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Research report

Construct validity of an operant signal detection task for rats

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Abstract

Many psychoactive drugs produce simultaneous effects on a variety of psychological processes. Behavioral measures in tasks designed to assess cognitive processes in rodents should be able to characterize and dissociate these multiple influences. The present study evaluated how error measures in a classic two-choice operant spatial signal detection paradigm were affected by procedural manipulations of the motivational state of the rat, stimulus properties, and alterations of the inter-trial interval. The experiments were conducted in a two lever operant chamber in which a cue lamp was mounted over each lever. The rats were trained to respond quickly to a short illumination of one of the cue lamps at one of three durations (100, 300 or 1000 ms), presented in a random order. The procedural manipulations were (1) to allow pre-session water access to the normally water-restricted subjects, (2) to vary the intertrial interval (ITI) between sessions, (3) to reduce the intensity of the discriminative stimuli, and (4) to manipulate the variability of the ITI within a session. Stimulus duration-dependent decreases of detection accuracy were observed following pre-session water access and when the intertrial interval was decreased. A reduction of stimulus intensity resulted in decreased accuracy at all stimulus durations. Varying the ITI within the session produced stimulus duration-independent alterations of detection accuracy but no change in the frequency of errors of omission. These findings show that distinct patterns of performance deficits result from manipulating different components of this task and that errors of omission and commission often co-vary and raise questions about the definitions of vigilance and sustained attention as these constructs apply to signal detection tasks that present spatially distinct stimuli.

Keywords: Sustained attention; Discrimination; Motivation; Vigilance

1. Introduction

Rodent sustained attention models are used for studying the neurobiological underpinnings of attention (e.g. [11–13,15,29]), assessing the disruptive and interactive effects of drugs [8,10] and environmental toxins (e.g. [9]) and for predicting the efficacy of pharmacotherapies for attention disorders [20,28,41]. One approach for establishing the construct validity of these tasks is to assess the effects of manipulations that theoretically should disrupt performance [44]. Relevant task dimensions for establishing validity in attention tasks include event rate, variability of stimulus presentation, and discriminability of stimuli. Performance is expected to decline due to increased demands on attentional processing as event rate is increased, as the variability of stimulus presentation becomes less predictable, and as discriminability decreases [35,36].

Many rat attention paradigms exist that are based on the signal-detection model. Signal detection paradigms seek to separate deficits resulting from changes in stimulus detectability from deficits resulting from changes in response properties [17,22]. A general category of signal detection tasks that have been used since the 1950s, especially in pigeons (e.g. [2,21,25,26,33,34]) and in rats (e.g. [4,18,19,21,32,37,39,40]), presents stimuli at two or more spatially distinct locations. This paradigm has the feature of using commercially available operant equipment, including

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wall mounted cue lights and retractable or fixed response levers or keys. In most of these tasks, the subjects are required to respond rapidly to a flash of the cue lamp which is presented randomly at the different spatial locations, and where stimulus duration is either fixed or varied among a range of short intervals of one second or less. To perform this task accurately, the subject is required to orient toward the front panel and to initiate a response within a short period after the flash. An intertrial interval separates stimulus presentations.

One of the challenges with any appetitive task similar to tasks described above is the consideration of when to consider a particular deficit a "pure" attentional deficit or a change in the motivational state or motoric capabilities of the organism. Traditionally, the dependent measures of interest include accuracy and omissions. An important feature of a two or more choice paradigm is that accuracy is potentially a "pure" measure of detection, in that any response, even if incorrect, would demand the same motor and motivational requirements. Omissions, on the other hand, are typically thought to reflect changes in the motivational state or motoric abilities of the animal. Recently, however, some researchers have argued that changes in omissions following increased task demands may also reflect changes in attentional processing, if there are not any concomitant changes in pharmacological manipulations or lesions that could alter motivation or motoric functioning [38]. A consideration of the pattern of changes in accuracy across stimulus durations compounds the challenge of interpreting whether a particular manipulation has specific effects on attention.

Two consistent patterns of deficits in choice accuracy (errors of commission) have been observed in this task when rats are given drugs known to affect sensory-attentional processes in humans when the duration of the sample stimulus is varied within session. One is a deficit in accuracy that increases as the stimulus duration decreases (a "duration-dependent" deficit). The other pattern is where accuracy is decreased at all stimulus durations (a "duration-independent" deficit). Delta-9-tetrahydrocannabinol (THC), the primary psychoactive ingredient in marijuana [37] and ethanol [16] produced reductions in choice accuracy only at the short stimulus durations. In contrast to THC and ethanol, cholinergic muscarinic antagonist scopolamine and glutamate NMDA receptor antagonist MK-801 produced decreases in discrimination accuracy at all stimulus durations and increased errors of omission (the absence of a response [37]).

The "duration-dependent" pattern of errors of commission/choice accuracy could be interpreted as indicating a selective disruption of sustained or focused attention if one assumes that short duration stimuli are more difficult to observe and therefore would require more effort to detect them. In contrast, "duration-independent" choice accuracy deficits are not obvious in their interpretation. One possibility is that they also result from changes in motivational or motor processes that would affect response tendencies resulting in indiscriminant responding at all stimulus durations. Alternatively, it is important to assess whether errors of omission are also affected by a manipulation (e.g. lesion or pharmacological treatment) that results in a "duration-independent" impairment in response accuracy. If the omission rate remains unaffected, one can more confidently assert that the changes in signal detection reflect disruptions of attentional processing.

The present experiments were conducted with two general goals in mind. First, we wanted to assess the effects of manipulating pre-task water availability to manipulate the motivational state of the animal during task performance. This manipulation was expected to increase the omission rate. Second, we wanted to validate the present task as a measure of attention in the rat by assessing the effects of manipulating task parameters known to be important for attention. These manipulations were expected to produce a pattern of results that could be interpreted in terms of changes in attentional processing.

2. Methods

2.1. Subjects

These experiments used male Sprague–Dawley rats (Taconic Farms, Germantown, NY). All rats were housed individually in a temperature-controlled room of 20–22 °C under a 0700 on/1900 off light–dark cycle. During periods of behavioral testing, the subjects were maintained on a 23.5 h water restriction routine on weekdays, and allowed free access to water on weekends. Behavioral testing was conducted Monday through Friday. Four of the experiments used the same fifteen rats (presession water access, between-session variation of the intertrial interval, relative frequency of stimuli to each position, and the luminance reduction experiments). The differential consequences of errors experiment used seven new rats and the within-session variation of the intertrial interval experiment used six new rats.

The rats also received water in the experimental setting as part of the experimental procedures. Food was continuously available in the home cage. Body weights were taken daily to ensure that they remained above 85% of ad libitum weights, and supplemental water was given if necessary. All procedures were performed in accordance with the NIH Guide for the Care and Use of Laboratory Animals [43] and were approved by the SUNY Institutional Animal Care and Use Committee.

2.2. Apparatus

Six identical standard operant conditioning chambers (MED Associates, Hatfield, VT) were used. A solenoid delivered water to a cup located in a recess between the response levers mounted on the front wall of the chamber. A cue lamp was located above each lever, and a speaker was mounted on the ceiling of the chamber. A Dell PC was used to control the operant schedule and to record data.

2.3. Baseline procedures

All rats were pretrained as detailed in a previous article [37]. After pretraining the subjects were trained on the vigilance procedure until performance stabilized at greater than 90% accuracy at the 1.0 s stimulus duration. A trial consisted of a brief 100 ms tone followed in 3 s by the onset of one or the other of the cue lamps with equal probability of occurrence on either side. The subject was required to press the signaled lever within a 3 s limited-hold period. This short limited-hold was designed to minimize the period that the information needed to be retained before a response was made. An intertrial interval (ITI) of 10 s separated the trials. A correct response to a signaled lever, within the 3 s limited-hold period, was followed by a 0.1 ml water reward. An incorrect press, a press prior to a cue presentation, or a press that occurred more than 3 s after the cue was presented, was followed only by immediate initiation of the ITI. The duration of the cue lamp was varied randomly within the trial to 100, 300, and 1000 ms, in order to assess detectability. The session duration was 30 min.

2.4. Experimental procedures

2.4.1. Pre-session water access

The subjects were randomly assigned to one of five conditions, according to a modified Latin square design. Water access was given on Tuesdays and Thursdays, with intervening Mon–Wed–Fri baseline sessions. In a Latin square design, subjects were allowed 3, 9, or 27 min of pre-session water access. An additional condition was conducted after the other conditions were completed where subjects were allowed continuous free access to water for 24 h prior to the start of the session.

2.4.2. Between-session variation of intertrial interval procedure

This experiment was conducted in successive 5 days, Mon–Fri blocks. The subjects were exposed to ITIs in a sequence of 10 s, 20 s, 30 s, then 5 s, before returning to the 10 s baseline ITI. The analyzed data are from the Friday session.

2.4.3. Luminance reduction procedure

Two conditions were created where the luminance levels of the stimulus lamps were reduced to approximately 9.3% and 1.5% of full baseline luminance by fitting light-blocking filters inside of the light covers. A photometer positioned in the center of the chamber was used to take luminance measurements prior to the start of each condition. All rats were exposed to a Tuesday session where stimulus luminance was reduced to the 9.3% of baseline level, a subsequent Thursday session where stimulus luminance was reduced to the 1.5% of baseline level, and intervening Mon–Wed–Fri baseline sessions.

2.4.4. Within-session variation of intertrial interval procedure

This experiment was conducted in successive 5 days, Mon–Fri blocks. The subjects were exposed initially to the 10 s baseline ITI and that included the standard 100 ms warning tone 3 s prior to the stimulus presentation. In the next condition, the tone was not presented on any trial. The following condition randomly presented ITIs of either 7 s, 10 s or 13 s, and no warning tone was presented. Next, the subjects were exposed to a condition where the ITI randomly took on values of either 3, 10 or 17 s, and no warning tone was presented. Finally, the subjects were returned to the first fixed 10 s ITI and warning tone condition. The analyzed data are from the Friday session.

2.5. Behavioral measures and statistical analyses

Errors of commission were calculated using a sensitivity index (SI) score that corrects for position biases [14,23]. Under neutral bias conditions, the SI tracks percent correct scores as follows:

$$(\%\,\text{Correct/SI}):\ 1.0/1.0;\ 0.99/0.98;\ 0.95/0.90;\ 0.90/0.80;\ 0.80/0.60;\ 0.70/0.40;\ 0.60/0.20;\ 0.50/0.0$$

This also offsets some of the variance compression that occurs as the ceiling is approached. Experimental manipulations were analyzed separately using repeated measures ANOVAs.

3. Results

3.1. Water preloads

The sensitivity index as a function of stimulus duration for water preloads (Fig. 1a) shows a main effect of water preloads on accuracy [$F(5,70) = 3.0$, $p < 0.0156$]. However, there also is an interaction between water preloads and stimulus duration [$F(10,140) = 2.5$, $p < 0.0088$]. Means comparisons between preload conditions across all stimulus durations yielded a significant difference between the 27-minute preload and no preload conditions ($p < 0.0195$), and a difference between the 24-h preload and the no preload conditions ($p < 0.0019$). Further means comparisons between preload and stimulus duration at the 100 ms stimulus duration showed a significant difference between the 27 min preload and the no preload condition ($p < 0.0106$), and the 1410 min preload and no preload conditions ($p < 0.0001$). Fig. 1b shows the number of omissions per session as a function of stimulus duration for water preloads. The main effect for water preloads was significant [$F(5,70) = 36.4$, $p < 0.0001$], but the interaction was not [$F(10,140) = 2.4$, n.s.]. Subsequent comparisons of means showed that all water preload treatments were significant when compared to the no preload condition ($p < 0.0001$).

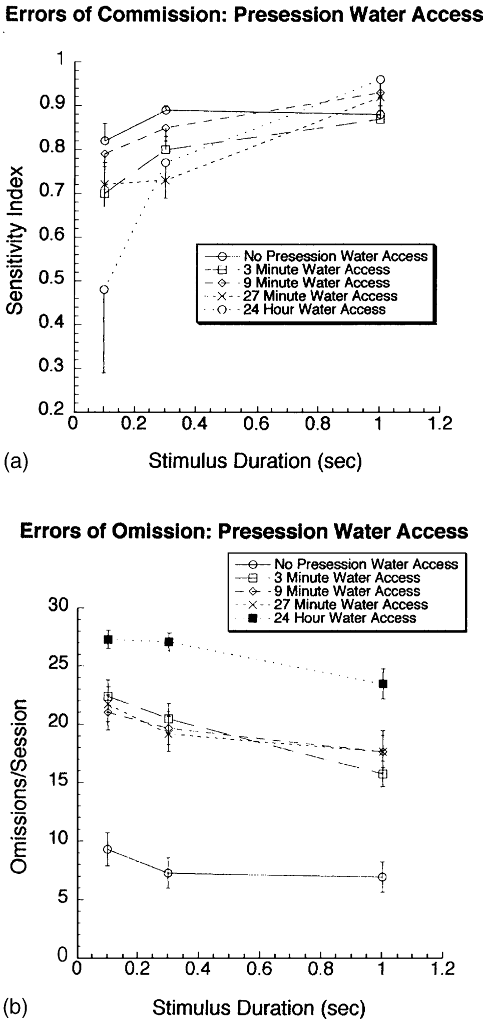

Fig. 1. The effects of water preloads on several performance measures of detection. The sensitivity index as a function of stimulus duration for water preloads: (a) a main effect and interaction between water preloads and stimulus duration and (b) the number of omissions per session increased as a function of stimulus duration for water preloads.

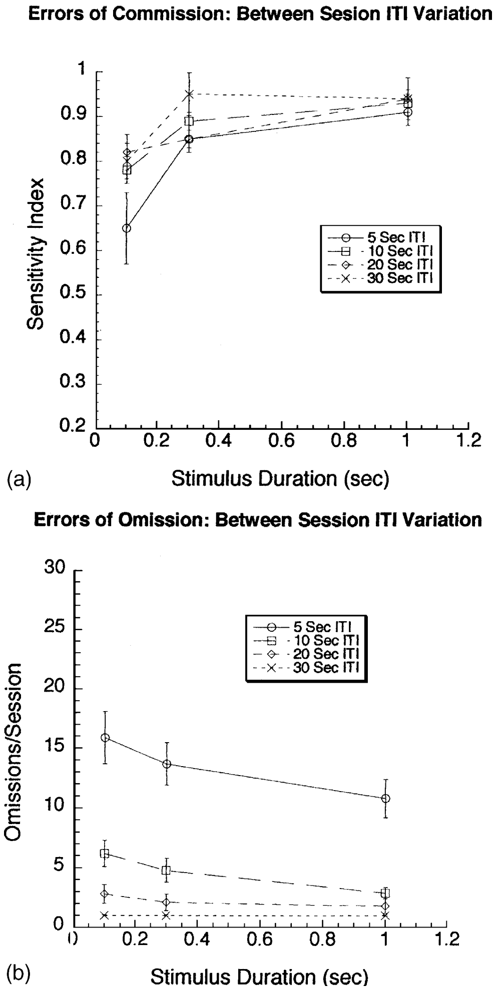

Fig. 2. The effects of varying the intertrial interval on several performance measures of detection. The 5 s ITI reduced accuracy relative to the 10 s ITI standard at the 100 ms stimulus duration, and the 30 s ITI increased accuracy relative to the 10 s ITI standard at the 300 ms stimulus duration. The 5 s ITI increased errors of omission relative to the 10 s ITI standard and the 30 s ITI decreased errors of omission.

3.2. Between-session ITI manipulation

The sensitivity index as a function of stimulus duration for intertrial interval (Fig. 2a) showed no main effect of intertrial interval on accuracy (F[3,42] = 1.8, n.s.), but a significant interaction (F[3,84] = 2.2, $p < 0.05$.]. Subsequent comparison of the means showed that the 5 s ITI sensitivity index was significantly different than the sensitivity index at the 10 s ITI ($p < 0.002$), and that at the 300 ms stimulus duration for the 30 s ITI sensitivity index was significantly different than the sensitivity index at the 10 s ITI ($p < 0.002$). Fig. 2b shows the number of response omissions per session as a function of stimulus duration for intertrial interval. The main effect on this measure was significant (F[3,42] = 32.9, $p < 0.0001$), the interaction was also significant (F[6,84] = 5.6, $p < 0.0001$). Subsequent comparison of the means showed that the 5 s ITI omissions were significantly different than the omissions at the 10 s ITI at all stimulus durations ($p < 0.0001$). Additionally, response omissions were significantly reduced relative to the 10 s ITI at the 30 s ITI condition at all stimulus durations ($p < 0.0001$).

3.3. Luminance reduction

The sensitivity index as a function of stimulus duration for the three filters (Fig. 3a) showed a main effect of decreasing stimulus salience on accuracy [F(2,24) = 129.6, $p < 0.0001$]. However, there was no significant interaction of filter degree [F(4,48) = 1.4, n.s.]. Subsequent comparisons of means revealed a significant difference between all luminance conditions ($p < 0.0001$). Fig. 3b shows the number of omissions per session as a function of decreasing stimulus salience. The main effect for filters was significant [F(2,28) = 21.8, $p < 0.0001$], while the interaction was not [F(5,56) = 0.92, n.s.]. Subsequent comparisons of means showed a significant difference between the 9.3% and 100% reduction

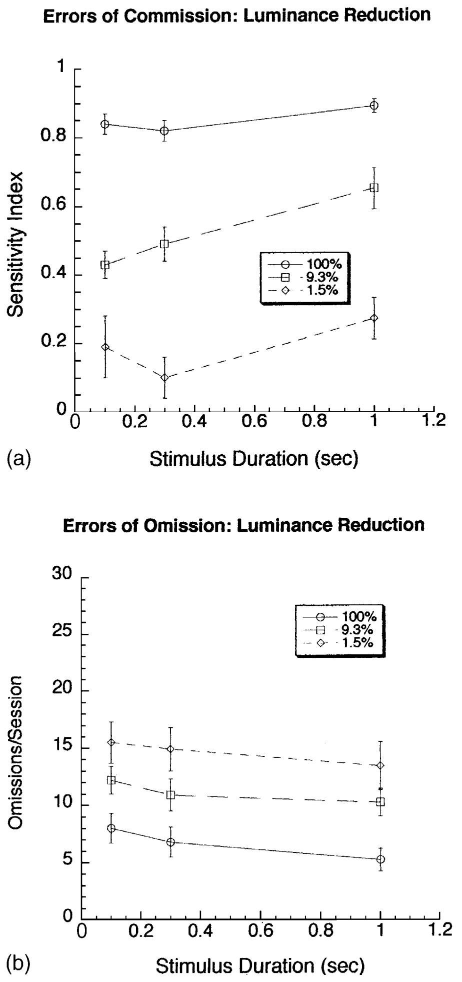

Fig. 3. Decreasing stimulus luminance reduced the sensitivity index as a function of stimulus duration (a), and increased the number of omissions per session as a function of stimulus duration for filters (b).

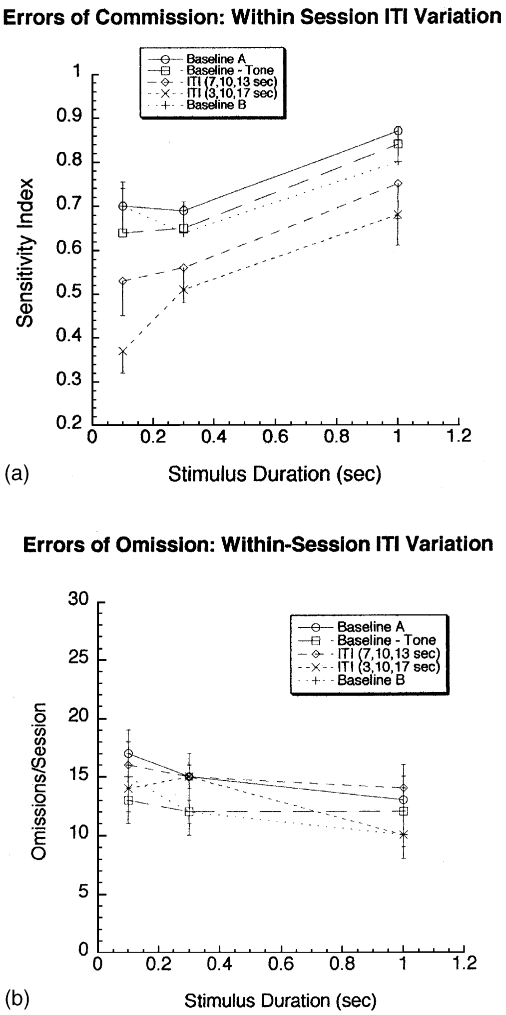

Fig. 4. The effects of within session variation of the intertrial interval. Baseline condition (10 s fixed ITI), baseline minus the standard 100 ms warning tone 3 s prior to the stimulus presentation, then variable ITI conditions and a return to the baseline condition. The highly varible ITI condition reduced the sensitivity index at all stimulus durations (a) and (b) the number of response omissions per session as a function of stimulus duration for intertrial interval. No significant effect of any manipulation was detected.

conditions ($p < 0.001$) and the 1.5% and 100% reduction conditions ($p < 0.0001$).

3.4. Within-session ITI manipulation

The sensitivity index as a function of stimulus duration for intertrial interval (Fig. 4a) showed a significant main effect of intertrial interval on accuracy ($F[4,20] = 4.9$, $p < 0.007$.), but no significant interaction ($F[8,40] = 0.86$, n.s.). Subsequent comparison using Fisher PLSD showed that the second variable ITI (3,10 and 17 s ITI) condition was significantly different than the baseline and baseline minus tone conditions at the 100 and 300 ms stimulus interval, but only from the baseline condition at the 1.0 s stimulus interval. Fig. 4b shows the number of response omissions per session as a function of stimulus duration for intertrial interval. No significant effect of any manipulation was detected on this measure ($F[4,20] = 0.43$, n.s.), nor was the interaction significant ($F[8,40] = 0.52$, n.s.). No change in position bias was detected ($F[4,70] = 0.77$, n.s.). There was also no change in the number of responses that occured during the ITI ($F[4,20] = 0.93$, n.s.) and after the ITI but prior to the stimulus onset ($F[4,20] = 0.91$, n.s.). Both generally average about one of each response per trial.

4. Discussion

4.1. Main findings

The two main goals of the present experiments were (1) to validate this task as a measure of attention in the rat by testing whether manipulations that are known to disrupt attention also disrupt performance in this task and (2) to test whether manipulating presession water access, which should alter motivation for reinforcement during the test sessions, produces a specific and different pattern of performance from more “attention-related” manipulations. When the event rate was increased (i.e. the ITI was decreased to 5 s) there was a decrease in accuracy at the shortest stimulus duration. The unaffected accuracy at the longer stimulus durations makes it unlikely that motivation or motoric deficits can explain the changes in performance. Omissions also increased when the event rate was increased and omissions decreased when the ITI was increased to 30 s (i.e. the event rate decreased). Thus, changes in the omission rate also appear to reflect the attentional demand of this task manipulation. Reducing the luminance of the stimuli also decreased accuracy and increased the omission rate regardless of signal duration. Taken together, these findings support the use of this task as a measure of attention in the rat. All water preloading conditions increased omissions, consistent with the expectation that this measure can reflect changes in motivation. Perhaps the most striking and unexpected finding was that 27 min and 24 h presession water access produced stimulus duration-dependent deficits in choice accuracy. The implications of the findings with water preloads, along with the other task manipulations are discussed more thoroughly below.

Manipulating the event rate, by altering the ITI, is a factor known to be important in human and animal attentional performance (see the manipulations of event rate in McGaughy and Sarter [27]). The rats must process signals more quickly when the ITI is decreased leading to a decrease in performance. In the present experiment, accuracy decreased at the briefest signal duration when the ITI was 5 s. This finding is particularly engaging because it suggests that the effort applied by the subject interacts with the properties of the stimulus. That is, the 100 ms stimuli may not be functionally equivalent to the stimuli at longer durations.

In contrast to the duration-dependent effects of the reinforcement manipulations, stimulus duration-independent deficits were observed when stimulus luminance was reduced and the ITI was systematically varied within-session. The first finding might be interpreted in two ways. First, decreasing the luminance of the sample stimulus could have brought the stimuli below the detection threshold. It is interesting then that the accuracy deficit increased as luminance decreased, suggesting that the 9.3% luminance level was above threshold. Alternately, the dimmed stimuli required so much additional effort by the animal to discriminate that a pattern of random responding (producing only about 50% of the possible rewards) became cost effective for the animal, even if the stimulus was above the psychophysical threshold for detection. Such an explanation cannot readily account for the stimulus duration-independent deficits following increases in the variability of the ITI because accuracy remains above chance performance and stimulus-duration dependent. In this task, increasing the uncertainty of when the stimulus would be presented appears to increase cognitive demands even when a relatively long duration stimulus is presented. Increasing the uncertainty appears to engage different cognitive processes from increasing event rate, because these two manipulations do not have similar effects across the stimulus durations tested in the present experiments. This dissociation indicates that these specific parameters should not be thought of as simply different ways to increase “cognitive load” but rather suggest the possibility that they engage different cognitive mechanisms that interact uniquely with the properties of the target stimulus.

The water preloads produced a predictable increase in errors of omission. However, one result that was unanticipated was that subjects in the first experiment completed 20–30 trials even after given 24 h of pre-session water access. This suggests that the extensive experience with the procedure and perhaps secondary reinforcers may partially maintain performance. However, an increase in errors of omission was also observed as stimulus luminance was reduced. This suggests that the response omissions measure may assess several processes, the first being the incentive value of the reward. Additionally, since animals may hesitate to respond if they fail to observe a stimulus, increased errors of omission may also assess enhanced susceptibility to distraction by contextual stimuli. A previous study has shown that lesions of basal forebrain corticopetal cholinergic neurons increase omissions in the five choice serial reaction time (5-CSRTT) task but the number of omissions were further increased by decreasing stimulus detectability and so to some extent the omission rate reflected the effects of increasing attentional demand [38]. This latter suggestion may explain the sensitivity of the omission rate to changes in the event rate and luminance.

The water preloads also, surprisingly, decreased response accuracy at the shortest stimulus duration. This result is consistent with evidence in humans that altering motivation affects sustained attention performance [42]. Bizarro and Stolerman tested the hypothesis that the effects of nicotine and amphetamine on attention could be confounded by alterations of motivation [1]. They found that the improvements in attention performance associated with nicotine were not likely due to motivational factors while amphetamine did produce effects consistent with a loss of motivation for reinforcement [1]. The present study indicates that manipulations typically thought to affect motivation (water preloading) can affect accuracy and produce a behavioral pattern similar to that produced by alterations of attention-related parameters. In particular, decreasing the ITI to 5 s produced a duration-dependent decrease in accuracy and an increase in omissions. As stated above, decreasing the ITI is typically thought to affect performance by increasing attentional demands due to increasing the rate signals must be processed. However, it could be argued that this manipulation also disturbs the molar relationship between responding and reinforcement and may, therefore, be having effects on motivation and subsequently on task performance. In other words, the rat is required to either increase accuracy or reduce errors of omission to maintain the same overall (session) rate of reinforcement at the long ITI conditions. In contrast, there would be less of a demand on the rat to do so at the short (5 s) ITI condition as compared to the 10 s ITI condition. The present data emphasize the importance of considering the consequences of task manipulations on response-reward relationships that may underlie changes in task performance.

4.2. Consideration of operationalization

Bushnell [6], in his noteworthy review of the construct validity of the many rodent attention paradigms, separated attention into five major categories: orienting, expectancy, stimulus differentiation, sustained attention, and parallel processing. He classified the present task as primarily measuring sustained attention. Indeed, the consistent observation that choice accuracy decreases as a function of decreasing duration of the stimulus and that maximizing the rate of reinforcement requires that the animal remained engaged and perhaps even "vigilant" is consistent with the validity of this classification. Furthermore, Bushnell argued that the major problem for tests of sustained attention involves quantifying and minimizing the false alarm rate". That is, a subject can report a high proportion of signals simply by responding frequently. . .". Once again, the present task also appears to avoid the second part of this problem (minimizing the rate) because a rat pressing at an extremely high rate but unguided by the stimuli will produce chance performance in the choice accuracy measure and reduce the reinforcement rate considerably. Finally, since the same motor response is required for correct or incorrect responses, this task appears to avoid motor confounds in its main measure of accuracy. The present data are most useful for adding complexity to the nature of this classification. Indeed, both errors of omission and errors of commission were affected by manipulations that would presumably alter the subject's sustaining of attention.

That this task measures vigilance is not so clear. Bushnell [7] has argued that procedures that truly measure vigilance are a subtype of sustained attention tasks in which stimuli are presented very infrequently "under boring, monotonous conditions, without feedback" (p. 263). This task certainly does not qualify in the first regard, as stimuli are presented many times a minute at fixed intervals, and the location of the stimulus is only uncertain at a $p = 0.5$. With regard to the second point, our data show that 24 h of pre-session water access still results in approximately twenty responses and argues against the task being "boring" to the animal, which is perhaps not surprising considering the limited behavioral options available to the rats in the home cage setting. Finally, feedback in the form of reinforcers is clearly a very important element in maintaining and shaping performance.

4.3. Future directions

The present results raise some general validity questions for all signal detection tasks that employ two or more spatially distinct stimuli and that appear to require sustained attention for successful performance. Given the ubiquitous of use of 5-CSRTT especially, it is perhaps most important to carefully consider to what degree the present results may generalize to this paradigm and other spatial detection task as well that require the orienting of the visual system toward the front of the chamber to monitor a stimulus array (e.g. [4,5,11–13,29,30,31,39]). One study has reported the effects of different food restriction levels and prefeeding on the performance of the 5-CSRTT [1]. Prefeeding increased response omissions and response latency, but had no significant effects on choice accuracy. Different level of deprivation did not affect response omissions or accuracy. A perhaps critical difference is that in the 5-CSRTT the animals initiate a trial with a food well nose poke. Some data using a variant of our present task suggest that allowing the animal to initiate the trial, but still presenting stimuli with reasonable degrees of uncertainty, partially protects the measures of choice accuracy from motivational alterations [24]. This may be another important issue requiring further study.

Another interesting question is to what degree hit, false alarm and omissions measures in a procedure using a single variable duration visual stimulus such as that used by Sarter and coworkers (e.g. [3,15,27,28]) might also be differentially influenced by manipulations that alter reinforcer efficacy. This may be a particularly useful study for understanding the similarities and differences between tests that employ single versus spatially separated distinct stimuli.

In conclusion, the present findings affirm the value of performing parametric procedural manipulations as a means of inferring what behavioral changes may be produced by neural/biochemical manipulations and for refining our thinking about the operationalization of cognitive constructs in rodents. If used cautiously and along with other tests that vary the difficulty, complexity and sensory modality of the detection discriminations, tasks such as this that employ spatially distinct choices may contribute to establishing the convergence of findings necessary to have confidence in theories of the neural underpinnings of attention.

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