	*b*	*a*	*se*	*%VAC*
71	FR *x* FI 30-s	1.27	-0.13	-0.00863	0.12	29.99
	FR *x* FI 60-s	0.91	0.01	0.00965	0.17	56.86
	FR *x* FI 120-s	1.08	-0.07	0.03602	0.10	98.70
	FR 1 FI *x*-s	2.70	-0.35	-0.00061	0.29	82.80
	FR 8 FI *x*-s	3.52	-0.77	-0.00335	0.09	97.76
	FR 16 FI *x*-s	1.71	-0.22	0.00317	0.18	95.31
72	FR *x* FI 30-s	0.78	0.35	0.04868	0.08	89.01
	FR *x* FI 60-s	0.76	-0.22	-0.00586	0.09	83.78
	FR *x* FI 120-s	0.85	-0.10	0.00519	0.06	94.60
	FR 1 FI *x*-s	3.02	-0.45	-0.00202	0.28	85.09
	FR 8 FI *x*-s	3.49	-0.75	-0.00271	0.14	96.11
	FR 16 FI *x*-s	2.72	-0.57	-0.00134	0.13	93.03
73	FR *x* FI 30-s	1.64	0.03	0.02313	0.05	95.26
	FR *x* FI 60-s	1.18	-0.09	0.00271	0.08	85.05
	FR *x* FI 120-s	0.74	-0.21	-0.00274	0.09	87.23
	FR 1 FI *x*-s	2.62	-0.32	-0.00243	0.21	78.94
	FR 8 FI *x*-s	3.35	-0.63	-0.00227	0.10	96.87
	FR 16 FI *x*-s	4.05	-0.84	-0.00247	0.09	98.11
74	FR *x* FI 60-s	1.72	-0.23	-0.01137	0.07	81.00
75	FR *x* FI 30-s	2.03	0.03	0.01223	0.07	91.29
	FR *x* FI 60-s	1.48	-0.09	0.00213	0.11	80.19
	FR *x* FI 120-s	1.16	-0.03	0.00154	0.07	74.25
	FR 1 FI *x*-s	3.32	-0.36	-0.00168	0.25	81.50
	FR 8 FI *x*-s	4.13	-0.74	-0.00171	0.13	97.44
	FR 16 FI *x*-s	4.42	-0.72	-0.00106	0.15	95.39
76	FR *x* FI 30-s	1.99	0.20	0.03747	0.13	75.19
	FR *x* FI 60-s	1.38	-0.13	-0.00315	0.12	51.00
	FR 1 FI *x*-s	2.49	-0.23	0.00010	0.22	81.37

the schedule-initiation immediacy functions remained relatively stable (flat) across increasing FR values in each particular FI condition, decreasing only slightly as the FR increased. For the five increasing functions, the flat portion of the function is followed by an upward sloping rise. For nine of the other 10, the functions curve abruptly downwards after the last data point.

Both the actual initial schedule-initiation immediacies and estimates of ln *L* tended to decrease (in five of nine, and six of nine instances, respectively) with larger FI values, while the *b* values became slightly larger negative numbers (in seven of nine cases), and the *a* values increased slightly (in five of nine cases).

Again, notwithstanding the negative *a* values, the left, middle and right panels of Figure 3.4 show that, for all hens, the schedule-initiation immediacy functions decreased steadily across increasing FI values in each particular FR condition. In all instances, the decreasing portion of the fitted function is followed by an upward sloping rise. While the individual initial schedule-initiation immediacy data points decreased with larger FR values, the estimates of ln *L* tended to increase (in six of eight instances) with larger FR values, the *b* values became larger negative numbers (in five of eight cases), and the *a* values increased (in five of eight cases).

The schedule-initiation immediacy data previously presented in Figure 3.3 are re-presented in Figure 3.5 for the increasing FR conditions. The schedule-initiation immediacy data that were previously presented in Figure 3.4 for the increasing FI conditions are re-presented in Figure 3.6. Straight lines were fitted to the medians using the robust regression analysis available in Matlab®. The parameters of these lines are displayed in Table 3.3, with the variances accounted for by the lines (*%VAC*), and the standard errors of the line estimates (*se*). The lines fitted to the schedule-initiation immediacy data accounted for between 8% and 94% of the variance of the data, and the *se* measures ranged from 0.08 to 0.51.

The left, middle and right panels of Figure 3.5 show that, for all hens (excepting Hen 71 in the FI 120-s condition), the schedule-initiation immediacy functions remained relatively stable (flat) across FR values, decreasing only slightly as the FR increased. The function fitted to the data from Hen 71 in the FI 120-s condition appears to be steeper than those of the other subjects, however, this is largely due to one aberrant point at FR 64. With larger FI values both the

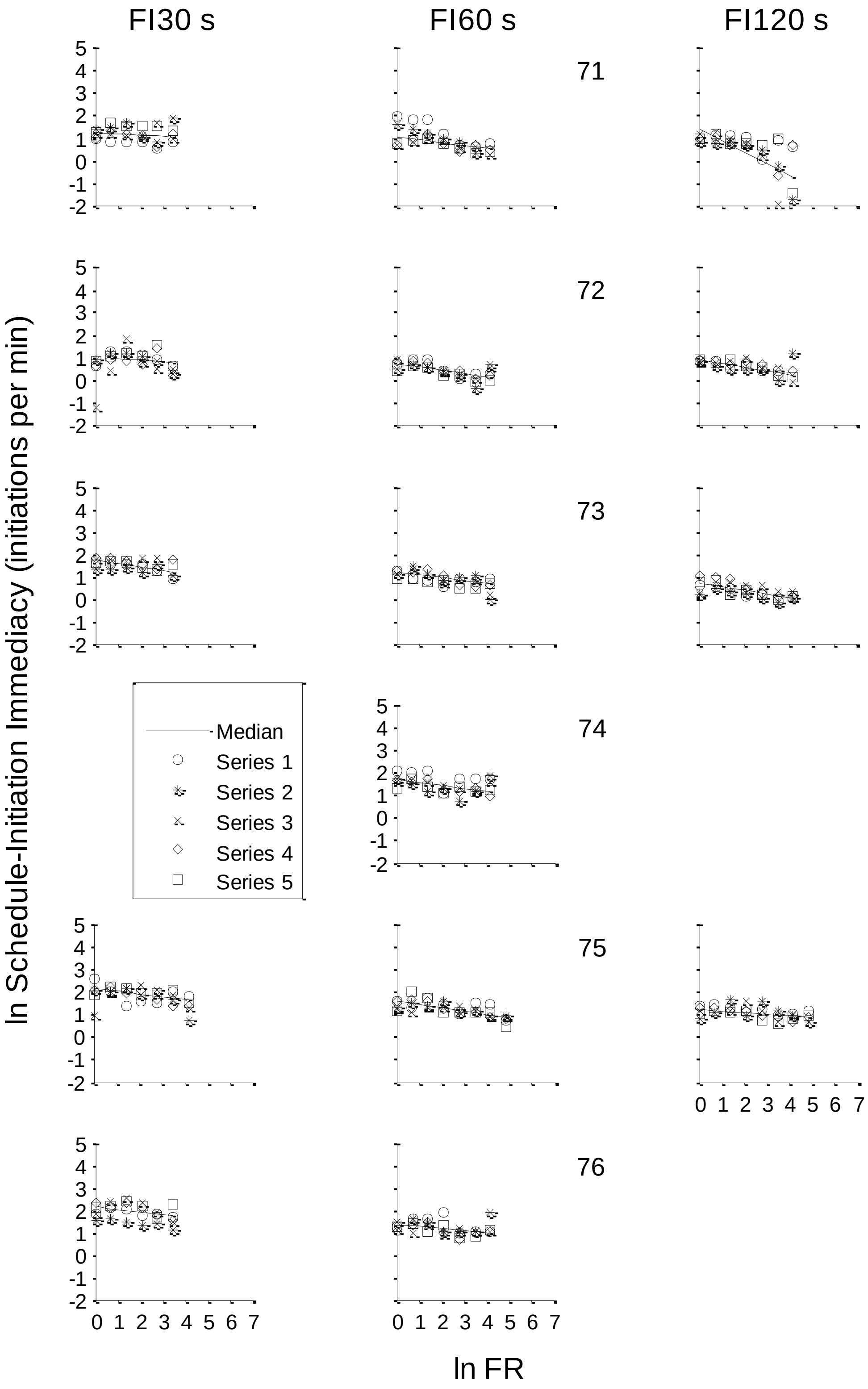

Figure 3.5. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using the robust regression analysis available in Matlab®.

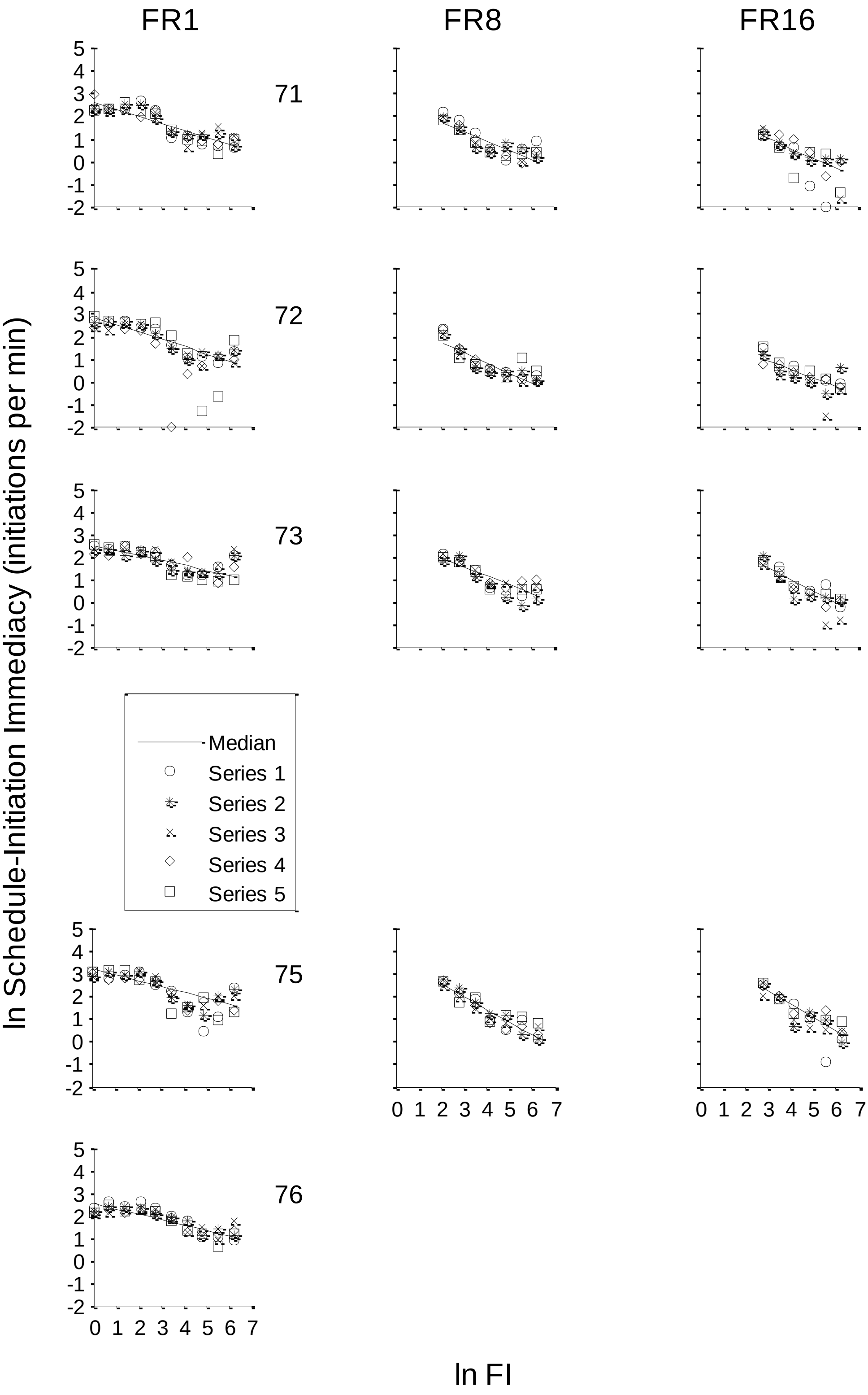

Figure 3.6. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using the robust regression analysis available in Matlab®.

Table 3.3.

The intercepts and slopes of the robust regression lines fitted to the natural logarithms of the median schedule-initiation immediacy data from each increasing FR and increasing FI condition. Also shown are the standard errors of the estimates (se) and the percentages of variance accounted for by the lines (%VAC).

Hen	Condition	Intercept	Slope	*se*	*%VAC*
71	FR *x* FI 30-s	1.24	-0.06	0.16	22.73
	FR *x* FI 60-s	1.04	-0.13	0.22	43.93
	FR *x* FI 120-s	1.42	-0.52	0.45	80.23
	FR 1 FI *x*-s	2.63	-0.31	0.33	82.10
	FR 8 FI *x*-s	2.52	-0.41	0.34	79.27
	FR 16 FI *x*-s	2.31	-0.43	0.51	87.12
72	FR *x* FI 30-s	0.98	-0.06	0.29	7.56
	FR *x* FI 60-s	0.71	-0.15	0.13	76.93
	FR *x* FI 120-s	0.90	-0.17	0.09	90.29
	FR 1 FI *x*-s	2.84	-0.32	0.38	78.13
	FR 8 FI *x*-s	2.65	-0.46	0.31	85.99
	FR 16 FI *x*-s	2.04	-0.38	0.20	89.11
73	FR *x* FI 30-s	1.74	-0.16	0.14	72.36
	FR *x* FI 60-s	1.20	-0.13	0.10	83.15
	FR *x* FI 120-s	0.71	-0.17	0.11	86.03
	FR 1 FI *x*-s	2.50	-0.22	0.38	53.36
	FR 8 FI *x*-s	2.68	-0.38	0.25	86.33
	FR 16 FI *x*-s	2.99	-0.51	0.25	89.92
74	FR *x* FI 60-s	1.69	-0.14	0.20	34.97
75	FR *x* FI 30-s	2.14	-0.12	0.17	63.50
	FR *x* FI 60-s	1.57	-0.15	0.14	76.52
	FR *x* FI 120-s	1.20	-0.07	0.08	67.50
	FR 1 FI *x*-s	3.16	-0.25	0.33	74.22
	FR 8 FI *x*-s	3.62	-0.56	0.22	94.39
	FR 16 FI *x*-s	3.97	-0.58	0.21	94.19
76	FR *x* FI 30-s	2.15	-0.12	0.26	28.83
	FR *x* FI 60-s	1.35	-0.09	0.15	47.76
	FR 1 FI *x*-s	2.52	-0.24	0.25	81.34

estimated intercepts and initial schedule-initiation immediacies at the smallest FR tended to decrease (in seven of nine and six of nine cases, respectively), while the slopes tended to increase (in six of nine cases).

The left, middle and right panels of Figure 3.6 show that the schedule-initiation immediacy functions decreased across FI values for all hens and conditions. While the individual initial schedule-initiation immediacy data points decreased with increasing FR across the three panels, the estimated intercepts of the lines increased in four cases and decreased in four cases. The slopes of the lines tended to become steeper with larger FR requirements (in seven of eight cases).

In sum, Figures 3.3 and 3.5 show that the schedule-initiation immediacies remained stable across most FR increases in the increasing FR conditions. Figures 3.4 and 3.6 show that the schedule-initiation immediacies decreased with increasing FI in the increasing FI conditions.

The schedule-initiation immediacies were also calculated and analysed using the mean between-operant unit pause durations from each session. These mean schedule-initiation immediacies were very similar to the median schedule-initiation immediacies presented, although they tended to give slightly more sloping functions in both the FR increasing and FI increasing conditions. Functions from the FR increasing conditions were still relatively flat, while the functions from the FI increasing conditions were decreasing.

The median schedule-initiation immediacy data previously presented in Figures 3.3 and 3.5 are re-presented in Figure 3.7 for the increasing FR conditions, and all hens. The same median data previously presented in Figures 3.4 and 3.6 are re-presented in Figure 3.8 for the increasing FI conditions. Here, the natural logs of the schedule-initiation immediacies at each FR (or FI) value are plotted for each FI (or FR) condition. One data point in each figure is outside the axes; the values are displayed on the relevant graphs.

Figure 3.7 shows that in general, for most hens and most FR values (in 49 of 60 instances), there tended to be a decrease in the schedule-initiation immediacy with increases in the FI. Additionally, in most cases, the schedule-initiation immediacies also tended to decrease as the FR increased, within each FI condition. This is not always exactly a monotonic decrease (it is monotonic in one case for Hen 72), however, the schedule-initiation immediacies at small FR

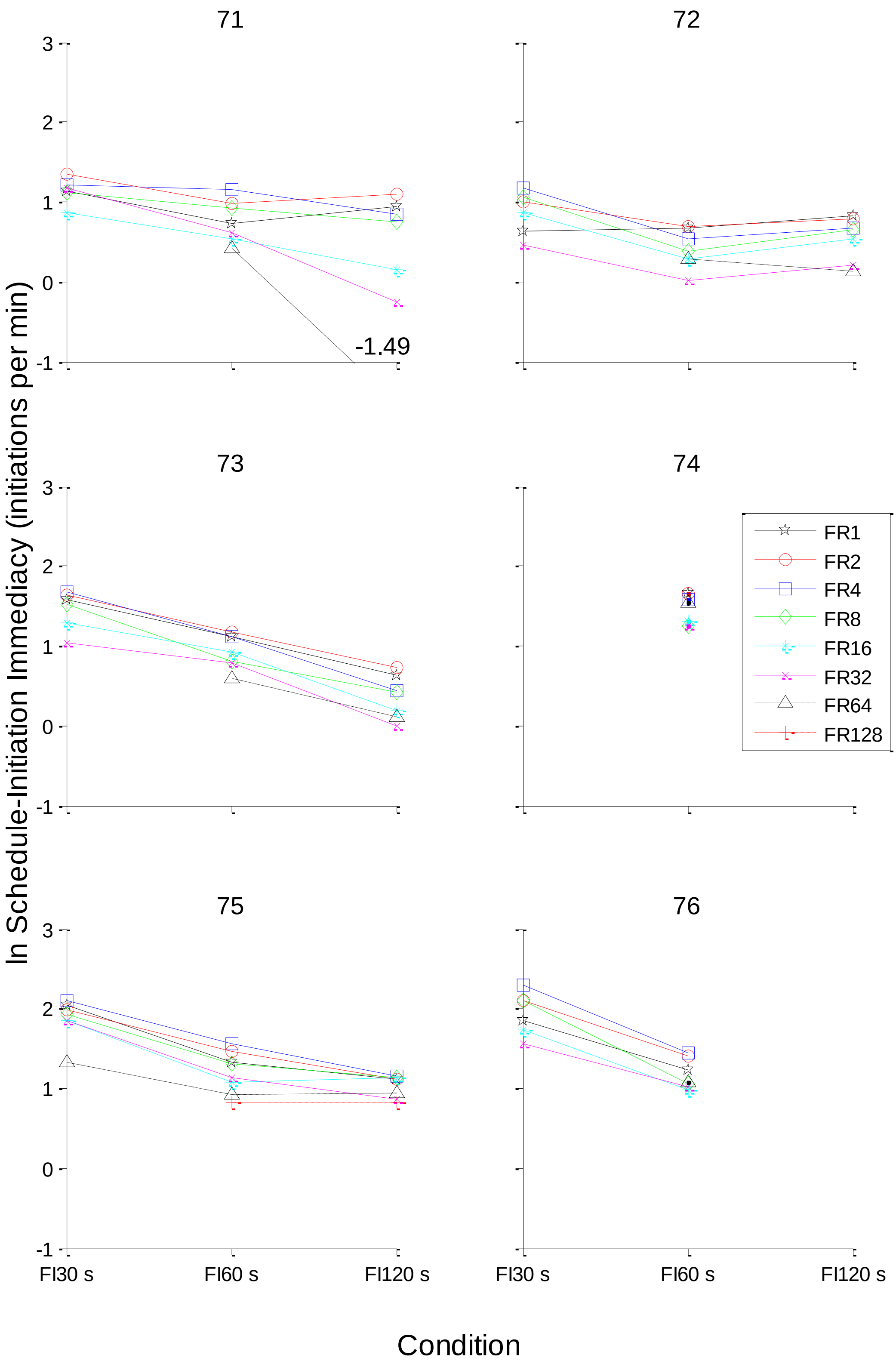

Figure 3.7. The natural logarithms of the schedule-initiation immediacy data, plotted against the increasing FR conditions for each FR value. The data are medians of the five most recently completed series of each condition.

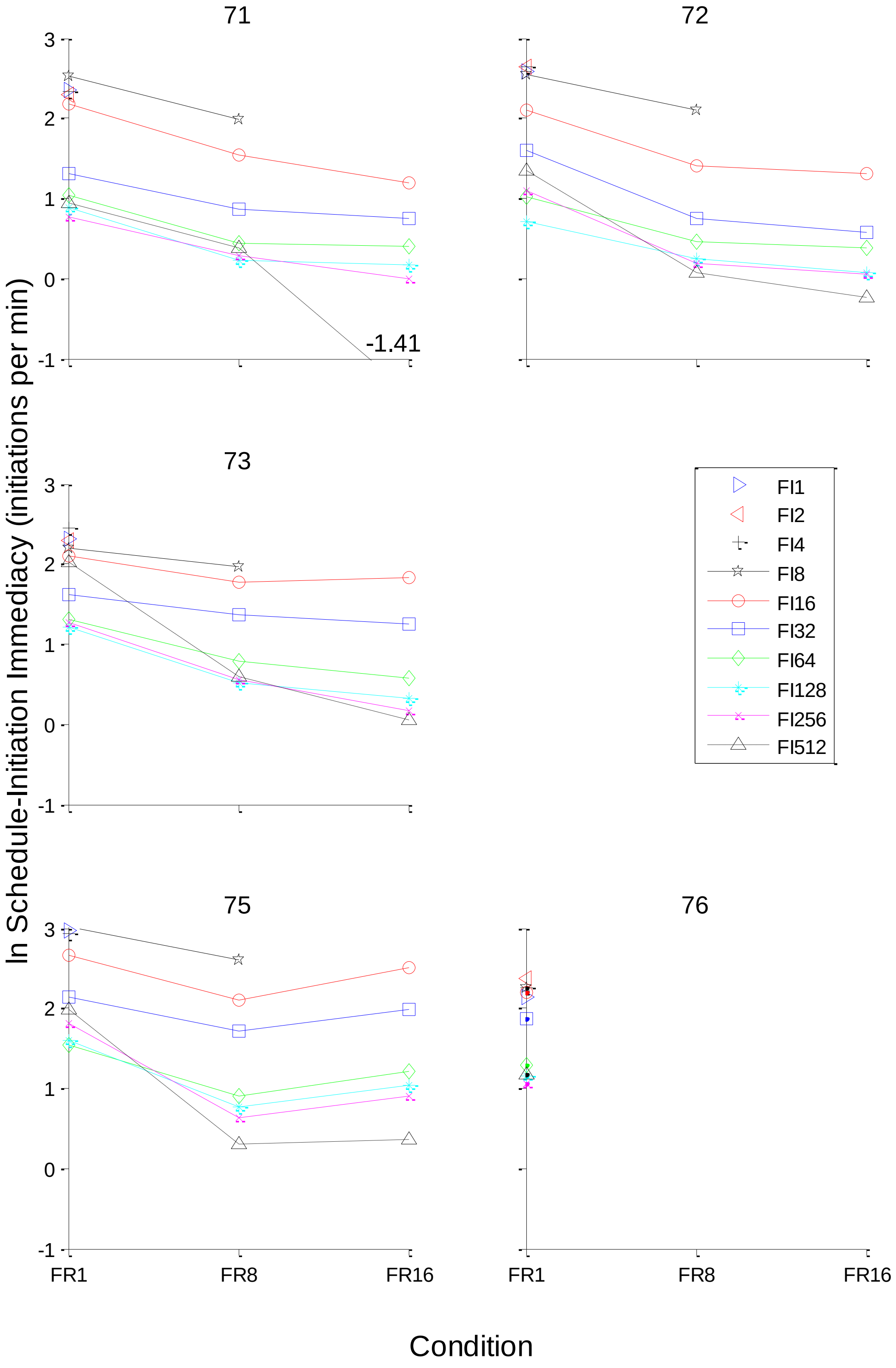

Figure 3.8. The natural logarithms of the schedule-initiation immediacy data, plotted against the increasing FI conditions for each FR value. The data are medians of the five most recently completed series of each condition.

values are generally amongst the highest values, and the schedule-initiation immediacies at the largest FR values are generally amongst the smallest values.

Figure 3.8 shows that, in general, for most hens and most FI values (in 41 of 48 instances), there tended to be a decrease in the schedule-initiation immediacy with increases in FR. In addition, in most cases, the schedule-initiation immediacies also tended to decrease as the FI increased, within each FI condition. This was a monotonic decrease in six of 13 cases and in the remaining cases, the schedule-initiation immediacies at small FI values are generally amongst the highest values, and the schedule-initiation immediacies at the largest FI values are generally amongst the smallest values.

Blackout Pecks

Blackout peck data are presented in Figure 3.9 for all hens in the increasing FR conditions. Blackout peck data for all hens in the increasing FI conditions are presented in Figure 3.10. Here, the numbers of blackout pecks (per reinforcer) are plotted against the natural logs of the FR or FI values. The blackout pecking data for the last five series of each condition are presented, and a line joins the median at each FR or FI value. It was found that the rates of blackout pecking did not systematically change across series.

Also examined were the durations of the FI schedules. It was found that the blackout pecks did not appear to extend the FI durations. That is, the FI durations experienced by the subjects were very close to those programmed by the experimenter.

The left, middle and right panels of Figure 3.9 show that the rates of blackout pecking were very low (generally below two pecks per reinforcer), excepting Hen 74 whose rate of blackout pecking in the FI 60-s condition, and Hen 75, whose rates of blackout pecking in the FI 60-s and FI 120-s conditions were slightly higher. Within condition, the rates of blackout pecking generally tended to either decrease (eight of 15 cases) or remain constant (seven of 15 cases) across FR increases. There were no consistent changes in blackout pecking across conditions.

The left, middle and right panels of Figure 3.10 show that, the rates of blackout pecking were very low (generally below two pecks per reinforcer), across most FI values, only increasing at the highest FI values (FI 512 s, FI 256 s,

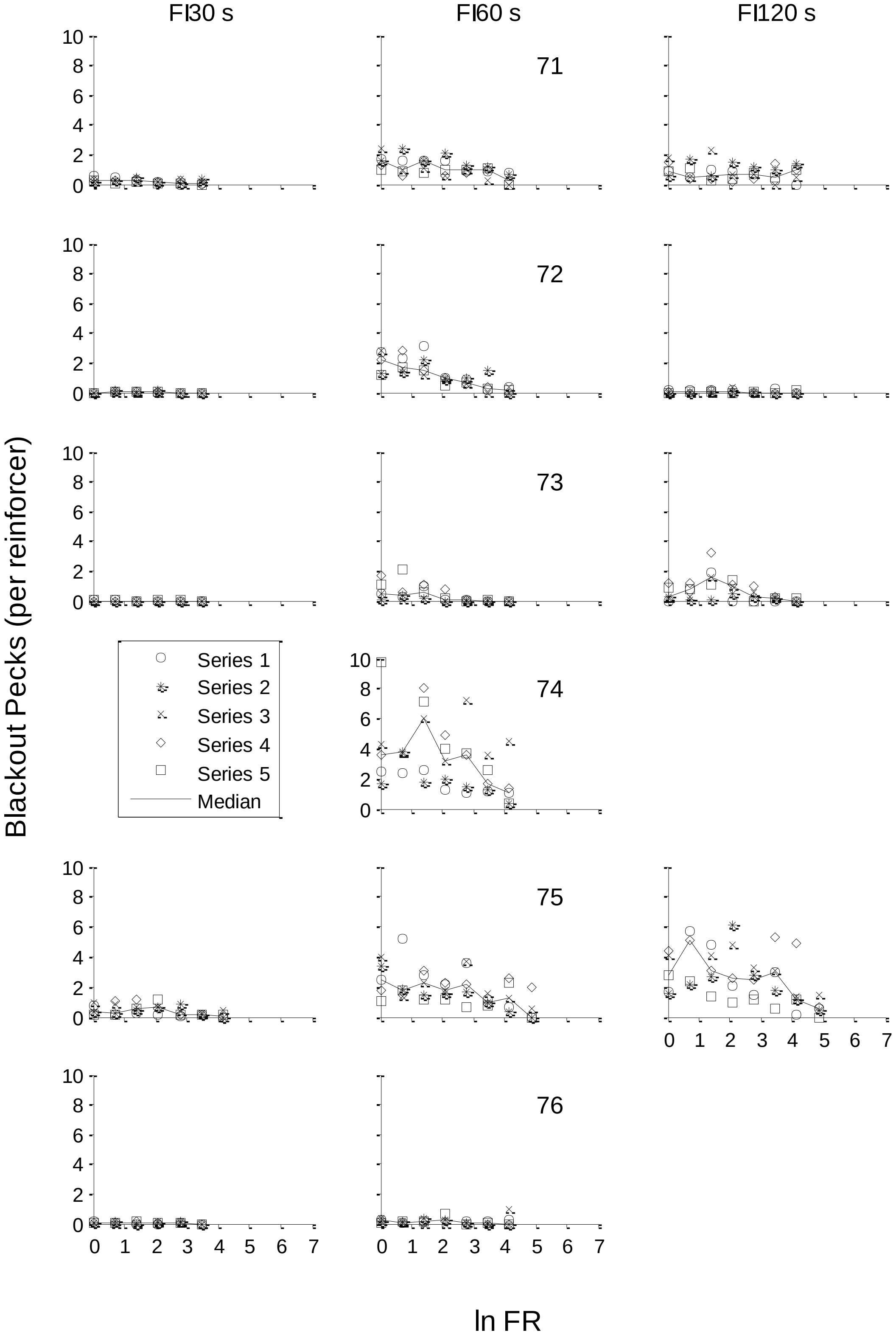

Figure 3.9. The number of blackout pecks per reinforcer plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

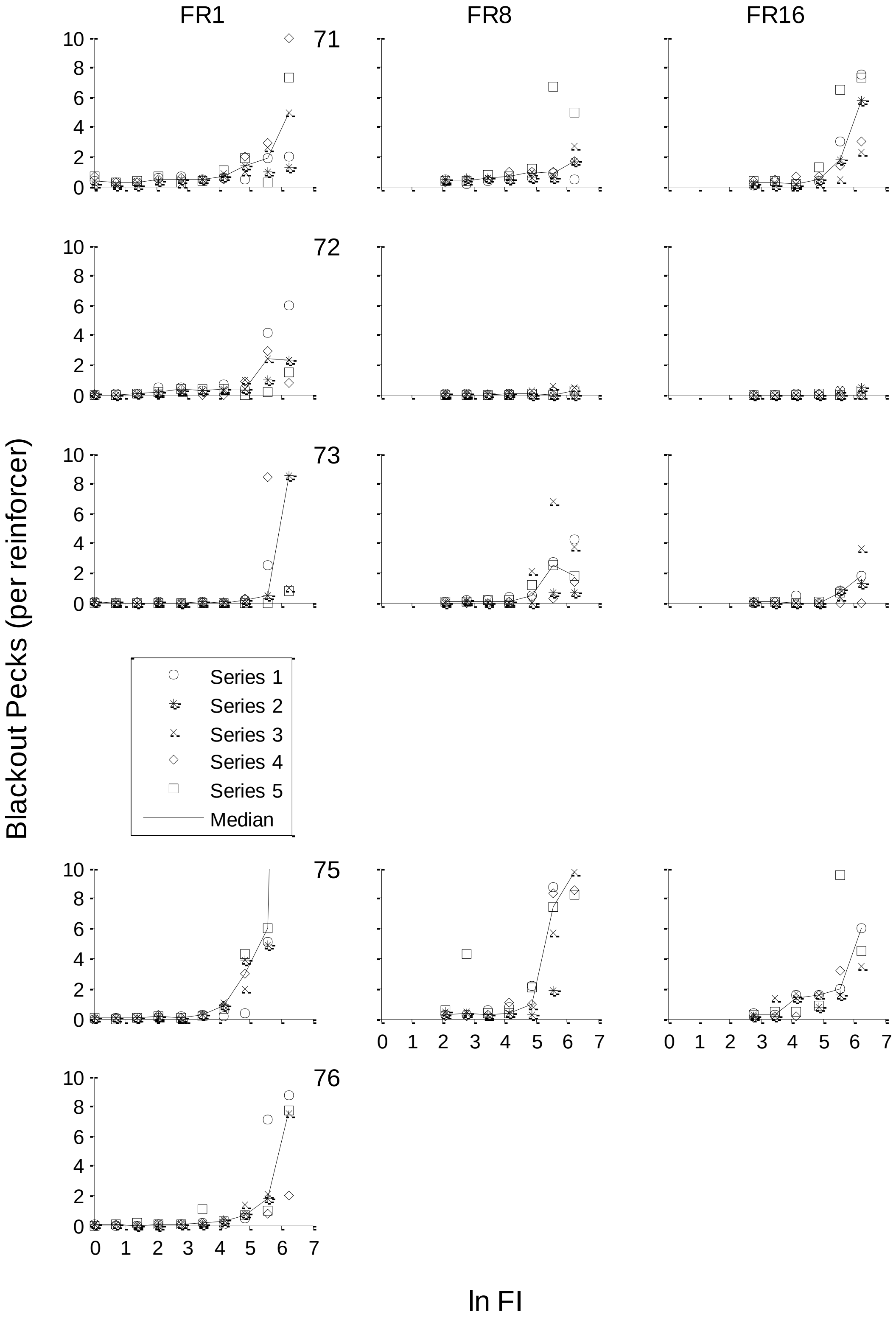

Figure 3.10. The number of blackout pecks per reinforcer plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

and for Hen 75 in the FR 1 condition, FI 128 s). There were no consistent changes in blackout pecking across conditions.

In sum, in both the increasing FR and increasing FI conditions, the rates of blackout pecking were low, and blackout pecks only rarely extended the FI durations.

FR-Incomplete Schedule Aborts

Presented in Figure 3.11 for all hens in the increasing FR conditions are the numbers of operant units that were aborted due to the failure of the subject to complete the FR requirement within the FI duration. Figure 3.12 presents FR-incomplete schedule abort data for all hens in the increasing FI conditions. The schedule aborts are plotted against the natural logs of the FR or FI values. The abort data for the last five series of each condition are presented, and a line joins the median at each FR or FI value.

The left, middle and right panels of Figure 3.11 show that FR-incomplete schedule aborts occurred effectively only at the two highest completed FR values. It was found that the other type of schedule abort due to the failure of the subject to perform the terminal response of the FI schedule occurred only very rarely.

The left, middle and right panels of Figure 3.12 show that virtually all FR-incomplete schedule aborts occurred only at the smallest durations of the FI schedule. Again, it was found that schedule aborts due to terminal response failure occurred very rarely.

In sum, in both the increasing FR and increasing FI conditions, schedule aborts due to the failure to complete the terminal FI response occurred very rarely. Schedule aborts due to the failure to complete the FR requirement occurred only during the largest FR values in the increasing FR conditions, and only during the smallest FI values in the increasing FI conditions.

Running Response Rates

Figures 3.13 and 3.14 present, for all hens, the mean running response rates (per s) for the increasing FR conditions and the increasing FI conditions, respectively. The mean running response rates at each FR or FI were calculated by dividing the total numbers of responses by the run time (time to complete the FR requirement), and plotted against the natural logs of the FR or FI values. The running response rates for the last five series of each condition are presented, and a line joins the median at each FR or FI value. It is not possible to calculate the

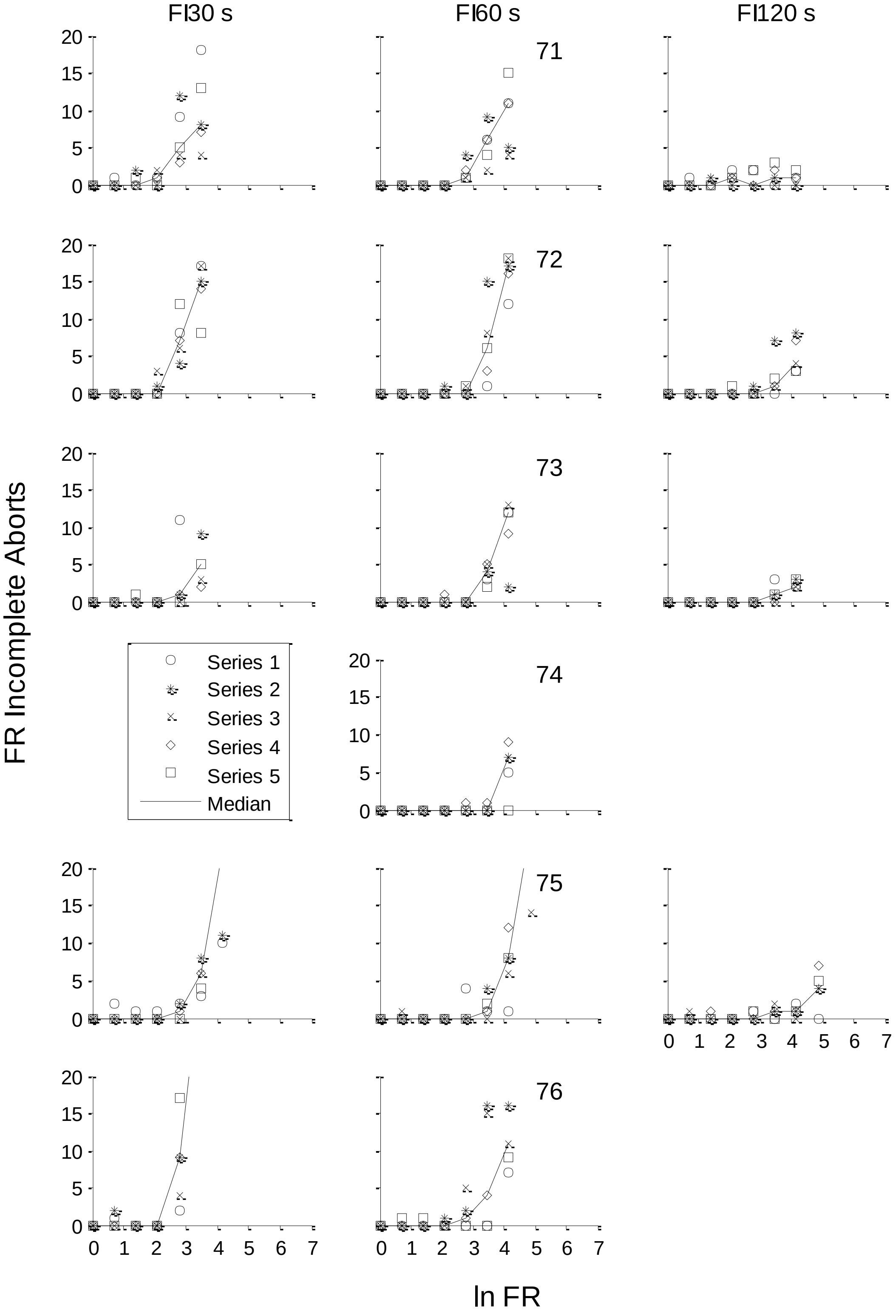

Figure 3.11. The total number of FR-incomplete schedule aborts plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

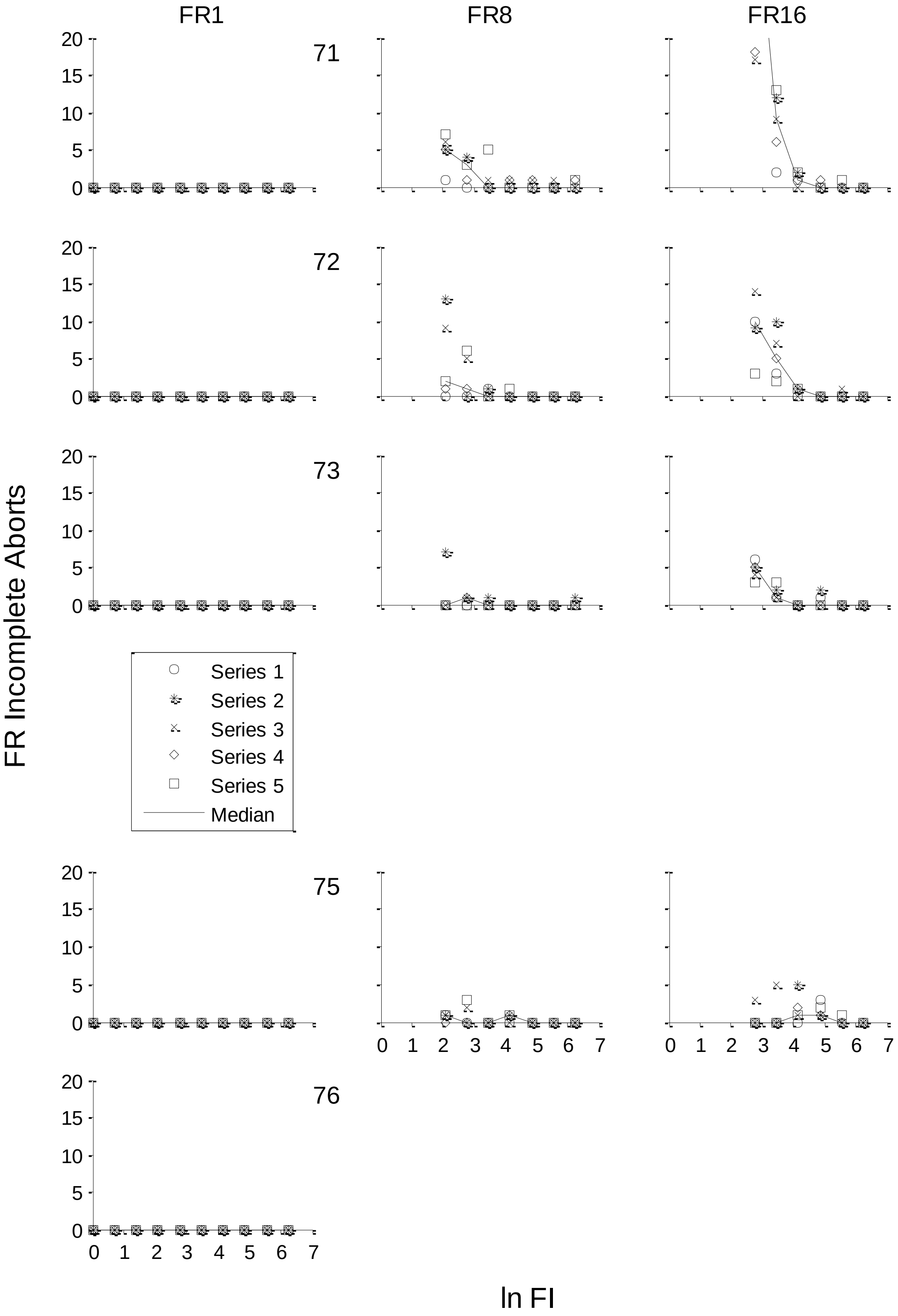

Figure 3.12. The total number of FR-incomplete schedule aborts plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

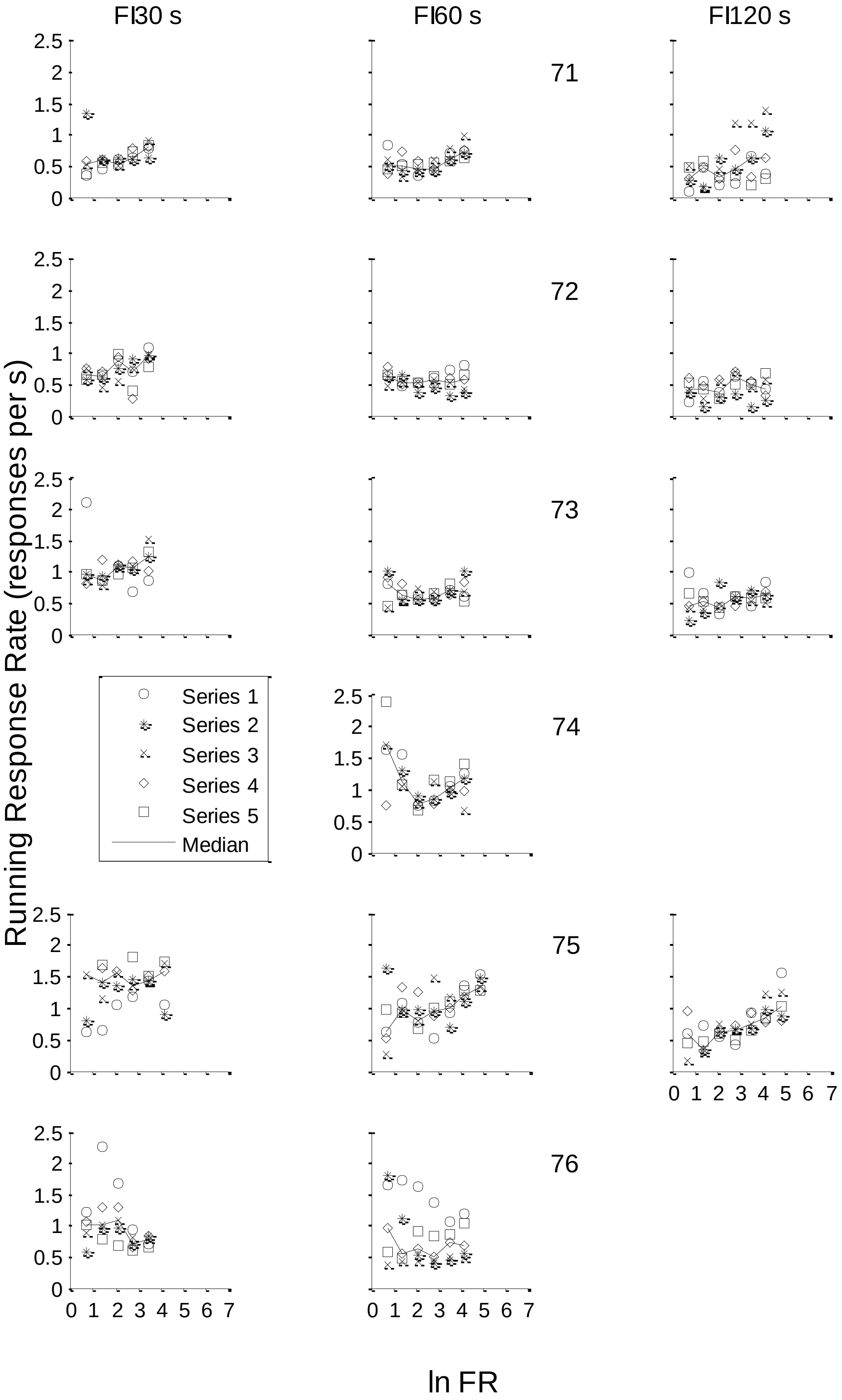

Figure 3.13. The running response rates (per s) plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

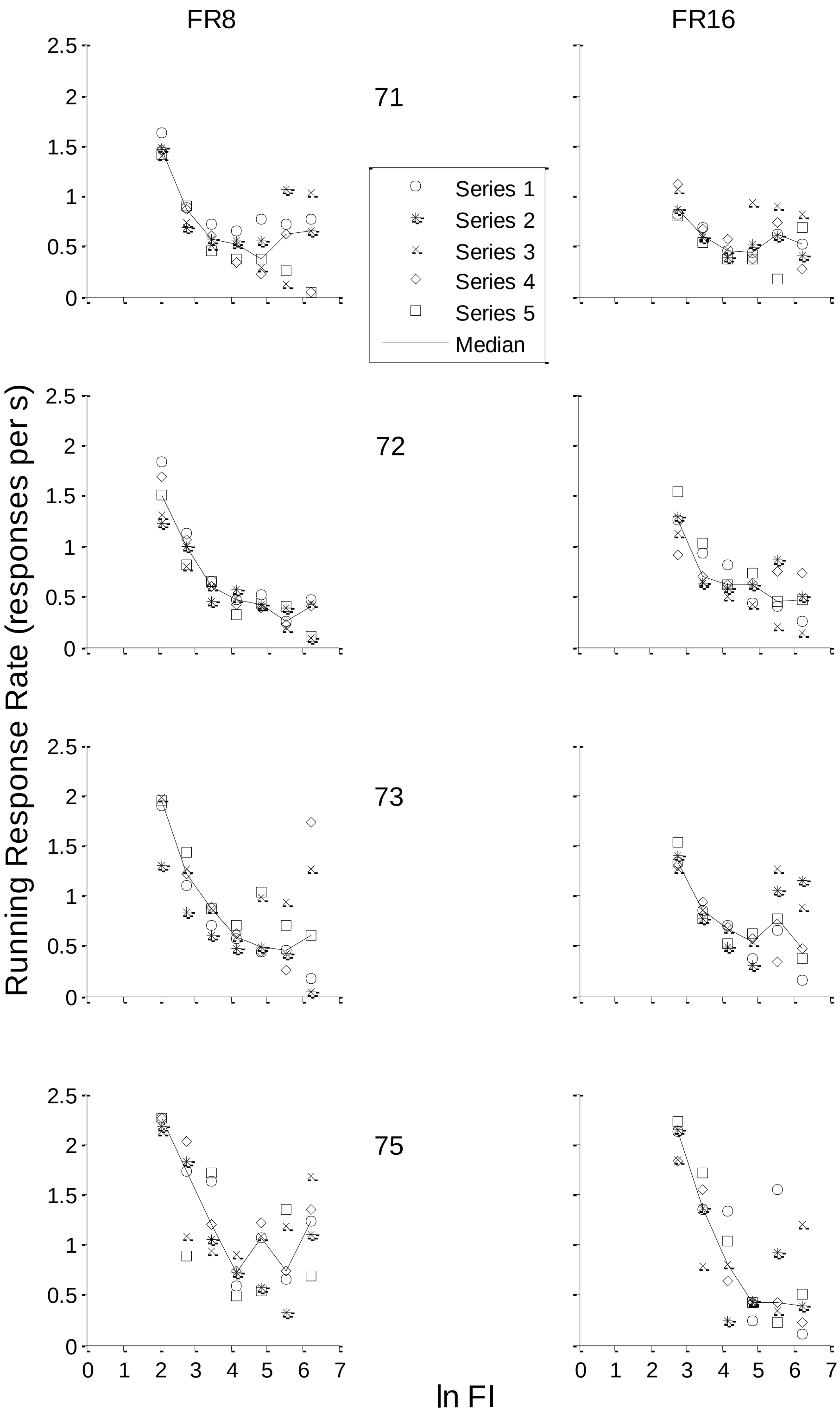

Figure 3.14. The running response rates (per s) plotted against the natural logarithms of the FI size in the FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted, and a line joins the median values.

running response rates at FR 1, which is why no figures are presented for the FR 1 FI *x*-s condition.

Figure 3.13 shows that as the FR increased in the increasing FR conditions, the running response rates tended to increase or remain constant. At each FR value, the running response rates tended to decrease with increased FI.

Figure 3.14 shows that in the increasing FI conditions the running response rates decreased with increasing FI. The running response rates were similar at each FI value in both the FR 8 FI *x*-s, and FR 16 FI *x*-s conditions.

In sum, in the increasing FR conditions, the running response rates tended to remain constant or increase with increases in the ratio, while in the increasing FI conditions, the running response rates decreased with increases in the interval.

Discussion

The primary aim of the current experiment was to separate the two parameters of FR schedule performance, controlling both the number of responses made and the duration of the schedule. By adapting a methodology similar to that used by Sealey et al. (2005), this aim was achieved. There were several ways in which the schedule requirements could have differed from those programmed by the experimenter, but the numbers of blackout pecks per reinforcer were small, in most cases fewer than two (Figures 3.9 and 3.10). Effectively the FR was experienced as programmed. Furthermore, analysis of the FI lengths confirmed that the FI durations experienced by the subjects were very close to those programmed by the experimenter.

The third way in which the schedule requirements could have differed from those programmed by the experimenter was that aborted trials of the conjunctive schedule might have varied the overall reinforcement rate. Terminal-response aborts occurred only very rarely, and thus had little effect on extending the FR or FI requirements. FR-incomplete aborts were also relatively rare, except under particular experimental conditions, in that they occurred only at the highest FR values in the increasing FR conditions, and occasionally at the smallest FI durations in the increasing FI conditions (Figures 3.11 and 3.12).

Even though aborted trials did not occur often, the aborts may have potentially altered the consumption rate data (presented in Figures 3.1 and 3.2) because the increased duration and response requirement mean that the consumption rate was lowered. A reduced rate of reinforcement at the highest completed FRs in the increasing FR conditions could mean that the consumption rate functions were more sloping than they would have been had the consumption rate been experienced as programmed. In the increasing FI conditions, a reduced rate of reinforcement at the shortest FI durations could mean that the consumption rate functions were less sloping than they would have been had the consumption rate been experienced as programmed.

For these reasons, the data from Figures 3.1 and 3.2 have been re-plotted in Figures 3.15 and 3.16 respectively. The numbers of trials that were aborted have been added to the numbers of reinforcers obtained in each session, giving the consumption rate that would have been experienced by the subjects had each attempted operant unit resulted in a reinforcer. Similarly to Figure 3.1 and 3.2,

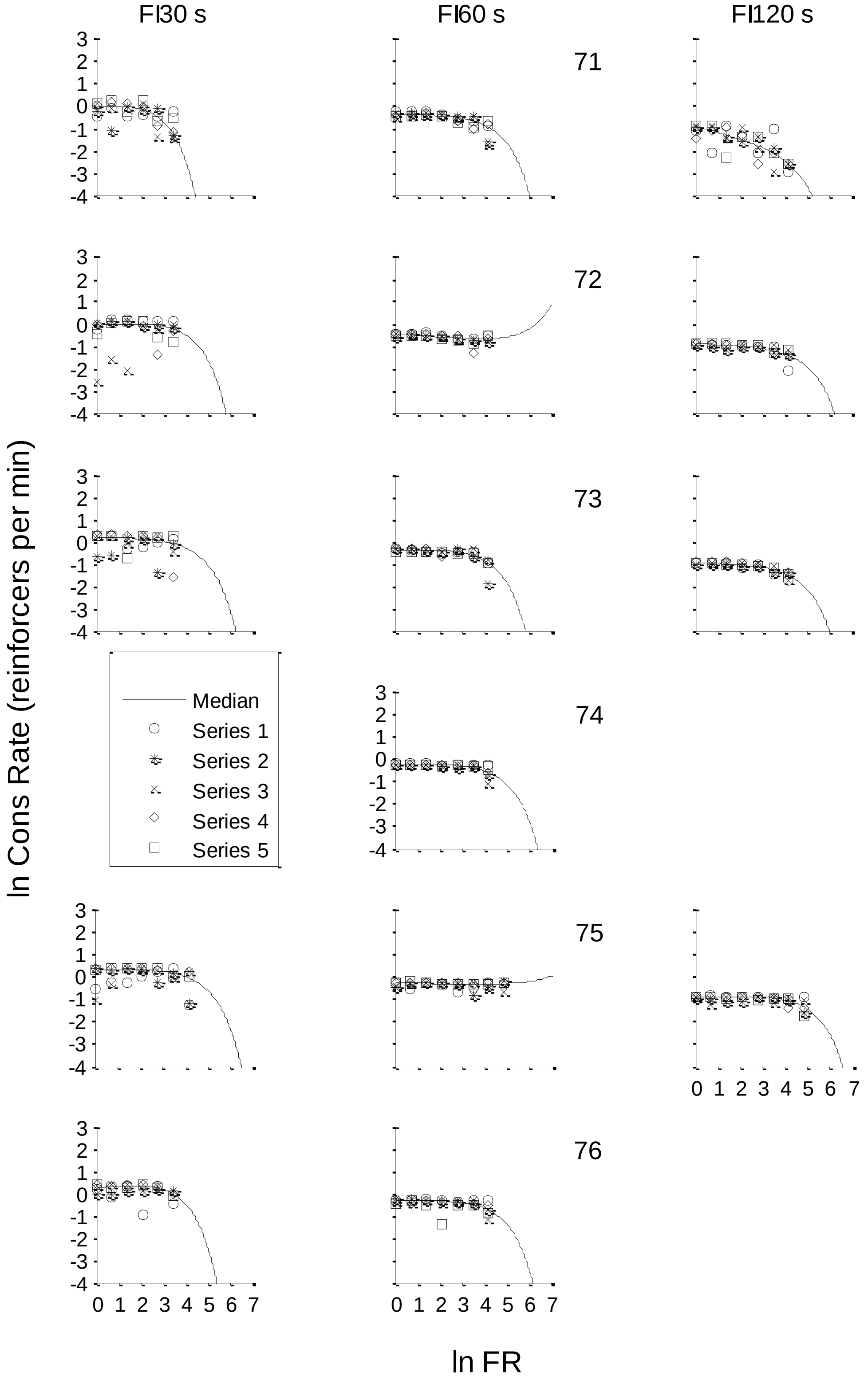

Figure 3.15. The natural logarithms of the consumption rate data (consumption plus FR-incomplete aborts), plotted against the natural logarithms of the FR size in the FR *x* FI 30-s condition, FR *x* FI 60-s condition and the FR *x* FI 120-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

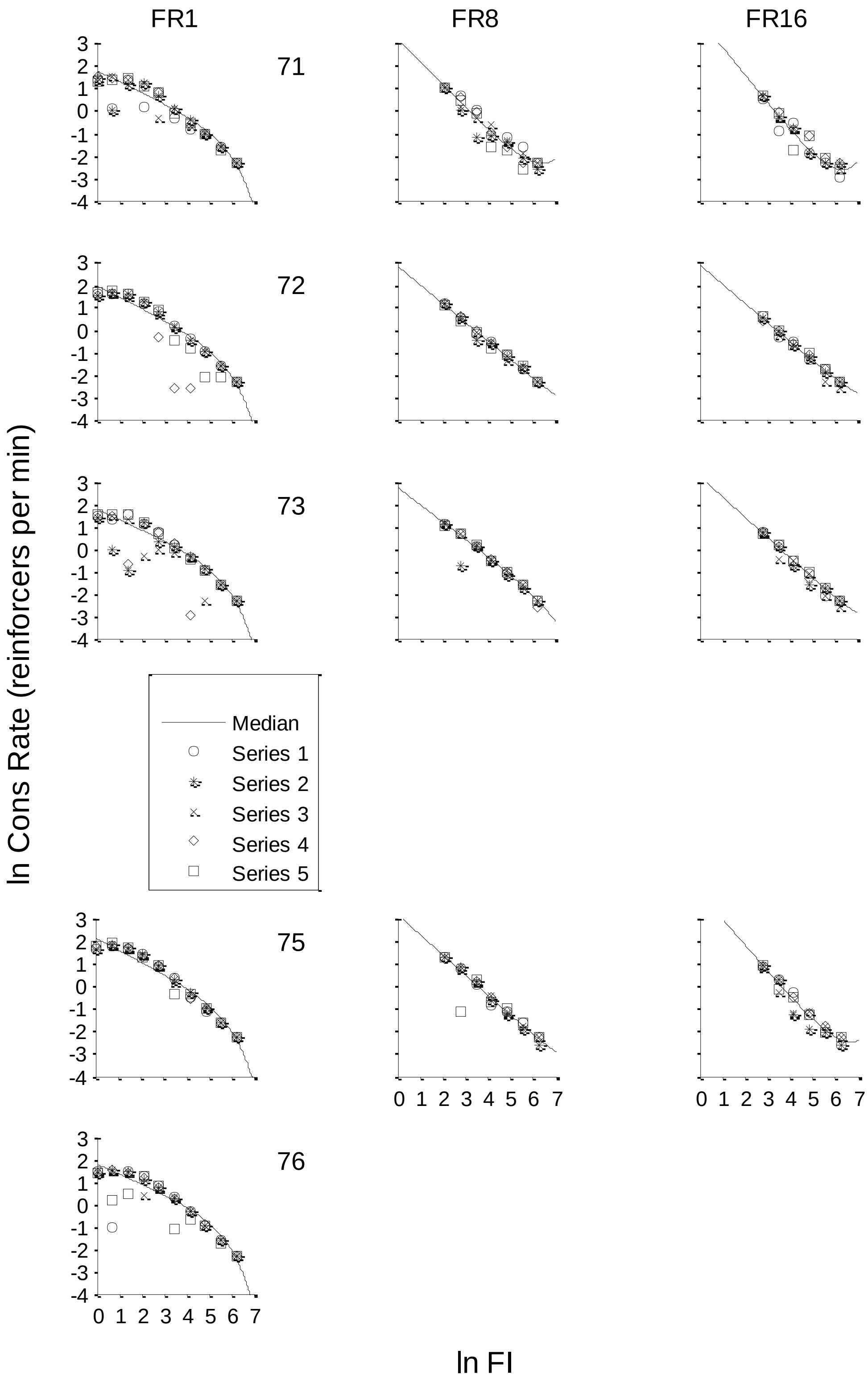

Figure 3.16. The natural logarithms of the consumption rate data (consumption plus FR-incomplete aborts), plotted against the natural logarithms of the FI size in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using Hursh et al.'s (1988) nonlinear equation (Equation 2.1).

the data from the five most recently completed series in each condition were plotted on a natural logarithmic axis. Lines were fitted to the medians of these data using Hursh et al.'s (1988) nonlinear equation (Equation 2.1), nonlinear regression, and the method of least squares. The resulting functions are very similar to the original consumption rate functions (Figures 3.1 and 3.2), highly inelastic across most FR values in the increasing FR conditions, and close to linear, with slopes close to negative 1.0, in the increasing FI conditions. However, as predicted, the addition of the aborted trials appears to have emphasised these characteristics, making the increasing FR functions still more flat across all FR values, and the increasing FI functions more sloping. Overall, the changes to the functions with the addition of the trial aborts are relatively small, and thus it appears that aborted trials had little effect on consumption rates.

The schedule-initiation immediacies during the increasing-FR fixed-FI conditions (Figure 3.5) show that of the 15 functions, 14 are relatively flat across increases in the FR. This indicates that in conditions when the response duration was held constant across sessions, the pauses between the operant units remained similar in duration even as the ratio increased. This is in contrast to Experiment 2 in this thesis, in which between-ratio pause durations were found to increase with increasing FR. However, the functions presented in Figure 3.6 from the increasing-FI fixed-FR conditions, have steep slopes. This indicates that in conditions when the duration was increasing across sessions, the pauses between the operant units tended to increase, even though the FR remained constant. This finding is similar to the results from Experiments 1 and 2 in this thesis, which found for each FR value, the between-ratio pause durations increased with increased schedule durations (from increases in the delay-to-reinforcement). All these results suggest that it is the duration of the schedule which has the greater effect on pausing.

Figure 3.13 shows that in the increasing-FR fixed-FI conditions the running response rates either increased or remained constant as the FR increased. This is dissimilar to typical running response rate functions, which tend to decrease with increases in FR, as was found in Experiment 2 of this thesis. Similarly to typical response rate functions, Figure 3.14 shows that in the increasing-FI fixed-FR conditions, the running response rates tended to decrease as the FI increased, even though the FR was the same across all sessions. When the running response rates at each FI value in Figure 3.14 are compared, they are similar in the FR 8 FI *x* and FR 16 FI *x* conditions. When the running response rates at each FR value in Figure 3.13 are compared, they tend to be fastest in the FR *x* FI 30-s condition and slowest in the FR *x* FI 120-s condition. Therefore, increases in the total duration of the operant unit resulted in decreases in the running response rate even when the FR was constant. However, increases in the FR when the total duration of the operant unit was fixed either resulted in constant or increasing running response rates. Thus the running response rate functions provide evidence that the duration of the schedule has a greater effect than the ratio requirement on behaviour in FR schedules in general, not just on pausing.

Further support for schedule duration influencing behaviour more than response requirement comes from the intercepts of the lines fitted to the functions from the increasing FR conditions (Table 3.3). In the increasing FR conditions, the larger the FI value, the smaller the intercepts of the fitted lines (in 10 of 12 paired comparisons). Also, as shown in Figure 3.7, for any particular FR, larger FI values gave smaller schedule-initiation immediacies (in 72 of 85 possible paired comparisons). This means that even though the FR was the same, pausing between operant units was longer when the schedule duration was longer. These intercepts are not directly related to the slopes of the lines.

The smaller effect of the response requirement is best shown in Figure 3.8 where, at each FI value (in 69 of 76 possible paired comparisons), larger FR values gave smaller schedule-initiation immediacies. Even though the FI was the same in each condition, pausing increased between operant units as the number of required responses increased. The only difference between conditions was the FR, which varied from FR 1 to 8 to 16 across conditions. Therefore, the effort of the response requirement does have some effect on behaviour.

Similarly to Bauman’s (1991), Neuringer and Schneider’s (1968), and Tsunematsu’s (2000) studies, the present findings indicate that it is the duration it takes to complete an FR that has more effect on behaviour than the response requirement (effort of completing the FR). However, it is likely that behaviour in FR schedules is influenced not by duration alone, but by a combination of the duration and the effort it takes to complete an FR schedule.

The schedule-initiation immediacies were the proposed measure of consumption for the present experiment because the duration of pausing between operant units was the only aspect of the conjunctive schedule which could vary with the subjects' behaviour. Previous research (e.g., Barofsky & Hurwitz, 1968; Felton & Lyon, 1966; Foster et al., 1997; Mazur, 1983), has found that between-ratio pause durations tend to increase as the FR increases. The present research shows that in conditions with an increasing FR and a fixed FI, the pause between operant units did not increase as much as in conditions where the FI was increasing and FR was fixed. If it were simply the effort involved in the completion of an FR requirement that results in pausing, it could be expected that the pauses between operant units or schedule-initiation immediacies would have remained constant in the increasing FI conditions. However, the present findings indicate that increasing the schedule duration results in larger changes in pausing than increasing the response requirement. A similar finding was evident in Experiment 1 of this thesis. The duration of the schedule was manipulated by increasing the delay-to-reinforcement, while the response requirement was FR 5 in all conditions. Between-ratio pausing was found to increase as the delay increased.

The results of the present study suggest that the use of FR schedules in behavioural economics is not directly analogous to price in consumer demand theory. Increases in the price of a commodity do not necessarily result in an increase in the duration it takes to pay for the commodity, as it does with an increase in the FR. It does take us longer to earn the money to pay an increased price for the commodity, however, this is not an immediate relation as it is in most animal studies. The present results suggest that changes in the duration may be responsible for most of the effects of an increasing FR requirement.

Other possible means of increasing the price analogue might be more appropriate. Alternatives to FR schedules may include using a conjunctive schedule, similar to that used in the present experiment, and thereby having control over duration, or using force as a way to increase the effort without increasing the duration. Sumpter et al. (1999) compared hens' demand for food using two different manipulations of price; increasing FR schedules and increasing force. Increasing the effort using increasing FR schedules necessarily increased the duration of the 'work' requirement, while increasing the force did not. The resulting demand functions in Sumpter et al.'s (1999) increasing FR condition were downward sloping and approximately linear, similar to those in the increasing-FI fixed-FR conditions in the present experiment. The demand functions they obtained in the increasing force condition were curvilinear; flat and inelastic across small force values, and becoming suddenly elastic at high force values, similar to the functions produced in the present experiments' increasing-FR fixed-FI conditions. However, in a similar experiment, Sumpter et al. (2004) noted that there seemed to be a clear force limit at which the hens ceased to respond when the price manipulation was force, restricting the range of forces that could be tested. In the present experiment the duration of the FI is a similar limiting factor on the size of the FR possible.

Perhaps a conjunctive schedule as used in the present experiment may be the best analogue to price. The use of an increasing-FR fixed-FI schedule would serve to maintain an approximately constant duration at all ratios. However, it would be necessary to anticipate the largest ratio that would be reached beforehand and ensure that this largest ratio could be completed within the FI. The largest ratio typically reached by hens working for wheat on increasing FR schedules is 1024. Assuming one response per s, the use of a conjunctive schedule could lead to very long sessions, especially at small FR values where consumption is typically greatest. Further, in the present experiment, all of the demand functions produced in the increasing FR conditions were flat and inelastic. These data suggest that the use of conjunctive schedules to assess demand may result in flat and inelastic demand functions. While flat and inelastic demand functions might be expected when the animal is responding to obtain food, they would not be expected for inessential commodities. Therefore further research needs to be conducted with a range of different commodities, some of which might be essential and some of which might be less essential (similar to the research of Matthews and Ladewig, 1994, but using conjunctive schedules) to determine what effect these schedules have on demand.

Another aim of the present experiment was to investigate a way to reduce the confound of fixed session length in behavioural economics. As pointed out earlier, as the FR increases, a fixed session length, especially in short sessions, restricts responding due to the increased time it takes to complete the ratio and, therefore, also restricts the resulting rate of consumption. The schedule-initiation immediacies presented in this experiment are independent of the duration of the operant unit and therefore are not confounded by the increases in time required to complete the schedule.

In the present experiment consumption rate (Figures 3.1 and 3.2) was, however, restricted in two further ways. In the increasing-FR fixed-FI conditions at large FR values the subjects could not complete the response requirement within the FI duration, and so the consumption rate decreased. In the increasing-FI fixed-FR conditions the consumption rate decreased as the FI increased. Therefore, as mentioned earlier, the schedule-initiation immediacies (Figures 3.3 through 3.6) may well be a better measure of demand than total consumption or consumption rate, both in the present experiment and other demand experiments. This is clearly shown in the increasing FR condition at the largest FR values reached. Even if only a few reinforcers were obtained during the session, the schedule-initiation immediacies were very similar to those at small FR values with the same FI. The use of a measure such as the schedule-initiation immediacy may help to avoid the confound of fixed session length. This experiment resulted in demand functions that are similar to those that would be found for the purchase of a commodity which shows virtually inelastic demand over a range of price rises, followed by a relatively abrupt reduction in consumption at some price.

In conventional demand experiments consumption rate arises from a combination of the overall response rate and the FR requirement. The point of maximal responding (P_{max}), which is often used to compare output across various conditions, coincides with the point where demand changes from inelastic to elastic. However, in this experiment, consumption depended jointly on the duration of the FI and the length of the between-operant unit pause. Hence, the point of maximal consumption will not coincide with the point of maximal responding, but will occur at the point at which both the FI and the pause are shortest. Consider the increasing-FR fixed-FI conditions. In the FI 60-s condition at FR 2, the rate of consumption was high, but overall response rate low compared to FR 64 where the rate of consumption was similar but the overall response rate was much higher. This is because the FR required 32 times as many responses over the same period of time. Consider the increasing-FI fixed-FR conditions. In the FR 8 condition at FI 8 s, the consumption rate was high and the overall response rate was approximately one per s. Whereas when the FI was 512 s, the consumption rate was lower and the overall response rate was approximately 0.02 responses per s. Admittedly in this case the higher consumption rate is associated with the higher overall response rate, but the relationship is not the direct one found normally by P_{max}. Therefore P_{max} is a measure that cannot be readily applied to the present procedure.

When FR is varied in a ‘more standard’ demand study (e.g., Foster et al., 1997) then it is clear that in short-sessions (e.g., 40 min) responding will fill the entire session at some FR value (e.g., FR 16) and limit overall consumption. Even when sessions are longer (but fixed) it is possible that at some FR value, responding would fill the entire session. This means that any length of session can potentially limit total consumption, if the FR is large enough, and hence create a confound in the data. Sumpter et al. (2004) argued that consumption rate is therefore a preferable measure to total consumption. However, it can be further argued that consumption rate is also limited and therefore confounded by the duration it takes to complete the FR requirement. It follows from the above example of responding filling the session in a fixed length session, in that, once this has happened, consumption rate (as well as total consumption) will necessarily fall with further increases in the ratio requirement. However, the schedule-initiation immediacy (calculated in the present experiment as the inverse of the between-operant unit pause) is not affected by constraints of session length. Thus, using conjunctive schedules of reinforcement with a fixed duration and increasing response requirement and schedule-initiation immediacies as a measure may help to overcome the confounding effects of a fixed session length and of changes in the time taken to complete the FR requirement.

However, using the present procedure still gives some potential problems when using a fixed session length. Although the fixed session duration (2400 s) worked perfectly well when comparing behaviour within each condition, this could have been confounding when the different conditions are compared. During the FR *x* FI 30-s condition, the subjects had sufficient time to obtain the maximum number of reinforcers available (40 in most conditions). That is, allowing 1200 s to complete 40 FI 30-s schedules, 120 s for 40 reinforcers 3 s in duration, and a small amount of extra time to ensure the completion of the terminal FI response and the restarting of the schedule, the 40 reinforcers could be obtained within approximately 1400 s. Similarly calculated, most of the available reinforcers could be obtained in the FR *x* FI 60-s condition requiring a minimum total session duration of 2600 s (slightly over the 2400 s allowed). However, the FR *x* FI 120-s condition would require a minimum total session duration of 5000 s to obtain 40 reinforcers. Perhaps, in each of these conditions, the total session durations should have been adjusted to allow for the consumption of the same maximum number of reinforcers, or all sessions should have been at least 5000 s in length.

Although the consumption rate was reduced in the FR *x* FI 60-s and FR *x* FI 120-s conditions compared to the FR *x* FI 30-s condition, all hens maintained a relatively constant rate of consumption across most FR values in all three conditions. Further, as previously mentioned, the schedule-initiation immediacies remained similar across all FR values, even when only a few reinforcers were obtained. If these schedule-initiation immediacies are used as the predominant measure of demand, consumption rate and session length are irrelevant. Thus, session length appears irrelevant to the results of the present experiment.

A problem in the present experiment, particularly in the increasing FI conditions, was that the range of values tested changed across conditions. In the FR 1 FI *x* condition, the FI values tested ranged from 1 s to 512 s. However, in the FR 8 FI *x* and FR 16 FI *x* conditions, the tested FI values ranged from 8 s and 16 s, respectively, to 512 s. This was necessary as the FR 8 and 16 requirements simply could not have been completed within the smaller FI durations. In the left panel of Figure 3.6 it appears that in the FR 1 FI *x* condition, FI durations up to 8 s had less effect on reducing the schedule-initiation immediacy than FI durations beyond 8 s. Because the data across small FI durations were more flat than the remainder of the function, this may have contributed to flatter overall slopes during the increasing FR 1 FI *x* condition, and the resulting steeper slopes that occurred with larger FR values. For this reason, the median data from Figure 3.6 were re-plotted in Figure 3.17, using the same range of FI durations (16 s through 512 s) in each condition. The resulting functions are remarkably similar to those in Figure 3.6 using the full range of data in each condition. In all panels, the schedule-initiation immediacy functions decreased with increasing FI duration. For the nine functions in which a smaller range of data was plotted, one became steeper, and eight became shallower than those in Figure 3.6. Therefore,

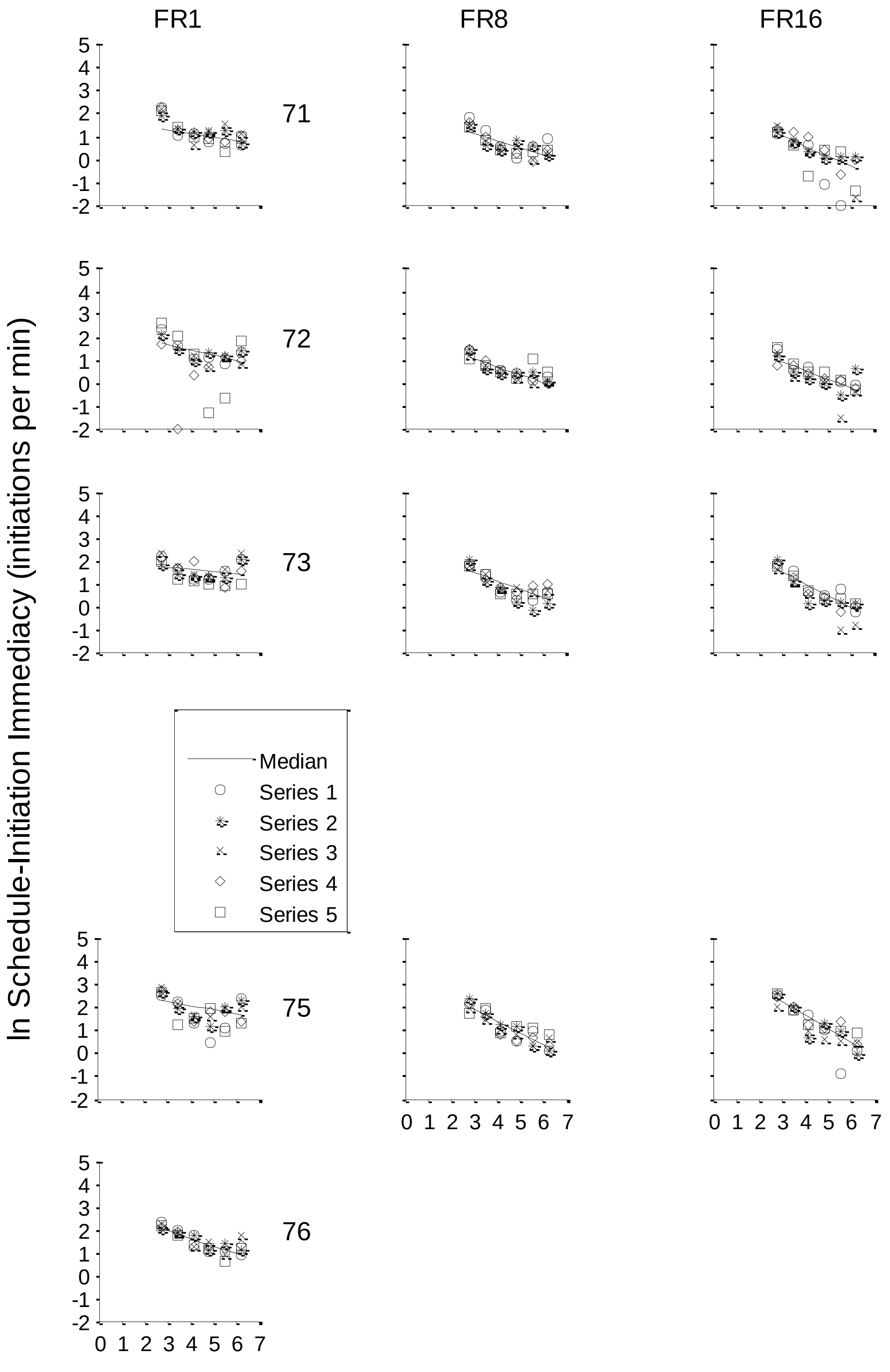

Figure 3.17. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FI size (range 16 s through 512 s) in the FR 1 FI *x*-s condition, FR 8 FI *x*-s condition and the FR 16 FI *x*-s condition. All data from the five most recently completed series of each condition are plotted. The lines were fitted to the median values using the robust regression analysis available in Matlab®.

it is likely that the differing ranges had no or little effect on the overall conclusions of the present experiment.

Another problem in the present experiment was interpretation of the functions fitted to the schedule-initiation immediacy data. In general, fitted curves have two main purposes. The first is to test for and explain the predictions of a theory, and the second is to allow interpolation or extrapolation to parameter values untested. Initially, Hursh et al.'s (1988) equation (Equation 2.1) was used to fit a function to the present schedule-initiation immediacy data (Figures 3.3 and 3.4, and Table 3.2). However, in many instances, the fitted curves sloped upwards beyond the last data point, resulting in illogical and meaningless predictions. One reason for the ill-fitting curves could be that the largest FR values reached by the subjects were not as high as those reached in typical demand studies. It is possible that the smaller range of FR values to which the functions were fit could have contributed to the resulting illogical parameters. To test this, the data from Figure 2.1 in Experiment 2 were re-plotted using FR values up to 64 for comparison. All 30 curves from all hens and delays were typical downward sloping demand functions. Therefore, the ill-fitting functions in this experiment are probably not a result of a small number of data points.

The u-shaped functions in Figures 3.3 and 3.4 suggest that as the FR or FI increased beyond those values tested in the present experiment, it could be expected that the schedule-initiation immediacies would increase, that is, durations of pausing between operant units would decrease. Thus, the parameter values from the Hursh et al. (1988) functions did not prove to be a good way of comparing conditions. A straight-line regression fit proved to be the best fit for the data, and the parameters of these allowed comparison of the various conditions (Figures 3.5 and 3.6, and Table 3.3).

However, analysis of the Hursh et al. (1988) and regression fits using the Akaike Information Criterion (Davison & McCarthy, 1987) indicated that the fits were equally good in the increasing FR condition, but that the Hursh et al. (1988) equation was superior in the increasing FI condition. Also, when the statistics (namely the standard errors and percentages of variance accounted for; Tables 3.2 and 3.3) of the fitted curves and the regression fits and are compared, the curve appears to approximate the data more closely. Comparing the statistics of the Hursh et al. (1988) equation and the regression fit, the Hursh et al. (1988)

equation yielded the smallest standard errors and largest percentages of variances accounted for in all 28 cases. This is because the Hursh et al. (1988) equation gives a curvilinear function. Such a function will fit curvilinear data more closely than a straight line, resulting in small standard errors and high percentages of variances accounted for. Although the curves generally fitted the data well, the predictions for larger (and untested) FR values were illogical. Although the standard errors and percentages of variance accounted for measures suggest the linear regression line is not as good a fit as the Hursh et al. (1988) equation, their slopes can be compared over various conditions, and the predictions for large FR values appear to be sensible. Further, when the overall variance in a data set is small, as it generally was in the present experiment, the fit of the line may involve a small standard error, but the percentage of variance accounted for can also be small as there is little variance for the line to account for. As the total variance in the data set increases, so does the percentage of variance accounted for, for any particular size of standard error.

From the last two series of Condition 2 (FR 1 FI *x* s) onwards, the maximum number of reinforcers that could be obtained in any one session was reduced from 50 to 40. Therefore, in Conditions 1 (FR *x* FI 60 s) and 2, the maximum number of reinforcers that could be obtained in any session was larger than Conditions 3 through 6. However, this did not appear to have any effect on the results. In the increasing FR conditions, the consumption rate at any FR was reduced in the FR *x* FI 60-s condition compared to the FR *x* FI 30-s condition, as well as in the FR *x* FI 120-s condition compared to the FR *x* FI 60-s condition (Figure 3.1). Further, the consumption rates were similar at any particular FI in the FR 1 FI *x*-s, FR 8 FI *x*-s and FR 16 FI *x*-s conditions (Figure 3.2).

Another methodological variation was that series were deemed to end differently in the increasing FR and increasing FI conditions. The increasing FR conditions were deemed to have ended when no reinforcers were obtained in two consecutive sessions, whereas in the increasing FI conditions series were ended after completion of FI 512 s. Perhaps a similar rule should have been used in this condition. However, it is likely that series would simply have continued until it was not possible for the subjects to gain a single reinforcer due to the FI duration being longer than the session time. The addition of such a rule in these conditions would have provided a maximum of two more data points to the figures within the total session time of 2400 s. The rate of consumption would have been greatly reduced, and, based on the data from the FI values tested, it is likely that the schedule-initiation immediacies would similarly have been reduced. Therefore, it is unlikely that any such data would offer any new or unexpected information.

In sum, the present experiment successfully separated the two parameters of FR performance, duration and response requirement, and found it is the duration of the schedule that has the most effect on behaviour. These findings mean that the use of increasing FR schedules in behavioural economics is not directly analogous to price in consumer demand theory. A fixed-duration conjunctive schedule of reinforcement as used in the present experiment may be a better analogue and the methods of data analysis used may help to overcome other confounds in behavioural economics, such as session length and consumption rate.

SUMMARY

The following section summarises these experiments to set the context for the general discussion. To this author’s knowledge, Experiment 1 is the first to examine the effects of delay-to-reinforcement on behaviour in multiple FR FR schedules. The main finding was that pausing between ratios was almost exclusively influenced by the upcoming ratio component and its associated delay. Pause durations increased as the delay-to-reinforcement in the upcoming schedule increased but did not change consistently in the other components (in which reinforcement was immediate). As pointed out in the discussion of Experiment 1, the increase is consonant with other research using multiple FR FR schedules that varied various parameters of reinforcement. This has shown pausing is also affected by the (signalled) upcoming reinforcer magnitude (e.g., Perone & Courtney, 1992), ratio size (e.g., Baron & Herpolsheimer, 1999), and force requirement (e.g., Wade-Galuska et al., 2005).

The running response rates in Experiment 1 were lower during ratio components in which an upcoming delay was signalled, and the overall response rates decreased monotonically with increasing delay in these components. Both the running and overall response rates did not consistently change during components in which reinforcement was immediate. Previous investigations of behaviour under multiple FR FR schedules have focussed on the between-ratio pause, and therefore most have not reported response rate data. However, Wade-Galuska et al. (2005) similarly reported lower running response rates for ratios that required larger forces than for smaller forces, and Perone and Courtney (1992) found running response rates to be slower before the small reinforcer and faster before the large reinforcer for one subject only.

Overall, the pausing data from Experiment 1 suggest that in multiple FR FR schedules an increasing delay-to-reinforcement functions in the same way as other parameters of reinforcement, by making conditions ‘more unfavourable’ (cf., Wade-Galuska et al., 2005). The response rate data support this. Based on these results, it could be expected that delay-to-reinforcement would change behaviour similarly to parameters such as reinforcer magnitude in other situations.

Given the findings from Experiment 1, suggesting that an increasing delay-to-reinforcement makes conditions increasingly unfavourable, Experiment 2 investigated the same range of delays-to-reinforcement and their effects on behaviour under increasing FR schedules, as used for generating demand curves.

The effects of delay-to-reinforcement were similar to but not as clear as those found in Experiment 1. At larger delays-to-reinforcement, the overall and running response rates at each FR value were lower, and pause durations longer than at smaller delays. Previous researchers investigating the effects of delay-to-reinforcement on behaviour under FR schedules have also found pause durations to increase with increasing delay (Azzi et al., 1964; Morgan, 1972; Topping et al., 1973). The reported effects of increasing delay on response rates are mixed. Azzi et al. (1964) found decreasing overall response rates with increasing delay as was found here. Morgan (1972) and Topping et al. (1973) found no consistent effect of delay on running response rates.

In Experiment 2, delay-to-reinforcement had only slight effects on the shape of the demand curves. Functions were fitted to the data using Hursh et al.'s (1988) nonlinear equation and Hursh and Silberberg's (2008) exponential equation. Neither model provided a better fit to the data. The only consistent effect of the different delays was that initial consumption tended to be largest in the 0-s delay condition and smallest in the 32-s delay condition. The findings were dissimilar to previously reported effects of reinforcer magnitude (e.g., Grant, 2005) and reinforcer quality (e.g., Foster et al., 2009) on levels of consumption at small FR values.

A delay-to-reinforcement necessarily extends the total time to reinforcement, which, in Experiments 1 and 2 was found to increase pause durations and decrease both overall and running response rates. In Experiment 2, increases in the pause durations and decreases in the running response rates were also found to occur as the FR increased. As mentioned in the general introduction, the increasing schedule duration that necessarily occurs with increasing response requirement is a confound when investigating behaviour under different FR schedules, especially in short sessions. Experiment 3 set out to control the schedule duration and vary both it and the number of responses required independently.

It was argued that total consumption and consumption rate were not sensible measures of behaviour in this conjunctive schedule procedure and therefore behaviour was also assessed using the schedule-initiation immediacy, measured as the inverse of the between-operant unit pause. In conditions in which the FR was increased and the FI was fixed, the between-operant unit pause durations and therefore the schedule-initiation immediacies remained relatively constant. In these conditions, the running response rates remained constant or increased as the FR increased. As the total duration of the schedule increased in the increasing-FI fixed-FR conditions, the schedule-initiation immediacies decreased, as did the running response rates, more similar to the findings of Experiments 1 and 2. Together, these findings indicate that it is the total duration of the schedule that has more effect on behaviour under FR schedules than the response requirement.

GENERAL DISCUSSION

There are several major conclusions that can be drawn from these three experiments. First, these data show that in stable behaviour under multiple FR FR schedules the between-ratio pause durations are influenced more by the signalled upcoming delay-to-reinforcement than by the preceding delay. This adds to the research suggesting that a signalled delay, like reduced reinforcer magnitude, increased force and larger response requirements, makes conditions increasingly unfavourable. Second, they also show that delay has a smaller effect on behaviour overall as the FR requirement gets larger. Thus effects seen at small FR values may not be found with larger FRs. This finding may account for some of the mixed findings in the literature. Third, the data suggest that delay influences behaviour under some FR values and schedules (e.g., multiple FR FR schedules) in the same way as other studies have reported for variables that make conditions less favourable. However, they do not change behaviour in some other schedules (e.g., single FR schedules, when the response requirement is increased session to session) in the same way as does varying reinforcer quality or magnitude. Fourth, these experiments also suggest that the duration of the inter-reinforcement interval is more influential than the number of responses required on pause length and response rates. Fifth, the data suggest that schedule-initiation immediacies are worthy of further study as they remove some of the problems inherent in the use of consumption measures, such as rate of delivery or total number obtained. In addition, the data from these experiments highlight the importance of considering the underlying distributions and within session behaviour when using measures of central tendency to summarise data.

Although many studies present means as summaries of individual data, in previous research it has been found that distributions of between-ratio pausing in FR schedules are positively skewed (e.g., Baron & Herpolsheimer, 1999; and Wade-Galuska et al., 2005). In such cases medians are likely to be a better measure of central tendency (Aron & Aron, 1999). In Experiments 1 and 2, it was found that between-ratio pausing distributions were positively skewed and had outliers in the tail (Figures 1.1 and 2.10). This was a small positive skew in Experiment 1, and in Experiment 2 the distribution became less skewed as the FR and delay increased. Therefore medians were used to summarise the data rather than means. Median data in the present set of experiments were compared to means and the median between-ratio pause durations showed less variability and were more orderly than the mean data. This resulted, to some extent, from the effect of the occasional extreme outliers on the mean. All of the above suggest that medians may be a better way to represent between-ratio pausing than means. In future research, distributions of between-ratio pause durations should be examined, and when the data are skewed and there are outliers, medians should be considered to summarise the data.

In the present experiment the mean overall response rates did not always reflect the within-session response rates accurately. This was a problem similar to the mean between-ratio pause durations not accurately reflecting their underlying distributions, as outlined above. The cumulative records of Experiment 2 (Figure 2.7) show that at small FR values responding took up only a small part of the session. Thus mean response rates were lower than the local rates of responding when the animals were responding. This means that mean response rates at small FR values may not appear very different from the mean response rates at larger FR values, in which local responding was slower but persisted across the whole session. As mentioned in the discussion of Experiment 2, rates of responding in each 5-min segment of the session were analysed (Figure 2.8). Such analysis was found to be a useful compromise between using means and cumulative records. Using the median of the segment rates also may be a way in which to summarise the data further. However, if the response rate data are skewed and there are many parts of the session in which no responding occurred, the median, like the mean, will not be a representative measure of the response rate. In such cases, the modal response rate (of the 5-min segments) may be the most accurate and representative way in which to summarise the data, as the mode is the only measure of central tendency that will not be influenced by skewness and outliers (McBurney, 2001). Another potential method for summarising response rates across a session may be to calculate the individual response rate for each ratio that occurs within the session, creating a distribution of the response rates, similar to the between-ratio pause distributions presented in Figures 1.1 and 2.10. Similarly, the median of these could be taken as the summary measure.

In these studies there are data from all three experiments that bear on the effects of the duration of the schedule versus the number of responses required. In Experiment 3 the between-operant unit pause durations and therefore the schedule-initiation immediacies remained relatively constant in conditions in which the duration was fixed and the ratio requirement increased (Figure 3.5). However, the schedule-initiation immediacies decreased as the schedule duration increased in conditions where the interval was increased and the ratio requirement was fixed (Figure 3.6). Thus, when the time was fixed and the ratio varied the schedule-initiation immediacies remained constant and when the time was varied and the ratio was fixed the schedule-initiation immediacies decreased. This suggests that the schedule duration was more influential on behaviour than the response requirement. In Experiment 1, pausing during transitions in which a delay was signalled was always longer than during transitions in which no delay was signalled. Further, as the delay durations were increased across conditions, pausing during transitions in which the delay was upcoming also increased. The ratio requirement in both multiple components was equal, and the only difference between components was whether or not there was a delay-to-reinforcement. If behaviour were a product of the ratio requirement alone, it could be expected that pausing would be the same during all multiple schedule transitions. Similarly, at most FR values examined in Experiment 2, between-ratio pause durations were longer with larger delays-to-reinforcement. Therefore these findings are further evidence that the total duration of the schedule requirement has more influence on between-ratio pausing than the response requirement.

The running response rate data from all three experiments also suggest that duration is more important than number. As the total duration of the schedule increased with increasing delay-to-reinforcement in Experiments 1 and 2, the running response rates decreased compared to no delay in Experiment 1, and decreased monotonically with increasing delay in Experiment 2. In Experiment 3, in conditions in which the FR increased but the FI duration was fixed, the running response rates either increased or remained constant. However, in conditions in which the FR was fixed and the FI duration increased, the running response rates decreased. Overall, these findings as measured by the running response rates or the between-ratio (or operant unit) pause durations further support the notion that the total duration of the schedule requirement has more influence on FR schedule behaviour than the response requirement. Further, it appears that this was the case regardless of whether the delay-to-reinforcement was at the end of the response requirement (Experiments 1 and 2) or part of the schedule requirement (Experiment 3).

In Experiment 2, there were only small effects of delay-to-reinforcement on behaviour under increasing FR schedules. Two different equations were used to describe the consumption data and both functions fit the data well. However, none of the parameters of either equation changed systematically with variations in the delay. The logged scale that is commonly used to plot the demand functions de-emphasises any effect on consumption at small FR values. This reduced the expected larger effect of delay-to-reinforcement on behaviour under small FR values. As mentioned earlier, in demand experiments the number of reinforcers that may be obtained is often restricted by session length and by the increasing time required to complete the schedule as the ratio is increased. Thus, using only consumption (measured as the total number of reinforcers obtained) may not necessarily provide the best possible assessment of demand. A better assessment of demand would include consideration of a measure that is not constrained by session duration.

In Experiment 3, it was argued that the schedule-initiation immediacy may be a better measure for assessing demand than either total consumption or consumption rate, both of which can be confounded by the duration of the session and by the time it takes to complete the ratio requirement. To provide a comparison, data from Experiment 2 were re-analysed using the schedule-initiation immediacies and robust regression. Figure 4.1 presents the median schedule-initiation immediacies calculated for the last completed series of each of the 0-s delay and 32-s delay conditions for each hen. In both conditions, the schedule-initiation immediacies were downward sloping, showing a decrease in the schedule-initiation immediacy as the FR increased. These functions are very similar to the schedule-initiation immediacy functions from the FI-increasing conditions presented in Figure 3.6. This suggests that it is the increase in the time it takes to complete the schedule that occurs as the FR increases that results in the decrease in the schedule-initiation immediacy. Further, the schedule-initiation immediacies were higher in the 0-s delay condition than the 32-s delay condition across all FR values. This also suggests that it is the increased time to complete the schedule, in this instance the delay compared to no delay, which results in the reduction in the schedule-initiation immediacy.

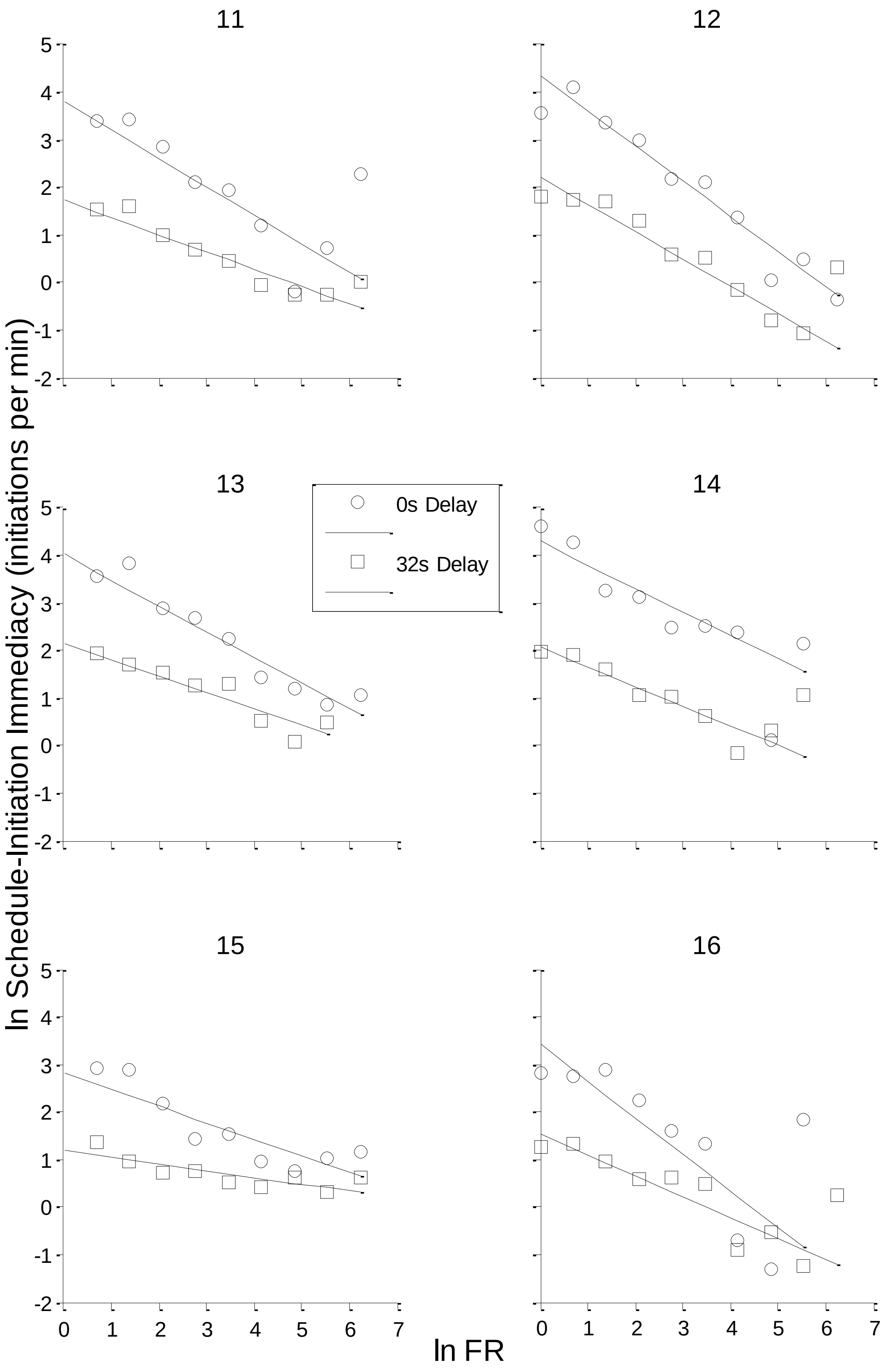

Figure 4.1. The natural logarithms of the schedule-initiation immediacy data, plotted against the natural logarithms of the FR size in the 0-s delay and 32-s delay conditions of Experiment 2. The data are the median schedule initiation immediacies of the last completed series in each condition. The lines were fitted using the robust regression analysis available in Matlab®.

The functions fitted to the schedule-initiation immediacy data are furthest apart at the smallest FR values, and become closer as the FR increases. This is likely to be because at higher FR values it takes longer to complete the schedule requirement and so the delay is a decreasing proportion of the schedule. As well as providing support for the schedule-initiation immediacy as a measure of demand, these functions also further support the notion that it is the duration of the schedule rather than the FR requirement that has more effect on between-ratio pausing.

As previously mentioned, using conjunctive schedules and using the schedule-initiation immediacies to assess demand require further investigation. The findings from Experiment 3 suggest that demand for food, when assessed using conjunctive schedules and the schedule-initiation immediacy, is highly inelastic. Other commodities that would be expected to show various degrees of elasticity of demand (e.g., dust bathing substrates) should be assessed in the same way to see if the elasticities of the schedule-initiation immediacies vary across commodities. The use of conjunctive schedules and of schedule-initiation immediacies should also be tested with larger FI durations than were used in Experiment 3, to allow the subjects to respond to FR values such as 512 and 1024, which are typically the largest FR values reached by hens under increasing FR schedules. Experiment 3 was conducted under short (40-min total time), relatively closed economic conditions (according to Hursh’s 1980 definition). It was argued in that discussion that consumption data from experimental sessions of any length may potentially be confounded by increasing the FR requirement and thus the duration required to complete the schedule. Such a confound does not apply to the schedule-initiation immediacy. Another potential test of the use of conjunctive schedules and the schedule-initiation immediacies as a way to assess demand would be to conduct a similar experiment with longer (e.g., 24-hr) sessions.

Wade-Galuska et al. (2005) suggested that conditions in their multiple schedules experiment became more unfavourable with an increasing force requirement in one of their schedule components. A similar finding is highlighted in Experiment 1, where conditions were worsened and improved, respectively, with the arrival of the delay and no delay components of the multiple schedules. In Experiment 3, the conditions in which the FI durations were increased (and the

FR fixed) appeared to be more unfavourable than did conditions in which the FR requirements were increased (and the FI fixed). Further, the larger the delay in Experiment 2, the more unfavourable the conditions, as shown by the lower response rates and the longer between-ratio pause durations. Hence, across all three experiments it was found that a delay-to-reinforcement, and thus reduced rate of reinforcement, appears to lower the value of the schedule compared to no delay, as shown by increased pause durations and reduced response rates. Further, as the delay or time to reinforcement increases, conditions become even more unfavourable and this effect is essentially independent of the response requirement.

Wade-Galuska et al. (2005) suggested that increased pause durations in favourable-unfavourable transitions may occur because the transition is aversive, and that the pause in responding prior to the initiation of the ratio requirement may be a means of escaping the aversive transition. Wade-Galuska et al. (2005) went on to suggest a functional similarity between pausing and escape, a finding supported by other research which has shown that animals will choose to escape from FR schedules (e.g., Appel, 1963; Azrin, 1961; Thompson, 1964). Azrin (1961) reported that pigeons would respond to a ‘time-out’ key that was simultaneously available when they were exposed to FR schedules, resulting in escape from the FR schedule. These periods of ‘time-out’ typically occurred during the pause preceding the initiation of the schedule requirement, and these durations of ‘time-out’ increased as the FR requirement increased. Appel (1963) and Thompson (1964) reported similar results. All of the above findings, including the data from this thesis, provide support for the suggestion of Wade-Galuska et al. (2005) that the period following reinforcement is essentially aversive and becomes more so as the total time to reinforcement increases.

Comparisons across these present experiments show that the effects of the addition of the same delay durations differ in intensity depending on the procedure used. In Experiment 1, the addition of delays between the final FR response and reinforcement had a large effect on responding and pausing in multiple FR 5 FR 5 schedules. The addition of the same delay durations to increasing FR schedules in Experiment 2 did not have as large an effect on behaviour. This may be due to the context in which the delay-to-reinforcement occurred. During the demand conditions, any one delay was in the context of the same delay. However, during the multiple schedule conditions, any one delay was either in the context of the same delay or in the context of no delay. It is possible that this worsening and improving of conditions intensified the effects of the delay values in Experiment 1.

One possible outcome of the worsening and improving conditions in the multiple schedules could have been positive behavioural contrast. Reynolds (1961) defined behavioural contrast as a change in the rate of responding in one (unchanged) component when conditions (the rate of reinforcement) are changed in the other component. This change in responding is relative to responding in that component when conditions were the same in both components. Positive behavioural contrast, in particular, is an increase in responding in the unchanged component when the rate of reinforcement is reduced in the other component. In Experiment 1, positive behavioural contrast might have been seen in the component in which there was no delay (the unchanged component), when the rate of reinforcement was reduced in the other component (with the addition of a delay-to-reinforcement). It was found that responding during the component in which there was no upcoming delay was faster than during the component in which a delay was upcoming. However, positive behavioural contrast was not found here as the rate of responding during the component with no delay upcoming did not increase relative to the rate of responding during that component when conditions in both components were identical.

In Experiment 1, using multiple schedules, delay-to-reinforcement increased pause durations similarly to reduced reinforcer magnitude (Perone & Courtney, 1992) and increased ratio size (e.g., Baron & Herpolsheimer, 1999). In Experiment 2, using increasing FR schedules, larger delays-to-reinforcement did not yield larger levels of initial demand as has previously been found with reinforcers of reduced magnitude or quality. This suggests that delay-to-reinforcement may or may not have the same effect on behaviour under FR schedules depending on the procedure used. It would be interesting to examine whether the same delays-to-reinforcement would have effects similar to other reinforcement parameters on behaviour in concurrent schedules. Perone and Courtney's (1992) findings that between-ratio pausing was shorter before a large reinforcer than before a short reinforcer are not similar to the 'magnitude of reinforcement' effect, and do not predict the results (across small FR values) of

Foster et al. (2009) and Grant (2005). However, as mentioned previously, the 'magnitude of reinforcement' effect has most commonly been found at small FR values. Perone and Courtney (1992) examined pausing at FR 80, a moderate FR size. A replication of Perone and Courtney's (1992) experiment using smaller FR values may produce data more similar to the 'magnitude of reinforcement effect' and may predict the results of Foster et al. (2009) and Grant (2005).

The seemingly differing intensities of the effects of delay-to-reinforcement that were found on FR performance in this thesis may be because Experiment 1 examined behaviour under only FR 5 schedules. Therefore the results from this experiment are not representative of all FR schedule behaviour. As previously mentioned, the small FR 5 schedule used means that all of the delay values that were examined added a large proportion of time to the duration required to gain reinforcement. If Experiment 1 were to be conducted with larger FR values, it might be expected that the same delay values used would have a lesser effect on behaviour. If this is the case, then the diminishing effects of delay on behaviour that were found as the FR increased in Experiment 2 could be predicted.

In Experiment 2, each delay duration was held constant while the FR was systematically increased. Each series of increasing FR schedules took at least three weeks to complete. A more clear comparison of the effect of a range of delays-to-reinforcement on a particular FR value might involve a procedure opposite to the one used in the present study. The FR value could be held constant while the delay is systematically manipulated. One caveat arises from consideration of reinforcer amounts delivered in the present research. In any research comparing the effects on behaviour of a reinforcer that is delayed with a reinforcer that is not delayed, reinforcer durations should be timed from the moment the subject's head enters the magazine to ensure that reinforcement duration is not altered by the addition of delay.

Across all procedures used in this thesis, increasing the total schedule duration at each FR value reduced response rates and increased pause durations, similarly to the effects of FR increases. The addition of a delay-to-reinforcement appears similar to adding a negative consequence or a punisher to the schedule. To this author's knowledge, the effects of delay-to-reinforcement on behaviour under FR schedules have never before been investigated so systematically.

These three experiments have each added to the knowledge of responding under FR schedules and also suggest an alternate measure of behaviour under increasing FR schedules. They show that the duration of the schedule has more effect on behaviour than the number of responses that are required. The calculation of the schedule-initiation immediacy may provide a better analogue of human spending than consumption rate and therefore help to reduce some of the confounding effects of session time in behavioural economics.

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