



PAPER

Why is visual search superior in autism spectrum disorder?

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Abstract

This study investigated the possibility that enhanced memory for rejected distractor locations underlies the superior visual search skills exhibited by individuals with autism spectrum disorder (ASD). We compared the performance of 21 children with ASD and 21 age- and IQ-matched typically developing (TD) children in a standard static search task and a dynamic search task, in which targets and distractors randomly changed locations every 500 ms, precluding the use of memory in search. Children with ASD exhibited overall faster reaction time (RT) relative to TD children, and showed no disruption in search efficiency in the dynamic condition, discounting the possibility that memory for rejected distractors augments their visual search abilities. Analyses of RT \times set size functions showed no group differences in slopes but lower intercepts for the ASD group in both static and dynamic search, suggesting that the ASD advantage derived from non-search processes, such as an enhanced ability to discriminate between targets and distractors at the locus of attention. Eye-movement analyses revealed that the ASD and TD groups were similar in the number and spatial distribution of fixations across the search array, but that fixation duration was significantly shorter among children with ASD. Lower intercepts in static search were related to increased symptom severity in children with ASD. In summary, ASD search superiority did not derive from differences in the manner in which individuals with ASD deployed their attention while searching, but from anomalously enhanced perception of stimulus features, which was in turn positively associated with autism symptom severity.

Introduction

Autism is a complex neurodevelopmental disorder diagnosed behaviorally on the basis of impairments and anomalies in three defining symptom domains: communication, reciprocal social interaction, and repetitive and stereotyped interests and behaviors (APA, 1994). Although not an explicitly defining feature of autism or autism spectrum disorder (ASD), abnormalities of visual attention or perception appear inherent in a number of behaviors observed in ASD. As has been well documented in several experimental investigations, these include heightened attention to visual detail and sensitivity to trivial changes in the visual environment (Burack, Enns, Stauder, Mottron & Randolph, 1997; Plaisted, 2000). Particularly intriguing is that atypical visual processing in ASD is often expressed in the form of *enhanced* performance relative to non-ASD individuals. For example, individuals with ASD have been found to excel in the Embedded Figures Task (Joliffe & Baron-Cohen, 1997; Shah & Frith, 1983), the Wechsler (1994, 1997) Block Design subtest (Caron, Mottron, Berthiaume & Dawson, 2006; Shah & Frith, 1993) and, the topic of the present study, visual search

(Kemner, van Ewijk, van Engeland & Hooge, 2008; O'Riordan & Plaisted, 2001; O'Riordan, Plaisted, Driver & Baron-Cohen, 2001).

In a typical visual search task, an observer looks for a target item among an array of distractor items and responds by indicating whether a target is present or absent. Search tasks range in difficulty from efficient feature searches, in which the observer's attention is immediately drawn to the target, to relatively inefficient searches, in which the observer must make multiple shifts of attentional focus, to search tasks which require the observer to foveate each item in order to determine whether it is a target or distractor. Search efficiency is estimated by varying the number of items in the search array (set size), measuring the time needed to complete the search and respond, and computing the slope of the reaction time (RT) \times set size function. Highly efficient searches yield slopes approaching 0 ms/item, while inefficient searches that require multiple deployments of attention but that do not require eye movements have slopes in the range of 20–60 ms/item.

Individuals with ASD have been found to excel relative to non-ASD individuals in visual search (Kemner *et al.*, 2008; O'Riordan, 2004; O'Riordan & Plaisted, 2001;

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O’Riordan *et al.*, 2001; Plaisted, O’Riordan & Baron-Cohen, 1998), particularly in relatively difficult searches that have moderately steep RT \times set size slopes, and thus presumably require multiple shifts of attention. Despite the robustness of this finding, the differences in brain organization and function that underlie superior search in ASD are poorly understood. Investigation of these differences can help to elucidate the neurofunctional underpinnings of ASD.

O’Riordan and colleagues (2001) proposed two processing differences that could potentially explain superior visual search skills in ASD: (1) enhanced memory for distractor locations already inspected, and (2) enhanced ability to discriminate between target and distractor stimulus features. According to the first explanation, enhanced memory of the search history (e.g. via inhibitory tagging, see Klein, 1988; Takeda & Yagi, 2000; Müller & von Mühlénen, 2000) would allow an observer with ASD to avoid re-attending to previously rejected distractors, thereby augmenting search efficiency. Although prior research indicates that memory for inspected locations plays at most a limited role in visual search among typical adults and children (Horowitz & Wolfe, 1998, 2003; Horowitz, Wolfe, Keehn, Connolly & Joseph, unpublished manuscript), memory may play a different role in the unusually developed visual search skills of individuals with ASD. This possibility is consistent with prior evidence that the ASD advantage in visual search becomes apparent only in relatively difficult searches requiring multiple deployments of attention through the search array. Enhanced memory for search locations, whether implicit or strategically applied, could thus explain ASD search superiority, but its role has not yet been investigated.

The second possibility is that enhanced discrimination might underlie search superiority in ASD. Supporting this possibility, O’Riordan and Plaisted (2001) demonstrated that, as with typical adults (Duncan & Humphreys, 1989; Wolfe, 1994), target–distractor discriminability was a principal rate-determining factor in visual search for children with ASD, and that their visual search superiority relative to typically developing (TD) children increased as a function of target–distractor similarity. They proposed that enhanced discrimination in ASD may derive from (a) superior top-down modulation of stimulus activation levels, resulting in increased excitation of target stimuli and increased inhibition of distractor stimuli, or (b) enhanced bottom-up perception of dissimilar stimulus features, either of which could lead to faster target identification in ASD. O’Riordan (2000) used positive and negative priming paradigms to investigate the role of top-down excitation and inhibition of stimulus representations in children with ASD engaged in visual search. She found that children with ASD did not differ from TD children in excitatory or inhibitory top-down control of stimulus representations, leaving open the possibility that the ASD advantage in search derived from enhanced bottom-up perception of stimulus attributes.

Our goal in the present study was to examine the contributions of both memory and enhanced perceptual processing to visual search superiority in ASD. To assess the role of memory, we used the *dynamic search* paradigm developed by Horowitz and Wolfe (1998, 2003). In dynamic search, targets and distractors are re-plotted randomly in new locations every 500 ms within a trial, rendering memory for the locations of previously inspected items of little benefit to search efficiency. If memory did play a significant role in search, search efficiency would be markedly diminished in the dynamic condition. More precisely, if there were perfect memory for prior attentional deployments in standard static search and no memory in dynamic search, then dynamic search slopes would be expected to be double that in the static condition, based on the mathematics of sampling. Under a sampling without replacement regime (perfect memory), finding a single target in n items will require an average of $(n + 1)/2$ samples, while under sampling with replacement (no memory) the same search will require $n + 1$ samples (Horowitz & Wolfe, 2003, p. 261). Horowitz and Wolfe (1998) found that, although accuracy was lower and RT was longer in dynamic than in static search, search slopes were equivalent between the two search conditions in typical adults. This finding has been replicated in typical adults (Gibson, Li, Skow, Salvagni & Cooke, 2000; Horowitz & Wolfe, 2003; von Mühlénen, Müller & Müller, 2003) and extended to TD children (Horowitz *et al.*, unpublished manuscript), indicating that visual search normally proceeds via sampling with replacement and that memory for prior attentional deployments makes at most a limited contribution to search efficiency.

The dynamic search paradigm provides an ideal means of testing the possibility that memory for prior search locations, despite its limited role in the search performance of typical individuals, might be a critical factor in the unusual search abilities of individuals with ASD. Accordingly, we compared the performance of children with ASD and age- and IQ-matched TD children in static and dynamic search. For both conditions, we used a moderately difficult search task in which participants were asked to look for a T among Ls that appeared in four orthogonal orientations. This spatial configuration task requires multiple shifts of attention, has been found to yield slopes of 25–30 ms/item in adults (Horowitz & Wolfe, 1998, 2003) and slopes that are slightly steeper in children (Horowitz *et al.*, unpublished manuscript), and is roughly comparable in difficulty to the search tasks used in prior research demonstrating ASD visual search superiority (Kemner *et al.*, 2008; O’Riordan, 2004, Experiment 2; O’Riordan *et al.*, 2001, Experiment 2). If enhanced memory for prior attentional deployments underlies superior search in ASD, children with ASD would be expected to exhibit a diminution of search efficiency in the dynamic condition relative to the static condition and to TD children. In addition to measuring

RT, we used eye-tracking to record participants' point of visual regard throughout each search trial. This provided further information about possible group differences in search strategies, whether based on differences in the use of memory or not.

We investigated the possibility that enhanced visual discrimination ability underlies superior search skills in two ways. First, by varying the number of items in the search display from trial to trial, we were able to derive an $RT \times$ set size function for each participant and to partition this function into slope and intercept (Sternberg, 1966). As noted above, the slope is typically taken as a measure of search efficiency. Slope reflects the RT cost of each additional distractor and is determined by the rate of attentional shifting between items as well as the ability to filter out irrelevant items. The intercept is the RT that would theoretically be observed if search were eliminated from the task. The intercept is assumed to be determined by non-search task components, including early preattentive perceptual processing of the stimulus features in the visual search display and speed of perceptual processing once attention has been directed to a potential target. Although we do not mean to suggest that slopes and intercepts divide neatly between attentional and perceptual processes in visual search, a finding of reduced intercepts for $RT \times$ set size functions in ASD would be consistent with the idea that enhanced perceptual processing undergirds ASD search superiority. Second, we used the eye-tracking data to examine any group differences in the deployment and spatial allocation of attention throughout the search array as compared to processing efficiency once a potential target was selected. Indications of increased speed of processing at the locus of selection would also be consistent with the hypothesis that enhanced perceptual discrimination abilities drive superior search skills in ASD.

Our final aim was to examine whether the information processing biases underlying superior visual search might be related to the core symptoms of ASD. Consequently, we assessed individual differences in visual search abilities, as measured by the slopes and intercepts of $RT \times$ set size functions, in relation to variation in communication, social, and repetitive behavior symptoms in participants with ASD. This allowed us to determine if the component processes tapped by search slopes and intercepts, and any neurofunctional differences they potentially index, might be of etiological significance with regard to the symptoms that are defining of ASD.

Methods

Participants

Participants were 21 school-age children and adolescents with ASD (17 males), all of whom were judged to meet DSM-IV (APA, 1994) criteria for autism or PDDNOS

by an expert clinician (first author), and an age-matched comparison group of 21 non-ASD children (17 males). Clinical diagnoses were confirmed using the Autism Diagnostic Interview-Revised (ADI-R; Rutter, Le Couteur & Lord, 2003) and the Autism Diagnostic Observation Schedule (ADOS; Lord, Rutter, DiLavore & Risi, 1999), both administered by specially trained examiners who had previously established inter-rater reliability. All children in the ASD group met diagnostic criteria for autism on the ADI-R, with the exception of two children who were one point below the diagnostic threshold in the repetitive behavior domain. On the ADOS, 16 children met diagnostic criteria for autism, three met for a less severe diagnosis of autism spectrum disorder, and two met ADOS criteria for autism in the social domain, but were below threshold in the communication domain. The latter two children met full criteria for autism on the ADI-R. The sample selection criteria conformed to guidelines for research diagnoses of ASD established within the National Institutes of Health Collaborative Programs of Excellence in Autism. Children with autism-related medical conditions (e.g. Fragile-X syndrome, tuberous sclerosis) were not included in this study.

Comparison group participants were a subgroup of a larger sample of TD children (Horowitz *et al.*, unpublished manuscript) who were selected to match the ASD group as closely as possible on age, sex, and IQ. All comparison group participants had no reported history of autism and were confirmed to be free of autism-related symptoms and of any other neurological or psychiatric conditions via parent report and expert clinical observation. Independent-samples *t*-tests confirmed that the ASD and TD groups were matched on age, $t(40) = 0.4$, $p = .69$. The groups were matched on nonverbal IQ, $t(40) = 0.0$, $p = .99$, but not on verbal IQ, $t(40) = 2.5$, $p < .02$, as measured with the Kaufman Brief Intelligence Test-II (Kaufman & Kaufman, 2004; see Table 1).

Apparatus

The experiment was presented with E-Prime 1.1 software on a Pentium IV 3.2 GHz/2 GB PC with a 19-inch LCD (refresh rate of 75 MHz). Participants were seated 57 cm from the monitor with eye level at center screen. Test responses were registered with a Cedrus button box

Table 1 Participant characteristics

	Autism ($n = 21$) <i>M</i> (<i>SD</i>) Range	Comparison ($n = 21$) <i>M</i> (<i>SD</i>) Range
Age	14;7 (2;8) 10;6–19;3	14;2 (2;11) 8;6–19;1
Verbal IQ	99 (19) 70–136	112 (15) 81–148
Nonverbal IQ	107 (10) 85–121	107 (14) 75–134

(model RB-420). Participants' point of regard was monitored with an ISCAN Model ETL-500 head-mounted, pupil-corneal reflection tracking system that allowed participants to move their heads freely during the test procedure. The eye-tracking computer registered each new screen image via a digital pulse programmed in E-Prime to coincide with the onset of each new experimental stimulus or inter-trial interval.

Stimuli

The target was the letter 'T' and the distractor was the letter 'L'. Letters were drawn in black Arial font on a gray background and were randomly displayed in any one of four orthogonal orientations. At the 57 cm viewing distance, the letters subtended 1.0 to 1.2 degrees visual angle ($^{\circ}$) in both dimensions, depending on orientation. There were 60 possible stimulus locations arranged on five concentric invisible circles. The circles surrounded a central fixation cross at eccentricities of 1.94 $^{\circ}$, 3.88 $^{\circ}$, 5.82 $^{\circ}$, 7.76 $^{\circ}$, and 9.70 $^{\circ}$. The innermost circle had four possible stimulus locations, the second eight, the third 12, the fourth 16, and the fifth 20.

In the static condition, a single search frame was generated for each trial, consisting of 15, 20, or 25 stimuli placed at randomly selected locations. In the dynamic condition, a new search frame was presented every 500 ms during a trial. Within a trial, each frame was the same with regard to the set size, target presence or absence, and the set of occupied locations. Across frames, the locations of individual stimuli were shuffled among the set of occupied locations. Figure 1 provides a simplified illustration of static and dynamic (target present) trials.

In the dynamic condition, when a target was present, it was displayed randomly in one of only four locations (one per quadrant), with the restriction that it could not appear at the same location on two consecutive frames. This measure was taken to defeat a simple 'sit-and-wait' strategy of attending to a single location (von Mühlhelen *et al.*, 2003). An observer who adopted this strategy would perform very poorly in the task because the likelihood of choosing an actual target location was quite low (i.e. 4/set size).

Procedure

The experimental task was to indicate via the button box whether the target stimulus was present (50% of trials) or absent (50% of trials). A trial began with a fixation cross ('+' drawn in the same font and size as the letter stimuli) presented alone for 1000 ms. With the fixation cross remaining on the screen, the first frame appeared. In the static condition this frame remained on the screen until a response was made or until 7000 ms had elapsed. In the dynamic condition, successive frames were presented every 500 ms until a response was made or until 7000 ms had elapsed. The appearance of the

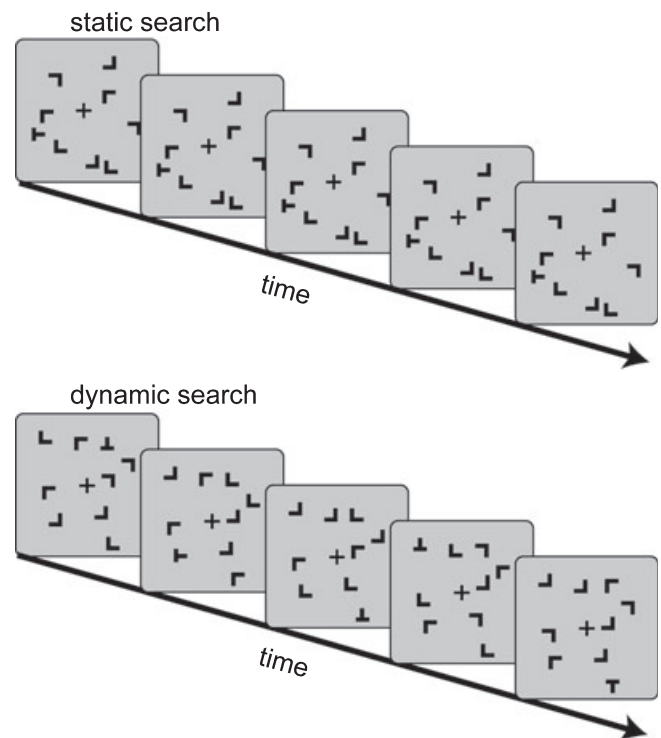


Figure 1 A simplified illustration of a static (upper panel) and a dynamic (lower panel) trial. In the static condition, the stimuli remained stationary in a randomly selected set of fixed locations for the duration of the trial. In the dynamic condition, a new search frame was presented every 500 ms. The stimuli appeared to move among the randomly selected set of fixed locations by randomly re-plotting them in any one of four orientations on each new frame.

fixation cross served to alert observers to the start of the trial, and provided a default initial fixation locus. However, observers were not instructed to maintain fixation and were free to move their eyes during the search task.

The experiment consisted of six 30-trial blocks. The blocks alternated between the two search conditions, always beginning with static. Within each 30-trial block, target presence and set size were varied in pseudorandom order. Before the first block of each condition, a demonstration was given and 18 practice trials were administered with corrective feedback. Participants were instructed to respond (with their dominant hand) as quickly as possible without making errors. These instructions were repeated after the practice trials and between test blocks.

Results

Data were analyzed with SPSS 15.0 for Windows. Data were not trimmed; instead, medians were used to reduce the influence of outliers. Unless otherwise noted, all statistical analyses were mixed-model repeated measures analyses of variance. Partial eta-squared (η_p^2) was used

as a measure of effect size. In all figures, error bars represent one standard error of the mean.

Search performance

Reaction time

Median RT data from correct responses are shown in Figure 2. We conducted an ANOVA with the between-subjects factor group (ASD, TD) and the within-subjects factors search type (static, dynamic), target presence (present, absent), and set size (15, 20, 25). There were main effects of target presence, set size, and search type. As is typical for visual search studies, RTs were slower for target absent trials than target present trials, $F(1, 40) = 253.1, p < .001, \eta_p^2 = .86$; target present searches can be terminated as soon as the target is detected, but when no target is found, the observer must search until he or she is convinced that a target is not likely to be found. As noted above, when a search task requires a relatively difficult discrimination (between Ts and Ls in four different orientations), search time increases as a function of the number of distractors. Accordingly, we also observed a set size effect, $F(2, 80) = 112.2, p < .001, \eta_p^2 = .74$. Consistent with prior studies comparing static and dynamic search, RT was faster in the static condition, $F(1, 40) = 14.6, p < .001, \eta_p^2 = .27$.

The most important findings from the RT analysis pertained to group effects. There was a main effect of group, $F(1, 40) = 7.3, p < .01, \eta_p^2 = .15$, with faster RT in the ASD than in the TD group. In addition, there were two-way interactions between group and search type, $F(1, 40) = 6.4, p < .02, \eta_p^2 = .14$, and between group and target presence, $F(1, 40) = 5.7, p < .02, \eta_p^2 = .13$. Follow-up ANOVAs revealed that the RT advantage of the ASD group over the TD group was larger in dynamic search, $F(1, 40) = 9.7, p < .01, \eta_p^2 = .19$, than in static search, $F(1, 40) = 3.5, p < .07, \eta_p^2 = .08$, and larger for target absent trials, $F(1, 40) = 7.8, p < .01, \eta_p^2 = .16$, than for target present trials, $F(1, 40) = 2.9, p < .10, \eta_p^2 = .07$. Finally, there was a three-way interaction between group, search type, and target presence, $F(1, 40) = 8.1, p < .01, \eta_p^2 = .17$. This interaction was analyzed with a series of one-way, between-group comparisons. These analyses revealed a statistically

significant ASD advantage on dynamic absent trials, $F(1, 40) = 11.2, p < .002, \eta_p^2 = .22$, a marginally significant ASD advantage on static absent trials, $F(1, 40) = 3.3, p < .07, \eta_p^2 = .08$, and non-significant group differences on both dynamic present, $F(1, 40), 2.6, p < .12, \eta_p^2 = .06$, and static present trials, $F(1, 40), 2.2, p < .15, \eta_p^2 = .05$.

Slopes of the RT \times set size functions for the target present and target absent conditions of the static and dynamic searches were computed from the median RT data reported above. As shown in Figure 3, slopes were actually steeper for static than for dynamic search, $F(1, 40) = 15.6, p < .001, \eta_p^2 = .28$, and slopes were steeper for target absent than for target present trials, $F(1, 40) = 31.4, p < .001, \eta_p^2 = .44$. There was no main effect of group on slopes, $F(1, 40) = 0.4$, or group interaction effects, demonstrating that search efficiency was consistently similar for the ASD and TD groups across search conditions. These findings indicated that memory for rejected distractors contributes no more to the search skills of children with ASD than to those of TD children.

Intercepts for the same RT \times set size functions are illustrated in Figure 4. Intercepts were higher for dynamic than for static search, $F(1, 40) = 35.7, p < .001, \eta_p^2 = .47$, and for target absent than for target present trials, $F(1, 40) = 35.8, p < .001, \eta_p^2 = .47$. Intercepts were consistently lower in the ASD than in the TD group, $F(1, 40) = 6.0, p < .02, \eta_p^2 = .13$, with no interactions between group and other factors. This finding is consistent with the possibility that non-search capacities, including enhanced perceptual processing of stimulus features, underlies ASD search superiority.

Error

Figure 5 displays rate of error as a function of the same variables analyzed for RT. An ANOVA on the raw error data revealed main effects of search type, $F(1, 40) = 79.0, p < .001, \eta_p^2 = .66$, target presence, $F(1, 40) = 18.5, p < .001, \eta_p^2 = .32$, and set size, $F(2, 80) = 17.7, p < .001, \eta_p^2 = .31$. The rate of error was higher for dynamic (9.2%) than for static (4.0%) search, was higher for target present (8.5%) than for target absent (4.7%) trials, and

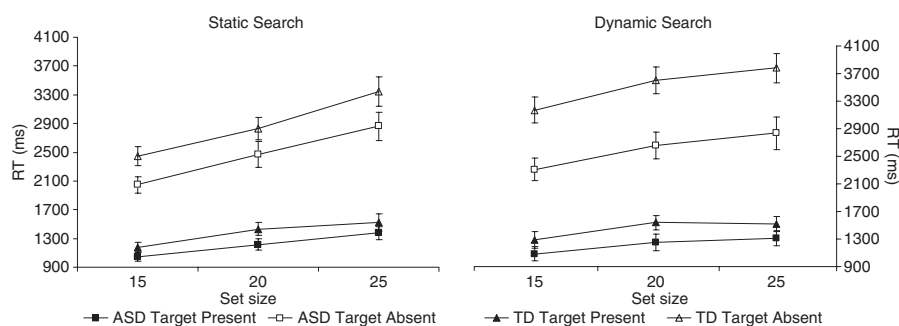


Figure 2 Median reaction time (RT) by group, search type, target presence, and set size.

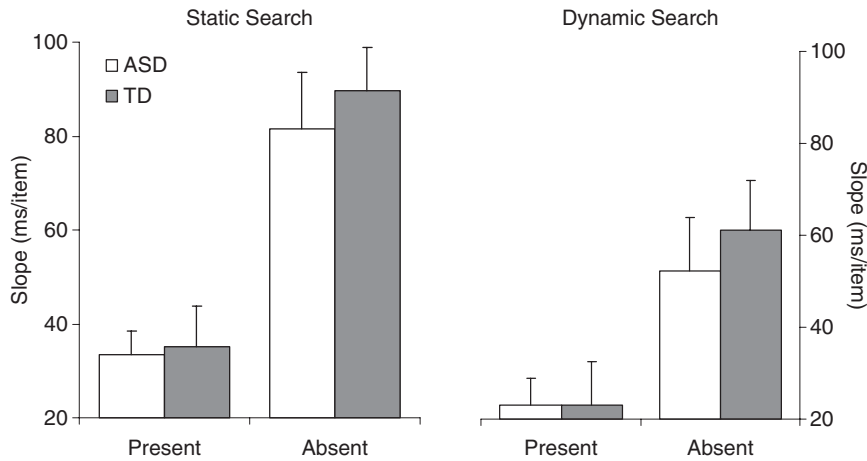


Figure 3 Median slope of the RT \times set size function by group, search type, and target presence.

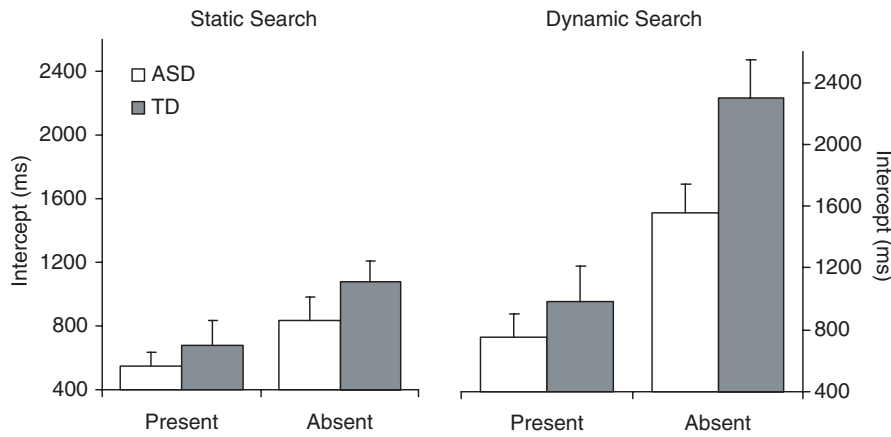


Figure 4 Median intercept of the RT \times set size function by group, search type, and target presence.

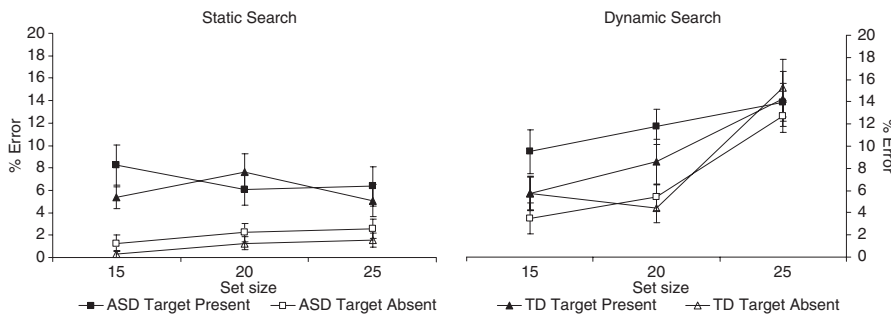


Figure 5 Percent error by group, search type, target presence, and set size.

increased as a function of set size. There was also a search type \times set size interaction, $F(2, 80) = 18.8$, $p < .001$, $\eta_p^2 = .32$, reflecting a higher increase in error with set size in dynamic relative to static search. There was no main effect of group, $F(1, 40) = 0.7$, nor were there any interaction effects between group and other experimental factors on error rate. Correlational analyses revealed no speed–accuracy tradeoffs in any condition for either group.

Eye-movement behavior

Eye position was continuously monitored from the start to the finish of each trial. Parameters for collection of raw point of regard (POR) data were set using ISCAN software. To count as a fixation, POR had to be maintained for at least five continuous data samples (80–85 ms at a sample rate of 60 Hz) within an area of 1° of visual angle. Eye-tracking data were successfully

collected for 18 of the 21 participants with ASD and all TD participants. The three ASD participants for whom eye-tracking data were not available did not differ from the other ASD participants in age, IQ, or search performance.

The eye-movement data were used to investigate potential group differences in attentional deployment and stimulus discrimination. Specifically, the measures of fixation frequency, saccade amplitude, and distribution of fixations by eccentricity and favored quadrant were used to determine if there were differences, as reflected in overt shifts of attention, in the way ASD and TD participants deployed their attention in searching for a target. Fixation duration provided an indication of processing efficiency at the locus of attention, relevant to the question of enhanced visual perception and discrimination in individuals with ASD.

Fixation frequency

Number of fixations per trial (Figure 6) was higher in the static ($M = 4.1$) than in the dynamic ($M = 3.6$) condition, $F(1, 37) = 12.3, p < .001, \eta_p^2 = .25$, and was higher in the target absent ($M = 5.2$) than in the target present ($M = 2.5$) condition, $F(1, 37) = 363.4, p < .001, \eta_p^2 = .91$. Fixation frequency increased with set size, $F(2, 74) = 12.3, p < .001, \eta_p^2 = .25$. However, there was no main effect of group on fixation frequency,

$F(1, 37) = 1.1$, nor were there any group interaction effects.

Fixation duration

Fixation duration (Figure 7) was longer in the dynamic than in the static search condition, $F(1, 37) = 86.8, p < .001, \eta_p^2 = .70$, was longer for target present than for target absent trials, $F(1, 37) = 92.5, p < .001, \eta_p^2 = .71$, and increased with set size, $F(2, 74) = 17.6, p < .001, \eta_p^2 = .32$. ASD participants made shorter fixations than TD participants, $F(1, 37) = 7.8, p < .01, \eta_p^2 = .17$. A group \times search type interaction, $F(1, 37) = 6.3, p < .02, \eta_p^2 = .15$, reflected the increased disparity between groups in fixation durations in the dynamic relative to the static search condition. Separate analyses of the data by search type showed a larger group effect in dynamic search, $F(1, 37) = 8.6, p < .01, \eta_p^2 = .19$, than in static search, $F(1, 37) = 3.1, p < .09, \eta_p^2 = .08$.

Saccade amplitude

Saccade amplitude is the average distance between consecutive fixations. Saccade amplitude was greater in the static ($M = 7.9^\circ$) than in the dynamic ($M = 7.7^\circ$) search condition, $F(1, 37) = 5.6, p < .05, \eta_p^2 = .13$, and for target absent ($M = 8.2^\circ$) than for target present ($M = 7.4^\circ$) trials, $F(1, 37) = 110.5, p < .001, \eta_p^2 = .75$. Saccade amplitude did not vary as a factor of set size,

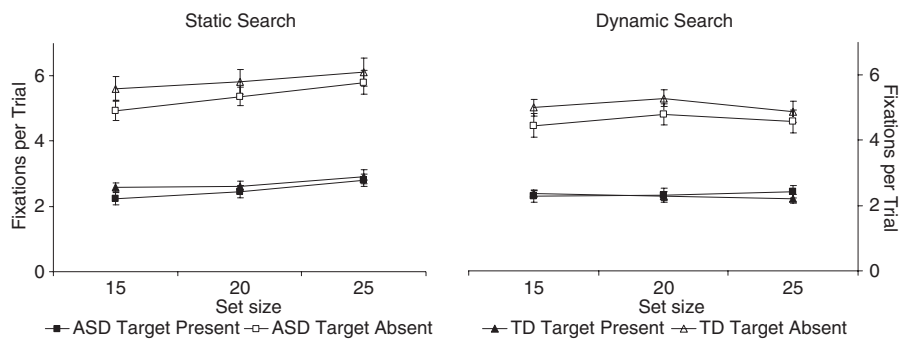


Figure 6 Median fixation frequency by group, search type, target presence, and set size.

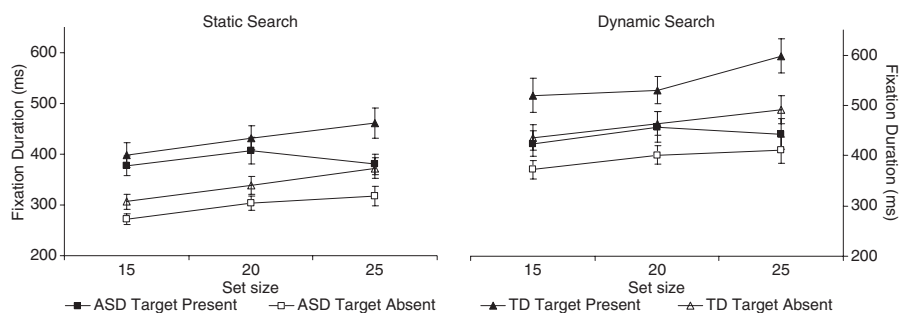


Figure 7 Median fixation duration by group, search type, target presence, and set size.

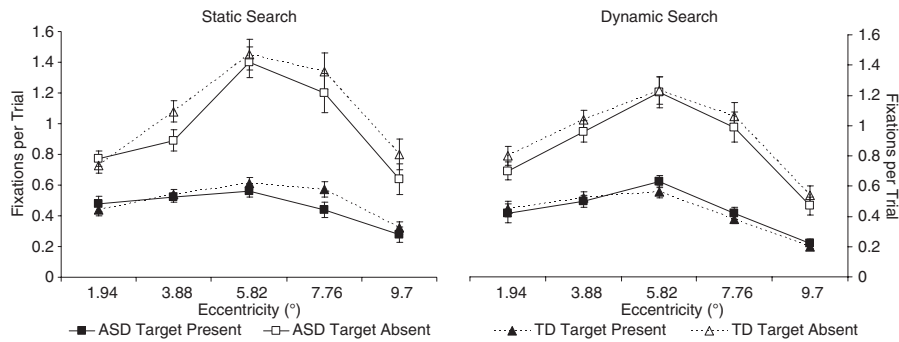


Figure 8 Distribution of fixations across stimulus eccentricities by group, search type, and target presence.

$F(1, 37) = 1.2$. There was no effect of group on saccade amplitude, $F(1, 37) = 0.4$, nor were there any group interaction effects.

Fixation distribution by eccentricity

Figure 8 plots the distribution of fixations for the ASD and TD groups by the five stimulus eccentricities comprising the search array. The distribution of fixations for target present trials was nearly identical between search types and between groups for the inner three eccentricities, all fairly flat and peaking at 5.82 degrees. However, whereas the distribution of fixations to the outer two eccentricities declined similarly between groups in the dynamic condition, fixations to the outer regions of the display declined more markedly in the ASD than in the TD group in the static condition. This difference was reflected in a three-way interaction between group, search type, and eccentricity, $F(4, 148) = 2.4, p < .05, \eta_p^2 = .06$. The target absent distributions were highly similar for the two groups. Across groups, the static and dynamic absent distributions peaked at 5.82 degrees, and the dynamic distribution declined more sharply for the outer eccentricities, $F(4, 148) = 10.6, p < .001, \eta_p^2 = .22$.

Fixation distribution by favored quadrant

This analysis was conducted to rule out the possibility that participants, whether ASD or TD, searched as

efficiently in the dynamic as in the static condition by means of a different search strategy, that is, by simply attending to a single area of the dynamic display and waiting for the target to appear there (von Mühlénen *et al.*, 2003). For each trial, each quadrant of the search display was ranked according to the number of fixations made within its boundaries. The number of fixations was then averaged across trials for the most favored quadrant, second most favored quadrant, and so on. These data are displayed in Figure 9. If participants tended to use a ‘sit-and-wait’ strategy, the dynamic distribution would be expected to fall at a significantly quicker rate than the static distribution and, in the extreme case, there would be no fixations outside of the first-ranked quadrant in the dynamic search condition. However, this was not the case. Although, as reported above, there were more fixations in static than in dynamic search and for absent than for present trials, the pattern was similar across conditions. The search type quadrant interaction was not significant in the ASD group, $F(3, 51) = 1.6, p = .21, \eta_p^2 = .09$, or in the TD group, $F(3, 51) = 1.6, p = .20, \eta_p^2 = .08$.

Visual search skills and autism symptom severity

Autism symptom severity in participants with ASD was assessed with Module 3 of the Autism Diagnostic Observation Schedule (ADOS) for children with fluent speech (Lord *et al.*, 1999). The ADOS involves a series

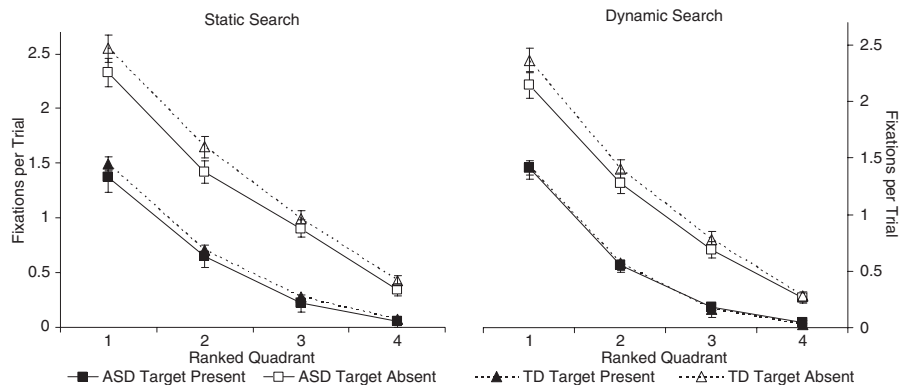


Figure 9 Distribution of fixations according to favored quadrant by group, search type, and target presence.

of experimenter-administered social events and presses designed to elicit behaviors relevant to an ASD diagnosis. Although the ADOS was designed as a classificatory instrument, its use as a continuous measure of symptom severity is supported by its ability to discriminate between autism and the less severe diagnosis of PDD-NOS in validation studies (Lord, Risi, Lambrecht, Cook, Lenventhal, DiLavore, Pickles & Rutter, 2000), and it has been used as a continuous measure of symptom severity in numerous published studies (e.g. Dapretto, Davies, Pfeifer, Scott, Sigman, Bookheimer & Iacoboni, 2005; Joseph, Tager-Flusberg & Lord, 2002). The ADOS symptom measures used were the summary scores from the Module 3 diagnostic algorithm for communication (possible score of 0–8), reciprocal social interaction (possible score of 0–14) and repetitive behavior (possible score of 0–8) symptoms, with higher scores indicating increased severity.

Correlational analyses were conducted to assess the degree of association between symptom severity and the slope and intercept components of the RT × set size function for the present and absent conditions of static and dynamic search (see Table 2). Intercepts for static present search were negatively associated with ADOS social symptom scores, $r(19) = -.56$, $p < .01$, indicating that lower intercepts were associated with increased autism symptoms (see Figure 10). There were no other statistically significant correlations between search and ADOS measures. Partial correlations controlling for the effects of age, $r(18) = -.61$, $p < .01$, verbal IQ, $r(18) = -.57$, $p < .01$, and nonverbal IQ, $r(18) = -.57$, $p < .01$, showed that the negative association between ADOS social score and static present search intercept was independent of each of these factors. Because intercepts can vary inversely in relationship to slopes, a partial correlation was conducted to ensure that the negative correlation between social symptoms and static present intercepts was independent of the sizeable, although non-significant, positive correlation between social symptoms and static present slopes (see Table 2). When variance

Table 2 Correlations between ADOS symptom severity scores and search slopes and intercepts

	ADOS scores		
	Communication	Social	Repetitive behavior
Search slope			
Static present	.25	.39	.28
Static absent	-.24	-.15	-.08
Dynamic present	.04	.21	-.11
Dynamic absent	-.13	.01	.09
Search intercept			
Static present	-.23	-.56**	-.30
Static absent	.27	-.02	.06
Dynamic present	-.05	-.18	.20
Dynamic absent	-.17	-.18	-.12

* $p < .05$; ** $p < .01$.

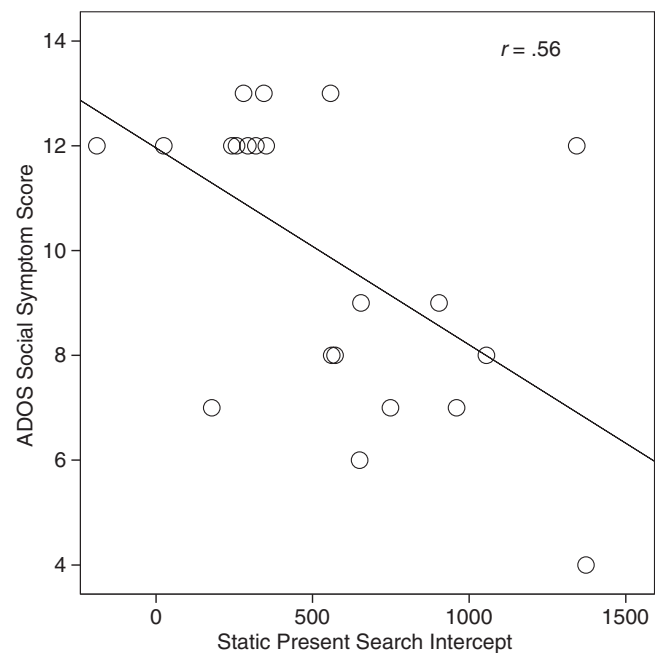


Figure 10 Negative correlation between the intercept of the RT × set size function for static present search and social symptom severity among ASD participants.

associated with static present slopes was partialled, the correlation between static present intercepts and ADOS social symptoms remained significant, $r(18) = -.45$, $p < .05$.

Discussion

We compared visual search performance in a group of rigorously diagnosed children with ASD and a comparison group of TD children who were matched on age and nonverbal IQ and found, consistent with prior research, that individuals with ASD significantly outperformed non-ASD individuals. Our primary goal, however, was to begin to identify the processing mechanisms that yield superior search performance in individuals with ASD. We considered mechanisms directly related to the process of search, and specifically the possibility that memory optimizes the deployment of attention through the search array in ASD, and we considered non-search mechanisms, most notably the possibility that facilitated perceptual processing resulting in enhanced discrimination of targets from distractors might boost visual search skills in ASD. Finally, we assessed the relationship between visual search superiority, and the specific processing differences contributing to it, and symptom severity in ASD participants. We outline our main findings below.

Search superiority in ASD is not due to memory

We examined the possibility that enhanced memory for the location of rejected distractors allows children with

ASD to sample the search array without replacement and thereby to augment their search efficiency. To do so, we compared children's search efficiency in a standard static search with search efficiency in a dynamic search condition, in which targets and distractors randomly changed locations every 500 ms, enforcing sampling with replacement and rendering memory for searched locations of little value. Like the TD comparison group, children with ASD showed no decrement in search efficiency in the dynamic relative to the static search condition, leading to the conclusion that memory does not play a special role in the visual search skills of children with ASD.

A possible objection to this conclusion is that participants may have used a radically different strategy in the dynamic condition, namely 'sitting and waiting' in one region of the search display until the target came to them (Geyer, von Mühlenen & Müller, 2007; Horowitz & Wolfe, 2003; von Mühlenen *et al.*, 2003). However, analyses of participants' eye movements indicated that they used similar search strategies in the two conditions. Participants from both groups appeared to search somewhat less actively in the dynamic condition. In dynamic as compared to static search, they made fewer fixations per trial (3.6 versus 4.1) that were of longer duration (462 versus 365 ms), and they made shorter saccades (7.7° versus 7.9°) and fewer fixations to the outer eccentricities of the search display. Nevertheless, the eye-movement data showed that participants searched the display in the dynamic condition rather than remaining fixated in one region, as would be expected if a sit-and-wait strategy were used. Furthermore, the distribution of fixations from most to least favored quadrants was the same in the static and dynamic conditions for both the TD and ASD groups. Had either group used a sit-and-wait strategy in the dynamic condition, fixations would have been concentrated in the most favored quadrant. Thus, the eye-movement data seem to rule out a fundamental difference in search strategy between the static and dynamic conditions and support the conclusion that individuals with ASD as well as TD individuals sample with replacement in visual search.

Our finding that participants' eye-movement behavior was not markedly different between static and dynamic search is at odds with results recently reported by Geyer *et al.* (2007). These authors found that the number of fixations and amplitude of saccades were several degrees of magnitude less in dynamic than in static search, showing that the two search conditions were associated with clear-cut differences in eye movements and suggesting that observers adopted a sit-and-wait strategy in the dynamic condition. The most likely explanation for these conflicting findings is the difference between studies in the refresh-rate of the dynamic stimuli. Whereas Geyer *et al.* used a frame duration of 117 ms in their dynamic search task, we used a frame duration of 500 ms. We chose this longer

presentation time to reduce the number of errors that occur with the shorter presentation time (Horowitz & Wolfe, 2003) as well as to allow the possibility of overt eye movements within a single frame, thus more closely approximating the conditions of static search, while at the same time greatly reducing the effectiveness of any memory-based search strategy.

Search superiority in ASD appears to derive from non-search processes

We further investigated the processing differences underlying ASD search superiority by comparing the slopes and intercepts of the RT \times set size functions for static and dynamic search between groups. If search superiority arose from the speed and efficiency with which participants with ASD shifted attention between items in the search display, we would expect the ASD group to exhibit shallower slopes than the TD group. In fact, search slopes did not differ between groups in either static or dynamic search, suggesting that children with ASD not only sampled the search display without replacement like TD children, but that they were otherwise similar to TD children in the manner in which they deployed their attention while searching.

While slopes were equivalent between groups, intercepts were uniformly lower in the ASD group in both static and dynamic search. According to the additive factors logic of Sternberg (1966), the intercept of the RT \times set size function is the portion of RT required by non-search aspects of the search task. These non-search factors can include initial, preattentive processing of basic feature information (e.g. color, orientation, size) as well as focal processing of stimulus features once attention has been deployed to a location of interest. In the present study, the critical configural information needed to distinguish a target (T) from a distractor (L) could not be perceived preattentively; rather, focal attention was required to discriminate between targets and distractors (Wolfe, 1992). Thus, it is likely that the ASD advantage reflected faster processing of individual items after they had been selected by attention. Additional support for the conclusion that the ASD advantage arose from non-search processes comes from our eye-movement findings. The number and spatial distribution of eye movements did not differ markedly between the two groups, with the exception that ASD participants made fewer saccades to the edges of the display in the static target present condition. However, the fixations of the ASD participants were significantly briefer, suggesting that they were able to make stimulus discriminations at the locus of attention more quickly than the TD participants.

Our results differed from those previously reported in the literature in that our ASD participants did not exhibit increased search efficiency (decreased RT \times set size slopes) relative to TD participants in either the static or dynamic condition. In prior studies, shallower search

slopes for individuals with ASD have either been explicitly reported (O’Riordan *et al.*, 2001) or can be inferred from group \times set size interactions showing a reduced increase of RT with set size in ASD (Kemner *et al.*, 2008; O’Riordan, 2004; O’Riordan & Plaisted, 2001; Plaisted *et al.*, 1998). One explanation for the difference between our and prior studies is the type of search stimuli used. Prior studies have used tasks in which preattentive processing of basic features could guide the deployment of attention. These have included the use of color in conjunction searches (O’Riordan, 2004; O’Riordan & Plaisted, 2001; Plaisted *et al.*, 1998) and orientation in searches for a vertical line among tilted lines (Kemner *et al.*, 2008; O’Riordan *et al.*, 2001). An improvement in search efficiency in these tasks could reflect an enhancement of preattentive processing in individuals with ASD. This explanation is in line with Kemner *et al.*’s (2008) finding that individuals with ASD made significantly fewer fixations than TD participants in searching for a vertical line target among tilted line distractors and their observation that many of their ASD participants were able to localize targets without moving their eyes. No benefit of this sort would be a factor in our study because no basic feature information differentiated targets, Ts, from distractors, Ls.

An ASD advantage in preattentive processing may also explain the difference in eye-movement behaviors observed in the present study and those reported by Kemner *et al.* (2008). Kemner *et al.* argued that either fewer or shorter fixations in their ASD participants would be consistent with enhanced discriminatory abilities underlying ASD search superiority, whereas longer fixations, which would allow increased extraction of information from the periphery of the fixation (Hooge & Erkelens, 1999), would be indicative of a different search strategy. Using the same feature search task administered by O’Riordan *et al.* (2001, Experiment 2), Kemner *et al.* found that their ASD participants were significantly faster than comparison participants at search. Further, supporting their enhanced discrimination hypothesis, they found that ASD participants made fewer fixations, although they did not differ from comparison participants in fixation duration. In contrast, we found that ASD participants made the same number of fixations as comparison participants, but the fixations were shorter. Both findings indicate enhanced discriminatory abilities, according to the logic of Kemner *et al.* Nevertheless, the difference is intriguing, and may reflect more efficient use of preattentive orientation information by ASD participants in Kemner *et al.*’s study. A preattentive advantage would not have been of much use with our stimuli, so ASD participants may have relied on briefer fixations to obtain their faster RTs.

Consistent with virtually all prior research on visual search in ASD, we found that the ASD search advantage was more prominent on target absent than on target present trials. There are several possible explanations for

this robust finding. O’Riordan *et al.* (2001) suggested that, because determining the absence of a target is more difficult than determining the presence of a target, the target absent condition may have simply provided a more sensitive measure of group differences in search skills. O’Riordan *et al.* (2001) also suggested that an enhanced ability to discriminate among stimuli may give individuals with ASD increased confidence in their judgment that no target is present. In other words, individuals with ASD benefited from a lower quitting threshold on absent trials that allowed them to terminate search more expediently (Chun & Wolfe, 1996). Such a decision-stage advantage would manifest itself in reduced intercepts, reflecting non-search components of task performance, which is precisely what we found. It may seem equally plausible that individuals with ASD terminated target absent searches more quickly than comparison participants simply because they were less motivated to keep looking and not because they had a perceptual advantage. However, if this were true, we would have expected a higher rate of error in the ASD group, which we did not find.

Also notable was our finding that children with ASD were less affected in their reaction time by the dynamic search manipulation than TD children. We propose two possible explanations for this. First, the consistently shorter fixation durations of ASD participants suggests that they were more able than TD participants to complete an inspection of an area of the display within the 500 ms presentation frame, which would have the effect of reducing median RT. Second, it is also conceivable that children with ASD were less distracted by the random re-plotting and reorienting of the search elements in each new search frame. Although speculative, the idea that the dynamic manipulation may have introduced less noise into the visual display for ASD participants is supported by recent evidence of impaired attentional prioritization of abrupt onset stimuli in ASD (Greenaway & Plaisted, 2005; Keehn & Joseph, 2008). In the context of dynamic search, reduced sensitivity to the repeated re-plotting of the search elements could have contributed to the RT advantage of ASD participants.

Participants with ASD not only exhibited consistently lower search intercepts than did TD participants, but intercepts in static search varied inversely with ADOS social symptom severity in the ASD group. In other words, individuals who showed evidence of an enhanced ability to discriminate between targets and distractors had higher levels of social symptoms, suggesting that enhanced visual perception, and the putative differences in brain organization and function that this perceptual enhancement reflects, may be of etiological significance in the development of autistic social impairment. Evidence of a relationship between atypically enhanced visual perceptual skills and increased symptom severity in ASD is in agreement with the findings of Joseph *et al.* (2002), who investigated IQ profiles in relation to symptom severity in ASD using the ADOS. They

found that children with ASD whose visual-perceptual skills were discrepantly higher than their verbal skills exhibited increased social symptom severity on the ADOS, and that this relationship was independent of children's absolute levels of verbal and overall cognitive ability. Nonetheless, we must consider our present finding preliminary and in need of further investigation given that it was limited to static present search and extended to neither the absent nor the dynamic search conditions.

Conclusions and implications

In conclusion, our findings suggest that non-search factors in general and enhanced visual perception in particular account for the visual search advantage exhibited by individuals with ASD. These findings fit with a growing corpus of literature indicating an abnormal enhancement of visual perceptual abilities in ASD (see Dakin & Frith, 2005; Mottron, Dawson, Soulieres, Hubert & Burack, 2006, for reviews). The neural bases of enhanced visual-perceptual discrimination in ASD remain to be determined. Two types of possibility have been considered. One is that local anomalies at the site of early visual processing, such as malformation of minicolumn microcircuitry (Casanova, Buxhoeveden & Gomez, 2003), result in an over-amplification of lower-level visual information (e.g. Bertone, Mottron, Jelenic & Faubert, 2005; Plaisted, Saksida, Alcantara & Weisblatt, 2003). The other is that disturbances in longer-range cortical connectivity, a possible outcome of early cerebral overgrowth (Lewis & Ellman, 2008), results in diminished top-down modulation or integration of lower-level perceptual processes (e.g. Courchesne & Pierce, 2005; Just, Cherkassky, Keller, Kana & Minshew, 2007). These possibilities are not mutually exclusive, and the underlying disturbances in brain organization (regionally non-specific abnormalities in rate of cerebral growth and in cortical minicolumn formation) hypothesized to cause them are not necessarily independent of one another. Innovations in non-invasive imaging methodologies for investigating brain structure and function at the macroscopic level, in conjunction with continued histological study of the brain at the microscopic level, promise to advance our understanding of the brain bases of differences in visual perception and attention in ASD.

Although preliminary, our finding of a link between enhanced visual perception and increased autism symptom severity may shed light on neurofunctional differences that underlie the development of the defining behaviors of ASD. It could be argued that atypical perceptual processing in children with ASD is a secondary effect of profound social-communicative deficits that alter the nature of the child's early environmental inputs and disturb the normal course of brain growth and organization. Studies showing that restricted interests (including unusual sensory interests)

become more pronounced over the preschool years in toddlers diagnosed with ASD (Charman & Baird, 2002; Cox, Klein, Charman, Baird, Baron-Cohen, Swettenham, Drew & Wheelwright, 1999) would seem to agree with this view. However, other evidence indicates that unusual visual sensory interests are present at the age of 2 (Lord, 1995) and as early as 1 year of age (Zwaigenbaum, Bryson, Roberts, Rogers, Brian & Szatmari, 2005) in children who develop ASD, which would make this view less tenable. At least two other distinct possibilities remain. First, the same fundamental defects in the regulation of brain ontogenesis in ASD may result in the co-occurrence of functionally dissociable abnormalities in visual perceptual processes and social-communicative competence. Second, atypicalities in visual perception and attention may contribute directly to abnormal social-communicative development in ASD, regardless of whether or not these functional anomalies arise from the same neuropathological processes. This seems especially plausible given that visual information processing is so vital to social-communicative functioning. Longitudinal behavioral research with young children with or at risk for autism will help to determine between these two possibilities and will have important implications for the development of more effective remedial and preventive treatments for ASD symptoms.

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