

# Directing Attention Based on Incidental Learning in Children With Autism Spectrum Disorder

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**Objective:** Attention is a complex construct that taps into multiple mechanisms. One type of attention that is underinvestigated in autism is incidentally or implicitly guided attention. The purpose of this study is to characterize how children with autism spectrum disorder (ASD) direct spatial attention based on incidental learning. **Method:** Children with high-functioning ASD and typically developing children engaged in a visual search task. For the first half of the study, over multiple trials, the target was more often found in some locations than other locations. For the second half, the target was equally likely to appear in all locations. We measured search performance for targets located in the high-probability and low-probability locations. **Results:** Children with ASD were able to direct spatial attention using incidentally learned information about the target's location probability. Although unaware of the experimental manipulation, children with ASD were faster and more efficient in finding a target in the high-probability locations than low-probability locations, and this bias dissipated after the target's location probability was even. The pace and magnitude of learning, as well as later adjustment to new statistics, were comparable between children with ASD and typically developing children. **Conclusions:** Incidentally learned attention is preserved in children with ASD.

**Keywords:** spatial attention, incidental learning, autism spectrum disorder, visual search, implicit learning

Autism spectrum disorder (ASD) is an early onset neurodevelopmental disorder that affects about 1% of children (Centers for Disease Control and Prevention, 2012). The core features are deficits in social communication and the presence of fixated interests and/or repetitive behaviors (Lord et al., 2000). Impairment in some executive functions (Ozonoff & Jensen, 1999) and diminished social orienting (Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998) implicate attentional abnormality in ASD (Allen & Courchesne, 2001). However, in ASD, attention may be relatively intact when it is driven by task goals or explicit instructions. Individuals with ASD perform as well as, or better than, typical control subjects when searching for a prespecified target (O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001), show a typical pattern of performance on Stroop tasks (Kennedy, Redcay, & Courchesne, 2006), and demonstrate relatively intact endogenous cuing (Wainwright & Bryson, 2002). In contrast, several studies have revealed impairment in orienting to exogenous cues, eye gaze, and abrupt onsets in ASD (Goldberg et al., 2008;

Greenaway & Plaisted, 2005; Harris, Courchesne, Townsend, Carper, & Lord, 1999). These studies suggest that, in the absence of explicit goals and instructions about how to prioritize attention, children with ASD may show an atypical pattern of attention. To test this hypothesis, the current study characterizes how children with ASD use incidentally learned information to guide spatial attention.

Unlike laboratory situations, explicit directions about how to prioritize attention are lacking in many daily activities. Fortunately, these activities also occur in relatively stable environments. Previous experience with stable environments can guide spatial attention, often without awareness. In *contextual cuing*, people find targets faster when they are presented in displays that occasionally repeat (Chun & Jiang, 1998). In *probability cuing*, people prefer to search locations that frequently contain a target (Geng & Behrmann, 2005; Jiang, Swallow, Rosenbaum, & Herzog, 2013). Both types of cuing occur even though participants are unaware of the visual regularities. With incidentally learned attentional cues, explicit instructions and goals are not available to help structure the task and mobilize goal-driven attention.

To allocate attention based on incidental learning, it is first necessary to learn an implicit cue and then to use the cue to guide attention. Previous research has shown that both typically developing children and children with ASD exhibit robust implicit learning in a range of tasks (Amso & Davidow, 2012; Brown, Aczel, Jimenez, Kaufman, & Grant, 2010; Reber, 1993). However, as noted by previous researchers (Brown et al., 2010), individuals with ASD may be impaired at using implicitly learned cues to guide attention.

Two studies using the contextual cuing paradigm have observed intact cuing in children with ASD. In these studies, chil-

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dren searched for a target among distractors. Unbeknownst to them, some search displays occasionally repeated. Both typically developing children and children with ASD demonstrated faster search reaction time (RT) on repeated displays than unrepeated ones (Barnes et al., 2008; Brown et al., 2010). These data suggest that repeated search displays can successfully cue spatial attention in ASD, even when cueing occurs incidentally. In contrast to these results, Pellicano et al. (2011) observed significantly impaired performance in a probability cuing paradigm. In that study, children searched for a target light in a room with floor lights. Unbeknownst to them, across multiple trials the target light was more often located in one side of the room than the other (the rich side of the room was constant throughout the experiment for a given individual). Whereas typical controls preferred to search the rich side in the first experimental block (the first 40 trials), children with ASD developed this preference only in the second block.

Several factors could lead to the discrepancy in the results from the contextual cueing and probability cuing tasks. First, it is possible that children with ASD are impaired at directing attention incidentally, but that contextual cueing did not reveal this impairment because it does not adequately measure attentional guidance. According to the guided search model (Wolfe, 1994), a hallmark of attentional guidance is increased search efficiency, which is indicated by a reduction in visual search slope (the additional time it takes to find a target for each item added to the display). When a cue (e.g., a salient color) guides attention, it decreases the amount of time that is spent attending to each item in the display and thereby reduces search slope (Wolfe, 1998). However, some studies have failed to find a reduction in search slope in contextual cueing (Kunar, Flusberg, Horowitz, & Wolfe, 2007; Rausei, Makovski, & Jiang, 2007), suggesting that contextual cueing may enhance processing after the target has been found. Intact contextual cueing in children with ASD may suggest that implicit learning is preserved (Brown et al., 2010), but does not rule out the possibility that attentional guidance by incidental learning is impaired. Probability cuing, on the other hand, is a clear example of attentional guidance based on incidental learning (Jiang, Swallow, & Rosenbaum, 2013). When a target is more often found in some locations than others, the rich locations are associated with faster RT and shallower search slope (Jiang, Swallow, & Rosenbaum, 2013). Impaired probability cuing (Pellicano et al., 2011), but

intact contextual cueing (Barnes et al., 2008; Brown et al., 2010), may indicate that incidentally learned attention is impaired in ASD.

However, a different explanation may also be possible. Whereas studies have repeatedly demonstrated a lack of awareness in contextual cueing (Chun & Jiang, 2003; Chaumon, Drouet, & Tallon-Baudry, 2008), probability cuing in large-scale foraging tasks such as that used by Pellicano and colleagues (2011) is associated with explicit awareness (Smith, Hood, & Gilchrist, 2010). Impaired probability cuing in children with ASD in that task may not reflect a deficit in incidentally learned attention, but rather difficulties in strategizing navigation paths.

To understand how children with ASD allocate attention based on incidental learning, it is necessary to choose an experimental paradigm that i) unequivocally measures attentional guidance, and ii) does not involve explicit strategies. A computerized probability cuing paradigm satisfies these criteria (Jiang, Swallow, & Rosenbaum, 2013; Jiang, Swallow, Rosenbaum, & Herzig, 2013). Because the computerized paradigm does not involve energy-expensive locomotion, there is much less need to optimize search paths. In addition, participants rarely become aware of the experimental manipulation in the computerized version (Geng & Behrmann, 2002; Jiang, Swallow, & Rosenbaum, 2013; Jiang, Swallow, Rosenbaum, & Herzig, 2013).

Here we characterize incidental learning of attention by probability cuing in children with ASD. Our study tested not only the acquisition of an attentional bias toward rich locations, but also the adjustment of that bias following a change in display statistics. Participants searched for a target fish among distractor fish and reported whether the target fish faced left or right (see Figure 1). For the first half of the experiment, the target was more often found in one quadrant (the rich quadrant, 50% of trials) than in any one of the other quadrants (the sparse quadrants, each 16.7% of trials). Which quadrant was rich was counterbalanced across participants but remained the same for a given participant. Participants were not told of the target's uneven location probability. If children with ASD are able to direct spatial attention based on incidental learning, then they should find targets faster when they are in the rich quadrant rather than the sparse quadrants. Furthermore, to examine the adjustment of the attentional bias to changes in display statistics, for the second half of the experiment, the

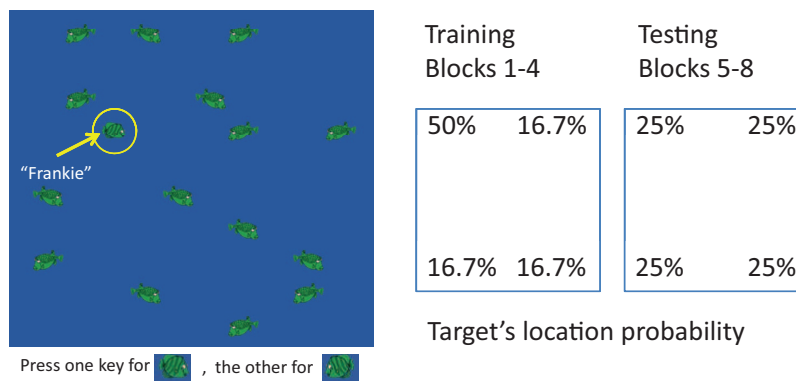


Figure 1. (A) A sample visual search display. (B) Target's location probability across the eight blocks of testing. The "rich" quadrant (labeled as 50%) was randomly selected and counterbalanced across participants.

target was equally likely to appear in all quadrants. Again, participants were not told how the target would be distributed. If children with ASD are sensitive to changes in the target's location probability, then their earlier bias toward the rich quadrant should diminish in this phase of the experiment. Age-, gender-, and IQ-matched typically developing children were also tested to assess whether incidentally learned attention is an area of significant impairment in children with ASD.

## Method

### Participants

**Sample size.** We tested a total of 38 children: 22 typically developing children (TD) and 16 children with ASD. The final dataset included 15 TD and 15 ASD children, excluding 1 child with ASD whose nonverbal IQ was below 80, and 7 TD children who could not be IQ matched. Children who were excluded showed similar patterns of results as those included in the study. The study protocol was approved by the University of Minnesota Institutional Review Board. We obtained written consent from parents/legal guardians as well as assent from the children.

**Sample age, gender, IQ.** The ASD sample included 13 boys and 2 girls with a mean age of 10.4 years (range: 6.5–13.5). The typical sample also included 13 boys and 2 girls, with a mean age of 10.8 years (range: 5.5–13.3). In addition to being matched on gender and age ( $p > .50$ ), the two groups were matched on nonverbal IQ, as assessed using the special nonverbal composite of Differential Ability Scales (DAS-II; Elliott, 2007). The nonverbal composite of DAS-II was based on four core subtests: recall of designs, block design, matrices, and sequential and quantitative reasoning. These scores were used to ensure that the ASD and typical groups matched on performance IQ. The mean nonverbal IQ was 106.3 in the ASD group (range: 84–149) and 109 in the typical group (range: 82–126),  $p > .50$ .

**Clinical assessment.** Children with ASD were recruited from the University of Minnesota Autism Spectrum and Neurodevelopmental Disorders (AS/NDD) Clinic ( $N = 12$ ) 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 upon the *Diagnostic and Statistical Manual of Mental Disorders, IV* [DSM-IV; American Psychiatric Association, 2000]), the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000), cognitive tests, and review of medical history. The community sample received a medical or school designation of ASD; their diagnosis was additionally confirmed with ADOS. All children scored in the autism ( $N = 14$ ) or autism spectrum ( $N = 1$ ) range on the ADOS.

Typically developing children were recruited from the community, excluding those with a history of psychiatric or neurological conditions.

**Social communication questionnaire.** To further validate group assignment, we asked parents to fill out the social communication questionnaire (SCQ), a 40-item screener based on the mandatory items from the original ADI (Rutter, Bailey, & Lord, 2003). A score higher than 11 on the SCQ usually raises red flags for ASD. In our sample, the mean SCQ score was 21.7 in the ASD

group (range 14–32) and 3.3 in the TD group (range 0–9), a difference that was highly significant,  $p < .001$ .

**Child behavior checklist.** Finally, parents completed the Child Behavior Checklist (CBCL; Achenbach, 1991), which allowed us to identify problem behaviors in children. We focused on scores related to DSM-IV attention deficit/hyperactivity disorder (ADHD), which may affect performance on our attention task. We examined whether probability cuing was impaired in children who scored in the clinical or subclinical range of ADHD on the CBCL.

### Probability Cuing

**Procedure and stimuli.** Participants sat approximately 40 cm from a 13 in. MacBook laptop. Each trial started with a fixation button ( $1.5^\circ \times 1.5^\circ$ ) with the word “GO” on it. The button was placed randomly within the central  $3^\circ$ . Participants clicked on the “GO” to start. The mouse click required eye–hand coordination and ensured that eye positions were approximately centered at the start of a trial. After 200 ms, a display including one target fish (“Frankie”) and several distractor fish was shown (stimuli were taken from Dixon, Zelazo, & De Rosa, 2010). The target fish shared the same color as the distractor fish. Frankie could be distinguished from the other fish by small differences in its shape (it was less elongated than the distractors) and texture (vertical stripes instead of scales). A random half of the items on the display involved distractors that faced the same direction as the target, whereas the other distractors faced the opposite direction. Each fish subtended  $1.75^\circ \times 1.25^\circ$ . The items were placed in a  $10 \times 10$  invisible matrix that subtended  $19^\circ \times 19^\circ$ . Item locations were random, with the constraint that there were an equal number of items in each quadrant. Participants were asked to find Frankie and indicate whether he faced left or right (see Figure 1). They pressed an arrow key to report Frankie's direction. Because Frankie's direction was randomly determined for each trial, left and right responses were equally likely in all conditions. The display was erased upon a key press response. Participants received auditory feedback about accuracy and were encouraged to respond as accurately and as quickly as possible.

The experiment was divided into eight blocks of 36 trials each. An experimenter wrote down trial number for which an obvious distraction occurred (e.g., the participant looked away). This occurred for less than 1.5% of trials in either group. The experiment took about 30 min to complete. Participants were allowed to take a break after each trial (trials were self-initiated), and were encouraged to take a break after each block. Breaks usually lasted less than 1 min.

**Design.** In the first four blocks of the experiment (training phase) the target's location probability was uneven across the display. The target was located in a high-probability, “rich” quadrant on 50% of the trials, and in each of the other three quadrants on 16.7% of the trials. The rich quadrant was randomly determined for each participant, but remained the same throughout the training. In the last four blocks of the experiment (testing phase) the target's location probability was even as the target appeared in each quadrant on 25% of the trials (see Figure 1).

In addition to manipulating target location probability and target quadrant, we also varied the number of distractor fish in each display (display set size), to estimate visual search slope, a standard measure of attentional guidance (Wolfe, 1998). Displays

contained one target fish and 7, 11, or 15 distractor fish. Display set size was manipulated to be orthogonal to the other factors. Trials of different set sizes were randomly intermixed in each block.

Participants were not informed of the target's location probability. At the completion of the experiment, we asked them whether Frankie was evenly distributed or more often found in some places than others. We also asked them to identify the rich quadrant.

## Results

Search accuracy was high: 98.1% for children with ASD and 98.3% for typically developing children. An analysis of variance (ANOVA) on group (ASD vs. TD), phase (training or testing), and target quadrant (rich vs. sparse) revealed no main effect or interaction with group, smallest  $p = .25$ . Accuracy was unaffected by any experimental manipulations, all  $ps > .12$ . No evidence of speed-accuracy trade-off was observed. As in other visual search studies (Wolfe, 1998), high accuracy validates the use of RT as a measure of search performance.

### Overall RT

In the RT analysis, we excluded incorrect trials (about 1.8%), trials with an obvious distraction (less than 1.5% in any group), and trials with an RT under 200 ms or over 3 standard deviations ( $SD$ ) of an individual's mean. Altogether fewer than 3% of trials were excluded. Due to the small number of trials per block, we first reported data across all set sizes. An analysis on set size was performed separately. Probability cuing was indexed by the main effect of target quadrant in the ANOVA.

As is apparent from Figure 2, both TD children and children with ASD were sensitive to the target's location probability. In the training phase, when the target's location probability was uneven, children were faster when the target was in the rich quadrant rather than the sparse quadrants. However, in the testing phase when the target's location probability became even, the bias diminished.

To confirm these observations, we conducted an ANOVA that used group (ASD or TD) as a between-subjects factor, and target quadrant (rich or sparse) and block (1–8) as within-subject factors. Probability cuing was present, resulting in a significant main effect of target quadrant,  $F(1, 28) = 21.14$ ,  $p < .001$ ,  $\eta_p^2 = .43$ . In

addition, target quadrant interacted with experimental block,  $F(7, 196) = 6.04$ ,  $p < .001$ ,  $\eta_p^2 = .18$ , indicating that probability cuing was greater in some blocks than others. This pattern was similar for both groups. Group did not interact with target quadrant,  $F < 1$ , neither was the three-way interaction among group, target quadrant, and block significant,  $F(7, 196) = 1.30$ ,  $p > .25$ .

As the experiment progressed, RT decreased, resulting in a main effect of block,  $F(7, 196) = 12.08$ ,  $p < .001$ ,  $\eta_p^2 = .30$ . There was a significant interaction between block and group,  $F(7, 196) = 5.39$ ,  $p < .001$ ,  $\eta_p^2 = .16$ . Children with ASD showed greater procedural learning (reduction in RT with practice) than typical children. As shown in Figure 2, children with ASD were slower than typically developing children at the start of the experiment, which gave them more room to improve with training. The main effect of group was insignificant,  $F < 1$ .

### Training Phase

The above analysis showed that probability cuing was greater in some blocks than others for both typical children and children with ASD. To quantify this change, we conducted separate ANOVAs on data from the training and testing phases. In the training phase, in which the target location probability was uneven, an ANOVA using group, target quadrant, and block (1–4) as factors revealed a significant main effect of target quadrant,  $F(1, 28) = 39.02$ ,  $p < .001$ ,  $\eta_p^2 = .58$ , but no interaction between target quadrant and block,  $F < 1$ . Probability cuing—the RT difference between rich and sparse quadrants—was significant for each block in the training phase, including block 1,  $ps < .001$ . The interactions between group and target quadrant was not significant,  $F < 1$ , neither was the three-way interaction between group, target quadrant, and block significant,  $F(3, 84) = 1.90$ ,  $p > .13$ .

Although the rapid emergence of probability cuing is consistent with previous findings (Jiang, Swallow, Rosenbaum, & Herzig, 2013), it might raise some concerns over experimental artifacts. However, it should be noted that the rich quadrant was randomly selected and counterbalanced across participants, ruling out potential confounds. Rich and sparse quadrants were objectively identical in all ways, save for the likelihood that a target would appear in one of them. In addition, experimental artifacts should lead to faster RT in the rich quadrant on the very first trial. This was not the case. For each participant, we identified the first trial for which the target was in the rich

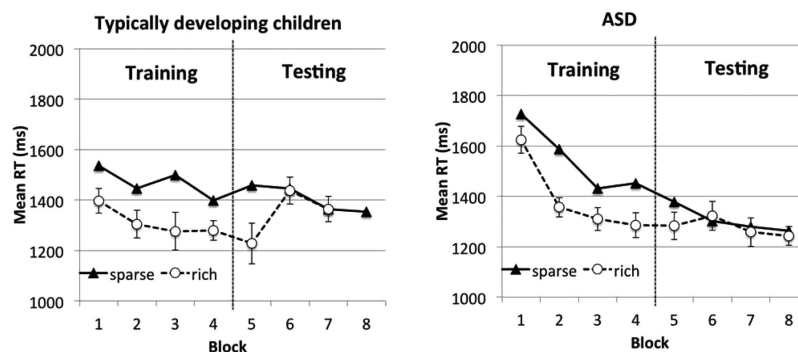


Figure 2. Mean search RT as a function of experimental block and target's quadrant. Error bars show  $\pm 1$  standard error ( $SE$ ) of the difference between the rich and sparse conditions.



quadrant, and the first trial for which the target was in a sparse quadrant. Paired-sample *t* tests showed no difference between the rich and sparse quadrants on their first trials,  $t(14) = -0.49$ ,  $p > .50$  in the ASD group (2,044 ms in the sparse condition, 2,151 ms in the rich condition), and  $t(14) = 0.68$ ,  $p > .50$  in the TD group (1,762 ms in the sparse condition, 1,650 ms in the rich condition).

The significant quadrant effect in the training phase of this experiment suggests that participants learned and used those statistics to guide attention. However, performance in this paradigm is also sensitive to short-term priming effects (Jiang, Swallow, Rosenbaum, & Herzig, 2013; Walthew & Gilchrist, 2006). The RT is faster when a target appears in the same location on consecutive trials. Immediate repetitions of the target's location happen more often in the rich quadrant than the sparse quadrants, allowing trial sequence effects to immediately speed up search in the rich quadrant. Thus, it is not clear whether children acquired any long-term knowledge regarding the target's location probability. To address this concern and to separate contributions of long-term learning from short-term priming, for each trial, we coded whether the target appeared in the rich or a sparse quadrant, and whether the target quadrant was the same as that of the preceding trial (see Figure 3).

An ANOVA on group (TD or ASD), target quadrant (rich or sparse), and quadrant repetition (repeat or nonrepeat) revealed significant main effects of quadrant probability,  $F(1, 28) = 8.77$ ,  $p < .006$ ,  $\eta_p^2 = .24$ , and quadrant repetition,  $F(1, 28) = 25.04$ ,  $p < .001$ ,  $\eta_p^2 = .47$ , but no interaction,  $F < 1$ . No other effects were significant,  $F_s < 1$ . RT was faster when the current trial's target quadrant was a repeat from the preceding trial, suggesting that performance was sensitive to short-term priming. However, RT was faster in the rich quadrant than sparse quadrants even when the target quadrant did not repeat on consecutive trials,  $t(14) = 2.50$ ,  $p < .025$  in the TD group, and  $t(14) = 3.27$ ,  $p < .006$  in the ASD group. These data clearly indicate that long-term, incidental learning of the target's likely location affected performance in both groups.

### Testing Phase

When the target's location probability became even, TD children and children with ASD adjusted their attentional bias to reflect the new visual statistics (see Figure 2). Participants continued to prefer the previously rich quadrant in the first testing block, but this preference dissipated in subsequent blocks. An ANOVA on group, target quadrant (previously rich or sparse), and block (blocks 5–8) revealed a significant interaction between target quadrant and block,  $F(3, 84) = 4.66$ ,  $p < .005$ ,  $\eta_p^2 = .14$ . Probability cuing from the uneven phase remained significant in block 5, the first testing block ( $p < .002$  when comparing previously rich and sparse quadrants), but was not significant in subsequent blocks ( $ps > .50$ ). None of the effects involving group were significant, all  $ps > .10$ .

### Search Slope: RT-Set Size Function

Visual search RT is influenced by many factors, including the guidance of attention through the display to potential targets and postsearch processes (e.g., the time needed to identify the target,

and the time to make a motor response; Wolfe, 1998). If probability cuing guides attention, then participants should be more likely to attend the high-frequency quadrant first. Because each quadrant contained an equal number of items, guidance to the high-frequency quadrant should reduce the number of items to be searched, and this should scale with display set size (e.g., with a set size of eight, two items are prioritized, with a set size of 16, four items are prioritized). Therefore, the advantage afforded by guidance from probability cuing should increase as display set size increases. In contrast, if probability cuing only affects postsearch processes, then the facilitation should be constant across set sizes. Our data supported the first prediction (see Figure 4). An ANOVA on group (TD or ASD), target quadrant (rich or sparse), and display set size (4, 8, or 12) revealed significant main effects of target quadrant,  $F(1, 28) = 38.29$ ,  $p < .001$ ,  $\eta_p^2 = .58$ , and set size,  $F(2, 27) = 14.03$ ,  $p < .001$ ,  $\eta_p^2 = .51$ , as well as an interaction between target quadrant and set size,  $F(2, 27) = 4.98$ ,  $p < .014$ ,  $\eta_p^2 = .27$ .<sup>1</sup> None of the effects involving group were significant, all  $ps > .10$ . The significant reduction in search slope provides strong evidence for the idea that probability cuing affected attentional allocation, rather than just the speed to discriminate the target or respond to it.

### Recognition

Fourteen children with ASD and all 15 TD children provided recognition data. The percentage of children who correctly identified the rich quadrant was 28.6% in the ASD group, and 40% in the TD group. Recognition accuracy did not differ significantly between the two groups ( $p > .20$ ). In addition, neither group performed significantly above chance ( $z_s < 1.34$  on a binomial test). To examine whether recognition accuracy corresponded to probability cuing, we calculated the RT difference between rich and sparse quadrants in the training (uneven probability) phase. In neither group did recognition accuracy correspond to probability cuing ( $ps > .20$ ). The size of probability cuing was 143 ms for children who correctly identified the rich quadrant, which was no greater than the 172 ms effect for children who guessed the wrong quadrant,  $p > .50$ . The relatively low recognition rate as well as the lack of correspondence between recognition and probability cuing, supported the characterization of probability cuing as incidental learning.

### Additional Analyses

**Correlation with nonverbal IQ and SCQ.** Probability cuing in the uneven phase did not correlate with nonverbal IQ (Pearson's  $r = .14$ ,  $p > .40$  across all participants;  $r = .23$ ,  $p > .40$  in the ASD group) or scores on the social communication questionnaire ( $r = -.04$ ,  $p > .80$  across all participants;  $r = -.11$ ,  $p > .50$  in the ASD group).

**ADHD.** *DSM-IV* oriented scores for ADHD were obtained from the CBCL. All typical children scored in the normal range (mean [ $M$ ] = 2.5). The ASD group exhibited significantly higher

<sup>1</sup> Because the sphericity assumption did not hold for the set size manipulation in repeated-measures ANOVA, here we report statistics from the multivariate test, which does not rely on the sphericity assumption. The degrees of freedom are therefore [2,27] rather than [2,56].

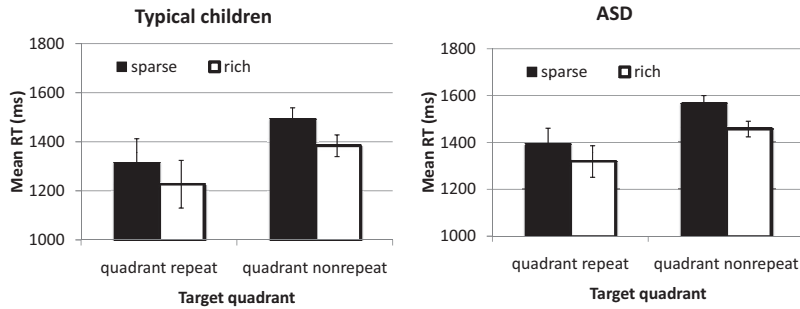


Figure 3. Results from the uneven phase. RT as a function of whether the target quadrant was rich or sparse, and whether or not it was a repeat from the preceding trial. Error bars show  $\pm 1$  standard error (SE) of the difference between the rich and sparse conditions.

ADHD behaviors ( $M = 7.1, p < .001$ ), with two children in the clinical range and four in the subclinical range for ADHD. These six children showed intact probability cuing (the RT difference between rich and sparse quadrants was 140 ms). Moreover, ADHD score in the ASD sample did not correlate with probability cuing as measured in the uneven phase (Pearson's  $r = .16, p > .50$ ).

**Discussion**

This study characterized incidentally learned attention in children with ASD. Our data showed that when a visual search target was more likely to appear in some locations than others, children with ASD were sensitive to the visual statistics and allocated spatial attention accordingly. Visual search was faster and more efficient when the target fell in the rich quadrant rather than the sparse quadrants. The attentional bias emerged rapidly within the first block (32 trials), and reflected both long-term learning of the target's location probability and short-term priming effects. Because probability cuing was greater at larger display set sizes, the benefit reflected a change in spatial attention, rather than increased speed in discriminating or responding to the target (Wolfe, 1998). In addition, children with ASD lacked an awareness of the visual statistics. They could not identify the rich

quadrant at above-chance levels, and those who failed to identify the rich quadrant showed just as much probability cuing as those who were successful. Finally, the size and pace of learning were remarkably similar between children with ASD and typical children. Thus, we found no impairment in incidentally learned attention in children with ASD. This finding does not rule out the possibility that suboptimal patterns of implicit learning may be observed in subpopulations with ASD (Gordon & Stark, 2007; Mostofsky, Goldberg, Landa, & Denckla, 2000). This possibility needs to be addressed in future research with a larger sample and with multiple tests of implicit learning.

Our data provided the clearest evidence, to date, for the preservation of spatial attention when guided by incidental learning in children with ASD. Intact probability cuing in our study contrasts with the slower learning in children with ASD observed by Pellicano et al. (2011), who examined probability cuing in a large-scale foraging task. In that task, the target was hidden in the floor lights, so subjects could not use item identity (e.g., a specific color or shape) to find the target. Several differences exist between these two studies. Pellicano et al.'s statistical manipulation was more obvious: the rich side was 4 times more likely than the sparse side to contain the target. In our study, space was divided into four

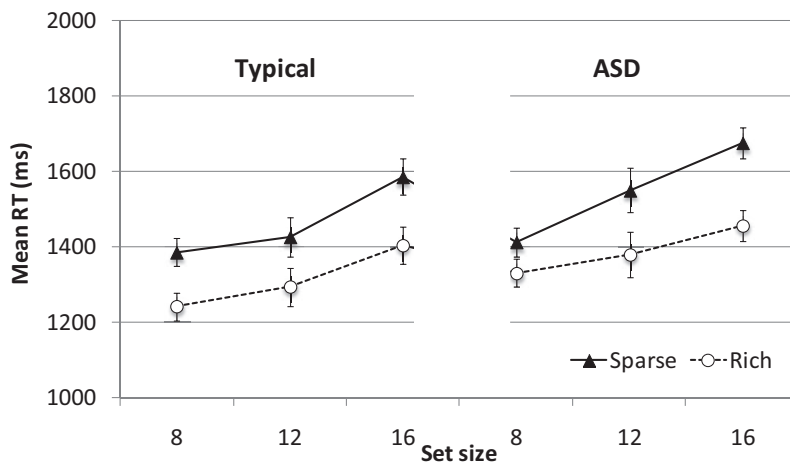


Figure 4. RT as a function of target quadrant and display set size during the training phase. Error bars show  $\pm 1$  standard error (SE) of the difference between the rich and sparse conditions.

regions, and the target appeared in the rich quadrant on half of the trials. In addition, participants in Pellicano et al.'s task had to move around a room, inspecting each location before finding the target. A previous study using the foraging task found unusually steep visual search slopes (700 ms/item; Smith, Hood, & Gilchrist, 2008). The laborious nature of search, along with a relatively obvious statistical manipulation, may have promoted explicit awareness and deliberate strategies. In fact, Smith et al. (2010) found that more than half of the participants spontaneously mentioned the target's uneven distribution, and many more correctly identified the rich side when prompted to. The incidental nature of probability cuing in our study is likely the main reason why probability cuing was preserved in children with ASD. Our data are therefore consistent with previous studies on implicit learning (Barnes et al., 2008; Brown et al., 2010). What is novel about our study is that we focused specifically on the guidance of spatial attention by implicit learning.

Another important aspect of probability cuing is its adjustment to changes in visual statistics. During the first block of the testing phase when the target's location probability became even, participants were still biased toward searching in the previously rich quadrant, but this bias disappeared in the following blocks. The adjustment further supported the claim that the early attentional bias reflected statistical regularities rather than experimental artifacts: the attentional bias disappeared when the statistics changed. The adjustment was complete for both children with ASD and TD children. Even though children with ASD show greater perseveration in executive function tasks (Maes, Eling, Wezenberg, Vissers, & Kan, 2011; Ozonoff & Jensen, 1999; Winsler, Abar, Feder, Schunn, & Rubio, 2007), they demonstrated flexibility in adjusting their attention to new, incidentally learned visuospatial statistics.

Although partly based on a lack of group difference, the characterization of probability cuing in children with ASD does not rest on affirming the null hypothesis. Our conclusion was drawn from the specific learning pattern of children with ASD. In the training (uneven) phase, probability cuing was inferred from a significant difference between the rich and sparse quadrants. In the testing (even) phase, the disappearance of the attentional bias manifested as a significant interaction between target quadrant and experimental block. Even without considering data from typical children, it is valid to conclude that i) children with ASD are sensitive to the target's location probability, and ii) the attentional bias rapidly adjusts to changes in visual statistics. The comparison group added to our conclusion by showing that the same pattern was observed in typically developing children. This study goes beyond the question of whether children with ASD perform better or worse than typical children. Rather, it provides a detailed look at the pattern of attention—its emergence and extinction as visual statistics change over time.

Our study does not clearly support the influential idea that children with ASD are superior at visual search, as compared with typically developing children (O'Riordan et al., 2001). Neither overall RT nor search slope was better in the ASD group than the TD group. While this may seem surprising, it is important to note that superior search was observed in only a subset of prior studies (e.g., Kaldy, Kraper, Carter, & Blaser, 2011; Joseph, Keehn, Connelly, Wolfe, & Horowitz, 2009; O'Riordan et al., 2001). In many others, children with ASD were either slower or not different, as compared with TD children (Barnes et al., 2008; Brown et

al., 2010; Keehn, Shih, Brenner, Townsend, & Mueller, 2012). These discrepancies require further investigation. We speculate that they may depend on the nature of search: Feature–feature conjunction search (e.g., color–letter conjunction) usually reveals superior performance in children with ASD, but configuration search (e.g., *T/L* search; Wolfe, 1998) may not be associated with an advantage.

## Future Directions

**Developmental change.** The rapid extinction of the attentional bias in the testing (even) phase of the study may seem logical, yet it contrasts with results from typically developing adults. In an analogous experiment using a *T/L* search task, typical adults showed rapid acquisition of probability cuing in the training (uneven) phase, but stubborn persistence of that bias in the testing (even) phase (Jiang, Swallow, & Rosenbaum, 2013; Jiang, Swallow, Rosenbaum, & Herzig, 2013). Future studies are needed to understand the developmental difference in the persistence of probability cuing.

**Changes in target location probability.** Our study introduced a change in target location probability in the testing phase by removing a bias toward a previously rich quadrant. This design allowed us to examine the extinction of incidentally learned attention. However, it did not test the pace at which participants could acquire a new attentional bias. In typically developing adults, when the target-rich region changed from one quadrant to another, adults gradually learned to prioritize the new rich quadrant (Jiang, Swallow, Rosenbaum, & Herzig, 2013). Future studies should examine whether the acquisition of a new attentional bias is affected by typical and atypical development.

**Covert versus overt attention.** Previous research using eye tracking has shown that probability cuing is a form of covert attention (Geng & Behrmann, 2005). Specifically, probability cuing was observed even when participants were not allowed to move their eyes during search (see also Jiang & Swallow, 2013). However, because we did not monitor eye movements in the present study, it is possible that the probability cuing measured here reflected both a preference to covertly attend to the target-rich quadrant, and a tendency to overtly saccade toward that quadrant. Future studies should examine whether the relative contribution of covert and overt attention is affected by autism.

**Generalizability.** Finally, it is worth noting that the generalizability of the study is limited by selection criteria and small sample size. It is possible that a study with a larger sample, particularly one that includes children with lower functioning autism, may yield different results. This is an important point to address in future research.

## Conclusions

The literature on attention and ASD is large and has produced mixed results. The inconsistencies may be explained in part by the heterogeneity of the ASD population, differences in how the ASD and typical groups were matched, and critically, different aspects of attention that were measured. The multifaceted nature of attention requires a strategy of divide-and-conquer (e.g., Ozonoff & Jensen, 1999). The current study is one step toward that goal. By demonstrating preserved probability cuing in children with ASD, we have ruled out incidentally learned attention as a source of impairment in ASD.

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