ATTENTION AS OPTIMIZATION:

REWARD-GUIDED EXPLORATION AND ITS LIMITS IN ADHD

by

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ADHD is a disorder marked by suboptimal attentional control and high distractibility. Additionally, individuals with ADHD exhibit longer reaction times. Do longer reaction times make distracted behavior more adaptive? Assuming that attention is directed in a reward-maximizing manner, we predicted that the cost for exploring the environment is lower for individuals with slower reaction times. Here, we first test the hypothesis that attention is directed in a reward-maximizing manner. We also test the hypothesis that individuals with ADHD make suboptimal decisions when directing attention. To measure attentional decision-making, $N = 42$ subjects participated in a task-switching paradigm in which correct responses were rewarded. Critically, only checking on-screen task cues allowed for correct performance. We calculated the cue checking frequency to measure exploration as a function of manipulated decision variables, one of which mimics RT differences between individuals with and without ADHD. We found that explorative behavior is indeed predicted by decision variables, indicating that humans use an optimization strategy to direct attention. Furthermore, slow reaction times predicted an increase in orientation to the environment. ADHD symptoms, however, did not correlate with the optimality of these decisions. These findings are congruent with the view that attentional resources are directed in a reward-maximizing manner. However, this study does not provide evidence for suboptimal attentional decision-making in individuals with ADHD.

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Introduction

Let's say you are running late to an important event. You have been to the venue once before, but it is in an unfamiliar neighborhood. Do you use a map, or trust your ability to navigate there from memory? Using a map requires you to take your attention off the road frequently and drive slower, but navigating from memory could result in a wrong turn, which would certainly make you late. Whether to check cues from the environment or rely on our own memory is a problem that individuals face every day. Checking the environment can ensure correct performance at a time cost, and relying on internal representations is time-efficient but increases the risk of making a costly mistake. In many situations, one can imagine an optimal balance between relying on external cues and internal representations that offers an individual the most efficient possible performance on a given task. Adapting to a changing optimal internal/external (I/E) balance is a challenge individuals must address in daily life. This optimum is context-dependent; it is affected by both individual differences and the environment. The factors that influence how individuals adjust their I/E balance to optimize performance remain inadequately understood and are underexplored in the current literature.

Individuals with attention-deficit/hyperactivity disorder (ADHD) display a number of traits which alter decision making and motivation. The *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) lists diagnostic criteria for ADHD such as "Often avoids, dislikes, or is reluctant to engage in tasks that require sustained mental effort" and "Is often easily distracted by extraneous stimuli" (American Psychiatric Association, 2013, p. 59). Additionally, although not an official symptom, many individuals with ADHD report experiencing periods of intense concentration with an inability to shift focus known as hyperfocus (Hupfeld et al., 2019). This curious polarity in symptomatology has particular relevance to I/E balance strategies in ADHD individuals. Hyperfocus could lead to an overreliance on internal representations and an inability to shift attention to environmental cues, whereas distractibility could lead to an overreliance on environmental cues. Given the current lack of a theoretical explanation for the existence of both distractibility and hyperfocus in ADHD individuals, the present study on I/E decisions seeks to bridge this gap. As discussed in the literature review, differences in reaction time in ADHD individuals may explain a propensity to excessively rely on the environment. Here, we test the hypothesis that attention is directed in a reward-maximizing manner. Additionally, we test the hypothesis that individuals with ADHD make suboptimal decisions when directing attention.

Literature Review

Two neurotransmitters are particularly relevant to ADHD: dopamine and norepinephrine. Dopamine is closely linked with reward-based motivation and modulates flexible cognitive control processes (Aarts et al., 2011). In other words, dopamine can help motivate individuals to pursue rewards and flexibly adapt to reward-based motivators. ADHD is associated with lower dopamine transporter availability (Volkow et al., 2011). Taken together, these findings allow for inferences on the relationship between dopamine and ADHD. Individuals with ADHD may express lower motivation to apply effort to tasks and flexibly shift between tasks as a result. This could lead individuals with ADHD to make suboptimal adjustments to their I/E balance.

Norepinephrine plays a crucial role in arousal and motivated behavior (España et al., 2016). However, the relationship between norepinephrine and motivated behavior is complex. A paper by Aston-Jones et al. (2005) details the effects of norepinephrine on task performance using evidence from monkey studies. The authors found that low norepinephrine levels can lead to drowsiness, low attention, and poor task performance. Surprisingly, high norepinephrine levels can also lead to poor task performance due to anxiety, over-arousal, and distractibility.

The authors put forward that optimal task performance occurs with moderate levels of norepinephrine, with the relationship between norepinephrine levels and task performance taking the shape of an inverted U. Individuals with ADHD have been found to have lower norepinephrine transporter availability (Ulke et al., 2019). This indicates that ADHD individuals not only tend to have lower baseline dopamine levels but also lower baseline norepinephrine levels. This provides evidence for the hypothesis that ADHD individuals will have lower motivation to complete tasks and a lower ability to flexibly adjust their I/E balance.

Additional evidence for the crucial role of dopamine and norepinephrine in ADHD symptoms can be found in one of the most commonly prescribed ADHD medications: methylphenidate (Piper et al., 2018). Methylphenidate blocks the reuptake of dopamine and norepinephrine (Challman et al., 2000). In other words, it blocks the reabsorption of the two neurotransmitters and allows for higher levels of dopamine and norepinephrine in the brain. Methylphenidate has also been found to be significantly efficacious in treating ADHD symptoms in adults (Faraone et al., 2004).

The explore/exploit tradeoff is particularly relevant to the present study. Exploration comes at a time cost, but may yield useful information. Exploitation maximizes known rewards but leaves an individual ignorant to changes in the environment that could allow them to garner larger rewards. A study by Addicot et al. (2021) examined the effect of methylphenidate on ADHD and non-ADHD individuals completing a six-armed bandit task, which measured explorative and exploitative decisions. Participants could choose between 6 bandit options, each with different monetary reward values. For every trial, reward values changed slowly for each bandit over time to encourage exploration. The authors found that ADHD predicted more exploratory decisions and fewer point totals. Surprisingly, methylphenidate did not significantly affect exploratory decisions in ADHD individuals, leading the authors to suggest that the increased exploratory decisions among ADHD individuals is not significantly related to dopamine or norepinephrine modulation. This leaves open the possibility that some other variable common to ADHD individuals is responsible for the increased exploratory behavior that has been observed in the literature.

Literature on reaction time in ADHD individuals has shown that they exhibit longer and more variable reaction times (Epstein et al., 2010, Tamm et al., 2012). Additionally, ADHD individuals have been found to be slower at switching between attentional sets (Luna-Rodriguez et al., 2018). Perhaps reaction time could provide an explanation for the increased exploratory behavior associated with ADHD. It could be that ADHD individuals rely on the environment more because it may be relatively adaptive for them to check more often. If reaction time is high, ADHD individuals may have a lower relative cost of checking the environment compared to those with faster reaction times, and thereby may be able to gain useful information that offsets the cost of their higher reaction time. This may be represented by the following equation:

$$Cost_{exploration} = \frac{t_{exploration}}{t_{exploitation}}$$

where $t_{exploration}$ represents the time to shift attention to environmental cues, and $t_{exploitation}$ represents the time to complete a task relying on internal representations. This equation predicts that longer reaction times ($t_{exploitation}$ in the denominator of the equation) make reliance on external cues ($t_{exploration}$ in the numerator of the equation) more adaptive. We seek to fill a gap in the literature on distraction in ADHD by developing an experiment that tests a rational basis for ADHD individuals to explore the environment more due to their longer reaction times. In the present study, we examine how ADHD affects individuals' ability to smoothly shift I/E balance strategies as the optimal strategy changes.

Methods

Procedure

As outlined in the OSF preregistration, 42 participants from the Human Subjects Pool at the University of Oregon were tested on a computer experiment programmed in PsychoPy 2024.2.0 (Peirce et al., 2019) and run on pavlovia.org. Participants provided informed consent and received course credit in addition to performance-based incentives. The experiment involved a visual search task. In each trial, a 4x4 array of letters divided into four quadrants appears in the middle of the screen. Each quadrant consists of the letters T and L, all but two of which are rotated by 90, 180, or 270 degrees. In each trial, there is one upright T and one upright L somewhere in the four quadrants. There were two possible tasks for participants to complete. One task was to identify the quadrant that has an upright T in it. The other task was to identify the quadrant that has an upright L in it. Only one of these tasks was active at a time and allowed the participant to respond correctly (pressing the keys U, I, J, or K corresponding to the correct quadrant on the keyboard). The upright T and L were never in the same quadrant. If the participant got a trial correct, they received one cent. If they pressed the key corresponding to the wrong quadrant, they lost one cent. Participants did not receive direct feedback for correct or incorrect responses. Participants could press the spacebar to look at a task cue which was located at the top of the screen and indicated which of the tasks was active. Which task is active and rewarded switched from trial to trial with a switch rate that the participants were told at the beginning of each block.

The experiment consisted of a 2x2x2 study design with 8 unique block types. Because each block is time-limited, participants must adjust to unique optimization problems in each of the different block types to maximize their rewards. In other words, participants must check cues at the optimal rate for their reaction time to earn the most money possible.

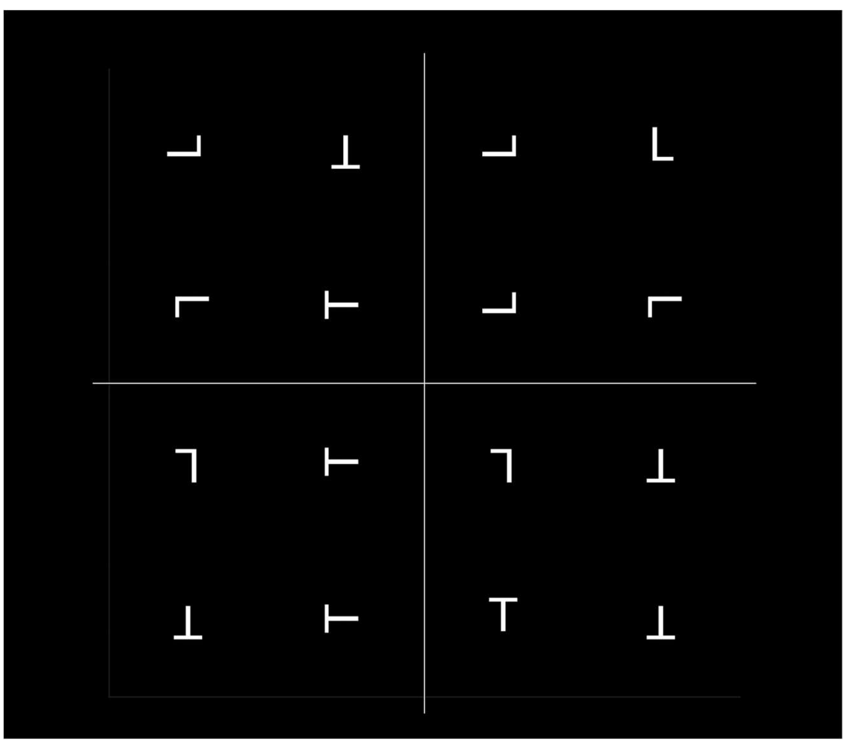
Manipulated Variables

Task switch rate, salience of the upright letter (whether the target letters are red or not), and presence of a placeholder in the cue location were manipulated in each block. Switch rate, being either 5% or 15%, was manipulated to influence uncertainty in the active task. When the switch rate is higher, a higher cue check rate is rational because the active task is more likely to have changed with every new trial. This increases the likelihood that participants' internal representations of the active task will become outdated and makes a higher cue check rate rational. Salience of the upright letter was manipulated to influence reaction time. This manipulation tests the hypothesis that a slower reaction time makes an increase in checking the environment a rational decision. The upright target letters are either white, like the rest of the letters, or red. When the target letters are white and blend in, reaction time is expected to slow, making a higher cue check rate more rational in this condition (see relative cost of checking equation on pg. 6). Presence of placeholders in the cue location is manipulated to influence the bottom-up strength of a reminder to check cues. In conditions with the placeholders present, task cues are always visible but the checkbox indicating the active task is not revealed until participants press the spacebar. When placeholders are present, the rational check rate should not change. However, we predict that participants with higher ADHD scores will check cues more often when placeholders are present due to heightened distractibility. After completing three practice blocks, participants complete 16 total 90-second blocks with every combination of task manipulations repeated once.

For optimal performance, it is crucial that participants adjust their check rate in different block types as switch rate and response speed change. If participants do not adjust their check rate to meet the unique demands of each block type, they will earn less rewards by the end of the experiment compared to participants who do. This is confirmed by simulations run for each participant in our data analysis that determined a participant's optimal check rate in each condition. Methods for the simulations are discussed in the data analysis section. Through this experiment, we first test the hypothesis that attention is directed in a way that maximizes rewards. We additionally hypothesize that ADHD traits will predict a reduced adjustment to changing optimal check rates.

Figure 1

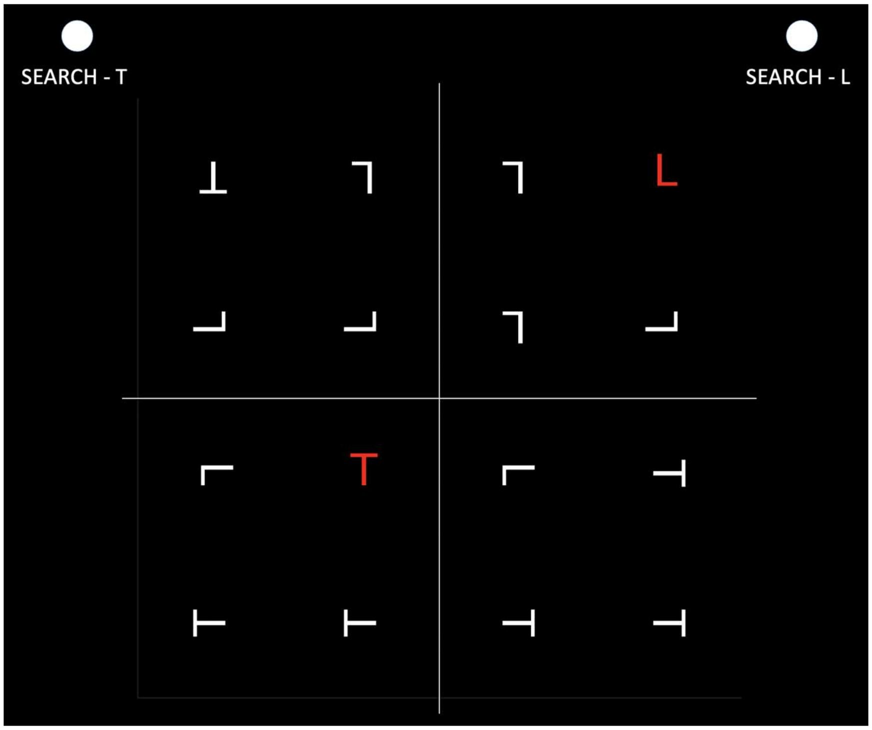
The Visual Search Task in the Slow Condition Without Placeholders



Note. This represents a trial in a block with the slow condition and the placeholders absent. Target letters (upright T and L) are white and blend in, slowing reaction time. Participants will only see the cues when the spacebar is pressed.

Figure 2

The Visual Search Task in the Fast Condition With Placeholders



Note. This represents a trial in a block with the fast condition and the placeholders present. Target letters are red to facilitate search. Participants will always see the cues in this block, but still must press the spacebar to reveal the checkbox indicating the active task.

Participants completed the Adult ADHD Self-Report Scale (ASRS-v1.1) (Kessler et al., 2005) and were each assigned an ADHD score. ADHD score was scaled from 1 to 5, with higher scores indicating more severe ADHD symptoms. Participants then completed a demographics form.

Data Analysis

Participants who checked cues more than 95% or less than 5% of the time across the experiment were screened out, and one participant did not complete the experiment. Of the 42 participants that began the experiment, 33 participants were included in the data analysis. Data analysis was completed in the R programming language (R Core Team, 2024).

To test the hypothesis that attention is directed in a way that maximizes rewards, a generalized binomial linear mixed-effects model was used. This model tested the effect of decision variables on cue check rate while accounting for multiple observations on the trial-level per participant. All factors were effect coded as -0.5, 0.5. This model was justified in that it allowed us to measure how participants adjusted their check rates in response to individual decision variables.

The hypothesis that ADHD traits will predict a reduced adjustment to changing optimal check rates was tested in a second model. Using a simulation approach, we determined the optimal check rate for each participant in each condition. Each check rate from 0 to 1 in 0.01 resolution was tested 1,000 times using each participant's average RT for trials with and without cue checking in each condition. The 1,000 simulations were averaged, and the check rate that obtained the maximum reward was used as the optimal check rate for each participant. We modeled the actual check rate of participants as a function of optimal check rate and ADHD score. A significantly positive coefficient for the optimal check rate would indicate that participants rationally adjusted check rates. An interaction with ADHD score would indicate that ADHD is associated with a difference in adjustment to the optimal check rate.

Results

A total of 33 participants were included in the data analysis. The mean ADHD score for participants was 2.97 (SD = 0.45). ADHD scores ranged from 2.06 to 3.78. Two of the three manipulated decision variables had a significant effect on cue check rate across all participants.

Consistent with expectations, reaction times in the slow condition were on average 1.41 seconds longer (SE = 0.04), $p < .001$, than in the fast condition. In trials where participants checked cues, reaction times were on average 0.82 seconds longer (SE = 0.04), $p < .001$, than in trials where they did not check cues.

Consistent with expectations, switch probability had a significant positive effect on cue check rate across participants ($p < .001$). Similarly, response speed had a significant positive effect on cue check rate across participants ($p < .001$), such that participants checked cues significantly more in the slow response speed condition. Placeholders in the cue location did not have a significant effect on cue check rate ($p = .297$). Interestingly, while there were no significant two-way interactions, there was a significant three-way interaction of placeholder, response speed, and switch probability on cue check rate across participants ($p = .002$). Contrary to our hypothesis that ADHD score would correlate with a reduced adjustment to the optimal check rate, there was not a significant interaction between ADHD score and optimal cue check rate on actual cue check rate ($p = .444$) using the mixed-effects model.

Table 1

Effect of ADHD Score, Cue Check, and Speed on Reaction Time

	Estimate	SE	t value	*p* value
Intercept	0.66	0.02	27.8	< .001
ADHD score	0.02	0.05	0.41	.683
Cue check	0.82	0.04	22.42	< .001
Speed	1.41	0.04	34.31	< .001
ADHD score × Cue check	0.02	0.08	0.22	.829
ADHD score × Speed	-0.14	0.09	-1.57	.126
Cue check × Speed	0.36	0.02	14.48	< .001
ADHD score × Cue check × Speed	-0.12	0.06	-2.07	.038

Note. Estimates reflect the difference in reaction time associated with each variable, holding all other variables at their average.

Table 2

Effect of Decision Variables on Cue Check Rate

	Estimate	SE	z value	*p* value
Intercept	0.70	0.41	1.71	.087
Placeholder	-0.20	0.13	-1.49	.135
Switch probability	0.57	0.16	3.56	< .001
Speed	0.39	0.12	3.29	< .001
Placeholder × Switch probability	-0.01	0.07	-0.15	.880
Placeholder × Speed	0.13	0.07	1.96	.050
Switch probability × Speed	-0.10	0.07	-1.52	.129
Placeholder × Switch probability × Speed	-0.41	0.13	-3.08	.002

Note. All estimates are reported in logits.

Table 3

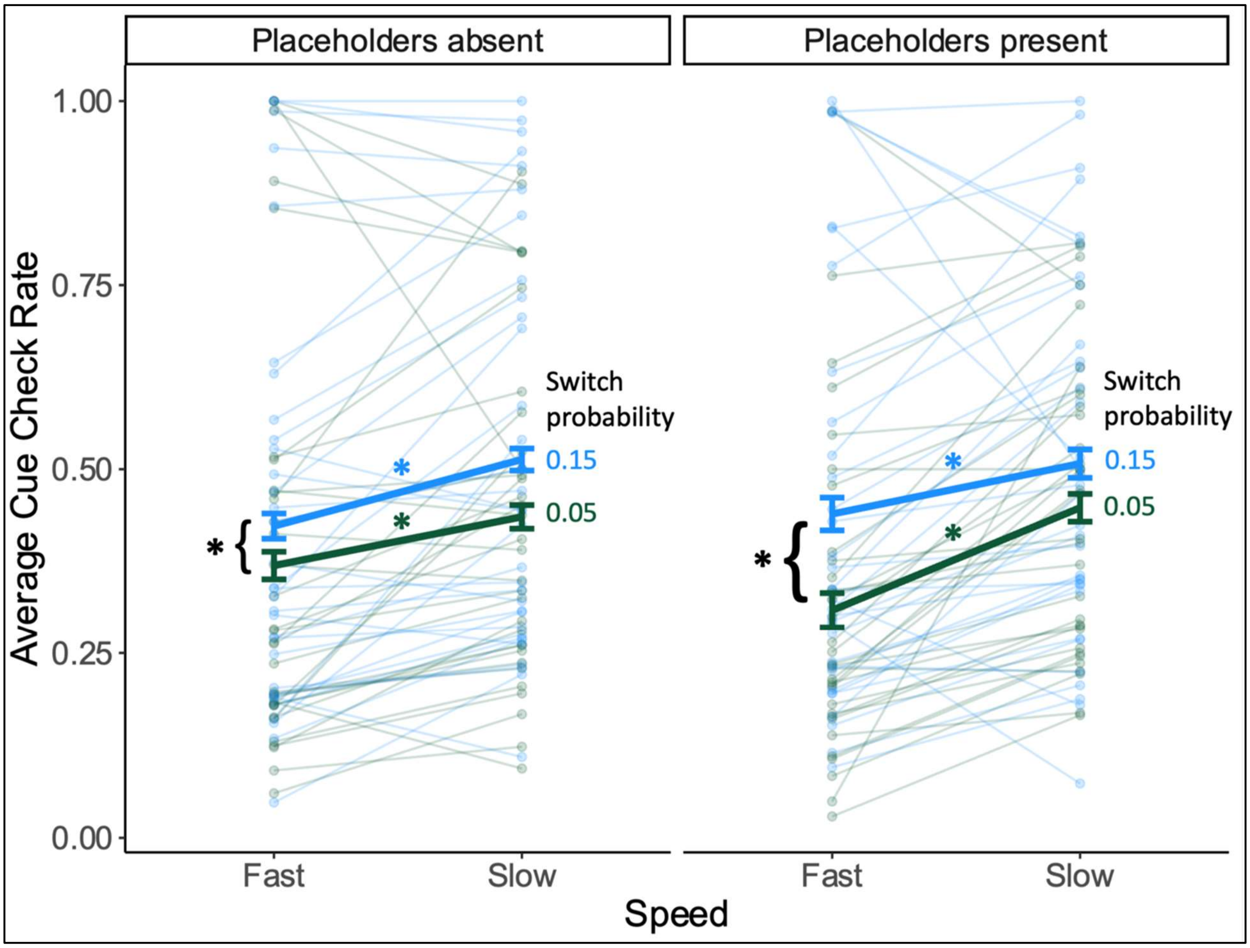
Effect of Optimal Check Rate, ADHD Score, and Placeholder on Cue Check Rate

	Estimate	SE	t value	*p* value
Intercept	0.321	0.038	8.357	< .001
Optimal check rate	0.187	0.033	5.677	< .001
ADHD score	0.057	0.092	0.622	.541
Placeholder	-0.01	0.015	-0.701	.484
ADHD score × Optimal check rate	0.059	0.076	0.769	.444
ADHD score × Placeholder	-0.036	0.033	-1.076	.283

Note. All estimates are reported in logits.

Figure 3

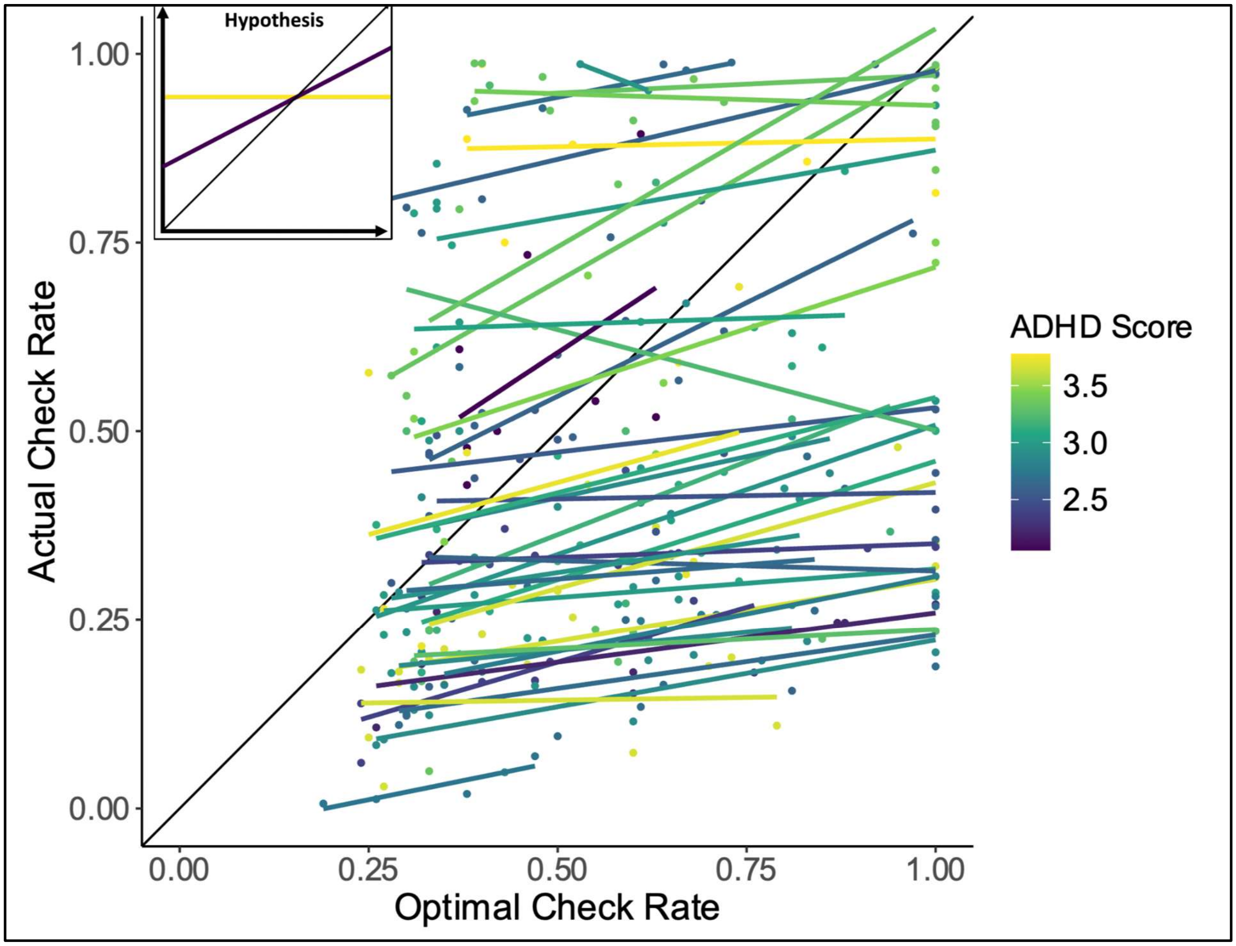
Effect of Decision Variables on Cue Check Rate



Note. Cue checking increased significantly across participants when reaction time was slowed and when task switch rate increased.

Figure 4

Effect of ADHD Score on Cue Check Rate



Note. On the x-axis, optimal check rate indicates the optimal check rate derived from the simulation for each participant given their average reaction time in each condition. On the y-axis, actual check rate indicates each participant's real average check rate in each condition. Each slope represents a single participant. Participant ADHD score is represented by the color of their slope. Flatter slopes indicate less adjustment to the optimal check rate. Contrary to our hypothesis (schematic in the top left), ADHD symptoms did not significantly correlate with a suboptimal cue checking rate.

Discussion

In summary, participants from the Human Subjects Pool at the University of Oregon completed a visual search task experiment consisting of a task-switching paradigm. Participants were assigned an ADHD score.

In support of our first hypothesis, cue checking significantly increased across participants when task switch rate increased and when reaction time was slowed with the response speed decision variable. This is congruent with rational predictions and suggests that humans use optimization strategies to direct attention. Presence of placeholders in the cue location did not affect cue check rate, which indicates that bottom-up strength of a reminder to check cues does not significantly increase orientation to the environment. This additionally suggests that humans are capable of ignoring distractors when it is rational to do so. However, in similar previous studies we conducted using eye tracking technology, placeholders did have a significant effect on cue check rate. A possible explanation for this difference in results is that a spacebar press requires more top-down control, which may not measure distraction as accurately as eye movements.

Contrary to our second hypothesis, ADHD score did not significantly correlate with a suboptimal cue check rate. While the results of the experiment successfully support the hypothesis that attentional resources are directed in a reward-maximizing manner, the experiment failed to show a significant correlation between ADHD and a suboptimal cue check rate. The potential reasons for this are varied.

A compelling explanation for the lack of a significant relationship between ADHD score and suboptimal cue check rate is that the use of spacebar press may have lacked construct validity. The present study was designed to test whether ADHD correlated with suboptimal decisions when directing attention. However, participants may have directed attention towards cues without pressing the spacebar. Because eye movements were not measured, it is unclear whether spacebar presses accurately captured attentional shifts. Further evidence for the lack of construct validity in spacebar presses is that placeholders did significantly affect cue check rate in prior similarly conducted studies using eye tracking technology. ADHD score significantly correlated with a suboptimal cue check rate in these previous studies. This provides evidence for the explanation that spacebar presses did not accurately capture attentional direction to cues.

The use of self-report as a measurement of ADHD score is a potential limitation of the present study. While self-report allows ADHD score to be measured as a continuous variable in this study, participant responses may have been subject to reporting biases. An alternative explanation for the present study's failure to replicate suboptimal attentional decisions in ADHD is that the sample of participants may have had a significantly more narrow range of ADHD scores compared to the population. This would explain the failure to replicate a suboptimal cue check rate in ADHD in the present study.

Future Directions

The present results support the hypothesis that humans use optimization strategies when directing attention. Despite this, it may have lacked construct validity in that spacebar presses were used to measure cue checking. Not all attentional shifts may have been captured by spacebar presses. Replication of the present study with eye tracking technology is warranted to directly measure attentional shifts. While it is possible that there truly is no difference among ADHD individuals in optimality decisions when directing attention, the significant results of ADHD and suboptimal cue check rate in previous studies necessitate the replication of the current study with eye tracking technology as a measure of cue checking.

Conclusion

Congruent with rational predictions, slower reaction times increased orientation to the environment. Similarly, higher task switch rates increased orientation to the environment. ADHD score did not significantly correlate with a suboptimal cue check rate. However, replication of the current experiment with eye tracking is warranted, as spacebar presses may not have captured all attentional shifts. These findings support the hypothesis that humans use optimization strategies to direct attention. However, we failed to replicate a difference in optimization strategy for ADHD individuals.

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