Effect of delayed reinforcement on lever pressing for wheel-running reinforcement

BY

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A thesis submitted to the

Department of Psychology

Mount Allison University

In partial fulfillment of the requirements for the

Bachelor of Arts degree with Honours

April 11, 2023

Abstract

Delayed reinforcement can be understood as the interposition of a period of time between the occurrence of a behaviour and the delivery of a reinforcer. The present study investigated the effects of delayed reinforcement on the lever-pressing behaviour of eight Long-Evans rats for wheel running as reinforcement. Under the baseline condition, rats pressed a lever on a variable-ratio (VR) 5 schedule for the opportunity to run for 60 s as a reinforcement. Sessions terminated when 20 reinforcements were completed. Once baseline stabilized, delay durations of 2, 4, 8, 16 and 32 s were introduced over five consecutive sessions on three occasions under light change and no light change conditions. In the light change condition, the chamber lights were extinguished during wheel running. Results showed the lever-pressing rates did not decrease with delay in the light change condition, but they did in the no light change condition. Under both conditions, PRP duration and wheel-running rates increased with delay. The lack of a delay of reinforcement gradient in the no light change was attributed to the light change functioning as a conditioned reinforcement. These findings extend delay of reinforcement to wheel-running reinforcement.

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Acknowledgements

I would like to extend my sincerest appreciation to my thesis supervisor, Dr. Terry Belke, for his invaluable feedback and patience during this research process. Your mentorship and expertise have not only enhanced my skills as a researcher but also broadened my understanding of experimental work and Psychology as a dicispline. Thank you for granting me this once-in-a-lifetime opportunity to work with a non-human species. This paper was also made possible thanks to the the support of the Psychopharmocology lab team; Jackie Jacobs-Voguels, Kennedy Hunt and my honours partner, Emily Escoffery. Our time in lab represented not only a space for indispensable learning but also some of my favourite memories; together you made the early mornings the best part of my day. Thank you to Dr. Mitchelle Lapointe for his time and commentary as my second reader and to my unofficial mentor, Dr. Louise Wasylkiw for her kindness throughout my time at Mount Allison University.

Finally, I would like to thank my parents for their unwavering love and encouragement that have enabled me to pursue my interests in Psyschology. I am especially grateful to my close friends, Mia, Meg, Nathan, Petter, and Angelica for their camaraderie and for listening to my many practice presentations. Last but not least, thank you to my Honours seminar professor, Dr. Nancy Garon for sharing numerous skills for successfully applying to graduate school, you made class so much fun. Together, each of you have empowered me to pursue my love of research at the undergraduate level and hopefully well into the future.

Effect of delayed reinforcement on lever pressing for wheel running

Delay of reinforcement occurs when a period of time is interposed between the occurrence of a behaviour and the delivery of a reinforcer. Since the strengthening effect of reinforcement depends on contiguity, as the delay interval is increased between an operant behaviour and a reinforcing consequence, the response-strengthening effect of reinforcement diminishes (Schneider, 1990). This delay effect has been investigated by assessing the effect of delaying reinforcement on already established operant behaviour (Sizemore & Lattal, 1977, 1978; Williams, 1976) and by assessing the difficulty of acquiring an operant behaviour when a reinforcement is delayed (Escobar & Bruner, 2007; Lattal & Gleeson, 1990; Skinner, 1938; Skinner, 1953). In general, when reinforcement for an established behaviour is delayed, the rate of responding decreases as the delay increases. This pattern has been extensively studied with different reinforcements under diverse conditions (Jarmolowicz, 2011; Jarmolowicz & Lattal, 2013; Sizemore & Lattal, 1977), but not yet on the lever-pressing behaviours in rats maintained by wheel-running reinforcement.

Given that there are no previous investigations of delay of reinforcement with wheel running as reinforcement, an overview of research literature on delay of reinforcement and the factors that influence delay of reinforcement gradients is provided before introducing the current study. Delay of reinforcement is examined in regard to the acquisition or maintenance of a behaviour. Early examinations of delayed reinforcement focused on acquisition in which delays were implemented to establish responding of a new behaviour. Acquisition aims to demonstrate a response rate above a behaviour's operant level (Escobar & Bruner, 2007). Previous research has shown that

with delays as long as 30 s, rats are still able to acquire lever pressing (Byrne et al., 1997; Critchfield & Lattal, 1993; Dickinson et al., 1992; Lattal & Gleeson, 1990; Sutphin et al., 1998; Van Haaren, 1992; Wilkenfield et al., 1992). More recent emphasis has been placed on the latter approach, that is, how implementing delays may change responding already maintained on various schedules of reinforcement. Delay of reinforcement in regard to maintenance evaluates whether a behaviour persists despite changes in reinforcement (DiBlasi & Portillo, 2017). When delays are imposed on behaviour established via immediate reinforcement, response rates generally decrease (Jarmolowicz, 2011; Jarmolowicz & Lattal, 2013; Pierce et al., 1972; Richards, 1981; Richards & Hittesdorf, 1978; Sizemore & Lattal, 1978; Williams, 1976).

Sizemore and Lattal (1978) studied the effects of unsignaled delay of reinforcement on behaviour previously maintained on variable-interval (VI) 60-s schedules. Pigeons' key-pecking response was examined on several tandem VI fixed time (FT) schedules for which the FT varied to assess the effect of different unsignaled delays of reinforcement. The researchers used delay durations of 0.5 s, 1 s, 4 s, and 10 s which produced a response rate reduction as a function of the increasing delay durations. These findings were later replicated and confirmed by Richards (1981) using the same delay durations. Richards (1981) compared the effects of using signaled and unsignaled delays on responding on a VI 60-s schedule and a differential reinforcement of a low rate (DRL) 20-s schedule. Similarly, they found that response rate decreased as the delay increased. The signaled delay of up to 10 s produced only moderate decreases while the unsignaled delays of 5 and 10 s produced large decreases in subjects'

responding. These findings demonstrated that even brief delay durations are capable of producing a delay of reinforcement gradient.

General features of delayed reinforcement

Delay of reinforcement is both impacted by contingencies (i.e., schedule, parameters, and delay duration) and imposes contingencies (i.e., changes to temporal contiguity). Its effects are determined by features such as the schedule of reinforcement and delay parameters that influence behaviour and how these variables interact with the target behaviour (Lattal, 2010). Furthermore, delay durations may be fixed, for which the time or responding requirement does not change, or variable, where the delay duration or requirements change across successive reinforcers. According to Lattal (2010), delay of reinforcement may be understood with respect to the following considerations. First, the effect of delayed reinforcement is best demonstrated by isolating the effect of the delays from other simultaneously operating variables. In determining whether there is a delay of reinforcement effect, changes to the response-reinforcer relationship by procedural manipulation (i.e., introducing a stimulus change) must be considered. Generally, these manipulations directly influence temporal contiguity, a major parameter of reinforcement. Contiguity refers to the occurrence of two or more events taking place simultaneously or nearly simultaneously (Lattal, 2010). Contiguity was also assigned a primary role in the effectiveness of reinforcement by Skinner (1953; Ferster & Skinner, 1957). It has been proposed that delay of reinforcement has its effects because disrupting response-reinforcer temporal contiguity weakens the correlation between responding and reinforcement (Baum, 1973).

A second question concerns the effects of delays on operant behaviour. Delay of

reinforcement procedures may differ substantially from one another making the effect of delay dependent upon the circumstances of investigation. Skinner (1938) was the first to examine operant responses using delayed rather than immediate reinforcement. He studied the lever-pressing behaviour of experimentally naïve rats using unsignaled delay up to 8 s. Since this initial investigation, the effects of delayed reinforcement on response-rate reduction have been studied using a variety of schedules and procedures (Jarmolowicz, 2011; Pierce et al., 1972).

Investigations of delay of reinforcement most often assess responding maintained on a variable-interval (VI) schedule (Pierce et al., 1972; Richards, 1981; Sizemore & Lattal, 1978; Williams, 1976). However, delay of reinforcement effects using VI schedules may not fully predict delay of reinforcement effects on ratio schedules because of the differently-arranged contingencies (Jarmolowicz, 2011). Therefore, Jarmolowicz and Lattal (2013) investigated the effects of delayed reinforcement on pigeons' responding on a fixed-ratio (FR) schedule where the delay duration was increased across successive sessions. Experiment I examined the effects of signaled and unsignaled delay on responding maintained on baseline FR 50 schedule. They used a progressive fixed delay (PFD) procedure with successive increasing delays of 1 s, 5 s, 10 s, 40 s, 80 s, 160 s, 320 s, and 640 s across sessions. The researchers found that post-reinforcement pause (PRP) increased in both signaled and unsignaled delays when accompanied by increases in the delay durations; however, response rate remained less affected under the influence of the signaled delay. These findings are consistent with studies using different schedules regarding response maintenance, which reported higher response rates in signaled than unsignaled delay conditions (Reilly &

Lattal, 2004; Richards, 1981). Despite the different contingencies pertaining to response and reinforcement rates on interval and ratio schedules, delays of reinforcement generally affect performance on these schedules similarly. By examining the effects of delayed reinforcement on an FR schedule, Jarmolowicz (2011) and Jarmolowicz and Lattal (2013) confirmed the inverse relationship between response rate and delay duration, demonstrating their generality to the ratio schedule in the present study.

Pierce et al. (1972) examined different delay of reinforcement procedures on VI lever pressing. Some exceptions to the typically observed inverse relationship between response rate and delay duration may be attributable to procedural differences. Therefore, an examination comparing these different procedures in a single experiment was necessary to help isolate their effect. Pierce et al. (1981) examined the effects of different delay procedures on VI responding using 10 s, 30 s, and 100 s delay durations. For each condition, lever presses initially produced a cue light and the reinforcer was delivered 0.5 s after onset of the light. In Experiment I, three procedures, (1) lever retraction during the delay, (2) a fixed-delay procedure, and (3) a resetting delay (differential reinforcement of other behaviour or DRO) procedure, produced no systematic differences across delay of reinforcement gradients (see Figure 1, left panels). Pierce et al. (1972) also found that as delay duration increased across the three procedures, PRP duration increased (see Figure 1, right panels). Pierce et al. (1972) concluded that response rate decreased as the delay duration increased and this relation remained unchanged by differences in the procedure. In addition, Pierce et al. (1972) reported that the different delay procedures produced no consistent differences in PRP, which was found to increase along with the delay

Figure 1.

Decreases in Response Rate and Increases in Post-reinforcement Pause Duration as Reinforcement was Delayed for 10 s, 30 s, and 100 s in Fixed Delay (FD) Condition, a Retracted Lever (RL) Condition, and a Resetting Delay (DRO) Condition Adapted from "Effects of different delay of reinforcement procedures on variable-interval responding," by C. H. Pierce, P. V. Hanford, and J. Zimmerman, 1972, *Journal of the Experimental Analysis of Behavior*, 18, p. 143.

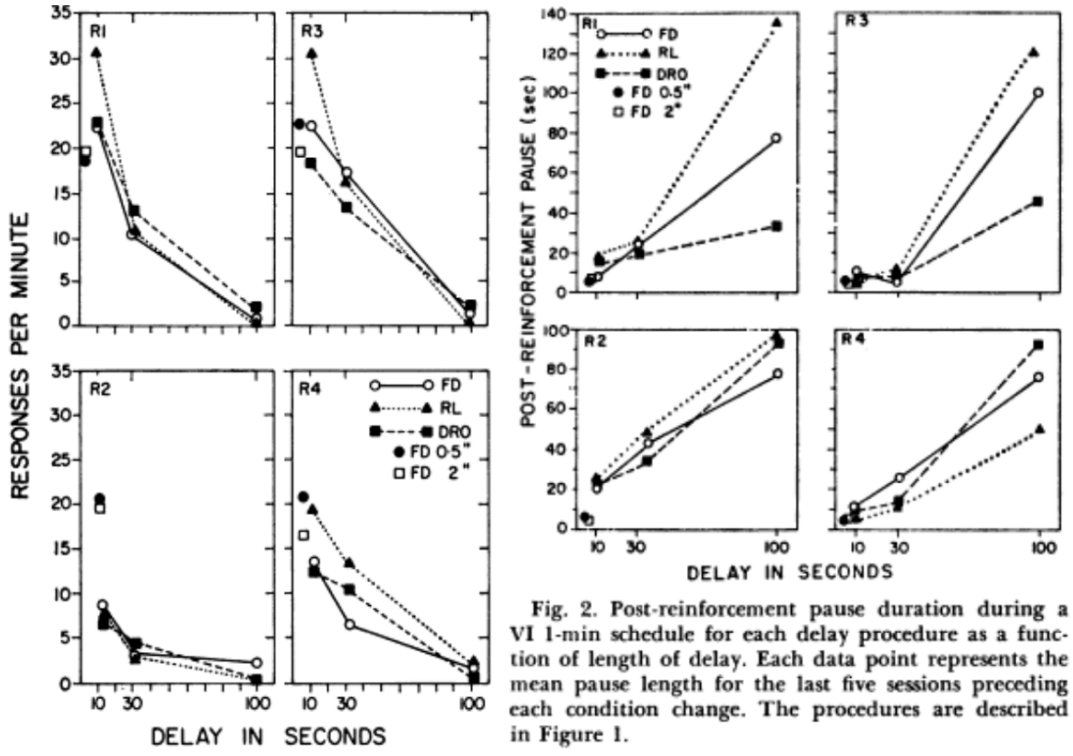


Fig. 2. Post-reinforcement pause duration during a VI 1-min schedule for each delay procedure as a function of length of delay. Each data point represents the mean pause length for the last five sessions preceding each condition change. The procedures are described in Figure 1.

duration. Pierce et al.'s (1972) results highlight the generality of the effect of delayed reinforcement across different procedures. These findings added to a growing body of literature confirming the conclusions of Neuringer (1969), who stated that the time and

contiguity between a response and reinforcement control the probability of that response.

Not all studies, however, found the typical decrease in responding with delayed reinforcement. Morgan (1972) examined rats' lever-pressing behaviour on an FR 9 schedule over a series of six sessions with signaled delays of 12 s, 3 s, and .75 s. A positive relation between PRP and delay duration was observed; however, no systematic relation between response rate and delay duration was reported. In providing the delays in a pseudo-random order, no delay duration was in effect long enough for performance to demonstrate a stabilized effect on responding. Even though delayed reinforcement has demonstrated a generally consistent effect across the literature, delay durations must be presented with sufficient time to produce a delay of reinforcement gradient. In sum, the effects of delayed reinforcement must be interpreted holistically in terms of their effect on behaviour due to the maintaining conditions of reinforcement and as outcome of the features of the delay itself.

Signaled versus unsignaled delay

Delay procedures may or may not include a programmed stimulus change indicating the start of the delay period prior to the presentation of a reinforcer. Imposing either signaled or unsignaled delays of reinforcement may alter other features of the environment, influencing behavioural changes nominally affected by imposing the delay (Lattal, 2010). Signaled delays generally maintain responding better than do unsignaled delays by virtue of developing conditioned reinforcement properties, eliciting or overshadowing effects on operant responding independently of the effects of delay (Lattal, 2010). Lattal (2010) proposed that preventing this conditioned effect and other

interrupting stimulus functions is simply accomplished by eliminating the signal. Several studies have employed unsignaled delays of reinforcement to examine more systematically the functional relation between the rate of response and the disruption of response-reinforcer temporal contiguity (Sizemore & Lattal, 1977; Sizemore & Lattal, 1978; Williams, 1976). When unsignaled delay values are varied, a delay gradient is observed that physically resembles the gradient obtained with signaled delays but with a lower response rate and steeper slope (Sizemore & Lattal, 1978; Richards, 1981).

Williams (1976) suggested there is only one delay of reinforcement procedure that prevents confounding between the response-reinforcer correlation and changes in contiguity. That is one that employs unsignaled delays and imposes no additional response requirement during the delay. He also suggested that unsignaled delayed reinforcement would maintain much lower rates of responding compared to signaled. Williams (1976) examined this procedure on pigeons pecking behaviour using a VI 2-min schedule and by introducing unsignaled delays of 3 s, 8 s, and 15 s. Although responding was highly variable, a substantial reduction in response rate was observed with the shortest 3-s delay. These findings are in striking contrast to studies in which delays shorter than 10 s produced little reduction in simple schedule response rates. Williams' (1976) results were limited by only examining unsignaled delay; however, his findings were later supported by Richards and Hittesdorf (1978), who found that a 10-s signaled delay maintained higher response rates than did a 10-s unsignaled delay on a VI schedule.

To test the generality of these previous findings, Richards (1981) examined the signaled and unsignaled delay procedures with varying delay durations. Pigeons key

pecking differences were observed by imposing signaled and unsignaled delays of up to 10 s on a VI 60-s schedule or (DRL) 20-s schedule. Interestingly, the delay of reinforcement gradient was steeper in the unsignaled delay condition, a finding consistent with the decrease in overall response rate seen with unsignaled, but not signaled delays, reported in other studies (Lattal & Ziegler, 1982). As seen in Figure 2 from Richards' (1972) study, signaled delays only moderately decreased responding, whereas unsignaled delays of 5 and 10 s produced larger decreases in responding. These findings both confirmed and extended those of Richards and Hittesdorf (1978). The shapes of the delay of reinforcement gradient are similar to those obtained on previous VI schedules comparing signaled and unsignaled delays.

As in the present study, Jarmolowicz (2011) used a rapid assessment of delay of reinforcement to examine key pecking on an FR 50 schedule. The primary aim was to employ delay of reinforcement procedures to rapidly examine the effects of delay duration and signals on responding under different FR requirements. Once a steady state of responding was established on a baseline FR 50, progressively fixed durations (PFD) were presented in a sequence of 1 s, 5 s, 10 s, 20 s, 40 s, 80 s, 160 s, 320 s, and 640 s delays across successive sessions. Each session was terminated after 60 reinforcements or when a subject's pause without responding reached 300 s. Four experiments were conducted where the delay durations in Experiments 1-3 changed from one session to the next. Conversely, Experiment 4 used a steady state design where each delay duration was held constant across a progressively fixed ratio (PFR) procedure where the ratio requirement increased through a sequence of FR 10, FR 50, FR 100, FR 200, FR 400, and FR 800 across successive sessions. Across all four experiments, the procedures

yielded an inverse relationship between delay duration and response rate, and were consistent despite schedule type and the FR requirements. Again, these results emphasize the generalizability of delayed reinforcement effect across schedule type and schedule parameters.

Figure 2.

Response Rates as a Function of Delayed Reinforcement with Signaled (Filled Circle) and Unsignaled (Open Circles) Delay Adapted from "A comparison of signaled and unsignaled delay of reinforcement," by R. W. Richards, 1981, *Journal of the Experimental Analysis of Behaviour*, *35*, p. 147. Copyright 1981 by the Society of the Experimental Analysis of Behaviour.

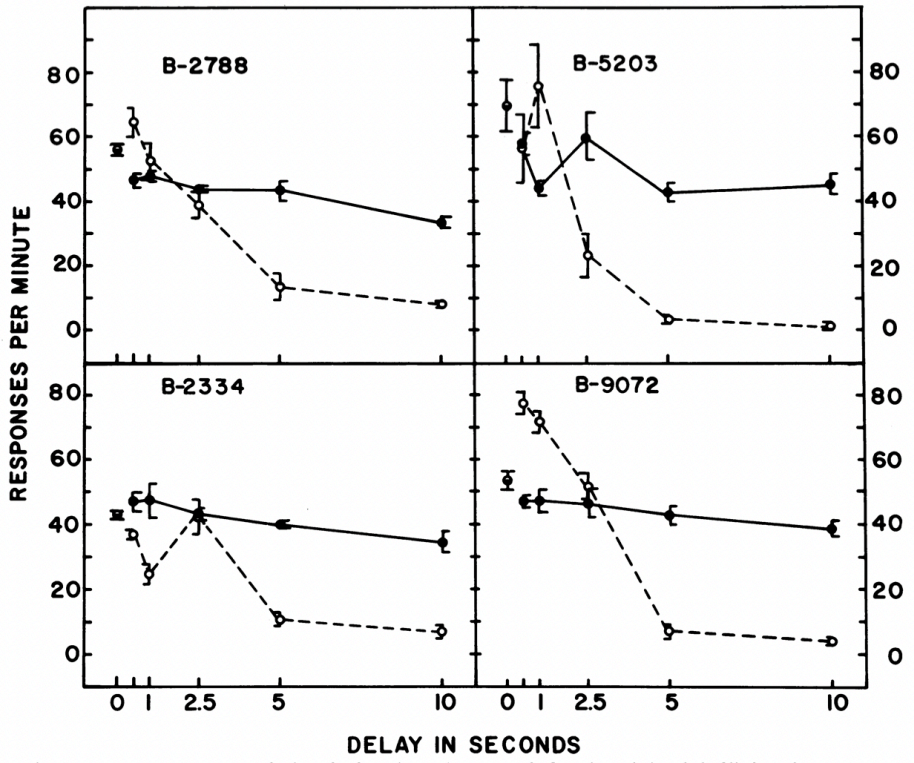


Fig. 1. Mean rate of response during the last six sessions at each duration of signaled (filled circles) and unsignaled (unfilled circles) delay of reinforcement with a VI 60-sec schedule. Brackets indicate one standard deviation above and below the means.

In contrast to other studies reporting response rate differences under signaled and unsignaled delays, Experiments 1-3 yielded no such effect. Rather, response rates differences were neither large nor consistent at any delay duration for three out of the four experiments. This inconsistency may be due to response rate differences for signaled and unsignaled delays required for delay durations to be held constant across a number of successive sessions. In contrast, the response rate differences found in Experiment 4 matched earlier findings for which response rates were higher in the signaled, relative to the unsignaled, delay conditions. Even though Experiment 4 used a PFR procedure, each delay was presented for three sets of the PFR schedule. Therefore, there was sufficient time for response rate differences between the signaled and unsignaled delay conditions to develop. Given that the current study also employed a rapid assessment and PFD procedure, Jarmolowicz's (2011) findings confirmed that these conditions produce a delay of reinforcement gradient; however, they are unlikely to produce a notable response rate difference between signaled and unsignaled delays.

Wheel running as a reinforcer

Although the general effect of responding on a delayed reinforcement has been examined across a variety of schedules and reinforcements, it has yet to be investigated with wheel-running reinforcement. As with other types of reinforcement, contiguity plays a role in the response-strengthening effect of an opportunity to run in a wheel as reinforcement for the operant lever press that produces it. Consequently, there is no theoretical reason to expect that delay of reinforcement should affect operant responding maintained by wheel-running reinforcement differently than other reinforcers. Despite this, wheel running does differ from more conventional reinforcements such as a bit of

food, a drop of sweetened liquid, or a drop of water. Unlike food and water reinforcers, wheel running does not involve the ingestion of a substance related to survival (Pierce et al., 2018). The value of wheel running, like the value of food, increases with decreases in food intake and body weight (Belke, 1996, 2004). Wheel-running reinforcers generate longer PRPs and lower response rates than conventional reinforcements (Belke, 1997; Belke & Dunbar, 1998; Belke & Hancock, 2003). Unlike food reinforcement, wheel-running reinforcement does not show a reinforcement magnitude effect (Bonem & Crossman, 1988). With food reinforcement, larger food amounts are more reinforcing than smaller amounts and rats respond at higher rates for larger food reinforcements (Bonem & Crossman, 1988). In contrast, longer wheel-running durations are not more reinforcing than shorter durations. Rats respond at lower rates for longer wheel-running durations and higher rates for shorter durations (Belke, 1997; Belke & Dunbar, 1998; Belke & Hancock, 2003). Reinforcement value appears to vary with rate, not amount of running (Pierce, et al., 2018). Whether or not these differences have an effect on how reinforcement delay will affect lever-pressing rates for wheel-running reinforcement remains to be seen.

In summary, delay of reinforcement effects have been widely reported for operant behaviour across a variety of contexts, under various schedules, and with different procedures (Sizemore & Lattal, 1977, 1978; Williams, 1976). Studies that include delays, accompanied by a distinct stimulus, generally report maintaining a higher response rate over the delays than those that are unsignaled (Richards, 1981; Richards & Hittesdorf, 1978). The present study aimed to determine whether delaying the opportunity to run in a wheel as reinforcement produces a delay gradient similar to

those found in previous investigations of delayed reinforcement using other types of reinforcers.

Method

Subjects

This experiment was conducted using eight female Long-Evans rats purchased from Charles River Laboratories in Saint-Constant, Quebec. Six rats were approximately one-and-a-half-years-old and two were almost one-year-old at the beginning of the experiment. All the rats had participated in previous experiments on wheel running. The holding room had a 12-h light/dark cycle (lights on at 0730) and was kept at a temperature range of 20–22 °C with relative humidity between 30% and 50%. The rats were dually housed in polycarbonate cages (48.3cm x 26.7cm x 20.3cm) covered with a stainless-steel wire lid with a food cradle and water apparatus. Rats were fed Prolab R-M-H 3000 lab chow, and food was restricted to maintain a body weight of 260 ± 10 g. This weight was 87% of the average adult female weight for this strain (300 g: Long-Evans Rat, Growth Chart, Charles River Laboratories, 2018). Reverse osmosis water was freely available in the home cages throughout the study. This research was conducted in accordance with the guidelines of the Canadian Council on Animal Care under a protocol approved by the Mount Allison Animal Care Committee.

Apparatus

Experimental sessions were conducted in four Med Associate (ENV-042) activity wheels (37 cm in diameter). The floors of the wheels had 72 metal bars, 4 mm in diameter, with a 10 mm space between each bar. The length and width of the opening of the wheel was 10 cm by 7 cm. Each wheel was equipped with a 4.5 cm retractable

lever (Med Associates ENV-112), a solenoid-operated brake, and two 24 VDC lights. A retractable lever was mounted at the opening of each wheel and when activated, a rubber tip attached to a metal shaft contacted the outer edge of the wheel to prevent it from turning (wheel brake). Twenty-four VDC lights were mounted on sides of the wheel frame to illuminate the interior of the wheel chamber. Wheel revolutions were recorded by a microswitch attached to the wheel frame. The wheels were situated in sound attenuating bays equipped with two fans for ventilation and to mask extraneous noise. Control of experimental events and recording of data were handled by a Borland Turbo Pascal 4.0 program run on PC computers interfaced to the wheel through the parallel port.

Procedure

Initial training of the rats to habituate them to the wheels was conducted over 18 sessions. Each session allowed for 30-min access to a free turning wheel. Following initial training, rats were placed on a variable-ratio (VR) 5 schedule across two illumination conditions. The first was a light change condition that took place over 80 sessions and was characterized by a programmed change in illumination when the reinforcement was available. When the response requirement was met in the illumination condition, the retractable lever retracted, the brake released, and the chamber lights turned off. The wheel was free to turn for 60 s after which the brake engaged, the chamber lights turned on, and the retractable lever extended to signal the rats may respond for the next opportunity to run. Each session ended after a maximum of 100 lever presses and 20 reinforcements had been received or when the session reached one hour. After responding stabilized, the delay of reinforcement procedure

began. A delay was inserted between the retraction of the lever and the release of the brake. Note that when the ratio requirement was met, the chamber lights extinguished and the lever retracted, but the brake did not release until the delay elapsed. The delay values were 2 s, 4 s, 8 s, 16 s and 32 s. Each delay value was in effect for one session and the five delays were presented across five successive sessions. After all delay values were completed, the rats returned to the baseline schedule. After a minimum of 15 baseline sessions, the rats were exposed to the same delay values across successive sessions once again. This sequence of baseline sessions followed by exposure to the delay values was carried out a total of three times per condition.

The no light change condition took place over an additional 62 sessions during which the offset of the chamber lights during the wheel-running reinforcement period was removed. In this condition, the chamber lights remained illuminated while the lever was extended and the wheel brake engaged and also when the lever was retracted and the wheel brake was released. Lever-pressing rates for a condition were averaged across the three assessments of consecutive delays in the light change and no light change conditions.

Dependent measures

In each session, total time, the number of revolutions, the time taken to complete the revolutions, and the post-reinforcement pause (PRP) duration were recorded for each of the 20 reinforcements and cumulatively over all 20 reinforcements. The PRP duration was measured as the time between the end of the wheel-running reinforcement and the first lever-pressing response. The completed number of lever presses and administered reinforcements in a session was also recorded. Local lever-pressing rates, expressed as

presses/min, were calculated as the total number of lever presses divided by the time spent lever pressing exclusive of the post-reinforcement pause duration. PRP duration for a session was calculated as the cumulative PRP over the entire session divided by the total number of reinforcements (i.e., 20). Wheel-running rates were calculated by dividing the total number of revolutions by the time taken to complete those revolutions. The result was expressed as revolutions/min.

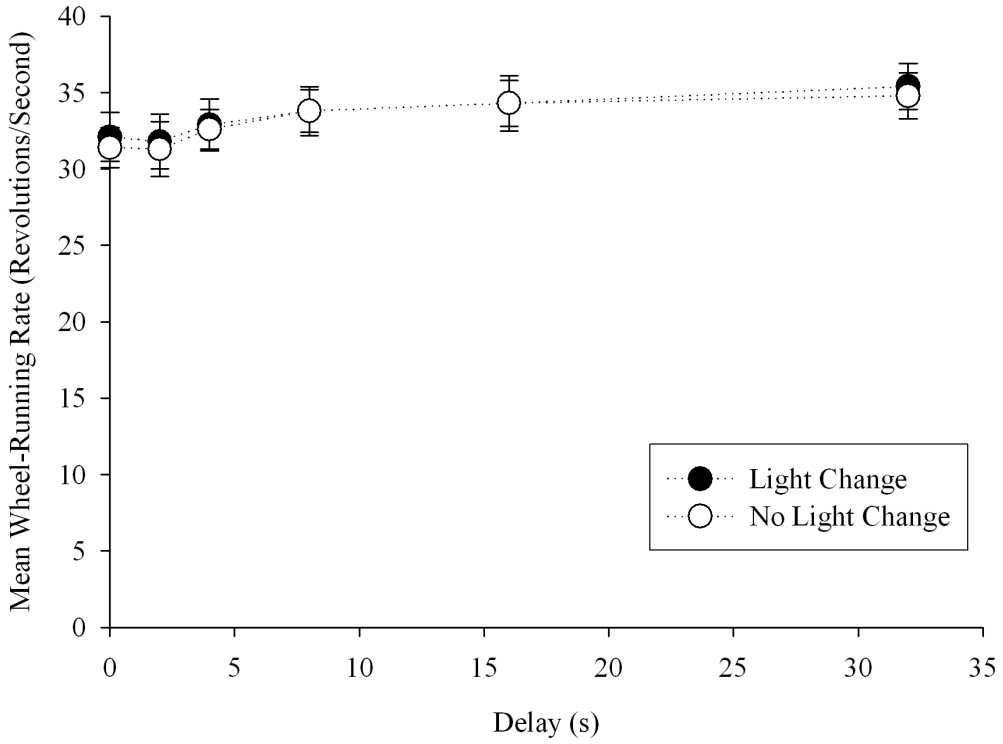
Results

Figure 3 depicts mean wheel-running rates (revolutions/min) for the light change and no light change conditions as a function of delay. Inspection of this figure suggests wheel-running rates increased with delay, but did not differ by lighting condition. A two-way repeated measures ANOVA showed no main effect of lighting condition, F (1, 7) = 0.06, p = .82, η_p^2 = .008, or lighting condition by delay interaction, F (5, 35) = 0.26, p = .93, η_p^2 = .04; however, there was a significant main effect of delay, F (5, 35) = 29.18, p = < .001, η_p^2 = .81. Mean wheel-running rates for 0 s, 2 s, 4 s, 8 s, 16 s, and 32 s were 31.74, 31.54, 32.76, 33.77, 34.32 and 35.10 revolutions/min. Table 1 in the Appendix shows wheel-running rates for each rat by delay collapsed across conditions.

Post-hoc Tukey's HSD comparisons showed that the mean wheel-running rates for the 8 s, 16 s and 32 s delays were all significantly higher than for the 0 s delay, all *ps* <.001. Rates for the 4 s, 8 s, 16 s, and 32 s delays were all higher than for the 2 s delay, all *p*s < .001, except for 4 s, p = .03. Rates generated by the 16 s and 32 s delays were significantly higher than for the 4 s delay, p = .002 and p < .001. Lastly, the wheel-running rate for the 32 s was significantly higher than for the 8 s delay, p = .02. All other values did not significantly differ, all *ps* > .05.

Figure 3

Mean Wheel-Running Rates by Delay for the Light Change and No Light Change Conditions



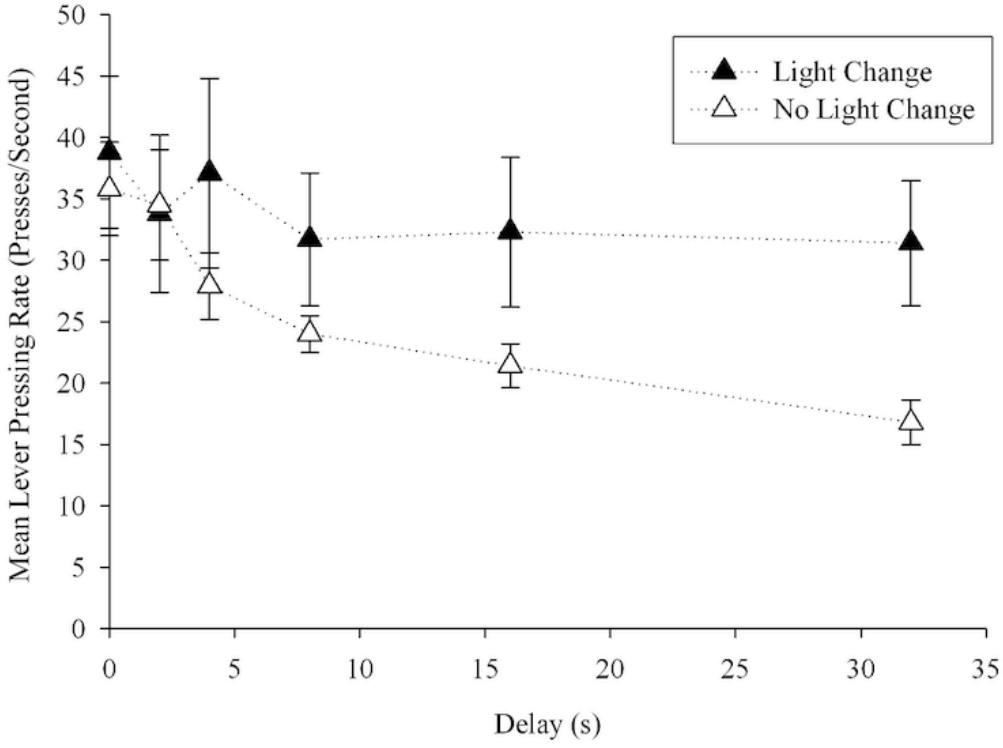
Note. Means and standard errors are presented

Figure 4 shows mean operant lever-pressing rates (presses/min) by delay for the light change and no light change conditions. Inspection of this figure shows no systematic change in lever-pressing with delay and large standard errors when lighting changed with completion of the lever-pressing requirement and onset of the delay. By contrast, when lighting in the wheel did not change, lever-pressing rates systematically decreased with delay. A two-way repeated measures ANOVA showed no significant main effect of lighting condition, F (1, 7) = 3.06, p = .12, η_p^2 = .30. There was, however,

a significant main effect of delay, F (5, 35) = 8.53, p = < .001, η_p^2 = .55 and lighting condition by delay interaction, F (5, 35) = 3.82, p = .007, η_p^2 = .35. Average lever pressing rates for 0 s, 2 s, 4 s, 8 s, 16 s, and 32 s were 37.31, 34.13, 32.54, 27.85, 26.86, and 24.10 presses/min. Mean lever-pressing rates collapsed across delays for individual rats are shown in Table 2 in the Appendix. Post-hoc Tukey's HSD comparisons showed that the mean lever-pressing rate for the 8 s, 16 s, and 32 s were all significantly lower than for the 0 s delay, p = .005, p = .002 and, p < .001. The rate generated by the 32 s

Figure 4

Mean Lever-Pressing Rate by Delay for the Light Change and No Light Change Conditions



Note. Means and standard errors are presented

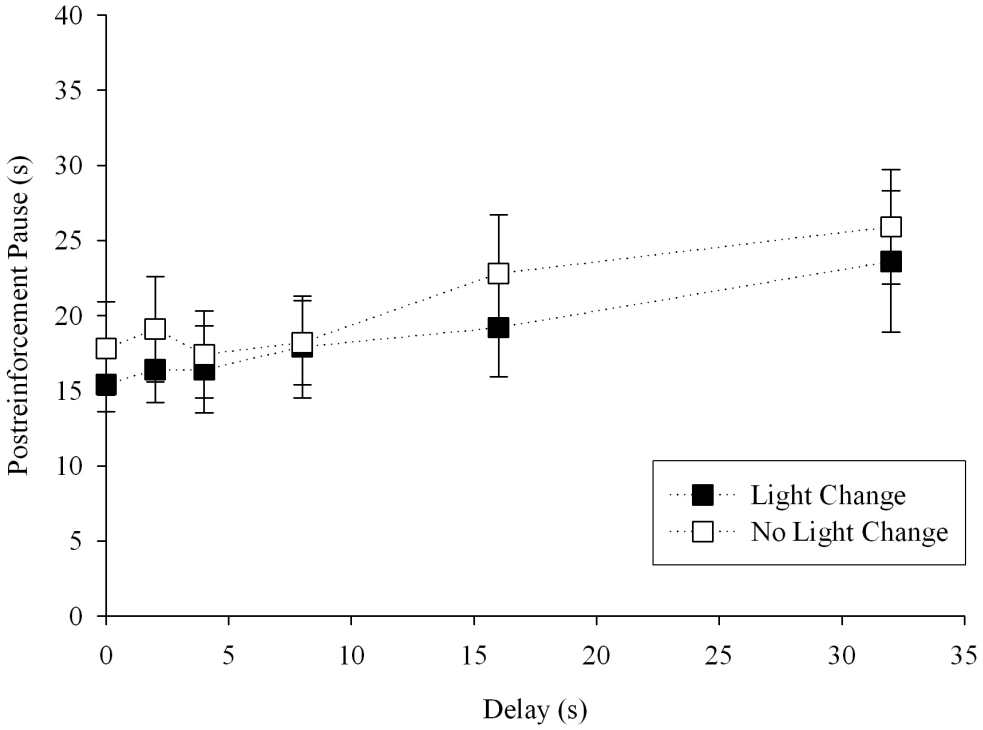
delay was significantly lower than for the 2 s and 4 s delays, $p = .002$ and $p = .02$. All other rates did not significantly differ, all *ps* > .05.

With respect to the interaction, the pattern of responding across the conditions changed with respect to the light change. Tukey's HSD comparisons revealed that for the light change condition there were no significant differences in lever-pressing rates between any delay durations, all *ps* > .05. By contrast, in the no light change condition, mean lever-pressing rates differed with delay. Mean lever-pressing rates for the 8 s, 16 s, and 32 s delays were all significantly lower than for the 0 s delay, *ps* <.001, except 8 s, $p = .008$. Rates for 8 s, 16 s, and 32 s delays were all significantly lower than for the 2 s delay, $p = .03$, $p = .002$ and, $p < .001$. Lastly, the mean lever-pressing rate for the 32 s delay was significantly lower than for the 4 s delay, $p = .02$. All other rates did not significantly differ, all *ps* > .05. Table 3 in the Appendix shows mean lever-pressing rates by delay for the light change and no light change conditions for each rat.

Figure 5 depicts post-reinforcement pause durations for the light change and no light change conditions as a function of delay. Inspection of this figure suggests PRP increased with delay but did not differ by lighting condition. A two-way repeated measures ANOVA showed no main effect of lighting condition, $F(1, 7) = 2.07$, $p = .19$, $\eta_p^2 = .23$, or lighting condition by delay interaction, $F(5, 35) = 0.58$, $p = .71$, $\eta_p^2 = .08$. There was, however, a significant main effect of delay, $F(5, 35) = 14.08$, $p = < .001$, $\eta_p^2 = .67$. Mean PRPs for 0 s, 2 s, 4 s, 8 s, 16 s, and 32 s were 16.60, 17.70, 16.90, 18.00, 21.00, and 24.80 s. PRPs across delay values for individual rats collapsed across conditions are shown in Table 4 in the Appendix.

Figure 5

Mean Post-Reinforcement Pause by Delay for the Light Change and No Light Change Condition



Note. Means and standard errors are presented

Post-hoc Tukey's HSD comparisons showed that the mean PRPs for the 16 s and 32 s delays were both significantly longer than the 0 s delay, $p = .008$ and, $p < .001$. Mean PRP for the 32 s delay was longer than for 2 s delay, $p < .001$. Mean PRPs for the 16 s and 32 s delays were longer than for the 4 s delay, $p = .02$ and $p < .001$. Lastly, mean PRP for the 32 s delay was longer than for the 8s and 16 s delays, $p < .001$ and $p = .04$. All other values did not significantly differ, all $ps > .05$.

Discussion

To summarize the key findings, a significant increase in wheel-running rate was observed across both illumination conditions. Lever-pressing rates did not decrease with delay when there was an illumination change asscoaited with wheel running, but did when there was no stimulus change between pressing and running. Therefore, only the no light change condition effectively demonstrated a delay of reinforcement gradient typified using delay of reinforcement procedures. These different findings across conditions allude to factors such as conditioned reinforcement maintaining responding in the light change condition. Consistent with existing studies of delayed reinforcement, a significant increase in PRP was observed across both lighting conditions when accompanied by increasing delays.

Regarding the effect of delay, no change in lever-pressing rate was observed in the light change condition; however, a noticeable decrease in lever pressing occurred in the no light change condition, an observation consistent with changes in lever-pressing rate seen in existing studies of delay (Jarmolowicz, 2011; Pierce et al., 1972; Reilly & Lattal, 2004; Richards, 1981; Sizemore & Lattal, 1978; Williams, 1976). The difference between conditions alludes to underlying factors working to maintain a high rate of response in the light change condition. The difference in the effect of delay on lever pressing between the two conditions resembles that which occurs between signaled and unsignaled delays (Azzi et al., 1964; Lattal, 2010; Madrigal et al., 2018; Richards, 1981). For example, Richards (1981) observed a marked decrease in pecking by pigeons with unsignaled delays of up to 10 s, but only small reductions with signaled delays. This observation is in accordance with previous studies that have maintained a high rate

of responding using signaled delays (McDevitt & Williams, 2001; Pierce et al., 1972; Richards, 1972) and more substantial response rate reductions using unsignaled delays (Sizemore & Lattal, 1977; 1978). These findings speak to the different effects produced using either signaled or unsignaled delays and suggests the light change condition used in the current study may have functioned similarly to a signaled delay.

In signaled delay investigations, however, a stimulus change occurs at the onset of the delay duration and remains present until the delivery of the reinforcer. In other words, a signal that was not present in the absence of any reinforcement delay is introduced into the procedure when there is a reinforcement delay. This differs from the procedure in the current study in that the change in illumination was present when there was and was not a reinforcement delay. In the current study the lights at the side of the wheel were illuminated prior to the completion of the lever-pressing criterion and the wheel brake disengaging for reinforcement. When the lever-pressing criterion was met, the retractable lever retracted, the brake released, and the lights at the side of the wheel were extinguished. When the wheel-running reinforcement duration elapsed, the brake was asserted, the lever extended, and the lights at the side of the wheel were illuminated. Thus, the absence of illumination was perfectly correlated with the opportunity to run as a reinforcement in the light change condition. As such, the offset of the lights functioned as a conditioned reinforcement for lever pressing. Unique to our study was that the programmed light change occurred with and without delay prior to reinforcement. Therefore, it is possible the offset of the light continued to function as a conditioned reinforcement for lever pressing when reinforcement delay was implemented and maintained responding across the series of delays.

On the other hand, in the no light change condition, there was no change in illumination associated with wheel running and therefore, no conditioned reinforcement presented contingent upon lever pressing. In the absence of a conditioned reinforcement, lever pressing systematically decreased as a function of increased delay duration indicating the diminishment of the reinforcing effect of wheel running.

It important to note that in the light change condition, the onset of reinforcement was not only marked by the change in illumination but also by the retraction of the lever and the release of the brake. In the delay condition, the release of the brake would have been delayed; however, the offset of the light and the retraction of the lever would still have occurred. Despite lever retraction being associated with the onset of wheel running when there was no delay, it did not appear to develop conditioned reinforcement properties maintaining response rate in the light change condition. In a similar delay of reinforcement procedure, Pierce et al. (1972) employed a retractable lever that produced a cue light which remained on during the delay duration and signaled the delivery of reinforcement. By comparing three unique procedures, (1) a retracted lever in which responding could not occur during delay, (2) fixed-delay in which responses during the delay had no scheduled effect on the delay duration and (3) a DRO condition in which each response during the delay restarted the delay, it was found that each produced similar effects of delay on responding on a variable-interval schedule. These findings point to the retractable lever used in the present study as having no procedural effect on the process of delayed reinforcement. This also points to the light as the primary instigator maintaining responding in the light change condition of the current study.

While the effect of delay of reinforcement on lever-pressing rates differed between the light change and no light change conditions, its effect on PRP duration did not. In both conditions, PRP duration increased with delay. Since PRP duration tends to vary inversely with lever-pressing rates as an index of reinforcement value, the decrease in lever-pressing rates and increase in PRP durations in the no light change would be consistent with a decrease in the value of the wheel-running reinforcement. However, in the light change condition, PRP duration increased despite no change in lever-pressing rates.

The increase in PRP is also consistent with findings by Jarmolowicz and Lattal (2013) and Pierce et al. (1972), using both signaled and unsignaled delay when accompanied by increased delays. Jarmolowicz and Lattal's (2013) investigation of the effect of signaled and unsignaled delay on key pecking on fixed ratio (FR) schedules showed that PRP durations increased with nominal delays for both signaled and unsignaled delays; however, the effect of delay on key-pecking rates did not differ by delay conditions. Meunier and Ryman (1974) found systematic increases in PRP durations in two out of three rats responding on FR schedules, but no change in responding with 0, 5, and 10 s delays. This points to a positive relationship between delay duration and PRP that remains uninfluenced by the type of delay and accompanying stimulus change.

Finally, wheel-running rates increased with delay. In this case, the increase in wheel-running rates reflects a motivational effect rather than a direct effect of delay. Belke and Heyman (1994) showed that withholding the opportunity to run for 45 min prior to the commencement of lever pressing for wheel-running reinforcement increased

wheel-running rates and the reinforcing efficacy of wheel running. Although the durations of withholding the opportunity to run were much shorter in the current study, it is likely that a similar effect occurred.

The current study extends the generality of delayed reinforcement as it is the first to demonstrate a delay of reinforcement gradient with wheel running as reinforcement. In addition, it also demonstrated that the delay of reinforcement gradient is not a robust phenomenon in that its occurrence depends on procedural parameters. In this particular study, the presence of a change in illumination that served as a conditioned reinforcement served to prevent the occurrence of a delay of reinforcement effect. When that aspect of the procedure was removed, a clear delay of reinforcement effect emerged. Thus, the present findings also contradict assumptions supporting the generality of delay-of-reinforcement effects regardless of procedural differences.

In sum, the different effects reported by various researchers (Jarmolowicz & Lattal, 2013; Lattal, 2010; Madrigal et al., 2018; McDevitt & Williams, 2001; Meunier and Ryman, 1974; Pierce et al., 1972; Reilly & Lattal, 2004; Richards, 1981; Sizemore & Lattal, 1977; 1978; Williams, 1976) are generally attributed to procedural differences, which suggest the need for further comparison of delay procedures. Some suggestions for future research include a replication of the current design but using sucrose as a reinforcer to compare the effects of delay with respect to reinforcer type. A replication of the present study using a programmed stimulus change, in lieu of the present study's light change condition, may also help to isolate the effect of the light under identical conditions.

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Appendix

Table 1

Mean Wheel-Running Rates by Delay Collapsed Across Lighting Conditions for Each Rat

Rat	Delay 0 s	2 s	4 s	8 s	16 s	32 s
NA 1	26.87	26.31	28.98	30.93	30.34	32.24
NA 7	33.46	33.35	34.63	34.41	35.19	36.33
NA 8	35.11	35.79	35.55	36.08	36.94	37.98
NA 10	29.55	27.35	31.40	31.80	31.70	31.42
NA 11	29.41	29.95	30.13	31.43	32.15	33.06
NA 16	35.66	36.39	36.88	38.43	40.03	39.77
NA 18	36.50	35.58	37.10	38.38	39.45	39.88
NA 22	27.34	27.61	27.38	28.73	28.78	30.10

Table 2

Mean Lever-Pressing Rates by Delay Collapsed Across Lighting Conditions for Each Rat

Rat	Delay 0 s	2 s	4 s	8 s	16 s	32 s
NA 1	58.04	56.49	48.51	43.74	50.93	48.24
NA 7	28.27	25.99	26.33	22.40	21.33	23.35
NA 8	30.70	28.09	26.77	26.59	29.94	24.39
NA 10	26.80	21.38	20.73	20.51	18.80	12.72
NA 11	43.55	39.08	32.36	24.91	23.17	28.59
NA 16	57.89	55.75	54.00	40.69	27.58	30.39
NA 18	29.93	26.15	28.22	21.16	19.32	16.42
NA 22	23.34	20.11	23.43	22.82	23.78	17.59

Table 3

Mean Lever-Pressing Rates by Delay for the Light Change and No Light Change Conditions for Each Rat

Light Change

Rat	Delay 0 s	2 s	4 s	8 s	16 s	32 s
NA 1	67.32	63.42	57.55	53.74	70.94	58.72
NA 7	28.09	25.98	28.41	23.89	23.42	28.92
NA 8	29.61	25.10	29.81	30.49	32.94	27.01
NA 10	25.67	24.14	21.70	20.04	17.48	16.27
NA 11	44.43	29.73	24.78	26.61	28.43	32.84
NA 16	63.43	62.16	82.90	57.56	39.84	45.74
NA 18	28.17	21.82	27.50	21.24	20.56	20.45
NA 22	23.59	17.78	24.53	20.36	24.55	21.20

No Light Change

Rat	Delay 0 s	2 s	4 s	8 s	16 s	32 s
NA 1	48.75	49.56	39.46	33.73	30.92	19.96
NA 7	28.45	26.01	24.24	20.90	19.23	17.77
NA 8	31.79	31.08	23.74	22.68	26.94	21.77
NA 10	27.93	18.61	19.77	20.99	20.11	9.17
NA 11	42.67	48.44	39.95	23.22	17.90	24.34
NA 16	52.35	49.35	25.09	23.83	15.32	15.04
NA 18	31.69	30.49	28.95	21.08	18.07	12.39
NA 22	23.10	22.44	22.33	25.28	23.01	13.98

Table 4

Mean Postreinforcement Pause (PRP) Durations by Delay Collapsed Across Lighting Conditions for Each Rat

Rat	Delay 0 s	2 s	4 s	8 s	16 s	32 s
NA 1	30.98	34.22	35.24	38.45	42.73	48.24
NA 7	11.89	9.59	11.67	11.92	11.90	12.80
NA 8	12.88	15.88	13.65	14.71	17.21	15.18
NA 10	11.82	13.83	13.06	14.17	15.02	25.34
NA 11	12.44	14.11	15.30	15.73	17.59	19.32
NA 16	19.60	20.47	17.70	18.12	24.80	29.30
NA 18	20.11	21.54	18.61	18.66	23.89	29.56
NA 22	13.07	12.24	10.32	12.50	15.10	18.48