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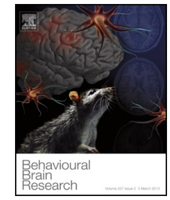


Research report

# Stop and look! Evidence for a bias towards virtual navigation response strategies in children with ADHD symptoms

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## HIGHLIGHTS

- Participants with ADHD symptoms less likely to reach trials to criteria on spatial navigation task.
- ADHD symptoms improved performance on the probe trial during spatial navigation task.
- Children with ADHD symptoms rely on caudate dependent response learning strategies.
- Repetition and reward strategies likely most effective for children exhibiting ADHD symptoms.

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## ABSTRACT

Studies in children show that the development of spatial competence emerges between seven and eight years of age. Multiple memory systems (hippocampus-dependent spatial and caudate nucleus-dependent response learning) are involved in parallel processing of information during navigation. As a hippocampus-dependent spatial strategy also relies on frontoparietal executive control and working memory networks that are impaired in ADHD, we predicted that children will be more likely to adopt a response strategy as they exhibit ADHD symptoms. We tested 285 healthy children on a virtual radial-arm maze paradigm in order to test this hypothesis. We found that children displaying at least one ADHD symptom were more likely to have a perfect performance on a probe trial, which suggests that they did not rely on environmental landmarks. Children with ADHD symptoms may primarily rely on caudate nucleus-dependent response learning strategies at the expense of hippocampus-dependent spatial strategies. Repetition and reward based learning strategies, which are hallmarks of response learning, may be most effective in children exhibiting ADHD symptoms.



## 1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is caused by the complex interplay of genetic and environmental risk factors. It is behaviorally characterized by the presence of inattention, hyperactivity, and impulsivity. Some ADHD symptoms are often found in most healthy children, but it is only when the number of symptoms is above a clinical threshold, and when there is functional impairment, that a diagnosis is made. Although ADHD is a clinical category, genetic, brain imaging, neuropsychological and clinical studies suggest that ADHD is the extreme and impairing end of a continuous quantitative trait [49]. This categorical definition fails to capture the whole variation in the normal population in terms of symptoms. Therefore we took the approach of assessing ADHD as a discrete variable in an epidemiological sample of twins, with a range going from 0 up to 18 symptoms.

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Functional imaging studies have related ADHD to hypoactivation in the frontoparietal executive control network, putamen, and ventral attention network [46]. Structural imaging studies detected reduced volumes in basal ganglia regions like the right globus pallidus, as well as the right putamen and caudate nucleus regions of the striatum. These findings are consistent with the classical model of ADHD as a disorder of deficient frontostriatal circuitry [53,54]. However, other brain regions such as the hippocampus [36] have also been implicated, perhaps as a result of other primary deficits.

There is evidence for a view of the cognitive deficits in ADHD that includes the frontal cortex. The frontal view suggests that executive dysfunction gives rise to the behavioral symptoms of ADHD [2], a claim which is supported by the observation that many of the deficits associated with ADHD are similar to those that follow damage to the frontostriatal circuitry. For example, like patients with damage to the frontal cortex, people with ADHD have been shown to have impairments with set shifting, response inhibition, working memory, and planning [26,40,41,43,45]. Recent studies have consistently correlated changes in prefrontal activity with striatal functioning during performance on tasks known to be affected in ADHD [3,11].

Persistent working memory deficits have also been demonstrated in children and adults with ADHD [48,1], especially when the tasks placed a high demand on central executive function (temporary storage, maintenance, and manipulation of information). A recent study has demonstrated that ADHD interfered with performance in a demanding conditional associative learning task [16] which utilized a method of learning dependent upon the frontostriatal network [20,25,35,16]. These results argue that deficits in a demanding, but not simple, conditional associative learning task are indicative of maladaptive prefrontal strategies during encoding, rather than of a primary functional deficit in the striatum.

In some studies, ADHD has been shown to produce deficits in memory tasks that are thought to depend on regions beyond the frontostriatal network. For example, children with ADHD showed impairments in a paired-associative learning task [8,12], which required learning to associate an arbitrary pair of words. This kind of associative learning is thought to rely on the medial temporal lobe (MTL) [14]). The MTL is a region not typically implicated in ADHD, as demonstrated in a number of studies showing preserved performance in MTL-dependent tasks [41]. Several authors have suggested that prefrontal dysfunction also causes deficits in more difficult paired-associative tasks [8]. Explicitly providing a learning strategy to children with ADHD increased performance in free recall memory tasks, which strongly suggests that the capability to form new memories is intact in ADHD, and that ineffectual contributions of the prefrontal cortex to the various memory systems are the cause of memory problems [9].

To date, no study has examined the interplay between learning dependent on the hippocampus versus that of the caudate nucleus part of the striatum in relation to ADHD. This is of particular interest because both systems interact with the prefrontal cortex, and a person's ability to utilize one system (i.e. caudate nucleus-dependent learning) over another in the same dual-solution task could provide valuable insight in the way in which information is encoded in children with ADHD. Therefore we have determined the type of learning strategy (hippocampus- and caudate nucleus-dependent) as a function of ADHD symptoms in an epidemiological sample [7]. In such a sample, ADHD symptoms are likely to be few, and above clinical threshold for a handful of children [37].

Navigation tasks are particularly well suited for investigating the role of memory systems during learning. It is well known that the striatum (which includes the caudate nucleus) is involved in stimulus-response learning in humans [5,18] and rodents [29,33,34,44]. Through repetition and habit formation, learning a series of stimulus-response associations allows for successful navigation along well-known routes [17]. On the other hand, the hippocampus is needed to form an abstract cognitive representation of space [5,18,31,34]. Cognitive mapping is a cognitively demanding mental feat. Forming a spatial representation of one's environment requires the association of space-defining stimuli in a reference frame that is independent of the viewer [31].

Previously, we have developed a virtual reality, human analogue of the radial arm maze, the 4-on-8 virtual maze (4/8VM), which can be completed using either cognitive mapping spatial strategy or a response strategy. Using this task, we have shown that approximately 50% of healthy adults spontaneously adopt a spatial strategy, with the other 50% using response a strategy [18]. We have also shown that spatial learners possess more grey matter in the hippocampus than response learners [5] and that they exhibit significantly greater fMRI activity in the hippocampus than response learners while navigating on the 4/8VM [18]. Response learners, on the other hand, were found to have activity in the caudate nucleus of the striatum [18]. Finally, we showed that the size of the hippocampus and caudate nucleus were negatively correlated [4,5], a finding that adds to the growing literature that describes the fact that either one of these two structures is used at a given time, possibly in a competitive manner [30,34].

Studies in children show that the development of spatial competence emerges between seven and eight years of age [22,32]. Two studies [6,24] have addressed the question of which memory system is preferentially active in children when faced with a task that can be solved using either the hippocampus- or the caudate nucleus-dependent learning. In Leplow et al.' study (2003), all the children over the age of 10 years old used a hippocampus dependent spatial strategy. The current investigation used our 4/8VM paradigm adapted for children [6]. Consistent with the study by [24], we also found that 8-year old children were more likely to spontaneously adopt a hippocampus-dependent strategy in the 4/8VM. However, response learning requires the association of body movements with a single position in the environment, while cognitive mapping requires learning the relationships between many items in the environment and a change of reference from body-centered to world-centered. Hippocampus-dependent spatial strategy thus requires complex initial encoding and effortful retrieval that depend on frontoparietal executive control and working memory networks. As ADHD is primarily related to deficits in these circuits, we predicted that children would be more likely to adopt a response strategy as they exhibit more ADHD symptoms.

## 2. Methods

### 2.1. Participants

From an initial sample of 299 eight year olds from the Quebec Newborn Twin Study [7], 285 children tested on the 4/8VM. Children were categorized as having used a hippocampus-dependent spatial strategy or a caudate nucleus-dependent response strategy based on verbal reports administered after the 4/8VM. Of the 285 children, 267 provided verbal reports and we were able to assess spontaneous strategy in 234 children in total. Among the remaining 234 children tested on the same version of the task (maximum of 8 errors before termination of a trial), 22 participants were excluded due to nausea, ($N = 5$)failure to cooperate, ($N = 8$) experimental error in administering the task, and ($N = 2$) failure to complete the task within the allotted time. The final sample used for analysis ($N = 223$) consisted of 115 boys and 108 girls and the average age for boys and girls combined was $8.43 \pm 0.11$ years old. Participants were screened for the presence of ADHD symptoms. Analysis of twin differences is beyond the scope of the current study, as is a detailed analysis of sex differences.

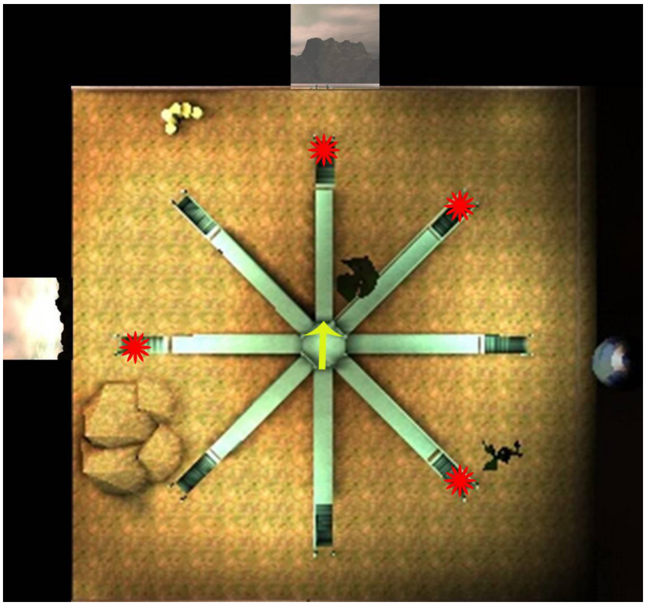

**Fig. 1.** An aerial view of the 4-on-8 virtual maze. Participants always started in the center oriented in the same direction (yellow arrow). Participants were required to learn which four paths contained reward tokens (red stars) located at the bottom of the pit, out of eight possible options. Participants could use one of two strategies. They could use a spatial strategy to remember the location of target pathways, i.e. using the relationship between environmental landmarks to remember the location of target pathways. Alternatively, they could use a response strategy, remembering the sequence of open and closed pathways from a single starting position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 2.2. Task

A commercially available computer game (Unreal; Epic Games, Raleigh, NC) was used to create a virtual environment and administer the virtual task on a computer screen. A child's version of the task was adapted from the environments that were used in previous studies [5,18]. The virtual environment was composed of an eight-arm radial maze with a central starting location. The maze was surrounded by a landscape (mountains and sunset), two trees, a planet, a pyramid, and a pile of boxes (Fig. 1). At the end of each pathway was a staircase leading to a spot where, in four of the eight open pathways, an object could be picked up. Therefore, there were no objects or cues that could indicate the location of the target objects from the center of the maze. The participants used a keypad with forward, backward, left turn, and right turn buttons to move within the environment. Before testing, the participants spent a few minutes moving in a virtual room that was different from the experimental environment to practice the motor aspects of the task. When the participants were comfortable using the keypad, the experimenter gave the instructions and the experiment started.

Participants always started a trial at the center of the radial maze. In the first stage of the task, participants were told to retrieve all four objects from the rewarded pathways. They were allowed to enter 16 pathways on the first trial and eight pathways on every other trial. Trials ended when they found all four rewards, or when they did not find all rewards within the limit of allowed entries. Participants were given a maximum of 10 trials (version 1, $N = 51$) but this was increased to 13 trials (version 2) before termination of the study, for the remaining sample of participants. To reach criteria participants were required to have completed three out of the last four trials without error. Participants were required to complete a minimum of three trials. For the participants who reached criteria, a second stage of the task, the probe trial, was presented. In the probe trial, walls were raised to conceal the landscape, and all landmarks were removed. Unbeknownst to participants, eight objects were present (one at the end of each pathway) and participants were instructed to enter the same four pathways as in the learning phase. The trial was over after four objects had been picked up. Thus, they were only allowed to enter four pathways. The following was the rationale of the probe trial: if participants were using a spatial strategy in which the landmarks present in the environment were relevant to perform the task, this change in the environment should result in an increase in errors. In contrast, if participants were using a response strategy, no increase in errors should occur since participants would remember a series of body movements from the regular starting position. Only participants who were able to learn the task were given the probe trial because probe performance would be random if the goal locations were never learned.

### 2.3. Determination of strategy

After participants completed the 4/8VM, they were asked to explain how they found each of the objects. A participant was categorized as using a response strategy when s/he mentioned numbering, counting pathways, or using an egocentric strategy to find all the objects (i.e. "I went down the pathway directly ahead, the one next to it, then skipped two pathways to the right, then skipped one pathway"). Note that a response strategy is not always egocentric, for example, if children memorized a pattern of visited pathways from a single external landmark, such as a tree. On the other hand, if the participant mentioned at least two landmarks and did not mention using a pattern (i.e. "One was beside the pyramid, one on each side of the tree and one next to the Earth"), s/he was categorized as a spatial learner. Given the fact that self-reports are less articulated in children than those of adults, strategies that were ambiguous (e.g., when participants could only report a strategy to find one or two of the goal pathways) or completely absent (e.g., "I just remembered where the pathways were") were excluded. The classification was done by two independent raters who were blind of the clinical status of the child. Cohen's κ was run to determine if there was agreement between the two raters, whether the children adopted a spatial or non-spatial strategy. There was substantial agreement between the two raters, $\kappa = .746$ (95% CI, .644 to .848).

### 2.4. Assessment of ADHD

The strength-based interview for behavior, parent edition (SIB-PE), was developed and used for this study. It is based on a previous clinical instrument: the parent interview for child symptoms (PICS) [19]. As the PICS, the SIB-PE provides specific criteria for probing and coding the presence of symptoms of inattention, impulsiveness and hyperactivity in order to assess ADHD. It is designed to elicit a precise narrative of the child's behavior, encouraging the informant (usually the parent) to describe the child's behavior in sufficient detail to allow the interviewer to determine whether the criteria for a strength (positive behavior) or symptom (negative behavior) have been met. The interview explores the subject's behavior in a number of specific and common childhood situations, two for each ADHD symptom. The interviewer probes the informant's responses in sufficient detail to separate the child's actions from potential informant bias, impressions or perceptions. The interviewer does not code the respondent's exact response, but rates the severity based on frequency, associated impairment, and extent of deviation from normal development. Using this approach in the KIDNET study, we documented high inter-rater reliability for diagnostic classification (ADHD $K = .78$), high intra-class correlation (.95 or greater for inattention, impulsiveness and hyperactivity dimensions), and high predictive validity. Unlike the PICS, the SIB-PE captures both strengths and weaknesses as they pertain to the diagnostic criteria probed for during the interview, rating each on a scale from −3 to +3, which allows for a continuous and normal distribution of the dimensions explored (in contrast to nearly all clinical scales and diagnostic interviews previously used). The score measures the impairment in functioning associated to the behavior which is conceptualized as the result of the interaction between impairment and adaptation: 5 dimensions are reflecting the severity of impairment associated to the behavior (age-appropriateness, improvement or deterioration over time, persistence across time and duration, pervasiveness, vulnerability to precipitating events) and 5 dimensions are reflecting the degree of adaptation to the behavior (effect on the child, effect on the family or significant others, coping strategies by the child, coping strategies by the family, family/social/cultural context). The SIB-PE was designed to cover the full phenotypic distribution of ADHD, from positive to negative behavioral manifestations as opposed to simple clinical symptoms or the lack thereof. Therefore, it can be used in both clinical and non-clinical control populations. In this study, we counted the number of symptoms identified through the interview, as a rating of −2 or −3 in one of the two situations tested for each ADHD symptom.

From the initial 299 children of the QNTS sample, 297 children were assessed for ADHD symptoms: 41.8% had no ADHD symptom (55.6% no hyperactive/impulsive symptom and 56.2% no inattentive symptom), 16.1% only 1 ADHD symptom, 10.4% 2 ADHD symptoms, 8.7% 3 ADHD symptoms, 6.4% 4 ADHD symptoms, 2.3% 5 ADHD symptoms, and 14.4% 6 or more ADHD symptoms. As the threshold of a diagnosis is 6 symptoms of the same subtype (hyperactive-impulsive or inattentive), only 10 children were diagnosed with ADHD-inattentive type, and 9 children with ADHD-hyperactive/impulsive type. Only one child was diagnosed with ADHD-combined type. The incidence of ADHD in our sample (7.8%) was thus similar to that in the normal North American population, about 6% [37].

### 2.5. Analysis

All analyses were done using SPSS version 15.0 and Microsoft Office Excel 2003. To analyze the relationship between strategy and probe performance in absolute space (mean = 1.9 errors, SD = 1.22), participants were divided into two groups based on the number of errors in the probe trial. If participants made zero error on the probe, they were considered “perfect probe performers”. To assess how ADHD symptom affects navigation, participants were again divided into two categories based upon whether they exhibited no symptoms, or one or more symptoms (hyperactive, inattentive, or both). In order to test the differences in proportion of motor strategy depending on ADHD symptoms, we used the Fisher’s exact test of independence, which is more conservative and accurate than the chi-square test, but one-sided as our predictions were clearly unidirectional.

## 3. Results

### 3.1. General performance

Of the 256 participants tested (excluding the participants for failure, nausea and experimenter errors only), 197 (77%) reached trials to criteria.

### 3.2. Strategy

Out of the included participants that we were able to classify ($N$ = 223), 188 participants used a spatial strategy (84.3%). Strategy did not significantly affect (p = .195) the proportion of children who reached trials to criteria (84.0%: 158/188 for spatial learners vs. 91.4%: 32/35 for response learners). Therefore both spatial and response learners were able to learn the task before being tested on the probe.

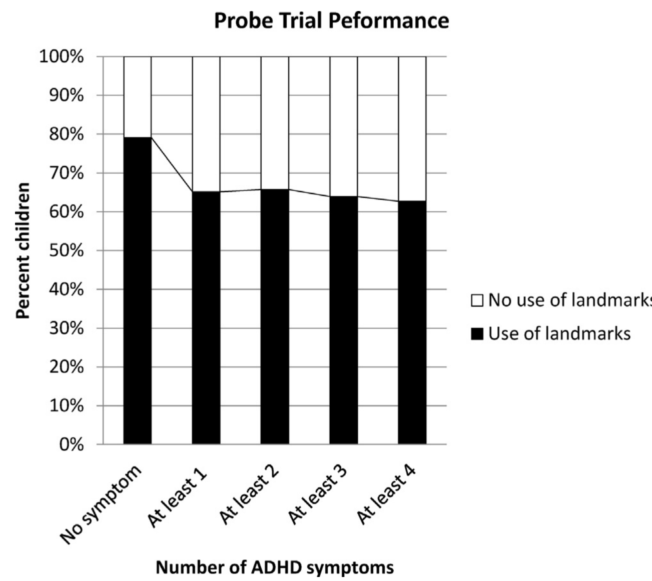


**Fig. 2.** Percent children who used landmarks as a function of number of ADHD symptoms. The presence of one ADHD symptom led to a significant decrease in use of landmarks evidenced by an increase in the proportion of perfect performers on the probe trial, i.e. no errors made during the probe trial ($p$ = .010). Perfect performance on the probe trial where all landmarks were removed is evidence of the fact that children were not using these landmarks during navigation, suggesting that they did not use a spatial strategy. These results show that the presence of only one ADHD symptom increased the proportion of children using the response strategy, without further increase with more symptoms.

Among all participants only 16.8% (32/190) had a perfect performance on the probe trial (no error) which is evidence that they did not require environmental landmarks in order to find target objects. However, among response learners, the proportion of perfect performers raised to 28.1% (9/32) while it was only 12.0% (19/158) among spatial learners ($p$ = .024). When landmarks were removed during the probe trial, response learners were twice as likely as spatial learners not to make any errors providing evidence for the fact that they completed the task without using the landmarks.

### 3.3. ADHD symptoms and performance in the 4-on-8 virtual maze

We predicted that the presence of ADHD symptom would increase the chances of navigating using a response strategy. The proportion of participants classified as response learners increased from 11.1% (11/89) among those displaying no ADHD symptoms to 19.4% (24/124) among those displaying at least one ADHD symptom. This difference was close to reaching statistical significance ($p$ = .066; one-sided).

Beyond the classification based on verbal reports, we expected the presence of ADHD to confer an advantage on probe performance since spatial strategies result in an increase in probe errors whereas response strategies do not. Among participants with at least one ADHD symptom, 34.9% (51/146) had a perfect performance on the probe trial (no error) where all landmarks were absent, as compared to 20.9% (23/110) among those with no symptom ($p$ = .010, one-sided). The differences were similar when comparing those with and without hyperactive/ impulsive symptom (35.1%: 39/111 vs. 24.1%: 35/145) ($p$ = .037), or those with and without inattentive symptoms (35.7%: 40/112 vs. 23.6%: 34/144) ($p$ = .024). Children displaying at least one ADHD symptom were more likely to perform better on the probe, providing evidence for the fact that they were using a response learning strategy. This difference in proportion did not increase with the number of symptoms, up to four or more (Fig. 2).

If the presence of at least one ADHD symptom conferred a paradoxical advantage for a perfect performance in the probe trial, we expected that ADHD nevertheless had overall a negative effect on learning the task. When comparing all the children with a maximum of 10 trials, having at least one ADHD symptom almost doubled the proportion of children who failed to learn the task to criterion (to complete three out of the last four trials without error): while only 16.7% (17/102) of participants with no symptoms failed to learn the task, 27.3% (36/132) of the participants with at least one ADHD symptom did not learn the task to criteria, ($p = .038$; one-sided). The proportion of children failing to reach criterion to success remained stable when the number of symptoms increased: 26.0%, 26.7%, and 30.0%, for at least 2, 3, and 4 symptoms, respectively.

We then compared children who presented different symptoms, i.e. children with at least one hyperactive/impulsive symptom to children with at least one inattentive symptom. The proportion of participants who failed to learn the task was 27.6% (27/98) in the hyperactive/impulsive group, while the proportion was 27.2% (28/103) in the inattentive group. This difference was nonsignificant ($p > 0.05$). We then compared each of these symptom groups to a group lacking that symptom. When we compared the hyperactive/impulsive group to children who lack this symptom, or when we compared the inattentive group to children who lack the inattentive symptom, we found the groups presenting the symptom to have a slightly elevated proportion of participants failing to learn the task (hyperactive/impulsive group: 19.1%, 26/136; inattentive group: 19.1%, 25/131) compared to the group lacking the symptom. The lack of a significant difference may be due to the fact that, when we compare children who have a certain symptom with children who lack that same symptom, the children lacking the symptom could still present other ADHD symptomatology, which impacts learning. Thus, the group lacking a specific symptom would still show a deficit in learning due to the presence of the other ADHD symptom, and this would prevent us from observing a significant difference between groups.

## 4. Discussion

We found that ADHD affected learning strategy during our virtual navigation task. The presence of at least one ADHD symptom increased the chance that a child would spontaneously adopt a caudate nucleus-dependent response strategy. This finding was supported by the relationship found between probe performance and ADHD symptoms. Children who displayed at least one ADHD symptom tended to report using a response strategy and were more likely to have a perfect performance on the probe (which was designed to dissociate spatial and response learners). Despite this paradoxical advantage, ADHD symptoms appeared as detrimental to reaching trials to criteria in the navigation task. This detrimental effect might explain why we did not find, as initially hypothesized, a progressive dosage effect, i.e. an increasing larger proportion of children with a perfect performance as the number of ADHD symptoms increased. As the number of ADHD symptoms increased, learning becomes more impaired, which may counterbalance the benefit of a response learning strategy in the probe trial. It is possible that children with some ADHD symptoms but who did not meet the success criteria would not have shown the same paradoxical advantage, as compared to those without any symptom, if they had performed the probe trial.

The interaction between presence of ADHD symptoms and probe performance is believed to be meaningful for several reasons. Probe performance, but not self-reported strategy, was influenced by the presence of ADHD symptoms. Probe performance was related to self-report of strategy in other adult studies [5,18]. The adult version of this task has demonstrated that response learners made significantly fewer errors in the probe trial than spatial learners. Further, adults that performed well on the probe showed caudate nucleus fMRI activity during the task [18] in contrast to activity in the hippocampus found in spatial learners who made more errors during the probe. Therefore, we take the current findings to provide support that the probe trial is a reliable way to dissociate verbally reported strategies in children.

We argue that the larger proportion of perfect performance in the presence of ADHD symptoms is the result of effective information encoding with the caudate nucleus-dependent response strategy as opposed to the hippocampus-dependent spatial strategy used in higher proportion in children without any ADHD symptoms. The spontaneous use of a response learning strategy was predicted to result from a deficit in prefrontal-dependent strategic processes. In Gitten et al.'s memory study, in which the effect of ADHD on performance in a frontostriatal-dependent learning task was investigated, deficits arose only in challenging learning situations, suggesting that the prefrontal cortex is the focus of the deficit. Inappropriate organization of information due to prefrontal dysfunction would affect both caudate nucleus-dependent and hippocampus-dependent learning because both structures interact with the prefrontal cortex during normal function. Since spatial strategies place greater demands on higher cognitive centers such as the hippocampus and certain regions of the prefrontal cortex [10], spatial strategies may be more sensitive to certain prefrontal deficits involving the orbitofrontal or the dorsolateral prefrontal cortex, and thus more sensitive to ADHD. Children with ADHD were shown to have reduced volumes of the left hippocampus and reduced functional connectivity between the left hippocampus and the left orbitofrontal cortex [38]. Children with ADHD with altered hippocampal structure and connectivity (who might display more depressive symptoms) could also be biased toward more caudate nucleus-dependent learning in addition to ADHD, as compensatory strategy. The competition between these memory systems has also been shown in healthy adults to be modulated by distraction [47]. These authors used a probabilistic classification task (PCT) in which subjects learn to classify stimuli into two categories, based on trial-by-trial feedback. Similarly to a spatial navigation task, the PCT can be learned either through a declarative memory strategy relying on the medial temporal lobe system, or through habit learning strategy relying on the striatum. The presence of a distracting task decreased the amount of declarative learning about the task. Without distraction, task performance was correlated with medial temporal lobe activity, whereas performance was correlated with striatal activity after dual-task learning conditions. The balance between striatal and hippocampus-dependent learning strategies appeared thus to be modulated either by the presence of distractors, or by the subject's own distractibility.

Moreover, ADHD symptoms, especially hyperactivity, could also prevent children from stopping to look and learn the relationships in their environment, whether it be in real or virtual environments. Studies have shown that the frequent movements of children with ADHD, as measured by gazes away from the task at hand, correlate with deficits in learning [27,28]. In the present study, frequent shifts of attention away from space-defining landmarks would prevent the formation of associations between bits of information separated by time and space, a kind of learning that is mediated by the hippocampus [21,42].

Finally, in ADHD, a hypofunctioning mesolimbic dopamine branch [50,51,52] is hypothesized to produce altered reinforcement of behavior and deficient extinction of previously reinforced behavior [39]. Reinforcement has to be intense and in close proximity of the response to be effective. Accordingly, children with ADHD opted more frequently for, less likely but larger, rewards than normal controls [13]. Conditions such as repetition and immediate reward, which are optimal for maximizing information encoding in the caudate nucleus [15,44], are also more effective in children with ADHD. People who regularly engage in striatal dependent reward seeking behavior are more likely to use response learning strategies when navigating [4]. In the 4/8VM task, participants learned to navigate through an immediate feedback, especially positive feedback when entering a rewarded pathway, which is well suited when the reward system is more biased toward ADHD sensitivity. Similarly, reward seeking behavior could engage the striatum and response learning, but also predispose to drug seeking behavior. We found that adult response learners in a similar virtual maze navigation task had smoked a significantly greater number of cigarettes in their lifetime than spatial learners, were more likely to have used cannabis, and had double the lifetime alcohol consumption [4]. Expectedly, children with ADHD were also more likely to develop disorders of abuse/dependence for nicotine, alcohol, marijuana, cocaine, etc. [23].

Children with ADHD have more difficulty in unstructured environments, like the playground, or when moving from one classroom to another, or to the cafeteria, the playground, etc. The present results suggest that favoring a response strategy (counting, using a non-spatial systematic pattern of open and closed pathways, etc.) when introducing them to a new spatial environment could help them to be better oriented, and less lost in space. However, one limitation of this study is that the children only showed some symptoms of ADHD, but well below clinical threshold for the large majority. Our results may extend to a clinical sample with ADHD if the participants are provided sufficient time and opportunity to reach the learning criteria and be given the probe test. In such a case, we predict that children with ADHD who require more trials to reach criteria will also be more likely to adopt a response strategy and perform well on the probe trial, as compared to healthy control children.

In summary, we found a significant interaction between the presence of ADHD symptoms and learning strategy during our virtual navigation task. Participants with one or more ADHD symptoms were less likely to reach trials to criteria. Paradoxically, displaying ADHD symptoms improved performance on the probe trial. This suggests that children with ADHD symptoms primarily rely on caudate nucleus-dependent response learning strategies at the expense of hippocampus-dependent spatial strategies. Repetition and reward based strategies, which are hallmarks of response learning, are likely to be most effective for navigation learning in children exhibiting ADHD symptoms.

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