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Spatial working memory in children with high-functioning autism: Intact configural processing but impaired capacity

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Abstract

Visual attention and visual working memory exert severe capacity limitations on cognitive processing. Impairments in both functions may exacerbate the social and communication deficits seen in children with an autism spectrum disorder (ASD). This study characterizes spatial working memory and visual attention in school-aged children with high-functioning autism. Children with ASD, and age, gender, and IQ- matched typically developing (TD) children performed two tasks: a spatial working memory task and an attentive tracking task. Compared with TD children, children with ASD showed a more pronounced deficit in the spatial working memory task than the attentive tracking task, even though the latter placed significant demands on sustained attention, location updating, and distractor inhibition. Because both groups of children were sensitive to configuration mismatches between the sample and test arrays, the spatial working memory deficit was not due to atypical organization of spatial working memory. These findings show that attention and working memory are dissociable, and that children with ASD show a specific deficit in buffering visual information across temporal discontinuity.

Keywords: autism spectrum disorder, spatial working memory, attention, configural processing

Introduction

Spatial working memory allows us to remember and update the spatial locations of people and objects during motion, viewer movement, and momentary occlusion. Daily activities such as crossing a busy street or remembering the locations of people and objects rely on spatial working memory. Impairment in spatial working memory may increase the difficulty of representing the locations of people and objects, potentially exacerbating the social and communication deficits experienced by individuals with an autism spectrum disorder (ASD). But do people with ASD have a deficit in spatial working memory? If so, what is the nature of that deficit?

Previous research has provided inconclusive evidence about whether people with ASD are impaired in spatial working memory (Barendse et al., 2013). In the spatial working memory task of the Cambridge Neuropsychological Tests Automated Battery (CANTAB), participants are shown several boxes and must discover a hidden token by touching boxes at several locations and avoid revisiting a box in which a token has already been found. Several studies have found that children with ASD show reduced efficiency in their search strategy: they are more likely to re-visit the boxes in which a token has already been found, suggesting that they have difficulty remembering spatial locations (Landa & Goldberg, 2005; Steele, Minshew, Luna, & Sweeney, 2007). However, this finding is not without challenge. First, some studies that used the CANTAB task did not find a statistically significant deficit in spatial working memory in individuals with ASD (Kaufmann et al., 2013; Yerys et al., 2009), and working memory deficits may be exacerbated by lower IQ (Salmanian, Tehrani-Doost, Ghanbari-Motlagh, & Shahrivar, 2012) or greater ADHD symptoms (Yerys et al., 2009). Second, success in the CANTAB task depends not only on remembering where a token is, but also on the ability to plan a sequence of movements and revise that plan dynamically. Reduced performance on the CANTAB task may not arise from impaired spatial working memory per se. It could reflect deficits in attention, planning, or other executive functions. In fact, when spatial working memory is assessed with a "cleaner" paradigm, the match-to-sample task, children with ASD performed equivalently to typically developing children (Ozonoff & Strayer, 2001). Thus, whether ASD is associated with a deficit in spatial working memory remains unclear.

A second unresolved question regards the nature of a potential working memory deficit. Research on typically developing adults has shown three key properties of spatial working memory. First, with regard to the *organization* of the memory content, spatial locations are stored relationally rather than individually (Brady & Tenenbaum, 2013; Orhan & Jacobs, 2013). Thus, instead of remembering the location of each object, typically developing adults remember the global configuration of all objects. Consequently, when asked to report whether a test item is in the same location as one of the memory items, performance is better if the other items remain in the same locations as before than if the other items are absent or have moved (Jiang, Olson, & Chun, 2000). Second, with regard to the *capacity* of spatial working memory, typically developing adults are limited in the number of spatial locations they can remember. Memory performance declines when more locations must be committed to memory (Brady & Tenenbaum, 2013; Jiang et al., 2000). Third, with regard to the *domain-general demand* of spatial working memory, typically developing adults show dual-task interference between a spatial working memory task and other tasks, such as verbal working memory, auditory word categorization, or attentive tracking (Fougnie & Marois, 2006; Makovski, Shim, & Jiang, 2006; Morey & Cowan, 2005). Thus, spatial working memory tasks exert domain-general, central demands on attention and executive functions. But which of the three properties – organization, capacity, and attention – are specifically impaired in ASD?

Previous studies on ASD and spatial working memory have not isolated the source of a potential memory deficit in people with ASD. The most influential theory is the information complexity account: the more complex the spatial working memory task is, the more obvious the memory deficit is (Barendse et al., 2013; Steele et al., 2007; Williams, Goldstein, & Minshew, 2006). Consistent with this theory, impairment on the CANTAB spatial working memory task is greater when there are more boxes (Landa & Goldberg, 2005; Steele et al., 2007). However, the concept of complexity is vague: it could mean bits of information (e.g., memory load), the number of cognitive processes necessary for developing efficient memory strategies, or other causes of increased task difficulty. Evidence for the former is mixed: people with ASD show larger memory deficits when the number of locations increases in the CANTAB task (Landa & Goldberg, 2005; Steele et al., 2007) but not in the match-to-sample task (Ozonoff & Strayer, 2001). In addition, some studies have revealed a spatial working memory deficit when people have to saccade to just one memorized location (Luna et al., 2002; Minshew, Luna, & Sweeney, 1999), suggesting that the number of locations may not be a key variable for memory deficits. On the other hand, if complexity refers to processes necessary for developing efficient memory strategies (Minshew & Goldstein, 2001), then the origin of a spatial working memory deficit may be in general planning and executive functions as opposed to working memory per se.

The present study addresses two questions about spatial working memory in ASD. First, is spatial working memory impaired in children with ASD, and if so, can the impairment be attributed to general intellectual deficits (i.e., lower IQ) and co-morbid ADHD? To this end, we tested high-functioning children with ASD, and age, gender, and IQ-matched typically developing children in a match-to-sample spatial working memory task. In this task, participants were shown several dot locations to remember. After a one-second blank retention interval, they were shown a test probe and had to determine whether the probe matched the location of one of the sample dots. This task is a variant of the change detection task (Rensink, 2002) and is now frequently used to assess spatial working memory in typical adults (for review, see Luck & Hollingworth, 2008). If children with ASD are impaired in spatial working memory, then they should perform worse in this task compared with typically developing children.

Second, what is the nature of the spatial working memory deficit: does it reflect atypical organization, reduced capacity, or impaired attention and central executive functions? To address this question, we included several conditions to narrow down the origin of the potential spatial working memory deficit.

First, we manipulated the match between the spatial configuration of the sample display and the test display to examine the possibility that ASD may be associated with atypical organization of spatial memory (*atypical organization hypothesis*). This hypothesis is consistent with theories that relate ASD to increased local processing, reduced global processing, or both (Happé & Frith, 2006; Mottron, Dawson, Soulières, Hubert, & Burack, 2006). To test this hypothesis, the test display contained the critical test probe along with dots that either matched the original sample locations (same configuration) or mismatched the sample locations (different configuration; Figure 1). Configural processing should yield better performance in the same-configuration condition than the different-configuration condition (Jiang et al., 2000; Jiang & Kumar, 2004). If children with ASD show a reduced tendency to encode the sample locations globally or an increased tendency to encode each location individually, then compared with typically developing children, their performance should be less influenced by configuration mismatch.

Second, we included an attentionally demanding multiple-object tracking task to test the possibility that an impairment in attention and other domain-general processes are the root cause of spatial working memory deficits in ASD (*impaired attention hypothesis*). In the attentive tracking task, participants were asked to track up to 3 target objects among a total of 8 objects that moved randomly for several seconds. Because the target objects are visually identical to the nontarget objects, the tracking task places significant demands on distributing spatial attention to multiple objects, sustaining attention over several seconds, and inhibiting nontarget objects (Cavanagh & Alvarez, 2005; Scholl & Pylyshyn, 1999; Wolfe, Place, & Horowitz, 2007). Compared with the spatial working memory task in which participants have to remember the locations of, say, 3 dots over a blank interval of 1 second, the attentive tracking task is just as, if not more, attentionally demanding. However, because the moving objects are constantly in view, tracking can be done by establishing spatiotemporal continuity using a spatial indexing process (Pylyshyn, 1989; Scholl & Pylyshyn, 1999). In contrast, locations in the spatial working memory task disappear momentarily and therefore must be retained in a memory buffer. If the spatial working memory deficit is attributable to domain-general attention and executive function deficits, then children with ASD should be just as impaired (or even more impaired) in the attentive tracking task. However, if the spatial working memory deficit is specific to the memory buffer, then performance on the attentive tracking task may be less impaired than that in the spatial working memory task.

Finally, to examine the *capacity limitation* of spatial working memory, we manipulated memory load. If spatial working memory has limited capacity, then both children with ASD and typically developing children should perform worse as memory load increases. In addition, the specific level of performance can be used to estimate memory capacity. As shown previously (Cowan, 2001; Pashler, 1988), performance in the change detection task can be used to infer memory capacity. Suppose participants need to remember N locations. If their capacity is C (where $C < N$), then when one of the C locations is probed, accuracy should be 100%, but when one of the other locations is probed, accuracy should be at chance (50%). Therefore, memory accuracy (M) is the weighted average of perfect performance on the C items and random guesses on the N-C items. That is:

$$M = [C*100\% + (N-C)*50\%] \;/\; N \qquad \text{--- Equation 1}$$

Because memory load N is known and memory accuracy M can be measured, it is possible to solve capacity C based on Equation 1. A lower C in children with ASD would suggest that they have a lower memory capacity compared with typically developing children.

It is important to note that a reduced memory capacity does not necessarily result in a more pronounced deficit at higher memory load. Suppose one child has a capacity of 2 locations; based on Equation 1 his memory accuracy would be 83.3% at load 3 and 66.7% at load 6. Suppose a second child has a capacity of 1 location; his memory accuracy would be 66.7% at load 3 and 58.3% at load 6. Although the second child has a lower capacity, the difference in performance between these two children is not greater when the load is higher. This example illustrates that capacity reduction does not necessarily lead to a more pronounced accuracy deficit at higher memory load. Instead, a reduction in capacity must be inferred based on a calculation of capacity (Equation 1).

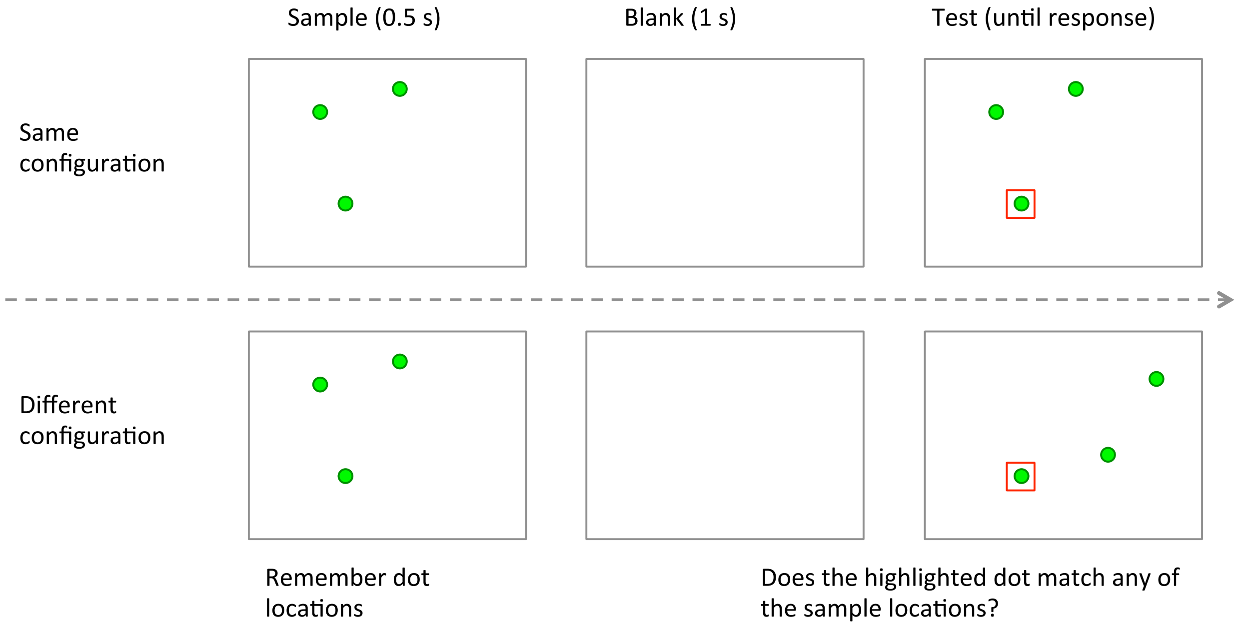

Figure 1. An illustration of the same configuration and different configuration conditions tested in the spatial working memory task. Participants encoded 3 or 6 locations in memory. They judged whether the dot highlighted by the red box matched any of the sample locations.

Method

Participants. We tested 45 children: 23 children with ASD and 22 typically developing (TD) children. Two children with ASD were excluded for failing to understand the spatial working memory task (one child did not perform the task, the other held down the same response key on all trials), and one TD child was excluded for being 1 year younger than the youngest of the ASD children. The final dataset included 21 ASD and 21 TD children. The University of Minnesota's Institutional Review Board approved the study protocol. We obtained written consent from parents and assent from the children. Children received a small cash prize for their participation.

Age, gender, and IQ match. The two groups of children were matched on age, gender, and nonverbal IQ. Table 1 shows participant characteristics. Due to the visuospatial nature of the tasks and the known communication deficits in children with ASD, we matched the two groups on nonverbal IQ. Nonverbal IQ was indexed by the special nonverbal composite of Differential Ability Scales (DAS-II; Elliott, 2007), including four subtests (recall of designs, block design, matrices, and sequential and quantitative reasoning) or by the performance subtest of Wechsler Abbreviated Scale of Intelligence (WASI), including two subtests (block design and matrices). As part of their diagnostic assessment, children with ASD already had prior IQ testing based on DAS-II or WASI. Therefore, we did not re-administer the IQ tests on these children. With the exception of 3 TD children who already had DAS-II scores from a previous study, all TD children received an IQ test using WASI (we chose WASI due to time considerations). Both WASI and DAS-II are standardized with the same mean (100) and standard deviation (15) and both have been empirically validated, including equivalence scores with the Wechsler Intelligence Scale for Children.

Table 1. Characteristics of children tested in this study. S.D. and range are shown in the parenthesis.

	ASD	TD	t-test
Sample size	21	21	
Gender	17 boys, 4 girls	18 boys, 3 girls	
Age (in years)	11.0 (S.D. = 2.4; range: 7-14)	10.9 (S.D. = 2.0; range 7-14)	$p > .90$
Nonverbal IQ	110.5 (S.D. = 18.9; [84-149])	111.9 (S.D. = 12.1; [82-128])	$p > .90$
SCQ (lifetime)*	21.2 (S.D. = 6.6; [8-32])	3.5 (S.D. = 3.1; [0-11])	$p < .001$
SNAP-IV ADHD	1.24 (S.D. = 0.4; [0.33-1.89])	0.47 (S.D. = 0.5; [0-1.5])	$p < .001$
ADOS calibrated severity score	7.3 (S.D. = 1.4; [5-10])	N/A	

** One child with ASD had an SCQ score of 8 (all others scored 14+). This child's parent may have under-reported the social communication difficulties. The child had a clinical diagnosis of "autism" and scored in the "autism" range on both ADI-R and ADOS.*

Clinical assessment. Children with ASD were recruited from the University of Minnesota Autism Spectrum and Neurodevelopmental Disorders (AS/NDD) Clinic (N=18) or the community (N=3). Children from the AS/NDD Clinic received comprehensive diagnostic evaluations by licensed psychologists with established research reliability, including a diagnostic interview (the Autism Diagnostic Interview-Revised [ADI-R; (Rutter, Le Couteur, & Lord, 2003)] or an interview based on the Diagnostic and Statistical Manual of Mental Disorders, IV [DSM-IV; American Psychiatric Association, 2000]), the Autism Diagnostic Observation Schedule (ADOS-2; Lord et al., 2000), cognitive tests, and review of medical history. Children from the community sample received comprehensive evaluation from their school districts, including parent interviews, classroom observations, ADOS, and cognitive testing. Their diagnoses were additionally confirmed with ADOS administered by a psychologist affiliated with the University of Minnesota's Autism Clinic. ADOS severity score was calculated based on ADOS-2, calibrated to a severity score that takes into account the child's age and language level (Gotham, Pickles, & Lord, 2009). All children scored in the autism (N = 19) or autism spectrum (N = 2) range on the ADOS (Table 1).

Typically developing children were recruited from the community and did not have a history of psychiatric or neurological conditions (as assessed through phone interviews with a parent and with SNAP-IV, see next).

Social Communication Questionnaire. Parents filled out the Social Communication Questionnaire – Lifetime version (SCQ), a 40-item screener based on the mandatory items from the original ADI (Rutter, Bailey, & Lord, 2003). A score of 11 and higher implicates ASD. We administered SCQ to ensure that none of the TD children rose above the cutoff (i.e., a score higher than 11). This was the case. With the exception of one child, the ASD and TD groups showed non-overlapping scores on the SCQ (Table 1).

ADHD assessment. Parents completed the Swanson, Nolan, and Pelham –IV (SNAP-IV) rating scale (Zolotor, Mayer, & Hill, 2004), a 90-item questionnaire that assesses several areas of problem behavior. Items 1-9 and 11-19 were averaged to produce a combined ADHD score (including inattention and hyperactivity/impulsivity). The rating was on a scale of 0-3, with 0 representing "not at all" and 3 "very much." The ASD group showed significantly higher scores than the TD group (Table 1).

Experimental procedure. Children were first shown a letter eye chart to screen for vision problems. All children passed the test and had at least 20/20 vision (glasses or contact lenses were allowed). They were then tested in two computerized tasks: a spatial working memory and an attentive tracking task. Approximately half of the children did the spatial working memory task before the tracking task, while the rest did the tracking task before the spatial working memory task. Children sat approximately 40 cm away from a 13" laptop. The majority of the children were tested in a quiet place at their homes.

Spatial working memory task. Participants clicked on a "Go" button in the middle of the display to initiate each working memory trial. Following a 200 ms delay, they were presented with a sample array of 3 or 6 green dots (the diameter of each dot was 0.6°) presented against a black background. The locations of the dots were randomly chosen from 64 possible locations in an 8 x 8 invisible grid (grid size: 20° x 20°). The sample array was presented for 500 ms, followed by a blank retention interval of 1000 ms. The sample duration and the blank intervals were chosen to minimize the contribution of iconic memory (Phillips, 1974). Participants were then shown a test array that contained the same number of dots as the sample array. One of the test dots – the critical test item – was highlighted by a red outline square (each side was 0.94°). The other dots on the test display were the contextual items. These contextual items were either presented at the same locations as the sample dots or in previously blank locations (randomly selected from the 64 possible locations). Participants were asked to judge whether the highlighted dot was in the same location as any of the sample dots. When the critical test item changed its location, it could appear in any of the empty cells in the 8 x 8 invisible grid. Participants pressed 's' if the highlighted dot matched one of the sample dots' locations, or 'd' if it was at a spot where there was not a dot before. Participants could take as much time as they wanted to make the response, although most responses were made quickly. Median RT was comparable between the ASD group (1.4s) and the TD group (1.47s). The test array was erased upon the response. Each correct response was followed by three rising tones that lasted a total of 300 ms; no tone followed an incorrect response. A cumulative score of the total number of correct trials was displayed after each trial.

Following 8 practice trials, participants completed 128 trials of the experimental test. These trials were divided randomly and evenly into 2 memory load conditions (3 or 6 dots), 2 configuration conditions (same-configuration or different-configuration between the sample and the test displays), and 2 change types (the critical test item was either in the same location as a sample dot or in a previously blank location).

Attentive tracking. The attentive tracking task was modeled after a previous study (Koldewyn, Weigelt, Kanwisher, & Jiang, 2013). In this task, participants were asked to track 2 or 3 objects among distractors at five different speeds. Participants pressed the spacebar to initiate each trial. They then saw a display of 8 red squares (1.3° x 1.3°) presented against a black background. A picture of a kitten was overlaid on each of 2 or 3 squares and participants were told to track all the kittens shown on that trial. When participants were ready, they clicked on one of the kittens, upon which all objects started to move randomly on the screen for 6 seconds. The objects could not occlude each other or move off the screen. The kittens remained in view for the first second of the motion phase, and were replaced by red squares that were identical to the nontarget squares for the next 5 seconds. When the squares stopped moving, participants were asked to click on the squares the kittens were hiding in. There was no time limit for making the response. Participants made either 2 or 3 clicks depending on the number of kittens they were supposed to track. The computer program did not allow more clicks than the number of kittens. After the responses, participants were shown where the kittens were, followed by a "meow" sound if they got at least one kitten correct. If they missed all kittens they heard a pre-recorded voice saying, "Oops, let's try again." Trial accuracy was calculated based on the number of kittens found (e.g., if the participant got one of the three kittens right, accuracy would be 33% on that trial).

Participants received 5 practice trials with one kitten to track. They were then tested on 40 experimental trials, divided randomly and evenly into two tracking load conditions (2 or 3 kittens) and 5 speeds (6.4°/s, 9.3°/s, 13.7°/s, 19.9°/s, or 28.8°/s; all objects on the same trial moved at the same speed). Although our main interest was in the track-3 condition (a total of 20 trials were in this condition), we included track-2 trials because they were easier and helped keep the children motivated in the task. For 4 participants (2 in the ASD group and 2 in the TD group) the program crashed after a varying number of trials; additional trials were administered. The number of trials for these participants ranged from 43 to 45 trials.

Results

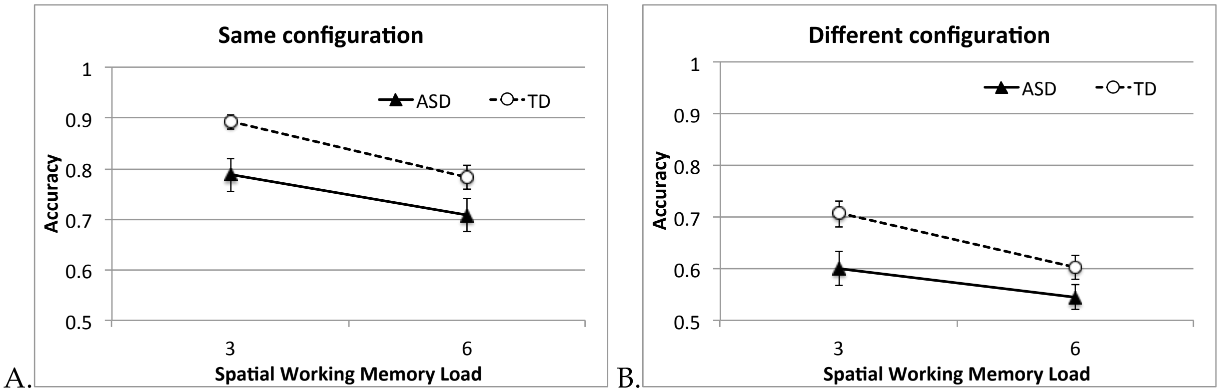

Figure 2. Results from the spatial working memory task. Error bars show ±1 S.E. of the mean.

In the spatial working memory task, participants had to decide whether a test location matched one of the sample locations (Figure 1). If children with ASD are impaired in spatial working memory, then their performance should be lower than that of age, gender, and IQ matched typically developing children. As shown in Figure 2, this was indeed the case. An ANOVA on group (ASD or TD), spatial working memory load (3 or 6), and configuration condition (same or different configuration) revealed a significant main effect of group, $F(1, 40) = 8.63$, $p < .005$, $\eta_p^2 = .18$. Accuracy in the ASD group was approximately 10% lower than that in the TD group. In addition, both groups of children showed evidence for limited memory capacity, as accuracy was significantly lower in the load-6 condition than the load 3-condition, $F(1, 40) = 46.25$, $p < .001$, $\eta_p^2 = .54$. Load and group did not interact significantly, $F(1, 40) = 2.35$, $p > .13$, $\eta_p^2 = .056$.

Might the memory deficit reflect atypical organization of the memory content, such as reduced configural processing or an increased tendency to remember individual locations in isolation from one another? If so, then the effect of configuration mismatch between the sample and test displays should be less pronounced in the ASD group than the TD group. This hypothesis was not supported by the data. The main effect of configuration was significant, $F(1, 40) = 143.87$, $p < .001$, $\eta_p^2 = .78$, but configuration did not interact with group, $F < 1$, $\eta_p^2 = .002$. The two groups of children showed equal sensitivity to the configuration manipulation, providing no evidence that children with ASD were less likely to rely on global configuration in spatial working memory. None of the other interaction effects were significant, all $F < 1$, $\eta_p^2 < .007$.

All results reported above were replicated when memory accuracy was log-transformed (log transformation is recommended by some statisticians when examining independence of two factors in accuracy; see Schweickert, 1985), or when performance was indexed by *d′* (Macmillan & Creelman, 2005). Table 2 shows the *d′* results.

Table 2. Spatial memory performance as indexed by d′. S.E. of the mean is shown in parenthesis.

	Same configuration		Different configuration	
	Load 3	Load 6	Load 3	Load 6
ASD	2.21 (0.3)	1.51 (0.3)	0.69 (0.2)	0.26 (0.2)
TD	2.94 (0.2)	2.01 (0.2)	1.33 (0.2)	0.59 (0.1)

The co-morbidity of ADHD with ASD raised questions about whether the spatial working memory deficit originated from ADHD. To address this question, we examined the correlation between ADHD characteristics (as indexed by SNAP-IV) and memory performance (the average of all 128 trials). As shown in Figure 3, ADHD characteristics did not correlate with spatial working memory performance in either the ASD group, Pearson's $r = -0.19$, $p > .18$, or the TD group, Pearson's $r = -0.05$, $p > .80$. Thus, although children with ASD scored significantly higher on SNAP-IV's ADHD items than TD children, the spatial working memory deficit was not accounted for by ADHD characteristics.

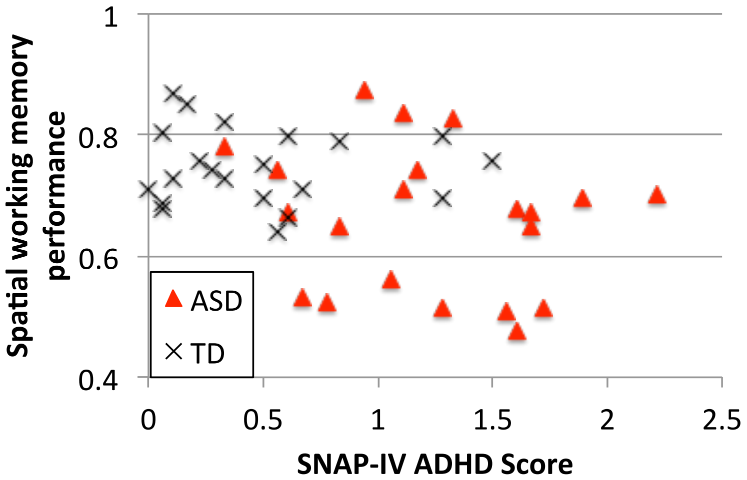

Figure 3. *A scatter plot of spatial working memory performance (across all trials) as a function of SNAP-IV ADHD scores. Each dot represents data from one child.*

Across the entire sample, performance on the spatial working memory task increased moderately with age, Pearson's $r = 0.33$, $p < .03$, and with nonverbal IQ, Pearson's $r = 0.29$, $p < .07$. However, because the two groups were matched on age and IQ, the group difference could not be attributed to age and IQ. In fact, the seven children with ASD who performed 2 standard deviations below the mean of the TD group had a wide range of age (7-13) and IQ (88-134) and did not differ significantly from other ASD children on age and IQ, $p > .20$.

To further demonstrate that the two groups of children differed in spatial working memory, in a final analysis we included age, IQ, and ADHD characteristics (SNAP-IV scores) as covariates in an ANCOVA. As expected based on the correlation analyses above, two of the covariates – age and IQ – accounted for a significant amount of variance (age: $F(1, 37) = 8.55$, $p < .006$, $\eta_p^2 = .19$; IQ: $F(1, 37) = 5.52$, $p < .02$, $\eta_p^2 = .13$). ADHD characteristics, on the other hand, did not contribute significantly, $F < 1$, $\eta_p^2 = .015$. Importantly, the two groups continued to differ significantly in the ANCOVA, $F(1, 37) = 4.39$, $p < .043$, $\eta_p^2 = .11$. This analysis showed that the group difference in spatial working memory was robust even after age, IQ, and ADHD characteristics were entered as covariates in our analysis.

There was a moderate negative correlation between spatial working memory performance and the ADOS calibrated severity: memory trended lower for children with a higher severity score, $r = -0.35$, $p = .12$. However, perhaps owing to the truncated range of the ADOS severity scores, the correlation was not significant.

Thus, children with ASD showed lower performance on a spatial working memory task compared with typically developing children. The group difference could not be accounted for by differences in IQ, age, or co-morbid ADHD. However, both groups of children were sensitive to the configuration manipulation, arguing against *atypical organization* as an account for the memory deficit.

Might the reduced memory performance be attributed to domain-general, attentional and executive dysfunction? To examine this possibility, the same participants also completed an attentive tracking task. We were particularly interested in tracking performance in the 3-object condition, which involved many similar attentional processes as the spatial working memory task's load 3 condition. Both tasks required sustained attention, memory updating, and an ability to deal with distractors. In fact, the demands for these processes were arguably higher in attentive tracking than in the working memory task. Therefore, if the spatial working memory deficit was due primarily to domain-general attention and executive function deficits, then children with ASD should be equally, or even more, impaired in the attentive tracking task.

Figure 4 shows tracking accuracy in the track-3 condition (a total of 20 trials). An ANOVA on speed and group showed a significant main effect of speed, $F(4, 160) = 35.46$, $p < .001$, $\eta_p^2 = .47$. However, neither the main effect of group ($F(1, 40) = 2.20$, $p > .14$, $\eta_p^2 = .052$), nor the group by speed interaction ($F < 1$, $\eta_p^2 = .024$) reached significance. When age, IQ, and ADHD characteristics were entered as covariates in the ANCOVA, we again failed to find significant group differences in attentive tracking, $F < 1$, $\eta_p^2 = .013$. In contrast, age accounted for a significant amount of variance ($F(1, 37) = 11.32$, $p < .002$, $\eta_p^2 = .23$; older children performed better, consistent with Koldewyn, Weigelt et al., 2013) while IQ showed a moderate effect ($F(1, 37) = 3.40$, $p < .08$, $\eta_p^2 = .084$).

To examine whether the spatial working memory deficit was greater than the attentive tracking deficit, we focused on data from the "same configuration, load-3" condition of the spatial working memory task (there were 32 trials in this condition; group mean was 78.7% (S.E. = 3.2%) in the ASD group and 89.3% (S.E. = 1.5%) in the TD group) and data from the "track-3" condition of the attentive tracking task (there were 20 trials in this condition; group mean was 89.4% (S.E. = 2.3%) in the ASD group and 92.9% (S.E. = 0.7%) in the TD group). We selected these conditions because they both involved retaining 3 locations and did not involve the additional distraction of a changed configuration. An ANOVA on task (spatial working memory or attentive tracking) and group (ASD or TD) revealed a significant main effect of group, $F(1, 40) = 8.11$, $p < .007$, $\eta_p^2 = .17$, showing lower performance in children with ASD than TD children. In addition, performance in the spatial working memory task was worse than the tracking task, $F(1, 40) = 17.20$, $p < .001$, $\eta_p^2 = .30$. Importantly, a significant interaction between group and task was observed, $F(1, 40) = 4.17$, $p < .05$, $\eta_p^2 = .094$. The performance discrepancy between the ASD and TD children was greater in the spatial working memory task than the attentive tracking task.

These results held when tracking performance was converted into a capacity measure (Hulleman, 2005), comparable to the capacity measure of the spatial working memory task (see Equation 1). The attentional capacity differed only slightly between children with ASD (Mean: 2.60; S.E. = 0.09) and TD children (Mean: 2.76; S.E. = 0.03), but the memory capacity showed a greater difference (ASD: 1.72, S.E. = 0.19; TD: 2.36, S.E. = 0.09), resulting in a significant interaction between the type of capacity (attention or memory) and group, $F(1, 40) = 5.63$, $p < .023$, $\eta_p^2 = .12$. These findings indicate that the spatial working memory deficit likely originates from the memory buffer itself, rather than a deficit in domain-general attention and executive functions.

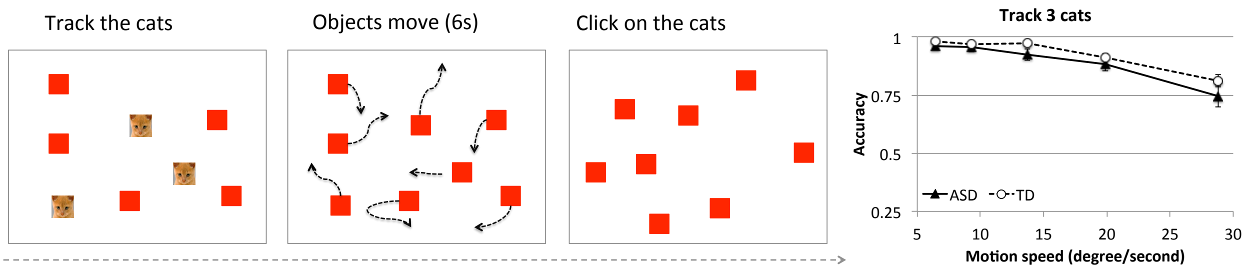

Figure 4. Left. An illustration of the attentive tracking task. Right: Accuracy in the attentive tracking task. Error bars show ±1 S.E. of the mean. Some error bars may be too small to see.

Could the spatial memory deficit be attributed to reduced memory capacity? To address this question, we calculated capacity based on Equation 1. The estimated memory capacity was significantly lower in children with ASD than TD children. This estimate was based on the same configuration conditions (there were 32 trials in load-3 and 32 trials in load-6). Children with ASD successfully committed 1.72 locations (S.E. = 0.19) to memory when asked to remember 3 dots, and 2.54 locations (S.E. = 0.39) when asked to remember 6 dots. In contrast, TD children successfully remembered 2.36 locations (S.E. = 0.09) when asked to remember 3 dots and 3.39 locations (S.E. = 0.28) when asked to remember 6 dots. The main effect of group was significant, $F(1, 40) = 5.51$, $p < .024$, $\eta_p^2 = .12$, and this effect held at both memory loads ($F < 1$ for the interaction between load and group). These data indicate that children with ASD have a lower capacity in their spatial working memory buffer.

General Discussion

Using a variant of the match-to-sample spatial working memory task, this study showed that school-aged children with high-functioning autism performed worse than age, gender, and IQ-matched typically developing children. The performance deficit did not correlate with ADHD characteristics and therefore is not likely accounted for by ADHD co-morbidity. Thus, consistent with a subset of the literature on ASD, our study shows that children with ASD have a deficit in spatial working memory (Landa & Goldberg, 2005; Luna et al., 2002; Minshew et al., 1999; Morris et al., 1999; Steele et al., 2007). Unlike the CANTAB spatial working memory task, the match-to-sample spatial working memory paradigm used in the current study is less reliant on developing an efficient search strategy and hence the impairment seen in our study is less likely attributable to planning or other executive dysfunctions.

The memory impairment seen in our study may seem to contradict that of Ozonoff and Strayer (2001)'s findings. In that study, children encoded an array of shapes in memory. Later, a probe shape was shown at the center of the display and children needed to identify the location of that shape on the sample display. Ozonoff and Strayer (2001) found no statistical difference in memory performance between children with ASD and typically developing children. They concluded that spatial working memory was unimpaired in children with ASD. However, a careful examination of Ozonoff and Strayer's data showed that a group difference may have occurred but was undetected. Ozonoff and Strayer included a load-1 condition, which produced ceiling performance in both groups. In the load-3 and load-5 conditions, children with ASD scored about 10% lower than TD children, a difference similar to what we found in the current study. Our study may have been statistically more powerful owing to a larger sample size, a cleaner test of spatial memory (rather than shape-location binding), and the inclusion of higher memory load.

An important contribution of the current study is the inclusion of conditions that allow us to identify the source of the spatial working memory deficit. First, our data are inconsistent with the atypical organization hypothesis. Although children with ASD showed lower performance on the spatial working memory task, they were just as sensitive as typically developing children were to the configuration mismatch between the sample and the test displays. This finding indicates that just like typically developing children, children with ASD have encoded the sample locations relationally, rather than individually. This finding is consistent with several recent studies showing an intact global-processing ability in children with ASD (e.g., Koldewyn, Jiang, Weigelt, & Kanwisher, 2013; White & Saldaña, 2011). Furthermore, because the spatial working memory task has no intrinsic perceptual grouping cues (i.e., the locations of the sample items are entirely random), the reliance on configural processing presents a compelling case of intact global processing in children with ASD. These data further argue against any strategic differences between the two groups. For example, if a child with ASD had used the screen corners to anchor their memory for the dots, then he or she should have been less influenced by changes in inter-dot relations. This, however, was not the case. Our data are therefore inconsistent with the explanation of spatial working memory deficits in ASD as based on weak central coherence, enhanced local processing, or other strategic differences.

Second, our results show that children with ASD have a lower capacity in retaining information in spatial working memory. The capacity estimates were about 25% lower at both load 3 and 6. The exact number of locations retained from these capacity estimates, however, should not be taken literally. Like typically developing adults, TD children and children with ASD demonstrate configural processing. They store spatial locations relative to each other, so an estimated capacity of 2 or 3 locations does not accurately capture how memory is organized. In fact, chunking of information in visual memory could yield high performance on displays involving up to 10 objects, even though the capacity is much lower (Brady & Alvarez, 2011). What these estimates do show is that children with ASD can retain less information than typically developing children.

Finally, the relatively intact performance on the attentive tracking task argues against domain-general attention and executive dysfunction as a plausible account for the reduced working memory performance. Consider the task demands of tracking 3 objects (along with 5 nontargets) relative to holding 3 static locations in a memory buffer. The tracking task requires people to sustain attention over at least 5 seconds of the motion phase, to constantly update the spatial locations of the targets during that time, and to actively ignore nontargets that could be confused for targets. These demands are arguably higher than those of the memory task. For these reasons, any domain-general attention and executive dysfunction should result in a greater deficit in the attentive tracking task than the spatial working memory task. Our finding was just the opposite. These data suggest that the problem with spatial working memory is specific to buffering visual information across temporal discontinuity. Whereas objects for attentive tracking are constantly in view, the sample locations in the spatial memory task disappeared for a moment before coming back. We suggest that the lack of consistent “object files” is particularly detrimental to performance in children with ASD.

Going beyond autism research, our study has implications for understanding capacity limitations in attention and working memory. A well-accepted view about these limitations is that a common mechanism underlies the capacity limitations in attentive tracking and in visual working memory (Cowan, 2001). Both appear to be limited to a magic number 4, and both rely on spatial representation in the posterior parietal cortex (Culham, Cavanagh, & Kanwisher, 2001; Todd & Marois, 2004). Other theories have considered working memory as attention sustained over time on internal representations (Chun, 2011), again linking attention with working memory. There is no doubt that attention and working memory share common cognitive and neural mechanisms, yet they also tap into unique systems. For example, dual-task interference between a visual working memory task and an attentive tracking task is much less than that between two visual working memory tasks (Fougnie & Marois, 2006). The current study suggests that despite substantial overlap in processing, attention and working memory are also different, as ASD affects primarily spatial working memory rather than attentive tracking.

The main difference between attentive tracking and spatial working memory is the continuity of objects over time. In attentive tracking, participants must remember which objects are tracking targets and which are nontargets, but all the objects are continuously presented for the entire duration of the task. Tracking can therefore be supported by the spatial indexing system that maintains the spatiotemporal continuity of objects (Pylyshyn, 1989; Scholl & Pylyshyn, 1999). This same system may support young infants’ ability to establish object permanence and continuity (Xu, Carey, & Welch, 1999). In contrast, the spatial working memory task requires one to bridge across temporal discontinuity, so visual information must be retained in a buffer. Because the visual system prefers new visual input, the memory buffer is vulnerable to interference from subsequent visual input (such as the test array; Makovski, Sussman, & Jiang, 2008).

Our study presents a single dissociation between spatial working memory and attentive tracking: children with ASD are more impaired in the former than the latter. If working memory and attention are indeed separable, then it should be possible to observe the opposite dissociation. One previous study on children with Williams Syndrome appears to show such a dissociation. Using an attentive tracking task similar to ours, O’Hearn, Landau, and Hoffman (2005) showed that people with Williams syndrome were particularly impaired in the moving condition of the task (attentive tracking), but not in the static condition. Because the static condition is primarily a test of spatial working memory, children with Williams Syndrome appear to show the opposite deficit as children with ASD. Due to differences in how spatial working memory is probed in O'Hearn et al. (2005) and in the current study, strong conclusions would require further research. Nonetheless, these findings, along with dual-task interference from typical adults, suggest that unique mechanisms are involved in attention and working memory.

The small difference in attentive tracking between children with ASD and TD children is consistent with the idea that core mechanisms of visual attention are relatively intact in children with ASD. This idea is further supported by recent research on other aspects of visual attention. For example, several studies have reported relatively intact attention abilities, including global/local attention (Koldewyn, Jiang, et al., 2013), attentional disengagement (Fischer, Koldewyn, Jiang, & Kanwisher, in press), endogenous attention (Grubb et al., 2013), and implicitly learned attention (Jiang, Capistrano, Esler, & Swallow, 2013). Together with the current study's finding on attentive tracking, these studies suggest that the core mechanisms of attention are relatively intact in children with ASD. Attentional deficits seen in daily behavior may reflect a disconnect between attention and other mechanisms that mobilize it (e.g., social salience), rather than a deficit in attention itself.

The relatively intact attention function in laboratory tasks may seem puzzling. How can children who show substantial ADHD characteristics perform normally on a range of attention tasks? We believe the answer may be that the ADHD symptoms are secondary to ASD and are not a direct reflection of the core mechanisms of attention. Deficits in social and communication skills may lead to high ratings on items such as "often does not seem to listen when spoken to directly," (item #3 on SNAP-IV) and repetitive behaviors or motor mannerisms may lead to high ratings on items such as "often fidgets with hands or feet or squirms in seat" (item #11 on SNAP-IV).

An important question about ASD is whether ASD is primarily a domain-specific condition that impacts social and communication skills, or whether it is a broad deficit that affects nonsocial as well as social domains. The relatively specific deficit in spatial working memory observed in the current study cannot be easily accounted for by deficits in social and communication skills. These data suggest that while ASD may be primarily a domain-specific condition, its impact is not exclusively social.

This study leaves several open questions. First, the relationship between reduced spatial working memory capacity and the social communication deficits in ASD is unclear. It is possible that reduced capacity to remember locations of partners in social interactions could increase the difficulty of social communication. However, owing to the relatively small sample size and the truncated range of autism severity scores, we could not validly assess the relationship between autism severity and the capacity of spatial working memory. Future studies employing a larger sample are needed to address this question. In addition, future research is needed to examine whether the deficit in memory buffer is restricted to retaining spatial properties of a visual display, or whether it is also seen when children must remember nonspatial properties such as shapes or face identities.

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