EFFECT OF REQUIRED RESPONSE FORCE USING A PEDALING TASK ON THE SENSITIVITY OF HUMAN PARTICIPANTS TO REINFORCEMENT CONTINGENCIES

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The present study assessed the effect of the required response force on sensitivity to reinforcement contingencies under concurrent schedules using a pedaling task with five human participants aged 23 to 31 years. We compared two levels of required response force using an ABAB design. No reliable differences in estimated sensitivity were found using a Generalized Matching Law model, indicating that the required response force, as was manipulated in the current pedaling task, does not influence sensitivity to reinforcement contingencies. Additional approaches are proposed to explore the impact of required response force on sensitivity. These include using discriminative stimuli, multiple exposures to schedules, increased reinforcement frequencies, using response forces that are experienced by participants as clearly different or implementing different response topographies.

Keywords: generalized matching law, human participants, pedaling, response effort, sensitivity to reinforcement contingencies

Regarding within-subject comparisons, sensitivity to contingencies is demonstrated when a contingency change affects steady-state behavior in an orderly manner. Conversely, insensitivity is described as a lack of change in behavior after a contingency change. Sensitivity can be quantified through choice studies related to the Matching Law (Madden et al., 1998).

The Matching Law (Herrnstein, 1961, 1970) specifies that the proportion of responses allocated to an alternative matches the proportion of reinforcers obtained. However, Baum (1974) noted deviations from strict matching, such as under-matching and over-matching, and proposed the Generalized Matching Law (GML). The logarithmic form of the GML equation is:

$$\log\left(\frac{B_1}{B_2}\right) = a\log\left(\frac{r_1}{r_2}\right) + \log k \qquad (1)$$

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Where B_1 and B_2 are response rates to each alternative in a concurrent schedule, and r_1 and r_2 are rates of obtained reinforcement. The parameter "k" represents the initial bias to respond to one alternative regardless of the contingencies, and "a" reflects sensitivity to the relative rate of reinforcement.

Later, Baum (1975) suggested that response counts could be translated into time allocation, assuming constant response duration. Thus, the law also applies to time spent on each alternative, leading to a second version of the GML, known as the Time Allocation Law (Baum & Rachlin, 1969):

$$\log\left(\frac{T_1}{T_2}\right) = a\log\left(\frac{r_1}{r_2}\right) + \log k \qquad (2)$$

Here, T_1 and T_2 represent the time allocated to each alternative in the concurrent schedule, while the other parameters remain the same as in Equation 1.

The sensitivity parameter "a" indicates how much behavior shifts with changes in reinforcement ratios. Values near zero indicate low sensitivity, and values near one indicate accurate matching (Madden et al., 1998). Non-human organisms usually show sensitivity between 0.5 and 1.3, although deviations occur (Baum, 1979, 1983; de Villiers, 1977; Wearden & Burgess, 1982). According to Baum (1974), factors such as discrimination, changeover delay, and deprivation can impact undermatching, which refers to a systematic deviation from the matching relation in the direction of indifference (for an extensive review of the Matching Law see Davison & McCarthy, 1988).

In studies with humans assessing the GML, results have varied (Horne & Lowe, 1993). Some studies showed matching (Bradshaw et al., 1976, 1979a, 1979b; Ruddle et al., 1979) while others observed insensitivity (Oscar-Berman et al., 1980; Schmitt, 1974). Kollins et al. (1997) found that sensitivity was more variable and generally lower for humans than for non-humans. The median sensitivity values were 0.70 for humans and 0.85 for non-humans indicating that humans are less sensitive to differences in reinforcement rates during concurrent schedules.

One way to promote matching behavior and enhance sensitivity to reinforcement parameters with humans is by increasing response cost. In an experimental study on vigilance, Baum (1975) required three adults to monitor two keys under conditions that included a cost for releasing a key and a changeover delay; increasing the cost brought participants' time allocation closer to the matching relation. McDowell and Wood (1985) also conducted an experiment with four adults using simple variable-interval schedules combined with reinforcement magnitudes, comparing phases with low and high force requirements. They found that response rate was more sensitive to changes in reinforcement magnitude under high-force conditions.

Other authors have argued that making contingencies more similar between species might yield more systematic results and suggested that response cost may be an important factor. Matthews et al. (1977) reported experimental evidence that students' behavior was more sensitive to contingencies under variable-ratio and variable-interval schedules when participants responded without specific instructions and were required to emit a consummatory response. However, in the introduction to their article, Matthews et al. argued that human responses might be sensitive to contingencies when they involve high force or response cost.

Research on the required response force as a proxy for response cost and sensitivity in concurrent schedules with human participants is limited. Chung (1965) conducted a study with non-human subjects, exposing pigeons to a concurrent VI 1-s VI 3-s schedule where the response force requirement of both keys varied across conditions. The study found that increased response force led to reduced responding to both alternatives, but proportionally more to the less rewarding alternative, potentially increasing sensitivity.

The scarcity of studies on response force in humans, particularly using concurrent schedules, highlights the need for further research. An important consideration in research on response cost and sensitivity is the choice of apparatus, since different devices can shape how participants experience and discriminate effort requirements. For human studies, tasks that naturally involve forceful responding may provide a clearer and more ecologically valid way of manipulating response cost than traditional key-press or button-press arrangements. In this regard, a stationary bicycle represents a suitable apparatus: pedaling is a continuous, measurable, and familiar activity that allows precise adjustment of the force required while maintaining participant engagement. Moreover, cycling tasks have been used successfully in other experimental contexts to sustain responding over extended periods without the discomfort or artificiality that can accompany high-force keyboard or lever presses (Ghaleb et al., 2020; Pilcher & Baker, 2016).

This study aims to evaluate the effect of required response force in a pedaling task with human participants on sensitivity to reinforcement contingencies in concurrent schedules using a stationary bicycle to manipulate the required force. Additionally, a secondary aim of this study is to evaluate the use of shorter exposure durations to concurrent schedules. Previous research suggests that organisms can quickly acquire matching behavior under specific conditions, allowing for reduced participant burden. Shorter sessions may help prevent common issues in human research such as fatigue, experimental dropout, and reduced attention, which can affect data quality and sensitivity measures (Lie et al., 2009; Klapes et al., 2020). Moreover, brief procedures can help maintain participant engagement and make within-subject comparisons across conditions more practical.

METHOD

Participants

Participants were four men (two aged 31, one 27, and one 23) and one woman aged 24, all of whom were Mexican nationals with an undergraduate degree and no prior experience in experimental tasks involving reinforcement schedules. This convenience sample was recruited through personal invitations from the researcher among individuals who met the main inclusion criteria: being adults (18 years or older) and having no prior exposure to operant tasks or reinforcement-schedule procedures. For confidentiality, participants were assigned anonymous identification codes (P1–P5) upon enrollment; these codes were assigned according to the order in which the experimental sessions took place, such that the first participant tested was labeled P1 and the last P5, with the code key stored separately and accessible only to the principal investigator. Participants received monetary compensation based on their performance in the experimental task, with no upper limit on potential earnings. No participants were excluded or withdrew from the study.

Setting

The experimental sessions took place in the "Decision Making and Stress" laboratory at the Center for Studies and Research in Behavior at the University of Guadalajara. The temperature in the lab was set to 22º C. Inside, there was a computer and monitor for the experimental task, as well as the stationary bicycle. Participants were instructed prior to arriving that they would perform a pedaling task on a stationary bicycle and were asked to wear comfortable clothing.

Apparatus

A commercially available stationary bicycle (Body Fit BF-HW3059A) was modified by Walden Modular Equipment to allow for automated control of the required force. This was achieved through an Arduino-based system that sent signals to an electric motor, which in turn adjusted the resistance by turning the bicycle's adjustment knob. This setup allowed for more precise control of resistance, which would otherwise have to be adjusted manually; additionally, a CNY70 Arduino sensor was installed on the bicycle to count the number of wheel rotations.

A computer keyboard was attached to a handlebar-mounted support for participant input. Task programming, data recording, and collection were done using a computer with GameMaker Studio® for Windows®. A 20-inch monitor displayed the task interface, and a Xiaomi Mi Band 4® smart bracelet was used to measure participants' heart rate.

Experimental Design

The experimental design consisted of two conditions, with different requirements for pedal force during the task. The target response was completing a 360-degree rotation of the bicycle wheel using the pedals. Participants were required to exert 107.9 Newtons during the higher force condition, and 34.32 Newtons during the lower force condition. Each condition included five pairs of concurrent VI VI schedules, as shown in Table 1, and ten values of interval duration were used for each VI schedule according to Fleshler and Hoffman's (1962) progression. A 3-s changeover delay (COD) was used to

Table 1

Experimental Design with the Values of Concurrent VI VI Schedules for Both Conditions

Schedule	VI Upper alternative (1)	VI Bottom alternative (2)
1	15s	60s
2	60s	30s
3	30s	30s
4	30s	60s
5	60s	15s

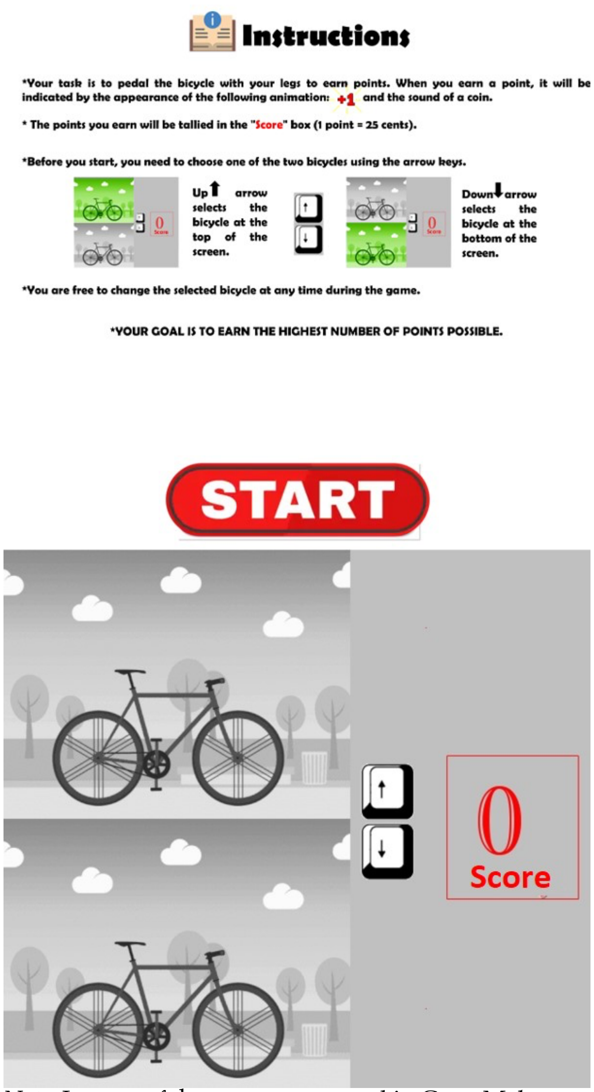
Note. Participants completed the five pairs of concurrent VI VI schedules under both force conditions (Lower Force = 34.32 N, Higher Force = 107.9 N). The order of conditions was pseudo-random: odd-numbered participants began with the Higher Force condition, and even-numbered participants began with the Lower Force condition. The five schedules were presented in the same order for both force conditions, from Schedule 1 to Schedule 5, with the upper and bottom alternative intervals as shown in the table.

prevent accidental reinforcement of the bicycle-switching response.

Three participants started in the higher force condition (P1, P3, and P5), and two started in the lower force condition (P2 and P4). Assignment to starting condition was pseudo-random, such that odd-numbered participants began in the higher force condition and even-numbered participants began in the lower force condition. After completing both conditions, a session was repeated one week later with the same participants resulting in an ABAB design.

Figure 1

Program



Note. Images of the program created in GameMaker Studio® (English language version)

Procedure

After obtaining informed consent, each participant completed the short version of the International Physical Activity Questionnaire (IPAQ) in Excel (Craig et al., 2003). The questionnaire contains questions about three types of activity: walking, moderate-intensity, and vigorous-intensity. Based on responses, participants' physical activity level in the past seven days was classified as low, moderate, or high for performance comparison.

Next, the program created in GameMaker Studio® was launched on the computer, displaying instructions in Spanish (see Figure 1 for the English version). Upon clicking "Start," the game interface appeared with two gray bicycle images, and the timer started running once one was selected using the arrow keys. The selected bicycle image lit up in green, while the other remained gray. As the participant pedaled, the selected bicycle image displayed an animation of wheels in motion with clouds in the background to simulate a ride.

The concurrent schedules were presented in the order shown in Table 1 with each schedule presented for 200 s and at least 120 s of rest between schedules. During the rest, participants could drink water and dismount from the bicycle. After the rest, participants were asked if they needed more time, or if they were ready to continue; in no case was additional rest time required. Each condition lasted approximately 25 min. These considerations, including short-duration schedules, were motivated by the need to collect data within a limited time in human research. This approach helps minimize attrition rates and maintains participant motivation (Lie et al., 2009).

At the end of the second day, points earned were summed and converted to Mexican pesos for payment. All five participants attended both sessions; therefore, no cases of absence occurred.

Data Analysis

Data analysis was performed using GraphPad Prism 7® software for Windows®. Sensitivity was calculated using simple linear regression, fitting the data of each condition to the GML equation (Baum, 1974) in its logarithmic version (Equation 2).

The dependent variable was the ratio of time that the participant spent responding in each alternative (time in minutes in alternative 1 divided by time in minutes in alternative 2), and the independent variable was the ratio of reinforcement rate (rate of points delivered in alternative 1 divided by rate of points delivered in alternative 2). To obtain the reinforcement rate, the total points delivered in each alternative were divided by the total duration of the concurrent schedule in minutes. The allocation of time to each alternative was measured using time counters programmed in GameMaker Studio®, which tracked the time while the corresponding bicycle for each alternative was selected, meaning that the selected bicycle appeared in green on the game interface, while the non-selected bicycle remained gray and its time counter stopped.

All matching analyses were conducted using the obtained reinforcement rates for each alternative, rather than the programmed rates, ensuring that sensitivity estimates reflect the

Table 2

Time Allocation Ratios (T1/T2) and Obtained Reinforcement Ratios (r1/r2) Compared to Programmed Schedule Ratios for Each Participant Across Schedules During the First Exposure to Both Lower-Force and Higher-Force Conditions

Participant	Schedule	Lower force		Higher force		Programmed ratio
		T1/T2	r1/r2	T1/T2	r1/r2	
1	1 (4:1)	2.85	5.50	-	-	4
	2 (1:2)	1.55	0.50	0.83	0.43	0.5
	3 (1:1)	0.97	0.86	1.09	1.00	1
	4 (2:1)	1.05	2.00	0.93	2.00	2
	5 (1:4)	0.73	0.27	0.82	0.29	0.25
2	1 (4:1)	1.35	3.00	1.04	3.00	4
	2 (1:2)	1.05	0.43	0.76	0.43	0.5
	3 (1:1)	1.23	1.00	1.51	1.17	1
	4 (2:1)	1.28	2.33	1.01	2.00	2
	5 (1:4)	0.96	0.33	0.77	0.38	0.25
3	1 (4:1)	1.99	4.33	1.91	3.67	4
	2 (1:2)	0.66	0.43	1.30	0.43	0.5
	3 (1:1)	1.21	1.00	1.49	1.00	1
	4 (2:1)	1.18	2.33	1.02	2.33	2
	5 (1:4)	1.23	0.38	1.18	0.30	0.25
4	1 (4:1)	1.17	2.67	1.46	2.33	4
	2 (1:2)	1.34	0.50	0.25	0.29	0.5
	3 (1:1)	0.32	0.29	0.29	0.29	1
	4 (2:1)	0.50	1.00	0.18	0.33	2
	5 (1:4)	1.30	0.50	-	-	0.25
5	1 (4:1)	1.01	2.67	0.59	2.33	4
	2 (1:2)	1.01	0.43	1.45	0.43	0.5
	3 (1:1)	1.49	1.17	4.17	3.50	1
	4 (2:1)	1.20	2.33	0.14	0.33	2
	5 (1:4)	0.51	0.25	2.11	0.43	0.25

Note. Dashes (-) indicate cases of exclusive preference for the richer alternative, where no responses or reinforcers were obtained in the leaner alternative.

actual contingencies experienced by participants.

RESULTS

Tables 2 and 3 present the time allocation ratios (T1/T2) and obtained reinforcement ratios (r1/r2) compared to the programmed schedule ratios for each participant, across both lower- and higher-force conditions, during the first and second exposures, respectively. In general, the obtained reinforcement ratios approximated the programmed schedule ratios, indicating that the concurrent schedules were successfully implemented. Nonetheless, some deviations were observed in individual cases, particularly under extreme ratios (e.g., 4:1 and 1:4), where the obtained reinforcement ratios tended to diverge from the programmed values. These discrepancies suggest variability in participants' allocation patterns across conditions, but without a clear systematic trend. Importantly, the sensitivity analysis was conducted using the obtained reinforcement ratios, ensuring that the estimates reflect participants' actual contact with the

Table 3

Time Allocation Ratios (T1/T2) and Obtained Reinforcement Ratios (r1/r2) Compared to Programmed Schedule Ratios for Each Participant Across Schedules During the Second Exposure to Both Lower-Force and Higher-Force Conditions

Participant	Schedule	Lower force		Higher force		Programmed ratio
		T1/T2	r1/r2	T1/T2	r1/r2	
1	1 (4:1)	1.28	2.67	1.15	3.00	4
	2 (1:2)	1.39	0.50	1.45	0.50	0.5
	3 (1:1)	1.00	1.00	0.88	0.86	1
	4 (2:1)	0.65	2.00	3.22	3.50	2
	5 (1:4)	1.51	0.43	0.59	0.23	0.25
2	1 (4:1)	0.89	2.67	1.17	3.00	4
	2 (1:2)	1.07	0.43	1.15	0.43	0.5
	3 (1:1)	1.06	1.00	0.97	1.00	1
	4 (2:1)	0.91	2.33	0.96	2.33	2
	5 (1:4)	1.45	0.33	0.97	0.38	0.25
3	1 (4:1)	0.90	3.33	1.70	4.33	4
	2 (1:2)	1.01	0.43	1.10	0.43	0.5
	3 (1:1)	1.39	1.00	1.55	1.00	1
	4 (2:1)	1.13	2.33	1.24	2.33	2
	5 (1:4)	1.27	0.38	1.00	0.27	0.25
4	1 (4:1)	1.32	2.33	0.89	2.33	4
	2 (1:2)	0.82	0.43	0.69	0.43	0.5
	3 (1:1)	0.81	0.86	1.12	1.00	1
	4 (2:1)	0.82	2.00	1.12	2.00	2
	5 (1:4)	0.72	0.38	0.65	0.33	0.25
5	1 (4:1)	1.79	3.67	2.36	4.00	4
	2 (1:2)	0.86	0.43	2.25	0.60	0.5
	3 (1:1)	0.80	1.00	0.70	0.86	1
	4 (2:1)	0.66	2.00	0.54	2.00	2
	5 (1:4)	0.58	0.38	0.81	0.33	0.25

Note. Dashes (-) indicate cases of exclusive preference for the richer alternative, where no responses or reinforcers were obtained in the leaner alternative.

Table 4

Simple Linear Regression Values (a = sensitivity, and R^2 = coefficient of determination)

Participant	Condition							
	Higher Force		**Lower Force**		**Higher Force**		**Lower Force**	
	a	**R^2**	***a***	**R^2**	***a***	**R^2**	***a***	**R^2**
P1	0.330	0.562	0.096	0.407	-0.236	0.332	0.396	0.525
P3	0.268	0.534	0.091	0.168	-0.075	0.179	0.158	0.647
P5	0.261	0.471	0.532	0.198	0.296	0.452	0.157	0.052
	Lower Force		**Higher Force**		**Lower Force**		**Higher Force**	
	a	**R^2**	***a***	**R^2**	***a***	**R^2**	***a***	**R^2**
P2	0.143	0.936	0.177	0.341	-0.178	0.780	0.010	0.010
P4	0.278	0.135	0.869	0.928	0.200	0.532	0.232	0.616

contingencies rather than the programmed schedules.

Table 4 shows the sensitivity values a and coefficient of determination R2 values for each participant during two exposures to the lower force (A) and higher force (B) conditions. There were two cases of exclusive preference for the richer alternative. This occurred with participant P1 during the first exposure to the high force concurrent VI 15 s VI 60 s (B) and participant P4 during the first exposure to the high force concurrent VI 60 s VI 15 s (B). We excluded these cases from the analysis using the GML equation, as dividing by zero or taking the logarithm of zero are mathematically impossible. The sensitivity value for these two participants in the first exposure to the higher force (B) condition was calculated based solely on the remaining four concurrent schedules. Sensitivity values close to indifference between alternatives were observed in most cases. Specifically, P1, P2, and P3 showed low or even negative sensitivity across both force conditions with no consistent differences between higher- and lower-force values. P5 also displayed low sensitivity overall, although slightly higher values were obtained under the high-force condition in the first exposure. In contrast, P4 was the only participant who consistently produced higher sensitivity values, particularly under the first exposure to the high-force condition (a = 0.869, R^2 = 0.928). Apart from this case, no systematic differences in sensitivity values were found between the high- and low-force conditions. Furthermore, the R^2 values were generally low, suggesting a poor fit of the data to the model, except for isolated cases such as P2 (lower force, first exposure: R^2 = 0.936) and P4 (higher force, first exposure: R^2 = 0.928) (see Appendix A for raw data).

Table 5 shows the heart rate measurements in beats per minute (bpm). Both maximum and mean heart rates during the corresponding condition are shown. Maximum heart rate increased from the first lower force exposure to the first higher force exposure in all but one participant, but no systematic increase was observed with average heart rate. No systematic change was observed in the second exposure to each condition.

Table 6 presents the number of wheel revolutions achieved under each condition. Most participants (P1, P3, P4, and P5) maintained a relatively stable number of revolutions across lower- and higher-force conditions, differing only by a few hundred revolutions. Participant P2 produced more revolutions in the lower-force conditions

Table 5

Maximum Heart Rates (bpm) (value before the diagonal) and Average Heart Rates (value after the diagonal) Obtained in Each Condition of the Experiment in Both Exposures

Participant	Condition			
	Higher Force	**Lower Force**	**Higher Force**	**Lower Force**
P1	134/119	172/138	143/112	177/143
P3	133/109	161/110	115/97	119/103
P5	117/96	118/91	114/91	122/95
	Lower Force	**Higher Force**	**Lower Force**	**Higher Force**
P2	167/139	172/138	149/116	118/83
P4	129/103	171/121	135/104	132/91

Table 6

Number of Wheel Revolutions Achieved through Pedaling under Each Condition.

Participant	Condition			
	Higher Force	**Lower Force**	**Higher Force**	**Lower Force**
P1	7686	7592	7790	7589
P3	7854	7897	7483	8004
P5	7368	7326	7421	7589
	Lower Force	**Higher Force**	**Lower Force**	**Higher Force**
P2	9068	7967	8589	7899
P4	7447	7068	7532	7415

compared to the higher-force conditions, but no systematic differences were observed for the other participants, indicating generally stable pedaling performance regardless of required force. This suggests that the pedal force manipulations may not have produced clearly distinct experiences across participants, consistent with the inconsistent heart rate and performance data.

DISCUSSION

The present study investigated effects of response force requirements on sensitivity to reinforcement contingencies in concurrent schedules using an ABAB design. Overall, no significant differences were found between the lower and higher force conditions across most subjects, suggesting that, contrary to Matthews et al. (1977), the force required in this study did not significantly influence sensitivity to reinforcement contingencies. At the same time, the results indicate that the modified stationary bicycle served as a feasible apparatus for conducting concurrent schedule experiments with humans, allowing precise automated control of force and sustained responding over extended periods. However, the natural experience of pedaling may have reduced the salience of force differences, which could help explain the lack of systematic effects. The study did not manipulate other variables known to affect sensitivity, such as discriminative stimuli (Horne & Lowe, 1993; Madden & Perone, 1999; Takahashi & Iwamoto, 1986) or prior exposures to individual schedules, which might explain the low sensitivity values.

An additional analysis was conducted using the Generalized Matching Law (Equation 1), taking response rate as the dependent variable instead of time allocation. Because the results were virtually identical to those obtained with the Time Allocation Law (Equation 2), only the time allocation data are presented. This provides convergent evidence that participants' behavior was generally consistent across different measures of allocation (Baum, 1975).

Krägeloh et al. (2010) noted that sensitivity in human experiments with concurrent schedules varies more widely than in non-human studies, with values ranging from 0.02 to 0.82. The current study supports this variability, with sensitivity values ranging from -0.236 to 0.296 in the lower force conditions and from 0.01 to 0.869 in the higher force conditions. Notably, the close correspondence between programmed and obtained reinforcement ratios strengthens confidence in the validity of the present procedure. This alignment suggests that the apparatus and schedule parameters effectively controlled reinforcement delivery, indicating that the observed variability in sensitivity values is more likely attributable to participants' allocation patterns and the response force manipulation itself, rather than to inconsistencies in reinforcement implementation. However, the differences in force requirements may have contributed to this variability, although the range used may have been insufficient to produce consistent effects. Future studies could test wider or individually calibrated force levels to better determine the role of response effort in human sensitivity to reinforcement contingencies.

The 200-s schedule duration was chosen to prevent fatigue from the pedaling task and to ensure that sessions remained brief, minimizing attrition rates and helping to maintain participants' motivation. Although similar brief-exposure procedures have been used in experiments with humans (Krägeloh et al., 2010; Klapes et al., 2020; Lie et al., 2009), the limitations of short sessions must be acknowledged. For instance, although Lie et al. (2009) reported a mean sensitivity of 0.56 by the final block of reinforcers, they themselves noted that limited exposure to contingencies likely constrained the emergence of higher sensitivity values, with median sensitivity remaining low. Similarly, Krägeloh et al. and Klapes et al. reported mean sensitivities of 0.47 and 0.64, respectively, though the latter employed higher reinforcement frequencies, which may have contributed to their results (Alsop & Elliffe, 1988). Taken together, these findings suggest that brief exposure durations, such as the 200-s schedules used in the present study, may inherently limit sensitivity estimates. Future research should consider maintaining short session-durations to preserve participant engagement, but increase both the number of exposures (e.g., multiple exposures to 200-second schedules) and the frequency of reinforcement to facilitate more extended contact with the contingencies and potentially yield more robust sensitivity estimates.

The response forces used (107.9 N and 34.3 N) also may not have been sufficient to produce different experiences for participants, as reflected by inconsistent heart rate measurements and wheel revolutions across force conditions. Additionally, the characteristics of the apparatus may have influenced these results: although the stationary bicycle was modified to allow precise automated control of resistance, the experience of pedaling may still have felt relatively natural or comfortable compared to tasks requiring high-force key presses or lever pulls, potentially reducing the salience of force differences between conditions. Measures should be included in future studies to confirm that the forces employed affect participants differently.

Experiments with pigeons (Chung, 1965; Davison & Ferguson, 1978; Hunter & Davison, 1982) have shown that varying the physical force required for responses did not result in a preference bias towards the lower force alternative. However, when different topographic requirements were used, pigeons showed a strong bias towards the lower-effort response, regardless of reinforcement rates. This may explain the absence of an effect in the present study, as the response topography was identical (i.e., pedaling) despite differing force requirements. Future adaptations of the apparatus could address this limitation by incorporating alternative response modes, such as pedaling in different directions, alternating between seated and standing pedaling, or using the keyboard mounted on the handlebar as an additional response option. Such modifications may allow clearer tests of how response topography interacts with effort to influence sensitivity to reinforcement contingencies.

It is also important to consider the potential influence of order effects on participants' behavior. In this study, the order of high- and low-force conditions was pseudo-randomized across participants, and the presentation order of schedules within each condition followed the sequence shown in Table 1. Despite this counterbalancing, subtle effects of prior exposure to a particular force level or schedule could have influenced responding, especially given the naturalistic pedaling task and the participants' familiarity with the apparatus. For instance, participants may have adjusted their effort based on experience in the first condition or developed anticipatory strategies, which could contribute to some of the variability observed in sensitivity and pedaling performance (Knauss et al., 2020). Future research could examine order effects more systematically, possibly by increasing the number of participants and incorporating additional counterbalancing strategies to disentangle the effects of force, schedule, and experience with the apparatus.

Finally, future research should explore incorporating more environmental conditions, such as discriminative stimuli, multiple exposures to schedules, higher reinforcement frequencies, forces that differentially affect participants, or varying response topography, to potentially increase sensitivity values and better understand the effects of required response force.

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Appendix

Table A1

Time allocated (in seconds; T1 and T2) and number of obtained reinforcers (r1 and r2) in both alternatives for each participant, across all schedules, under the first exposure to both the lower-force and higher-force conditions.

Participant	**Schedule**	**Lower force**				**Higher force**			
		T1	**T2**	**r1**	**r2**	**T1**	**T2**	**r1**	**r2**
1	**1 (VI 15s VI 60s)**	148.02	51.97	11	2	199.99	0.00	16	0
	2 (VI 60s VI 30s)	121.43	78.56	3	6	90.97	109.02	3	7
	3 (VI 30s VI 30s)	98.61	101.38	6	7	104.15	95.84	6	6
	4 (VI 30s VI 60s)	102.53	97.46	6	3	96.12	103.87	6	3
	5 (VI 60s VI 15s)	84.65	115.34	3	11	90.37	109.62	2	7
2	**1 (VI 15s VI 60s)**	114.85	85.15	9	3	101.97	98.02	9	3
	2 (VI 60s VI 30s)	102.29	97.7	3	7	86.44	113.55	3	7
	3 (VI 30s VI 30s)	110.18	89.81	7	7	120.25	79.74	7	6
	4 (VI 30s VI 60s)	112.1	87.89	7	3	100.48	99.51	6	3
	5 (VI 60s VI 15s)	97.84	102.15	3	9	87.24	112.75	3	8
3	**1 (VI 15s VI 60s)**	133.02	66.97	13	3	131.26	68.73	11	3
	2 (VI 60s VI 30s)	79.26	120.73	3	7	113.15	86.84	3	7
	3 (VI 30s VI 30s)	109.55	90.44	7	7	119.61	80.38	7	7
	4 (VI 30s VI 60s)	108.08	91.91	7	3	101.02	98.97	7	3
	5 (VI 60s VI 15s)	110.11	89.88	3	8	108.43	91.56	3	10
4	**1 (VI 15s VI 60s)**	107.74	92.25	8	3	118.6	81.39	7	3
	2 (VI 60s VI 30s)	114.67	85.32	3	6	40	159.99	2	7
	3 (VI 30s VI 30s)	48.65	151.34	2	7	45.14	154.85	2	7
	4 (VI 30s VI 60s)	66.6	133.39	3	3	30.8	169.19	1	3
	5 (VI 60s VI 15s)	113.17	86.92	3	6	0	199.99	0	15
5	**1 (VI 15s VI 60s)**	100.53	99.46	8	3	74.22	125.77	7	3
	2 (VI 60s VI 30s)	100.37	99.62	3	7	118.45	81.54	3	7
	3 (VI 30s VI 30s)	119.77	80.22	7	6	161.28	38.71	7	2
	4 (VI 30s VI 60s)	109.06	90.93	7	3	24.25	175.74	1	3
	5 (VI 60s VI 15s)	67.38	132.61	2	8	135.64	64.35	3	7

Table A2

Time allocated (in seconds; T1 and T2) and number of obtained reinforcers (r1 and r2) in both alternatives for each participant, across all schedules, under the second exposure to both the lower-force and higher-force conditions.

Participant	**Schedule**	**Lower force**				**Higher force**			
		T1	**T2**	**r1**	**r2**	**T1**	**T2**	**r1**	**r2**
1	**1 (VI 15s VI 60s)**	112.2	87.79	8	3	107.14	92.85	9	3
	2 (VI 60s VI 30s)	116.26	83.73	3	6	118.41	81.58	3	6
	3 (VI 30s VI 30s)	100.16	99.83	7	7	93.67	106.32	6	7
	4 (VI 30s VI 60s)	79.09	120.9	6	3	152.59	47.4	7	2
	5 (VI 60s VI 15s)	120.21	79.78	3	7	73.92	126.07	3	13
2	**1 (VI 15s VI 60s)**	94.36	105.63	8	3	107.78	92.21	9	3
	2 (VI 60s VI 30s)	103.31	96.68	3	7	107.02	92.97	3	7
	3 (VI 30s VI 30s)	102.93	97.06	7	7	98.61	101.38	7	7
	4 (VI 30s VI 60s)	95.5	104.49	7	3	97.72	102.27	7	3
	5 (VI 60s VI 15s)	118.47	81.52	3	9	98.29	101.7	3	8
3	**1 (VI 15s VI 60s)**	94.54	105.45	10	3	126	73.99	13	3
	2 (VI 60s VI 30s)	100.46	99.53	3	7	104.54	95.45	3	7
	3 (VI 30s VI 30s)	116.3	83.69	7	7	121.64	78.35	7	7
	4 (VI 30s VI 60s)	106.27	93.72	7	3	110.88	89.11	7	3
	5 (VI 60s VI 15s)	111.72	88.27	3	8	99.86	100.13	3	11
4	**1 (VI 15s VI 60s)**	113.7	86.29	7	3	94.21	105.78	7	3
	2 (VI 60s VI 30s)	90.18	109.81	3	7	81.85	118.14	3	7
	3 (VI 30s VI 30s)	89.38	110.61	6	7	105.87	94.12	6	6
	4 (VI 30s VI 60s)	90.25	109.74	6	3	105.63	94.36	6	3
	5 (VI 60s VI 15s)	83.98	116.01	3	8	78.72	121.27	3	9
5	**1 (VI 15s VI 60s)**	128.31	71.68	11	3	140.52	59.47	8	2
	2 (VI 60s VI 30s)	92.32	107.67	3	7	138.37	61.62	3	5
	3 (VI 30s VI 30s)	88.6	111.39	6	6	82.5	117.49	6	7
	4 (VI 30s VI 60s)	79.61	120.38	6	3	70.49	129.5	6	3
	5 (VI 60s VI 15s)	73.61	126.38	3	8	89.64	110.35	3	9