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Rats show molar sensitivity to different aspects of random-interval-with-linear-feedback-functions and random-ratio schedules

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Abstract

Three experiments examined the impact of various aspects of reinforcement contingencies on responding maintained by free-operant schedules by food-deprived rats. Experiment 1 demonstrated that random interval (RI) and random-interval-with-positive-response-reinforcer-feedback (RI+) schedules maintained similar rates of responding at a variety of reinforcer frequencies. Experiment 2 demonstrated that a random ratio (RR) schedule maintained higher rates than RI or RI+ schedules, except at high rates of reinforcement, where response rates were similar on all schedules. Experiment 3 again demonstrated that RR schedules produced higher response rates than either RI or RI+ schedules, but modification of the RI+ schedule to prevent ratio strain enhanced response rates relative to a RI schedule. Together these results reveal a pattern of interacting factors in schedule controlled behavior: at high rates of reinforcement, this factor overrides the impact of other controlling factors, but as reinforcement rate decreases the joint impact of IRT reinforcement, response-reinforcer feedback functions, and ratio strain are observed.

Key words: molar, molecular, variable interval, variable interval with linear feedback, inter-response times (IRTs).

Free-operant schedules of reinforcement produce highly consistent patterns of behavior across a wide range of species (see Schoenfeld, 1970; Zeiler, 1977), and they have been used to investigate the factors that influence instrumental responding in many different domains (e.g., Baum, 181; Lattal and Neef, 1996; Peele, Casey, and Silberberg, 1984). It is accepted that any theory of schedule-controlled behavior has to acknowledge the multiple influences that are exerted by such free-operant contingencies (see Lattal, 1991; Schoenfeld, 1970, for reviews). For example, the rate at which reinforcement is delivered in any given time period has a profound influence over behavior (e.g., Davison and McCarthy, 1988; deVilliers, 1977; Herrnstein, 1970). This factor impacts on choice between different response alternatives (see Baum, 1981; Tanno, Silberberg, and Sakagami, 2010); rates of responding emitted to a single manipulandum (e.g., Baum, 1981; Bradshaw, Szabadi, and Bevan, 1976); and the tendency of an organism to commence a bout of responding (see Bowers, Hill, and Palya, 2008; Reed, 2011; Shull, Gaynor, and Grimes, 2001). The temporal distribution of reinforcers across time, in addition to their rate of delivery, can also shape behavioral patterns on free-operant schedules (e.g., Ferster and Skinner, 1957; Gallistel, 1990); as can be seen on fixed interval (FI; Dews, 1978) and fixed ratio (FR; Ferster, Appel, and Hiss, 1962) schedules. Similarly, the availability of alternative sources of reinforcement (Burgess and Wearden, 1986), and the costs associated with a response (see Bradshaw and Reed, 2012; Collier and Rovee-Collier, 1981; Reed and Yoshino, 2008; Rider and D'Angelo, 1990), both impact on observed schedule performance.

However, even when the rate and patterning of reinforcement over time are held constant, differences in performance supported by various schedules can still emerge. This finding suggests a range of further factors that impact on free-operant behavior (see McDowell and Wixted, 1986; Morse, 1966; Peele et al., 1984; Tanno and Silberberg, 2012).

A finding that has generated considerable theoretical debate in this context is that higher rates of response are observed on a random ratio (RR) schedule compared to a random interval (RI) schedule (e.g., Cole, 1994; Ferster and Skinner, 1957; Peele et al., 1984; Reed, 2007a; Zuriff, 1970), even when all the aspects of contingencies mentioned above are otherwise identical on the two schedules (but see Baum, 1993).

Two theories have been suggested to account for the higher response rates on RR schedules relative to RI schedules – 'molecular' views (e.g., Morse, 1966; Peele et al., 1984), and 'molar' views (e.g., Baum, 1981; McDowell and Wixted, 1986). Molecular theories suggest that the reinforcement of particular inter-response times (IRTs) is primarily responsible for response rate differences on schedules when all other aspects of the contingency are controlled. For example, RI schedules tend to reinforce long IRTs that would drive down response rates relative to RR schedules which have no such contingency (see Morse, 1966; Peele et al., 1994; Tanno and Silberberg, 2012). Alternatively, molar views suggest that the response-reinforcer feedback function is important in the control of free-operant behavior (e.g., Baum, 1981). On an RR schedule there is a linear relationship between the rate of response and the rate of reinforcement, which should act to reinforce high rates of responding. This linear relationship is not present on an RI schedule; on which, increases in response rate are not strongly associated with increases in reinforcement rate.

Although most direct tests of these two sorts of theory have tended to favor the molecular view (see Cole, 1999; Peele et al., 1984; Reed, Soh, Hildebrandt, DeJongh, & Shek, 2000; Tanno and Sakagami, 2008), there are some suggestions that molar control can be seen under some conditions, especially when rates of reinforcement (see Baum, 1993; Cole, 1994), or rates of response (McDowell and Wixted, 1986; Reed, 2007a), are high. Given this, several theorists have suggested that these two views should not be seen as mutually exclusive (see Cole, 1994; Reed, 2007a; Shimp, 2014; Tanno et al., 2010), and an important line of investigation is to determine when these aspects of free-operant contingencies exert prime influence over behavior.

A schedule of reinforcement that has been employed to tease apart the influence of the molar and molecular aspects of a free-operant contingency (see Cole, 1999; McDowell and Wixted, 1986; Reed, 2006; Reed, 2007a; 2007b; Reed et al., 2000) can be termed the random-interval-plus-linear-feedback (RI+) schedule (McDowell and Wixted, 1986). The RI+ schedule has the molar properties of an RR schedule (i.e., a linear function relating response rate to reinforcement rate), but the molecular properties of a RI schedule (i.e., it differentially reinforces long IRTs). Thus, whether the rates of response on this schedule are similar to a RI schedule or to a RR schedule is taken to indicate whether the molecular or molar aspects of the contingency, respectively, are more influential (see Cole, 1999; McDowell and Wixted, 1986; Reed, 2007a).

The response-reinforcer feedback function of a RI+ schedule is given by the following equation (equation 1): $a = (i / n) * b$; where, i = the time from the last reinforcement to the present moment; n = the number of responses made during the period i; b = the equivalent RR value; and a = the interval currently scheduled to give reinforcement. A couple of numeric examples may serve to illustrate how this schedule works. Assume that the RI+ schedule was to have the molar character of a RR-30 schedule. Assume also that the time from the last reinforcer was 60s, and that 60 responses had been made during that time. In this case, the interval to reinforcement given a response would equal (60/60)*30 = 30s. During this 30s, at 60 responses per minute, 30 responses would be emitted before the interval would time out. If 30 responses had been made during that 60 s period, then the interval would be: (60/30)*30 = 60s. During this 60s, if responses were being emitted at 30 responses per minute, then 30 responses would be emitted prior to the reinforcer. Alternatively, if 120 responses had been made during the 60s period, the interval becomes (60/120)*30 = 15s. During this 15s, at 120 responses per minute, then 30 responses would be emitted prior to the reinforcer. Thus, the interval varies inversely with the rate of responding, and each reinforcer is delivered for about 30 responses.

McDowell and Wixted (1986; see also Reed, 2007b) studied the effects of RI+ and RR schedules in human subjects who were required to press a lever for a financial reinforcement. McDowell and Wixted (1986) found that similar response rates were produced on the RR and RI+ schedules that they studied – a finding that suggested that behavior was being controlled by the molar aspects of the schedules, which were identical in the two schedules. Apparent sensitivity to the molar aspects of the schedule was also noted in humans by Reed (2007b), who found differences between the response rates on RI+ (that had a linear response-reinforcement feedback function) and a RI schedule (that did not have a linear feedback function). In contrast, Reed et al. (2000; see also Cole, 1999; Reed, Hildebrandt, DeJongh, and Soh, 2003) found that rats' response rates on a RI+ schedule were similar to those on a RI schedule when the schedules were matched for reinforcement rate, and that both the RI and the RI+ schedules produced similar reinforced IRTs to one another, and much longer than those reinforced on the RR schedule (see also Cole, 1999; Reed et al., 2003). Thus, these latter studies with rats did not find compelling evidence of any impact of the molar contingency on the rats' performance.

Apart from the species difference between the studies, there are a number of further issues that have sparked investigation into the conditions under which the molar and molecular aspects of the contingencies influence behavior (see Cole, 1994; Reed, 2006; 2007a). In the studies using humans, the subjects responded at a high rate throughout the experiment (McDowell and Wixted, 1986; Reed, 2007b). These high response rates might have allowed the subjects' behavior to contact the contingency in such a way that they experienced the differential reinforcement of high rates of responding on the RI+ schedule. Indeed, when subjects receive high rates of reinforcement, and emit correspondingly high rates of response, Baum (1993) noted little difference in the rates of response between RI and RR schedules. Similarly, Cole (1994) noted some evidence for sensitivity to molar aspects of tandem RI RR and tandem RR RI schedules. Reed (2006; 2007a) investigated this possibility using rat subjects performing on RI+ schedules, and found some evidence of a molar sensitivity when conditions were in place that maintained the rats' high rates of response. This finding of greater molar sensitivity also accords with exceptions to the otherwise good fit between the predictions of some molecular IRT theories and the response rates observed on various schedules of reinforcement (see Tanno and Silberberg, 2012).

The view that there are some conditions involving the maintenance of high rates of responding under which molar control of behavior can be exerted on a RI+ schedule accords with another finding reported by Cole (1999; see also Reed et al., 2003), who noted that the RI+ schedule was incapable of supporting behavior in some rats. Indeed, several other studies using rats have often noted severe strain in responding on RI+ schedules, sometimes to the point of extinction of responding (see Reed, 2003; 2006; Reed et al., 2007). Ratio strain/extinction is particularly likely on a RI+ schedule as pauses from responding can dramatically extend the required interval prior to the delivery of reinforcement (see Cole, 1999, for a discussion). These considerations suggest that the response costs involved in the contingency (see Rider and D'Angelo, 1990), and the possibility of differential schedule strain, may be important in determining when some organisms can show sensitivity to the molar aspects of the schedule.

The current series of studies investigated whether there are particular conditions under which the behavior on a RI+ schedule will approximate to that of an RR schedule and display higher response rates than a RI schedule. This finding has been taken to indicate sensitivity to the molar response-reinforcement feedback function (McDowell and Wixted, 1986). The above considerations suggest that this sensitivity might vary parametrically with the nature of the schedule – being more likely with shorter RI+ values (cf Cole, 1999), and when responding can be maintained (see Reed, 2006; 2007a). However, the lack of systematic investigation of the role of RI+ values in the current literature makes such a suggestion, although theoretically interesting, in need of confirmation.

Experiment 1

The above discussion suggests that when the schedule requirements are low, and/or response rates are high, then some degree of sensitivity to the molar characteristics of a schedule is observed (Baum, 1993; Cole, 1994; Reed, 2007a). For example, Cole (1994) noted no difference between the response rates produced on tandem RR RI, and tandem RI RR, schedules that were equivalent to one another in terms of their response-reinforcement feedback functions (despite differential reinforcement of IRTs on the two schedules) when using short ratio values (around 5). Whereas, Peele et al. (1984; see also Reed and Hall, 1988) noted higher response rates on tandem RI RR schedules than on tandem RR RI schedules that were equivalent to one another in terms of their molar characteristics using high ratio values (> 100). There are two possible explanations for this pattern of results that are supported by the existing data. Firstly, it may be that molar sensitivity is more likely when reinforcement occurs more frequently (see Cole, 1994) – as it may allow more opportunity to learn about the relationship between responding and reinforcement. If this is the case, then a RI+ schedule with a short ratio-equivalent value should support higher rates of response than an RI schedule matched for reinforcement rate. Secondly, it may be that high experienced rates of reinforcement would tend to promote higher numbers of response-initiation responses (i.e., those responses which start a bout of responding; see Bowers et al., 2008; Shull et al., 2001). On short schedules with minimal response requirements for reinforcement, response-initiation responses will comprise a higher proportion of all responses, and impacting these responses will tend to have a larger effect on overall response rates. If that is true, than most schedules, irrespective of molar feedback function, will show high rates of response (see Baum, 1993).

Method

Subjects

Thirty-two male Lister rats served in the present experiment. The subjects were three months old at the start of training, had a free-feeding body-weight range of 320-355g, and were maintained at 85% of this weight throughout the experiment. The subjects had previously served in a study of classical conditioning, but they were naïve with respect to lever pressing, and to all the schedules that were used in the experiment. The subjects were housed in groups of four, with water constantly available in the home cage.

Apparatus

Four identical operant conditioning chambers (Campden Instruments Ltd.) were used. Each chamber was housed in a light and sound- attenuating case, ventilated by a fan that provided background masking noise (65-db[A] above background). Each chamber had two levers, both of which were permanently inserted into the chamber, but only one of which (the left) was operative during the experiment. The lever required a response force of .40N to depress. Reinforcement consisted of one 45-mg food pellet, and this was delivered to a centrally located food hopper that was covered by a clear Perspex, hinged flap.

Procedure

The subjects received two sessions of magazine training on a random time (RT) 60-s schedule. They then received two, 20-min sessions of lever press training with a continuous reinforcement (CRF) schedule. All subjects were then transferred on to an RI-30s schedule (where each successive second was assigned the same probability, p = 1/30, of satisfying the interval requirement, such that the next response would be reinforced) for 4, 30min sessions of training.

The subjects were then randomly assigned to four equally-sized groups (n = 8). Two groups were exposed to a RI+ schedule, such that the feedback function relating the rate of response to the rate of reinforcement was either the same as an RR-10 or an RR-30 schedule. The inter-reinforcement interval on the RI+ schedule was determined by the function given in equation 1, above: (i / n) * b; where i = the interval between the last reinforcement to the present time; n = the number of responses made during the period i; and, b = the equivalent RR value (i.e. 10 or 30). Thus, the relationship between rates of response and rates of reinforcement should be the same on this RI+ schedule as on an RR-30 schedule. The other two groups were exposed to a RI schedule that was yoked to a RI+ schedule; one of these groups was yoked to the RI+(10) group, and one was yoked to the RI+(30) group. One rat in each RI-y group was paired with a master rat in a RI+ group (the same pairing was in force for the whole study). Whenever the latter subject earned a food pellet on the RI+ schedule, reinforcement was made available to the yoked RI subject. The experiment was conducted for 40 sessions, where each session lasted for 30 min.

Results and Discussion

Figure 1 about here

Figure 1 displays the group-mean response rate averaged over the last 4 sessions of training for all groups. Inspection of these data shows that the RI+(10) and the RI-y(10) groups emitted higher response rates than the RI+(30) and the RI-y(30) groups. The RI+(10) emitted a somewhat higher rate of response than the RI-y(10) group, but this pattern of results was not noted for the longer (30) schedules.

These data were subject to a number of analysis, a two-factor between-subject analysis of variance (ANOVA) with schedule type (RI+ versus RI), and schedule value (10 versus 30) was conducted initially on these data. In addition, the effect size (and its 95% confidence limits) was computed, as well as the Bayes Factor and the probabilities of the hypothesis (null and alternate) being true given the obtained data. The latter statistics were employed to determine whether any conclusions that depended on a null result for one group of rats were likely due to power issues.

These analysis revealed a significant effect of schedule value, $F(1,27) = 15.21$, $p < .001$, *partial* $eta^2 = .360$, 95% *CIs* = .122:.531, *Bayes Factor* = .001, $p(H_o/D) = .004$, $p(H_1/D) = .996$. The low Bayes Factor (BF), low probability of the null hypothesis being true ($p(H_o/D)$), and high probability of the alternative hypothesis being true ($p(H_1/D)$), supports the rejection of the null hypothesis. There was no main effect of schedule, $F(1,27) = 1.10$, *p*

$> .40$, *partial eta*^{2} = .039, 95% CIs = .000:.200, *Bayes Factor* = 2.99, $p(H_o/D)$ = .749, $p(H_1/D)$ = .251, and no significant interaction between the two factors, $F(1,27) = 1.84$, $p >$ .30, *partial eta*^{2} = .064, 95% CIs = .000:.239, *Bayes Factor* = 1.98, $p(H_o/D)$ = .664, $p(H_1/D)$ = .336. Both rejections seem justified given the low Bayes Factor, weak $p(H_o/D)$, and moderately high $p(H_o/D)$ values.

The responses were also collated into 200ms response bins, and these data were subject to the types of analyses described by Shull et al. (2001) for examining patterns of IRTs on different schedules of reinforcement. A frequency distribution of IRTs was created, and the proportion of the responses falling into each bin calculated for the total responses emitted during the last four sessions. The logs of these proportions were then taken, and a log survivor plot was created. These log survivor plots typically produce a distinct pattern of data (Shull et al., 2001), and often comprise a sharply decreasing initial portion, followed by a portion with a shallower negative gradient. This is interpreted as reflecting the presence of two different types of responding: a set of shorter IRTS, reflecting within-burst responding; and a set of longer IRTs, classed as burst-initiation responses. Once this break point is identified, the number of responses falling into the pre-break point (burst responses), and those falling after the break point (initiation responses), and their rates, can be calculated for each subject. Typically, when reinforcement frequency declines, the number of response initiations decline; moreover, RR schedules have a lower rate of initiation but a greater rate of burst responses than matched RI schedules (see Reed, 2010; Shull et al., 2001).

Figure 2 about here

The group-mean initiation and burst rates are shown in Figure 2. Inspection of the group-mean initiation rates shows higher initiation rates for the RR+10 and RI-y(10) schedules compared to the RR+(30) and RI-y(30) schedules. There was little difference between the RR+ and RI schedules at each schedule value. A two-factor ANOVA (schedule type x schedule value) revealed a significant effect of schedule value, $F(1,27) = 8.38$, $p < .01$, *partial eta*^{2} = .237, 95% *CIs* = .020:.461, *Bayes Factor* = .08, $p(H_o/D) = .078$, $p(H_1/D) = .922$. There was no main effect of schedule type, $F < 1$, $p > .50$, *partial eta*^{2} = .013, 95% CIs = .000:.182, *Bayes Factor* = 4.55, $p(H_o/D) = .820$, $p(H_1/D) = .180$, nor was there a significant interaction between the two factors, $F < 1$, $p > .80$, *partial eta*^{2} = .002, 95% CIs = .000:.087, *Bayes Factor* = 5.35, $p(H_o/D) = .842$, $p(H_1/D) = .156$.

Inspection of the group-mean burst rates shows that these were higher for the RI+(10) and RI-y(10) schedules than for the RI+(30) and RI-y(30) schedules, with rates tending to be slightly higher in the RI+ than the RI-y schedules. A two-factor ANOVA (schedule type x schedule value) revealed a significant effect of schedule value, $F(1,27) = 6.56$, $p < .05$, *partial eta*^{2} = .195, 95% *CIs* = .006:.423, *Bayes Factor* = .19, $p(H_o/D) = .161$, $p(H_1/D) = .840$. There was no main effect of schedule type, $F < 1$, $p > .30$, *partial eta*^{2} = .032, 95% CIs = .000:.226, *Bayes Factor* = 3.37, $p(H_o/D) = .771$, $p(H_1/D) = .229$, nor was there a significant interaction between the two factors, $F < 1$, $p > .50$, *partial eta*^{2} = .016, 95% CIs = .000:.191, *Bayes Factor* = 4.34, $p(H_o/D) = .812$, $p(H_1/D) = .187$.

The group mean rates of reinforcement per min averaged across the last 4 sessions were: RI+(10) = 5.68 (± 2.02); RI-y(10) = 5.64 (± 1.98); RI+(30) = .87 (± .58); and RI-y(30) = .83 (± .59). A two-factor between-subject ANOVA (schedule type x schedule value) revealed a significant effect of schedule value, $F(1,27) = 79.83$, $p < .001$, *partial eta*^{2} = .747, 95% CIs = .578:.819, *Bayes Factor* = $.183^{e-9}$, $p(H_o/D) = .183^{e-9}$, $p(H_1/D) = 1.00$, but there was no main effect of schedule $F < 1$, *partial* $eta^2 = .001$, 95% CIs = .000:.019, *Bayes Factor* = 5.66, $p(H_o/D) = .850$, $p(H_1/D) = .015$, or interaction between the two factors, $F < 1$, *partial* $eta^2 = .005$, 95% CIs = .000:.082, *Bayes Factor* = 5.64, $p(H_o/D) = .849$, $p(H_1/D) = .151$.

The group mean reinforced IRT, averaged across the last four sessions, were: RI+(10) = 1.72 (± 1.51); RI-y(10) = 2.17 (± 1.32); RI+(30) = 3.54 (± 1.51); and RI-y(30) = 3.93 (± 1.01). A two-factor between-subject ANOVA (schedule type x schedule value) revealed a significant effect of schedule value, $F(1,27) = 13.28$, $p < .001$, *partial* $eta^2 = .330$, 95% CIs = .099:.506, *Bayes Factor* = 0.01, $p(H_o/D) = .001$, $p(H_1/D) = .991$, but no main effect of schedule, $F < 1$, *partial* $eta^2 = .026$, 95% CIs = .000:.062, *Bayes Factor* = 3.79, $p(H_o/D) = .791$, $p(H_1/D) = .209$, or interaction between the two factors, $F < 1$ *partial* $eta^2 = .001$, 95% CIs = .000:.016, *Bayes Factor* = 5.65, $p(H_o/D) = .850$, $p(H_1/D) = .151$.

The current results demonstrated that response rates were sensitive to the rates of reinforcement that were received, with the groups obtaining higher rates of reinforcement (from a shorter ratio-equivalent value on the RI+ schedule) responding faster than the groups with lower rates of reinforcement. This is consistent with findings from interval schedules previously (see deVilliers, 1977; Herrnstein, 1970). These groups also emitted higher rates of response-initiation responses than the groups with leaner interval schedules, consistent with previous findings from RI schedules (see Shull et al., 2001). However, there was little evidence that the groups exposed to RI+ schedules responded at higher rates than those exposed to RI schedules with a matched rate of reinforcement. This finding is consistent with previous demonstrations using higher RI+ values, and with the force of response (i.e. .4N) required in this study (see Cole, 1999; Reed, 2007a; Reed et al., 2003).

The only indication that there was some sensitivity to the molar feedback function was on the RI+(10) schedule, on which response rates were numerically higher than those on the yoked RI schedule. This finding would be consistent with sensitivity to molar feedback functions at high rates of reinforcement, and/or low ratio values (see Cole, 1994). However, the RI+ versus RI difference in the current study was not statistically reliable, nor was there any indication in the molecular analyses that the two schedule types were differentiable from one another. This result is equally consistent with the finding reported by Baum (1993), that is, RI schedules and RR schedules show equally high rates of response at high rates of reinforcement, despite differences in the molar feedback functions between them. The suggested mechanism for this is that when the response-initiation responses comprise a relatively high proportion of all responses (such as with short schedules), as these responses are highly sensitive to increases in reinforcement rate (see Bowers et al, 2008; Reed, 2011; Shull et al., 2001), then behavior rates tend to come together irrespective of other influences.

The interpretation of these data as not showing molar sensitivity is also supported by the pattern of response rates seen as the schedule value increased from RI+(10) to RI+(30). In the current study, the rates of response declined as the ratio-equivalent value increased and the reinforcement rate decreased. This would be expected if the RI+ schedule was behaving as a RI schedule (see deVilliers, 1977). In contrast, an increase in ratio value in this range might have been expected to generate an increased rate of response on a RR schedule (see Baum, 1993; Ferster & Skinner, 1957; Reed & Hall, 1988).

Experiment 2

The findings from Experiment 1 suggested that there was little sensitivity to the molar feedback function on a RI+ schedule, even at high rates of reinforcement (or short ratio values). However, the slightly ambiguous nature of the results prompts a replication of these findings, and an extension to compare the rates of response on these schedules with equivalent RR schedules. The latter investigation is also important in order to establish whether or not RI+ performance differs from RR performance with the same molar feedback function, and also whether behavior on the two schedules follows the same pattern as the required ratio value is increased. If subjects are sensitive to the molar feedback function, then, despite differences in reinforced IRTs, response rates on the RI+ and RR schedules should be greater than those on the corresponding RI schedule. Rates of responding should also show an increase between a ratio value of 10 and 30, before showing a decrease after that point (see Baum, 1993; Reed, 2007). In contrast, if there is no sensitivity to the molar feedback function under the current conditions, then the RR schedule should show higher rates of response than the interval-based schedules at all values, with the possible exception of short values (i.e., an RR-10), on which both ratio and interval performance can be observed to be quite similar to one another (Baum, 1993; Cole, 1999).

Method

Subjects and Apparatus

Fifty-four experimentally-naive male Lister rats served in the present experiment. The subjects were three months old at the start of training, had a free-feeding body-weight range of 320-355g, and were maintained as described in Experiment 1. The apparatus was as described in Experiment 1.

Procedure

The subjects received two sessions of magazine training on a VT 60-s schedule. They then received two, 20-min sessions of lever press training with CRF schedule. All subjects were then transferred on to an RI-30s schedule (where each successive second was assigned the same probability, $p = 1/30$, of satisfying the interval requirement, such that the next response would be reinforced) for 4, 30min sessions of training.

The subjects were then randomly assigned to nine equally-sized groups ($n = 6$). Three groups were presented with an RR schedule, where each response had the same probability of reinforcement, but this probability differed across the groups. One group (RR-10) was placed straight onto an RR-10 schedule (i.e., each response had a 1/10 probability of reinforcement), and received 40, 30-min session of training with this schedule. A second group (RR-30) initially received one session each at the following ratio values: 10, 15, 20, 25, and then responded on an RR-30 schedule (i.e., each response had a 1/30 probability of reinforcement), and received 36 30-min sessions of training on this final schedule value. The final RR group (RR-60) received one session on each of the following values: 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and thereafter responded on an RR-60 schedule (i.e., each response had a 1/60 probability of reinforcement), and received 30 sessions of training on this final schedule value.

Three groups were exposed to a RI+ schedule, such that the feedback function relating the rate of response to the rate of reinforcement was either the same as an RR-10, RR-30, or RR-60 schedule of reinforcement. The inter-reinforcement interval on the RI+ schedule was determined as described in Experiment 1. The value ratio-equivalent value was increased as for the RR groups, described above.

The other three groups were exposed to a RI schedule that was yoked to a RI+ schedule. One of these groups (RI-y(10)), was yoked to the RI+(10) group; one (RI-y(30)) was yoked to the RI+(30) group; and one (RI-y(60)) was yoked to the RI+(60) group. The yoking procedure was as described in Experiment 1.

Results and Discussion

Figure 3 about here

Figure 3 displays the group-mean response rates, averaged over the last four sessions of training, for all nine groups. Inspection of these data shows that the RR schedules typically had higher rates of response than the RI+ and RI groups, although this difference was less pronounced at the lowest ratio value (10). The response rates on the RR schedules displayed an inverted-U relationship to the ratio requirement; being highest on the RR-30 schedule, and lower on the RR-10 and RR-60 schedules. Response rates were similar on the RI+ and RI schedules, with the possible exception of the lowest value (10), where the RI+ schedule had slightly higher rates than the RI schedules. Response rates on both the RI+ and RI schedules decreased as the equivalent ratio value on the RI+ schedule increased.

A two-factor between-subject ANOVA (schedule type x schedule value) was conducted on these data, and revealed significant main effects of schedule value, $F(2,45) = 13.20$, $p < .001$, *partial* $eta^2 = .370$, 95% CIs = .168:.499, *Bayes Factor* = .0002, $p(H_o/D) = .0002$, $p(H_1/D) = .999$, and schedule type, $F(2,45) = 15.62$, $p < .001$, *partial* $eta^2 = .410$, 95% CIs = .207:.533, *Bayes Factor* = $.355^{e-5}$, $p(H_o/D) = .355^{e-5}$, $p(H_1/D) = .999$, and a significant interaction between the two factors, $F(4,45) = 2.50$, $p < .05$, *partial* $eta^2 = .182$, 95% CIs = .000:.287, *Bayes Factor* = .569, $p(H_o/D) = .362$, $p(H_1/D) = .637$.

Simple effect analyses for schedule type at each schedule value revealed no effect of schedule type at the lowest ratio value (10), $F(2,45) = 1.73$, $p > 0.20$, *Bayes Factor* = 8.49, $p(H_o/D) = .895$, $p(H_1/D) = .106$. There was a significant effect of schedule type at the intermediate ratio value (30), *F*(2,45) = 17.34, *p* < .001, *Bayes Factor* = 2.86^{e-5}, *p(H$_o$/D)* = 2.86^{e-5}, *p(H$_1$/D)* = .999, and a weaker effect at the highest ratio value (60), *F*(2,45) = 3.36, *p* < .05, *Bayes Factor* = .87, *p(H$_o$/D)* = .446, *p(H$_1$/D)* = .534. Tukey's Honestly Significant Difference (HSD) tests conducted on the 30 and 60 values revealed that, at both schedule values, the RR-30 schedule differed from each of the other two schedules, *p*s < .05.

Additionally, simple effect analyses conducted for schedule value for each schedule type, and revealed that there was only a significant quadratic trend for the RR schedule, *F*(1,45) = 17.27, *p* < .001, *Bayes Factor* = .02, *p(H$_o$/D)* = .017, *p(H$_1$/D)* = .983, but only significant linear trends for the RI+, *F*(1,45) = 7.54, *p* < .01, *Bayes Factor* = .02, *p(H$_o$/D)* = .021, *p(H$_1$/D)* = .979, and RI, *F*(1,45) = 8.95, *p* < .01, *Bayes Factor* = .284, *p(H$_o$/D)* = .221, *p(H$_1$/D)* = .777, schedules.

Figure 4 about here

The group-mean initiation and burst rates are shown in Figure 4. Inspection of the group-mean initiation rates shows higher rates for the RR-10, RR+10, and RI-y(10) schedules compared to the RR-30, RR+(30), and RI-y(30) schedules, which in turn has higher response-initiation rates than the RR-60, RR+(60), and RI-y(60). Except for at the lowest ratio value (10), the RI+ and RI-y schedules tended to have higher rates of initiation than the RR schedules. A two-factor ANOVA (schedule type x schedule value) revealed a significant effect of schedule value, *F*(2,45) = 13.61, *p* < .001, *partial eta^2* = .377, 95% *CIs* = .142:.530, *Bayes Factor* = .0001, *p(H$_o$/D)* = .0001, *p(H$_1$/D)* = .999. There was no significant main effect of schedule type, *F*(2,45) = 1.51, *p* > .20, *partial eta^2* = .063, 95% CIs = .000:.205, *Bayes Factor* = 9.40, *p(H$_o$/D)* = .903, *p(H$_1$/D)* = .096, and there was a marginally significant interaction between the two factors, $F(4,45) = 2.10$, $p < .08$, *partial eta*^{2} = .157, 95% CIs = .000:.291, *Bayes Factor* = .98, $p(H_o/D) = .496$, $p(H_1/D) = .504$.

Simple effect analyses for schedule type at each schedule value, revealed no significant simple effect of schedule at the lowest ratio value (10), $F < 1$, $p > .50$, *Bayes Factor* = 8.76, $p(H_o/D) = .897$, $p(H_1/D) = .102$. There was a significant effect of schedule type at the intermediate ratio value (30), $F(2,45) = 2.98$, $p < .05$, *Bayes Factor* = 0.53, $p(H_o/D) = .348$, $p(H_1/D) = .651$, and at the highest ratio value (60), $F(2,45) = 3.12$, $p < .05$, *Bayes Factor* = .15, $p(H_o/D) = .128$, $p(H_1/D) = .872$. Tukey's HSD tests conducted on the 30 and 60 values revealed that, at both schedule values, the RR-30 schedule had a lower initiation rate than each of the other two schedules, *p*s < .05.

Inspection of the group-mean burst rates shows that these tended to be higher for the RR schedules than for the RI+ and RI-y schedules. The burst rates followed the same trend as the overall response rates in Figure 1; with an inverted U-function being evident for the RR schedules, but a downwards linear-trend being evident for the RI+ RI-y schedules. A two-factor between-subject ANOVA (schedule type x schedule value) was conducted on these burst-rate data, and revealed significant main effects of schedule value, $F(2,45) = 8.48$, $p < .001$, *partial eta*^{2} = .274, 95% CIs = .061:.440, *Bayes Factor* = .001, $p(H_o/D) = .001$, $p(H_1/D) = .990$, and schedule type, $F(2,45) = 11.55$, $p < .001$, *partial eta*^{2} = .339, 95% CIs = .110:.498, *Bayes Factor* = .355^{e-5}, $p(H_o/D) = .355^{e-5}$, $p(H_1/D) = .999$, and a significant interaction between the two factors, $F(4,45) = 3.90$, $p < .01$, *partial eta*^{2} = .257, 95% CIs = .023:.398, *Bayes Factor* = .001, $p(H_o/D) = .001$, $p(H_1/D) = .999$.

Simple effect analyses for schedule type at each schedule value, revealed no effect of schedule type at the lowest ratio value (10), $F < 1$, $p > .70$, *Bayes Factor* = 17.13, $p(H_o/D) = .945$, $p(H_1/D) = .055$. There was a significant effect of schedule type at the intermediate ratio value (30), $F(2,45) = 20.49$, $p < .001$, *Bayes Factor* = 0.11, $p(H_o/D) = .100$, $p(H_1/D) = .899$, and a weaker effect at the highest ratio value (60), $F(2,45) = 3.02$, $p < .05$, *Bayes Factor* = .97, $p(H_o/D) = .461$, $p(H_1/D) = .534$. Tukey's HSD tests conducted on the 30 and 60 values revealed that, at both schedule values, the RR-30 schedule differed from each of the other two schedules, *p*s < .05.

Additionally, simple effect analyses conducted for schedule value for each schedule type revealed that there was only a significant quadratic trend for the RR schedule, $F(1,45) = 25.82$, $p < .001$, *Bayes Factor* = 3.15^{e-7}, $p(H_o/D) = 3.15^{e-7}$, $(H_1/D) = .999$. There were no significant trends for the RI+, largest $F(1,45) = 9.27$, $p < .01$, *Bayes Factor* = 2.20, $p(H_o/D) = .687$, $p(H_1/D) = .312$, and a small significant linear trend for the RI, $F(1,45) = 3.66$, $p < .05$, *Bayes Factor* = .98, $p(H_o/D) = .494$, $p(H_1/D) = .506$, schedules.

Table 1 about here

Table 1 displays the group mean rates of reinforcement per min, averaged across the last four sessions of training, and also the group-mean reinforced IRTs, averaged across the last four sessions. Inspection of the rates of reinforcement shows that the RR reinforcement rates were somewhat higher than the other two schedules, especially at the higher ratio values. The reinforcement rates for the RI+ and RI schedules were similar to one another at any given schedule value (as might be expected given the yoking procedure). As the schedule value increased, the rates of reinforcement declined for all schedule types. A two-factor between-subject ANOVA (schedule type x schedule value) revealed significant main effects of schedule value, $F(2,45) = 157.32$, $p < .001$, *partial* $eta^2 = .875$, 95% CIs = .807:.903, *Bayes Factor* = 1.54^{e-23}, $p(H_o/D) = 1.54^{e-23}$, $p(H_1/D) = .999$, and schedule type, *F*(2,45) = 5.52, $p < .01$, *partial eta*^{2} = .197, 95% CIs = .035:.336, *Bayes Factor* = .24, $p(H_o/D)$ = .193, $p(H_1/D)$ = .807, but there was no significant interaction between the two factors, $F < 1$ *partial eta*^{2} = .068, 95% CIs = .000:.087, *Bayes Factor* = 443.71, $p(H_o/D)$ = .998, $p(H_1/D)$ = .002. The Bayes Factors, and probabilities of the hypotheses being true given the data, support the null hypothesis testing analyses.

The group-mean reinforced IRTs were shorter for the RR schedule than for the other two schedule types, which tended to be relatively similar to one another. A two-factor between-subject ANOVA (schedule type x schedule value) revealed significant main effects of schedule value, *F*(2,45) = 4.99, $p < .05$, *partial eta*^{2} = .181, 95% CIs = .026:.320, *Bayes Factor* = .23, $p(H_o/D)$ = .190, $p(H_1/D)$ = .810, and schedule type, *F*(2,45) = 11.28, $p < .001$, *partial eta*^{2} = .334, 95% CIs = .135:.466, *Bayes Factor* = .001, $p(H_o/D)$ = .001, $p(H_1/D)$ = .999, but there was no significant interaction between the two factors, *F*(4,45) = 1.88, $p > .10$, partial eta^2 = .143, 95% CIs = .000:.241, *Bayes Factor* = 49.69, $p(H_o/D)$ = .980, $p(H_1/D)$ = .020. Tukey's HSD conducted on the mean IRTs for each schedule type averaged across all schedule values revealed that RR schedule differed from each of the other two schedule types, *p*s < .05. Tukey's HSD conducted on the mean IRTs for each schedule value averaged across all schedule types revealed that the IRTs at the longest value (60) differed from the other two schedules values, *p*s < .05.

These data replicate several findings that have been found previously: the RR schedules had higher response and burst rates than the RI schedules at longer ratio values (see Peele et al., 1994; Zurrif, 1970). There was also a RR versus RI+ difference at these longer ratio values (see Cole, 1994; Reed, 2007a). These data suggest little role for the impact of the feedback function at these greater ratio schedule parameters. The subjects exposed to different RR schedule values also displayed a quite different pattern of response rates, compared to the subjects responding on other schedules. The inverted-U pattern on the RR schedule has been noted previously (see Baum, 1993; Ferster and Skinner, 1957; Reed and Hall, 1988), whereas the other two schedules displayed a relationship that was closely tied to the rates of reinforcement they experienced, which is reminiscent of behavior on interval schedules (see deVilliers, 1977). The molecular analyses of the schedule also showed that the micro-structure of RR responding was differentially affected by increases in ratio value compared to that seen on the RI+ and RI schedules. These results suggest that there are multiple influences on RR schedule performance, but these are not seen in the other two schedules, and they also suggest that RR and RI+ schedules are not controlled by the same mechanisms.

The above differences in response rate between the schedules were not observed statistically at the lowest ratio value (10). Although the pattern of response rate differences between the schedules was in the predicted direction (i.e., RR > RI+ > RI; see also Experiment 1), the RI schedule was statistically indistinguishable from the RR schedule. This finding was also found previously by Baum (1993) for this rate of reinforcement. These findings suggest it is not sensitivity to the molar feedback function that is responsible for this effect, but the rate of reinforcement obtained.

As in Experiment 1, it could be argued that there may be some evidence of sensitivity to molar feedback function, and that the failure to obtain a statistically significant demonstration of this could simply be a power issue. However, the Bayes Factor and the associated strong probability of the null hypotheses being true suggest that power was not the issue. Nevertheless, to address further this possibility, the data from the RI+(10) and RI-y(10) groups from Experiments 1 and 2 were pooled, and this gave mean response rates of: RI+(10) = 49.00 (+ 18.41), and RI-y(10) = 37.47 (+ 12.95). A t-test conducted on these data found no significant difference between the groups, $t(26) = 1.91$, $p > .10$, $d = .367$. Based on this calculation it would require 234 rats (for a $p < .05$ and with 80% power) to get a significant effect. This suggests that while there may be some evidence of an effect of the molar feedback function on rates of response, it is not as important a factor as the rate of reinforcement or rate of reinforcement.

Experiment 3

The previous two experiments have shown that a RI+ schedule does not support behavior in the same manner as a RR schedule, with the possible exception of when the rates of reinforcement were very high (see also Cole, 1999). However, as noted in the General Introduction, a potential problem with the RI+ schedule in terms of maintaining levels of responding is the susceptibility of responding on this schedule to ratio strain and/or extinction (see Cole, 1999; Reed et al., 2000; 2003). If the rate responding drops on a RI+ schedule, then the time to the next reinforcement increases, and this makes extinction more likely if the time to reinforcement becomes very long (see Cole, 1999). Thus, it might be suggested that, if an organism does not maintain relatively high rates of response, then it cannot contact molar contingencies – and only when manipulations are put in place to maintain responding do response rates on a RI+ and RR schedule become similar to one another (see Reed, 2007).

To assess the degree to which RI+ schedules are differentially sensitive to extinction, the pattern of responding on the various schedules studied in Experiments 1 and 2 were examined. The number of subjects that emitted particularly low rates of responding (indicative of extinction and/or ratio strain) was explored, and, to this end, a response rate of 10 responses per min (or less) was selected as a criterion for ratio strain. The percentage of rats displaying this low level of responding on the various schedules is displayed in Figure 5, and this reveals a higher percentage of rats with potential ratio strain on the RI+ schedule than on the RR and the RI schedule, and increasing numbers of rats displayed potential strain on the RI+ and RR schedule as the ratio requirement increased. These data are in line with previous investigations of ratio strain (see Ferster and Skinner, 1957; Rider and D’Angelo, 1990), and in terms of RI+ responding (see Cole, 1994; Reed et al., 2003).

Figure 5 about here

Considerations such as these, lead Cole (1999) to explore whether reducing the potential impact of the RI+ contingency on the time to reinforcement might alleviate extinction/ratio strain effects. This alteration of the RI+ contingency allowed to the timer responsible for scheduling the RI+ reinforce to shorten if response rates increased above 60 responses per min, but, once the time had been shortened, it did not increase again if the response rate fell. It was hoped that this would allow behavior to be related to outcomes directly, as on a RR schedule, but would not differentially make the RI+ schedule produce extinction. Cole (1999) presented some data on the effects of this schedule, but with only four participants it was difficult to interpret the outcome. Given this, the current experiment compared performance on an RR, RI+, yoked RI, and a modified RI+ schedule.

Method

Subjects and Apparatus

Forty experimentally-naive male Lister rats served in the present experiment. The subjects were three months old at the start of training, had a free-feeding body-weight range of 315-335g, and were maintained as described in Experiment 1. The apparatus was as described in Experiment 1.

Procedure

The subjects received two sessions of magazine training on a VT 60-s schedule. They then received two, 20-min sessions of lever press training with CRF schedule. All subjects were then transferred on to an RI-30s schedule (where each successive second was assigned the same probability, *p* = 1/30, of satisfying the interval requirement, such that the next response would be reinforced) for 4, 30min sessions of training.

The subjects were then randomly assigned to five equally-sized groups (*n* = 8). One group (RR-30) initially received one session each at the following ratio values: 10, 15, 20, 25, and then responded on an RR-30 schedule (i.e., each response had a 1/30 probability of reinforcement), and received 36, 30-min sessions of training on this final schedule value.

Two groups were exposed to a RI+ schedule, such that the feedback function relating the rate of response to the rate of reinforcement was either the same as an RR schedule of reinforcement. For one group (RI+), the inter-reinforcement interval on the RI+ schedule was determined as described in Experiment 1. The value ratio-equivalent value was increased as for the RR groups, described above. The other RI+ group – RI+(mod) – responded on this schedule, as described above, but with a modification as described by Cole (1999), from which the following description is taken. The modified version of the RI+ schedule prevented the loss through pausing of gains in reinforcement rate made previously by rapid responding. This was achieved by permitting the minimum required inter-reinforcement interval to shorten when the response rate rose above 60 responses per min, but, once shortened, the required reinforcement interval did not lengthen again when the response rate fell below that rate. Thus, on the modified RI+, within any inter-reinforcement interval, the longest period was always the shortest time that had been created to that point, based on response rate.

The other two groups were exposed to a RI schedule that was either yoked to a RI+ schedule, or to the RI+(mod) schedule. The yoking procedure was as described in Experiment 1.

Results and Discussion

Figure 6 about here

Figure 6 displays the group-mean response rates, averaged over the last four sessions of training. Inspection of these data shows that the RR schedules, typically, had higher rates of response than the RI+ and RI-y groups. However, the RI+(mod) schedule produced an intermediate rate of response between the RR and RI+ schedules. A between-subject ANOVA was conducted on these data, and revealed significant main effect of schedule, $F(4,35) = 5.17$, $p < .005$, *partial* $eta^2 = .371$, 95% CIs = .103:.483, *Bayes Factor* = .15, $p(H_o/D) = .129$, $p(H_1/D) = .871$. Tukey's HSD tests revealed that the RR schedule had a significantly higher response rate than each of the other schedules, and the RI+(mod) schedule had a higher rate than the RI-y(RI+), RI-y(RI+mod), and the RI+, schedules, *p*s < .05.

Figure 7 about here

The group-mean initiation and burst rates are shown in Figure 7. Inspection of the group-mean initiation rates shows higher initiation rates for the RI+30 and RI-y(RI+) and RI-y(RI+mod) schedules compared to the RR+(30) and RI+(mod) schedules. The RI+(mod) schedule group had a higher rate of initiation than the RR schedule. A one-way ANOVA conducted on these data revealed a significant effect of schedule value, $F(4,35) = 4.21$, $p < .01$, *partial eta*^{2} = .325, 95% *CIs* = .035:.471, *Bayes Factor* = .62, $p(H_o/D)$ = .383, $p(H_1/D)$ = .618. Tukey's HSD tests revealed that both the RR and RR+(mod) each had lower initiation rates than each of the other three schedules, all *p*s < .05, none of the other pairwise comparisons was statistically significant, all *p*s > .05.

Inspection of the group-mean burst rates shows that these were higher for the RR than for the other schedules, and were next highest in the RI+(mod) schedule. A one-way ANOVA conducted on these data revealed a significant effect of schedule value, $F(4,35)$ = 23.75, $p < .001$, *partial eta*^{2} = .731, 95% *CIs* = .539:.810, *Bayes Factor* = 6.38^{e-9}, $p(H_o/D)$ = 6.38^{e-9}, $p(H_1/D)$ = .999. Tukey's HSD tests revealed that the RR schedule had a higher burst rate than each of the other schedule, all *p*s < .05, and the RR+(mod) had a higher burst rate than each of the RI schedules, all *p*s < .05, none of the other pairwise comparisons was statistically significant, all *p*s > .05.

The group mean rates of reinforcement per min averaged across the last 4 sessions were: RR = .81 (± .65); RI+ = .81 (± .65); RI+(mod) = 1.59 (± .94), RI-y(RI+) = .86 (± .67), and RI-y(RI+mod) = 1.57 (± .92). An ANOVA revealed a significant effect of schedule value, $F(4,35) = 4.40$, $p < .005$, *partial eta*^{2} = .335, 95% CIs = .071:.449, *Bayes Factor* = .48, $p(H_o/D)$ = .323, $p(H_1/D)$ = .675. Tukey's HSD tests revealed that the RI+(mod) and RI-y(RI+modified) schedules each had significantly higher reinforcement rates than each of the other schedules, *p*s < .05.

The group mean reinforced IRT averaged across the last 4 sessions were: RR = .71 (± .15); RI+ = 3.36 (± 1.34); RI+(mod) = 3.03 (± 1.62), RI-y(VI+) = 3.38 (± .72), and RI-y(RI+mod) = 2.84 (± 1.08). An ANOVA revealed a significant effect of schedule value, $F(4,35) = 8.09$, $p < .001$, *partial* $eta^2 = .480$, 95% CIs = .214:.579, *Bayes Factor* = .003, $p(H_o/D) = .003$, $p(H_1/D) = .997$. Tukey's HSD tests revealed that the RR schedule had significantly shorter IRTs than each of the other schedules, *p*s < .05.

The current results suggest that when the RI+ contingency was modified to overcome the potential extinction problems inherent in this schedule at longer ratio values, response rates increased over and above those that are typically seen on a RI schedule, or on a standard RI+ schedule. This suggests that when response rates are maintained, subjects can show some degree of sensitivity to the molar characteristics of the contingency. However, the fact that rates on the modified RI+ schedule were still lower than those on an RR schedule, despite higher rates of reinforcement, suggest that performance on the latter schedule is controlled by more than just molar feedback functions. The two main differences were in terms of the molecular structure of responding, such as the reinforced IRTs which were shorter on the RR schedule, and the tendency to show ratio strain: 3/8 rats on RI+ schedule, but only 1/8 rats on the modified RI+ schedule, and no rats on the RR schedule, showed low rates of response (less than 10 responses per min).

General Discussion

The current series of experiments aimed to investigate the factors which control performance on free-operant schedules of reinforcement, and, in particular, those which operate on the RI+ schedule (McDowell and Wixted, 1986). This schedule has been used as a test bed for a number of theories, notably molecular views of performance that suggest responding is primarily controlled by the reinforcement of IRTs (e.g., Morse, 1966; Peele et al., 1984; Platt, 1979), and molar views which suggest that the feedback function relating response and reinforcement rates primarily drives responding (e.g., Baum, 1981; McDowell and Wixted, 1986). Although previous work has tended to suggest that RI+ performance is similar to RI schedule performance (see Cole, 1999; Reed et al., 2000; 2003), a result favoring molecular viewpoints, there have been a number of findings that suggest the RI+ schedule can maintain higher rates than a RI schedule (e.g., McDowell and Wixted, 1986; Reed, 2007a; 2007b), favoring a molar interpretation. The different pattern of results across the studies suggests that, rather than being an either/or question in relation to molecular and molar aspects of the contingency, a better question might be to investigate the circumstances under which such factors operate (Cole, 1994; Reed, 2007a), and also to acknowledge the myriad of alternate factors that mediate performance of schedules of reinforcement. The current series of experiments explored the parameters under which RI+ performance was more RI- or RR-like in nature, and, in doing so, attempted to identify the conditions under which various factors predominate in the control of free-operant behavior.

Experiments 1 and 2 both established that, under conditions in which rates of obtained reinforcement were high, there was little to differentiate the rates of responding across RR, RI+, and RI schedules. This pattern of data has been found for RR and RI schedules previously (see Baum, 1993), and has been indicated in the results of Cole (1999) for RI+ schedules. That there was little differentiation between the schedules at these parameters, suggests that neither the reinforcement of IRTs nor the molar feedback function controls performance, but that rate of reinforcement is the critical factor (see Baum, 1993). The dominance of reinforcement rate on these rich schedules may be attributable to the fact that behavior on schedules of reinforcement comprises a number of components (see Bowers et al., 2008; Reed, 2011; Shull et al., 2001): importantly, response-initiation responses, and response-bouts (consisting of a number of responses). The response-initiation responses are particularly sensitive to rates of reinforcement on any schedule type (see Reed, 2011; Shull et al., 2001; Shull and Grimes, 2003). When these responses comprise proportionally higher numbers of the overall responses, such as on short value schedules (e.g., short RR and RI schedules), where response-bouts cannot contain many responses prior to the delivery of reinforcement, then the impact of reinforcement rate may be seen equivalently across all types of schedules. The analysis of this micro-structure of responding suggests that it is similar at the low values across all schedules, but alters as the schedule values increase.

As the ratio length of the schedule increases, and the influence of response-initiation responses is relatively less pronounced than that of within-bout responses (see Shull et al., 2001), it is increasingly seen that responding on a RR schedule is emitted at a higher rate than on a RI and a RI+ schedule. This is typically taken to reflect the operation of the reinforcement of longer IRTs on the temporally-based schedules (see Morse, 1966; Peele et al., 1984; Reed et al., 2000). The current studies similarly demonstrated that this was the case, especially when the value of the ratio involved was greater than 30 (Experiments 1, 2, and 3; see also Cole, 1999; Reed et al., 2003). That the RI+ schedule did not maintain rates of response as high as a RR schedule on these schedules replicates this work, and suggests that the factors controlling behavior on these two schedules, at these schedule parameters are different. As the RI+ schedule in Experiments 1 and 2 also generated rates which approximated to those on a RI schedule with the same rate of reinforcement (see also Cole, 1999; Reed et al., 2000) implies that the positive nature of the molar feedback function on the RI+ schedule, which is not present on the RI schedule (see McDowell and Wixted, 1986), was not primarily responsible for driving those response rates. That the reinforced IRTs on the RI and RI+ schedules were similar to one another, and both longer than those seen on the RR schedules, suggests that this factor may play a stronger role in performance (Peele et al., 1984; Tanno and Silberberg, 2012).

However, two findings from the current studies suggest that a further factor may also be at play in determining rates of response on schedules with a positive relationship between response and reinforcement rate. Experiment 2 demonstrated the typical inverted-U relationship between response rate and ratio value for RR schedules, with peak responding being observed between a 30 and 60 value (see also Baum, 1993; Ferster and Skinner, 1957; Reed and Hall, 1988). The fact that responding declines at high ratio values is consistent with both, a reduction in the obtained rate of reinforcement (Baum, 1981; deVilliers, 1977; Herrnstein, 1970), and also the development of ration strain/extinction (Anger and Anger, 1976; Rider and D'Angelo, 1990) – with greater ratio values tending to lead to greater periods of strained responding (Anger and Anger, 1976; Davenport, 1969). An examination of the numbers of rats with low rates of response across Experiments 1, 2, and 3 supports this view. This finding is also likely to explain the low rates seen in the RI+ schedule, on which rats are even more likely to show periods of strained responding (see also Experiments 1, 2, and 3). Thus, these results suggest that one aspect of the RI+ schedule that does differentiate it from both RI and RR schedules is its susceptibility to strain. Response rates on RI+ schedules have been noted to decrease suddenly and rapidly (see Cole, 1999; Reed et al., 2003). This may be a product of the highly variable nature of the number of responses required per reinforcer on these schedules (which will vary as a function of local response rate in a manner not programmed on RR schedules).

The fact that putting in place procedures to maintain responding on RI+ schedules both alleviates apparent strain, and supports higher rates of responding on a RI+ schedule than on an equivalent RI schedule lacking a positive molar feedback function between response rates and reinforcement rates (see Experiment 3), suggests that, if responding can be maintained at high enough levels, then it may contact the molar aspects of the contingency. Indeed, those studies which have seen some evidence of molar sensitivity have used subjects and apparatus which tend to maintain high rates of response (McDowell and Wixted, 1986; Reed, 2006), or have produced manipulations that have supported such rates of responding (Cole, 1999; Reed, 2007).

Although rates on RI+ schedules can be seen to be higher than those on RI schedules matched for reinforcement rates (see Experiment 3), they do not approach those seen on RR schedules (see Experiments 1, 2, and 3). This suggests that both molar and molecular process are operating to generate rates on RR schedules, a finding that concords with that of Dawson and Dickinson (1990) who compared rates of response on a RR, RI, and a RR schedule that did not differentially reinforce short IRTs. The latter schedule produced rates intermediate between the former two, suggesting that IRT reinforcement alone was not sufficient to explain the response rates (see also Platt, 1979).

In summary, the current series of experiments have shown some conditions under which the various factors that could control free-operant performance appear to operate. When the obtained rates of reinforcement are particularly high, then this factor appears to override any others that might be operating, such as the reinforcement of IRTs or the influence of molar response-reinforcer feedback functions. It is suggested that this effect might be due to the impact of rates of reinforcement on ‘response-initiation’ responding, which would be relatively more frequent among all types of responses (i.e. response-initiation and within-burst) on reinforcement-rich schedules; hence, tending to obscure the impact of factors operating through other mechanisms (i.e. IRT reinforcement) on within-burst responses. However, as the rate of reinforcement becomes lower, it appears that both the reinforcement of IRTs and the molar response-reinforcer feedback function, jointly act to determine responding. As the effects of both of these factors are to produce higher rates on RR schedules, but only the molar aspects would increase rates on RI+ schedules, the former schedule tends to have higher rates when reinforcement rates have dropped from being very rich. The interaction of the two factors is potentially responsible for the different relationship between response rate and ratio on RR (or ratio-equivalent value on RI+) schedules. As IRT reinforcement plays a role in RR schedule responding, and as there are more within-burst responses to be impacted by this factor as the schedule value increases, then this tends to drive rates up at intermediate ratio values However, since IRT reinforcement is not acting to increase rate son a RR+ schedule, then rates only decrease as the ratio-equivalent value increases due to the drop in rate of reinforcement, and ‘worse’ response-reinforcer feedback function. Moreover, the sensitivity to ratio strain on RI+ schedules also negatively impacts rates on this schedule, especially as the schedule value increases. Thus, although a variety of factors can be shown to impact on schedule performance, the current study has begun to identify the conditions under which each will exert the most critical influence of operant responding.

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Table 1: Results for Experiment 3. Group mean (95% confidence intervals) reinforcers per min and reinforced inter-response times. RR = random ratio schedule (10, 30, or 60); RI+ = variable interval with an equivalent feedback function to an RR-10, RR-30, or RR-60 schedule; RI = variable interval yoked to the RI+ schedule.

Group	Reinforcers per min	Reinforced IRT (s)
RR-10	4.31 (3.40 – 5.23)	0.72 (0.44 – 0.99)
RR-30	1.99 (1.80 – 2.17)	0.43 (0.33 – 0.52)
RR-60	0.49 (0.20 – 0.79)	1.57 (0.23 – 2.90)
RI+(10)	3.79 (2.82 – 4.77)	1.62 (1.21 – 2.04)
RI+(30)	0.93 (0.21 – 1.67)	3.53 (1.29 – 5.77)
RI+(60)	0.25 (0.07 – 0.43)	6.65 (0.72 – 12.58)
RI-y(10)	3.77 (2.78 – 4.75)	3.53 (2.87 – 4.20)
RI-y(30)	0.93 (0.18 – 1.67)	3.72 (2.48 – 4.98)
RI-y(60)	0.25 (0.08 – 0.42)	4.33 (2.56 – 6.11)

Figure 1: Results from Experiment 1. Mean response rates for all four groups. RI+ = random interval with an equivalent feedback function to an RR-10 or RR-30 schedule; RI = random interval yoked to the RI+ schedule. Error bars are 95% confidence intervals.

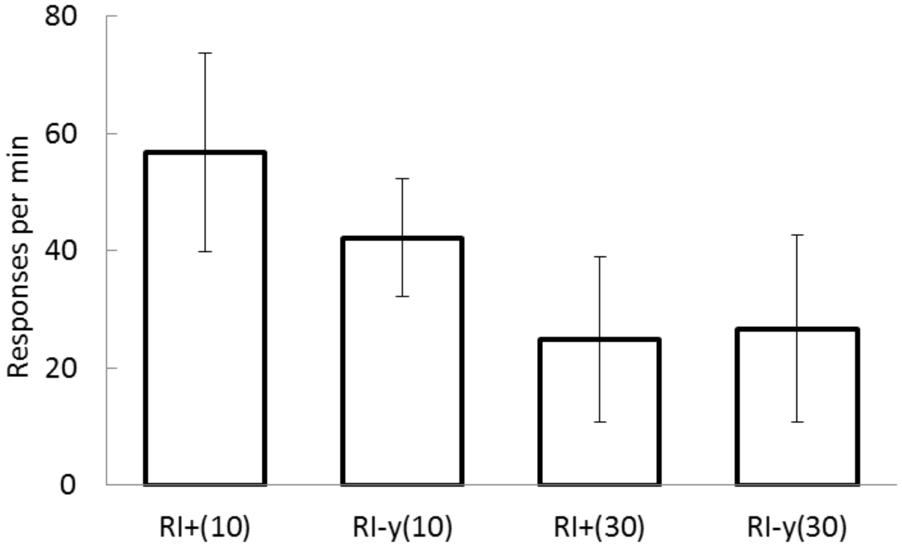

Figure 2: Results from Experiment 1. Group-mean rates of response initiation and burst responses for the four groups. RI + = random interval with an equivalent feedback function to an RR-10 or RR-30; RI = random interval yoked to the RI+ schedule. Error bars are 95% confidence intervals.

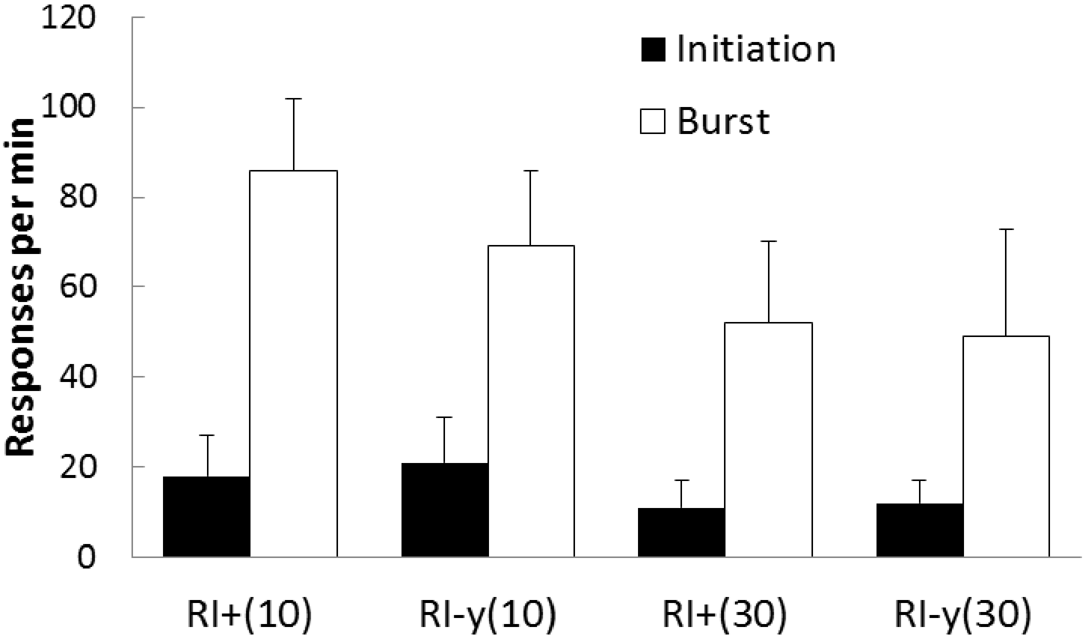

Figure 3: Results from Experiment 2. Mean response rates for the four groups. RR = random ratio schedule (10, 30, or 60); RI+ = random interval with an equivalent feedback function to an RR-10, RR-30, or RR-60 schedule; RI = random interval yoked to the RI+ schedule. Error bars are 95% confidence intervals.

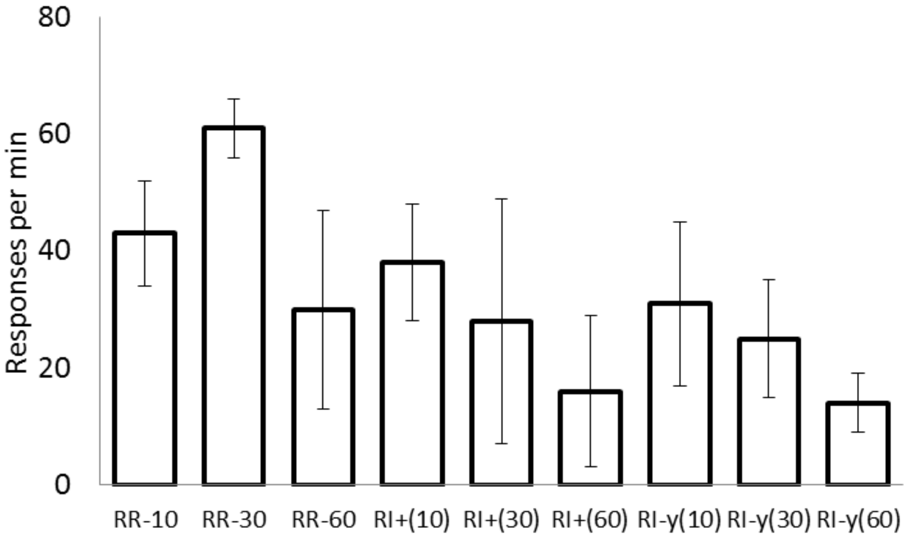

Figure 4: Results from Experiment 2. Group-mean rates of response initiation and burst responses, for the four groups. RR = random ratio schedule (10, 30, or 60); RI+ = variable interval with an equivalent feedback function to an RR-10, RR-30, or RR-60 schedule; RI = random interval yoked to the RI+ schedule. Error bars are 95% confidence intervals.

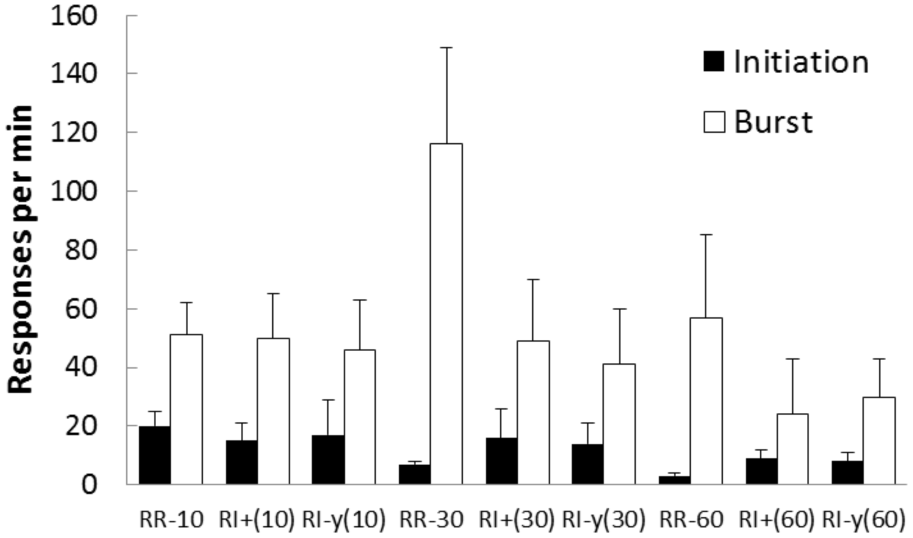

Figure 5: Results from Experiments 1 and 2. Percentage of rats showing potential ratio strain (response rates less than 10 per min) in each schedule condition in Experiments 1 and 2 combined. RR = random ratio schedule (10, 30, or 60); RI+ = random interval with an equivalent feedback function to an RR-10, RR-30, or RR-60 schedule; RI = random interval yoked to the RI+ schedule.

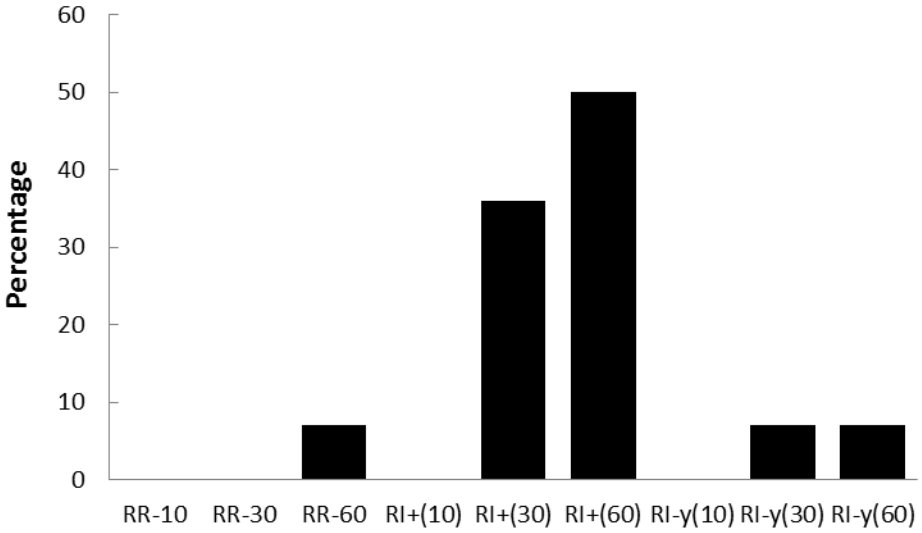

Figure 6: Results from Experiment 3. RR = random ratio schedule; RI+ = random interval with an equivalent feedback function to an RR schedule; RI+(mod) = random interval with an equivalent feedback function to an RR schedule with modification to prevent ratio strain; RI-y(RI+) = random interval yoked to the RI+ schedule; RI-y(RI+mod) = random interval yoked to the modified RI+ schedule. Error bars are 95% confidence intervals.

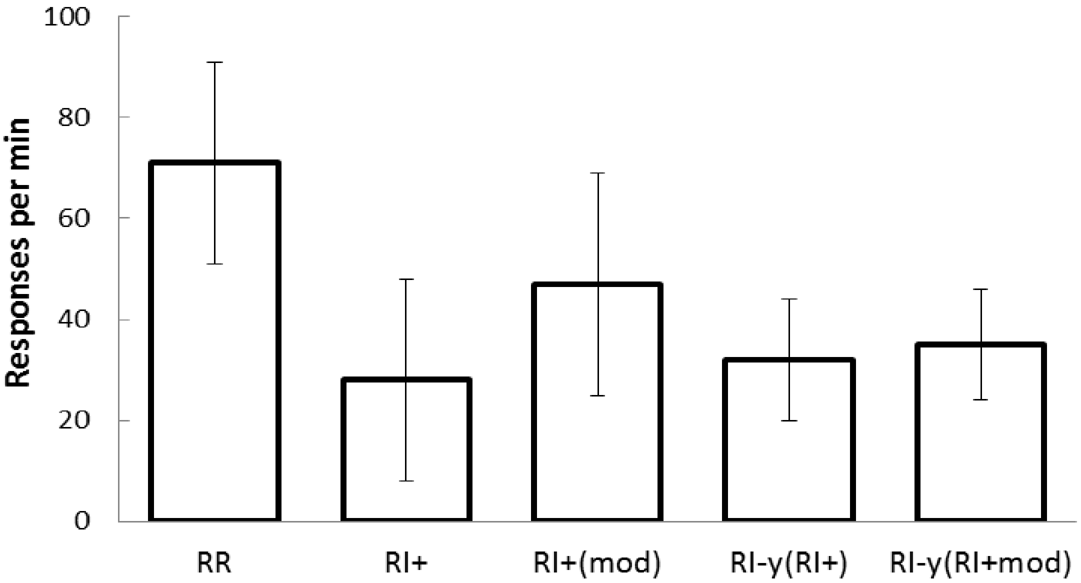

Figure 7: Results from Experiment 3. Group-mean rates of response initiation and burst responses, for the four groups. RR = random ratio schedule; RI+ = random interval with an equivalent feedback function to an RR schedule; RI+(mod) = random interval with an equivalent feedback function to an RR schedule with modification to prevent ratio strain; RI-y(RI+) = random interval yoked to the RI+ schedule; RI-y(RI+mod) = random interval yoked to the modified RI+ schedule. Error bars are 95% confidence intervals.