

Eye Movement Difficulties in Autism Spectrum Disorder: Implications for Implicit Contextual Learning

Anastasia Kourkoulou, Gustav Kuhn, John M. Findlay, and Susan R. Leekam

It is widely accepted that we use contextual information to guide our gaze when searching for an object. People with autism spectrum disorder (ASD) also utilise contextual information in this way; yet, their visual search in tasks of this kind is much slower compared with people without ASD. The aim of the current study was to explore the reason for this by measuring eye movements. Eye movement analyses revealed that the slowing of visual search was not caused by making a greater number of fixations. Instead, participants in the ASD group were slower to launch their first saccade, and the duration of their fixations was longer. These results indicate that slowed search in ASD in contextual learning tasks is not due to differences in the spatial allocation of attention but due to temporal delays in the initial-reflexive orienting of attention and subsequent-focused attention. These results have broader implications for understanding the unusual attention profile of individuals with ASD and how their attention may be shaped by learning. *Autism Res* 2013, ●●: ●●–●●. © 2013 International Society for Autism Research, Wiley Periodicals, Inc.

Keywords: autism; eye movements; visual search; implicit learning; contextual cueing

Introduction

Objects never occur in isolation; they covary with other objects, creating a rich array of contextual associations that the visual system can exploit [Oliva & Torralba, 2007]. Learning of such contextual information is an important ability because it enables us to search and recognise objects faster. Implicit contextual learning refers to our ability to automatically memorise contextual associations in the environment and to use this learned information to enhance our search performance in future encounters within the same environment [Chun & Jiang, 1998]. For instance, from repeatedly searching for a computer file (target object) among numerous computer files (distractor objects), some incidental learning may occur that is likely to facilitate future search.

In a laboratory setting, this type of learning is typically tested using a visual search task in which participants are presented with a series of computerised displays and are required to locate targets that are embedded among configurations of similar distractor items [Chun & Jiang, 1998]. In this task, some of the displays, unbeknownst to the participants, are repeated during the course of the experiment. On these repeated trials, the target and its context of distractors are exactly the same. Although participants are typically unaware of the repetition, they are able to locate the target more rapidly than when the target is embedded within a novel context. Chun and

Jiang [1998] termed this effect contextual cueing because implicit learning of visual context cues attention to the target, facilitating search.

Studies that have measured eye movements during the contextual cueing task have increased our understanding of the way in which learning facilitates visual search [van Asselen, Sampaio, Pina, & Castelo-Branco, 2011; Brockmole & Henderson, 2006; Hout & Goldinger, 2012; Neider & Zelinsky, 2006; Peterson & Kramer, 2001; Tseng & Li, 2004]. Peterson and Kramer [2001] showed that in repeated displays, *fewer fixations* were required before the target was located, and the proportion of initial fixations that landed on the target was greater for repeated displays. Hout and Goldinger [2012] termed this effect the spatial mapping hypothesis. Moreover, it has been shown that learning of the distractor items results in faster processing and recognition of these items, which itself leads to *lower fixation duration* [van Asselen et al., 2011]. Hout and Goldinger [2012] termed this the rapid identification and dismissal hypothesis.

The study of eye movement measures also offers new insights on the unusual profile of visual attention in individuals who have autism spectrum disorder (ASD). ASD is diagnosed due to impairments in social communication, social interaction, together with repetitive and rigid patterns of behaviour [American Psychiatric Association, 2000; Wing & Gould, 1979]. Atypical visual attention patterns have increasingly been recognised

From the Wales Autism Research Centre, School of Psychology, Cardiff University, Tower Building, Cardiff, UK (A.K., S.R.L.); Department of Psychology, Goldsmiths, University of London, New Cross, NW (G.K.); Department of Psychology, Durham University, South Road, Durham, UK (J.M.F.)

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Address for correspondence and reprints: Anastasia Kourkoulou, Psychiatry Department, Medical School, Aeginition Hospital, National and Kapodistrian University of Athens, 72 V. Sofias Avenue, 11528 Athens, Greece. E-mail: kourkouloua@gmail.com

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alongside these clinical features [for reviews, see Ames & Fletcher-Watson, 2010; Simmons et al., 2009]. Numerous studies show superior visual search in those with ASD for embedded figure detection [Falter, Plaisted, & Davis, 2008; Jarrold, Gilchrist, & Bender, 2005; Jolliffe & Baron-Cohen, 1997; de Jonge et al., 2007; Pellicano, Gibson, Maybery, Durkin, & Badcock, 2005; Ropar & Mitchell, 2001; Shah & Frith, 1983] and for block design tasks [Caron, Mottron, Berthiaume, & Dawson, 2006; Happé, 1994; Shah & Frith, 1993]. Both the embedded figures and the block design tasks can be regarded as forms of visual search, and the bulk of evidence suggests superior performance in these tasks by people with ASD [Simmons et al., 2009].

Nevertheless, the picture becomes less clear when visual attention is studied by employing visual search tasks. While faster or equal search performance has been shown in certain tasks [Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; Kemner, Van Ewijk, Van Engeland, & Hooge, 2008; O’Riordan, 2004; O’Riordan & Plaisted, 2001; O’Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O’Riordan, & Baron-Cohen, 1998], slower responding has been reported in others. Slower responding is documented in contextual cueing studies. These reveal that while individuals with ASD detect targets more rapidly on repeated trials than non-repeated trials, showing that they are able to make use of context, nevertheless, they are slower to respond compared with typically developing (TD) individuals [Barnes et al., 2008; Brown, Aczél, Jiménez, Kaufman, & Plaisted-Grant, 2010; Kourkoulou, Leekam, & Findlay, 2012]. Slower responding in ASD has been detected in both global and local repeated contexts, and therefore, it cannot be attributed to a difficulty in processing global context information [Kourkoulou et al., 2012]. It is also detected in novel trials as well as repeated trials, suggesting that slower responding is not specific to material that is memorised and learned.

The most perceptible distinction that exists between tasks that show faster or equal search performance and those of contextual cueing relates to the way that attention is controlled in each set of tasks. In the first set of tasks, attention is most effectively directed towards target objects that are dissimilar from other distractor objects. Spatial attention to the target is controlled by the saliency of stimulus features in a *stimulus-driven* manner (e.g. searching for a red X among a set of black Xs) or by an observer’s goal in a *goal-driven* manner (e.g. knowing that the target is red biases attention towards red items) [Navalpakkam & Itti, 2006]. Evidence that faster visual search is associated with inspection time (a measure of speed of processing) has been used to argue that enhanced visual search abilities in ASD may be at least partly explained by faster speed of processing abilities [Brock, Xu, & Brooks, 2011]. This proposal is in accor-

dance to the enhanced perceptual capacity claim of the Enhanced Perceptual Functioning Model [EPF; Mottron, Dawson, Soulières, Hubert, & Burack, 2006].

In contrast, in contextual cueing studies, attention is *experience-driven* because incidental learning that is formed by previous experience is what speeds visual search [Jiang, Swallow, Rosenbaum, & Herzig, 2012b]. What is unresolved is whether this incidental learning speeds visual search because it guides spatial attention or because it lowers response thresholds [Hout & Goldinger, 2012; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Kunar, Flusberg, & Wolfe, 2008]. What is more certain is that experience-driven attention is an automatic form of attention because it does not require an intention to learn or the intention to use prior experience for performing the task effectively [Jiang, Swallow, & Rosenbaum, 2012b] and it biases attention for a long time [Jiang, Swallow, Rosenbaum et al., 2012a]. Based on these findings, Jiang et al. [2012a] concluded that experience-driven attention may constitute a source of attention that is distinct from the other two sources of goal-driven and stimulus-driven attention.

The idea that variable performance in ASD depends on how attention is controlled is reminiscent of findings beyond visual search tasks. For instance, children with ASD voluntarily attend to the local level in Navon-type tasks, but they are also able to attend to the global level if instructed to do so [Iarocci, Burack, Shore, Mottron, & Enns, 2006; Plaisted, Swettenham, & Rees, 1999]. According to the EPF model [Mottron et al., 2006], performance in these Navon-type tasks reveals that by default, the perception of individuals with ASD is more locally oriented than that of TD individuals. In the social domain too, it has been shown that people with ASD perform more like TD individuals in conditions where there are instructions or cues about what to select, but they show poorer performance when their attention builds upon their experience (experience-driven attention) resulting in a preference for attending to objects vs. faces [e.g. Fletcher-Watson, Leekam, Benson, Frank, & Findlay, 2009; Kikuchi et al., 2011; Kuhn, Kourkoulou, & Leekam, 2010; López, Donnelly, Hadwin, & Leekam, 2004]. It has been proposed that the impairments that people with ASD show in orienting and shifting attention spontaneously towards social stimuli such as faces is due to the complexity and unpredictability that characterises such stimuli [Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998]. Difficulties in the fast disengagement of attention have also been reported in individuals with ASD [e.g. Kikuchi et al., 2011].

It is well known that the shifting of attention in space while searching for an object is followed by eye movements [Findlay, 2004]. Two common oculomotor measures that have been used to study the spatiotemporal evolution of visual search in ASD are fixation frequency

and fixation duration. Joseph et al. [2009] found that the ASD and TD groups were similar in fixation frequency and concluded that superior search in ASD could not be due to enhanced memory of previously visited locations because if this was true, then fixation frequency would be smaller for children with ASD. Instead, the authors found shorter fixation duration in children with ASD and supported that superior visual search in ASD is related to non-search factors and more specifically to enhanced discrimination abilities at the current focus of attention. Kemner et al. [2008] also found shorter fixation duration in a group of children with pervasive developmental disorder.

In the present study, an analysis of fixation frequency and fixation duration during the contextual cueing task allowed the spatial (fixation frequency) and temporal (fixation duration) aspects of saccade programming to be tested. We hypothesised that if slower search in ASD in the contextual cueing task is associated with reduced learning for distractor locations that are already inspected, this would result in a greater number of fixations because items would be refixated. If this “spatial hypothesis” is true, then it goes against the idea of impaired attention shifting in ASD. If slower search is because more time is spent at the current focus of attention (i.e. longer fixation duration), then this would suggest that more time is needed to identify and reject familiar distractors and to relate the visual representation to the internalised representation. If this “temporal hypothesis” is true, then it goes against evidence of enhanced discrimination abilities that are found in other type of visual search tasks and points to difficulties in the disengagement of attention.

We also varied the size of the repeated context in the search displays based on recent findings [Brady & Chun, 2007; Olson & Chun, 2002] showing that the contextual cueing Reaction Time (RT) benefit can be obtained from repetition of just the local context (i.e. the immediately surrounding the target region). Thus, we contrasted a “whole context” condition in which the entire display is repeated across blocks, with a “local context” condition in which only two items located immediately adjacent to the target were repeated. In both conditions, the local configuration is repeated, but whereas in the local context condition, there are changing sections; in the whole context condition, the entire displays remain unchanged across repetitions.

Method

Participants

Fifteen individuals (12 males) with ASD aged 17–22 years were recruited from a special college for autism. All had been diagnosed with high-functioning autism or Asperger’s syndrome by experienced clinicians according

Table 1. Participant Demographic Characteristics (Means with Standard Deviations in Brackets)

Group	Age in years	WASI		
		Verbal	Non-verbal	Full-scale
ASD	19 (1.6)	98.3 (15.5)	104.2 (12.9)	101.3 (12.4)
TD	21 (4.1)	97.6 (9.8)	107.1 (10.3)	102.7 (9.5)

WASI, Wechsler Abbreviated Scale of Intelligence.

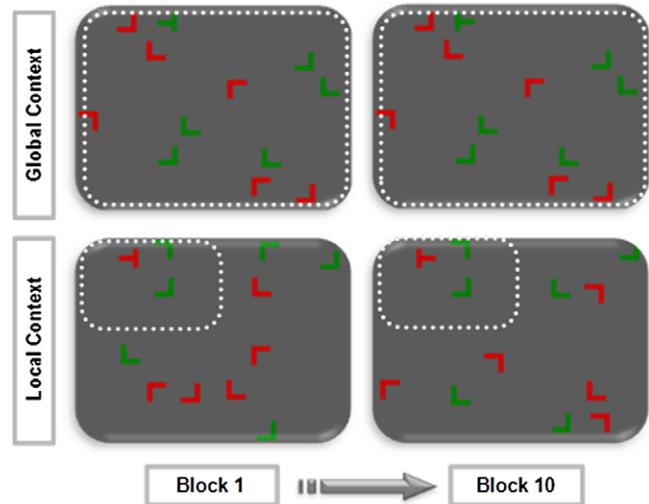


Figure 1. Example stimuli of the whole context and local context conditions used in the experiment.

to the Autism Diagnostic Observation Schedule [Lord et al., 1989] and/or the Autism Diagnostic Interview-Revised [Lord, Rutter, & Le-Couteur, 1994]. A comparison group of 18 TD individuals (16 males) aged 18–34 years was recruited from mainstream further education colleges. All participants obtained full-scale intelligence quotient (IQ) scores above the average range (IQ > 80) [Wechsler Abbreviated Scale of Intelligence; Wechsler, 1999]. They reported normal or corrected-to-normal visual acuity and took part in this study as paid volunteers. Six individuals with ASD and three TD individuals participated in both the present study as well as in our recent study [Kourkoulou et al., 2012].

Demographic characteristics of the two groups are presented in Table 1. The groups were group-wise matched for chronological age, $t(31) = 1.35$, $P = 0.19$; verbal IQ, $t(31) = 0.16$, $P = 0.87$; non-verbal IQ $t(31) = 0.72$, $P = 0.48$; and full-scale IQ, $t(31) = 0.36$, $P = 0.72$.

Display

As depicted in Figure 1, each visual search display was made up of 12 items (11 distractors and one target) that appeared in an invisible 8×6 grid and subtended

approximately 37×28 degrees in visual angle. The distractor items were L shapes rotated in four orientations (0° , 90° , 180° , or 270°) and presented at randomly chosen locations. The target item was a T shape rotated 90° either to the left or to the right with equal probability. Participants responded by pressing one of the two keys on the keyboard depending on where the tail of the target “T” pointed to the left or to the right. They pressed the “Z” key for a target pointing to the left and the period “.” key for a target pointing to the right. They were asked to respond as accurately and as quickly as possible. Each display consisted of an equal number of red and green items presented against a grey background. Similarly to Brady and Chun [2007], the total display was made up of four equally sized rectangular areas, and within each area, there were three items in order to prevent a greater number of stimuli appearing on one side of the display more than the other. Also, in line with Brady and Chun’s [2007] study targets were more likely to be aligned to items within the same quadrant rather than across quadrants. The target quadrant contained one target item and two other distractor items, while the distractor quadrants always contained three distractors. The size of the stimuli and their jittered positions were identical to the ones used in the original article [Chun & Jiang, 1998, Experiment 1).

Design

Participants completed 16 blocks of trials; the first ten blocks were the learning session, the next four blocks were the transfer (test) session, and the last two blocks were the recognition session.

Learning. Sixteen trials were tested in each block, divided into two conditions: *whole context* and *local context*. Each included eight trials. Each trial contained one target and 11 distractors. In both conditions, a certain target location was always repeated across different blocks, but the distractor sets might not be repeated. In the *whole context* condition, the entire distractor set was exactly repeated from one block to the other. In the *local context* condition, only the two distractors most adjacent to the target (termed the target region) were repeated. In both context conditions, the target appeared in the same location within any particular configuration. The target’s identity (left or right T) was randomly chosen on each trial.

Transfer. A transfer session was initiated immediately after the last learning block, without new instructions. Each block included 16 trials, half of which were the same as those in the learning session. These will be referred to as *repeated* trials. The other trials were transfer trials, in which the distractor sets were newly generated. These were the *novel* trials. Repeated and novel

trials were randomly intermixed within a block; each block included three conditions: *whole context*, *local context*, and *novel*.

Recognition. A recognition test was administered at the conclusion of the search task. The recognition test was similar to that used in previous contextual cueing studies [Chun & Jiang, 1998; Olson & Chun, 2002]. The test is administered to assess participants’ knowledge about whether they had noticed that there was a repetition across blocks. Participants were not informed at the beginning of the experiment about this test. In the recognition test, first the computer displayed a question asking, “Did you notice whether certain displays were being repeated?” and then the computer displayed 32 trials in random order. Sixteen trials were from the repeated set (eight *whole context*, eight *local context*), and 16 trials were novel trials that were not previously seen during the search task. Participants responded by pressing either a YES or a NO button on a response button box.

Procedure

Participants were not informed that some displays were repeated during the experiment and were simply instructed to search for the target and respond to it as accurately and as quickly as possible. Prior to the experimental session, participants completed a nine-point calibration procedure that served to map the output of the eye tracker on the display’s position. Calibration was repeated if the mean error of a point was above 0.5° . Each visual search trial started with a 500 msec fixation period followed by the search display that remained on the screen until the participant made a response. This procedure allowed us to perform a drift correction and ensured that participants fixated the centre of the screen. At the end of each block, participants were allowed to take a break. Before the learning session started, participants received 16 trials of practice in order to increase familiarity with the task. Practice trials are similar to the subsequent test (learning and transfer) trials, in that each trial display contained a T target among 11 L-shaped distractors and participants were instructed to search for the target. None of the practice trials were used as learning or transfer trials.

Apparatus

Eye movements were recorded using an SR Research EyeLink II System (Kanata, Ontario, Canada) that has a 500-Hz sampling rate and 0.01° spatial resolution. The system uses infrared cameras on a headset to transmit information about the participants’ head and pupil positions to the eye tracker. The experiment was run using

Experiment Builder (SR Research's built-in software) and displayed on a 21-inch cathode ray tube monitor (75 Hz). All the stimuli were generated with a program that was written by the department's information technologist officer using Visual C++. Although viewing was binocular, only the dominant eye was monitored by the eye tracking system. The right eye was monitored in 9 out of 15 individuals with ASD and in 10 out of 18 TD individuals. A chi-square test confirmed that there was no association between group and eye dominance, $\chi^2(1, n = 33) < 1$.

Results

Manual RT Analysis

Trials were excluded from analysis if a response was incorrect (1.2% of ASD trials and < 1% of TD trials) or was not made within 5 sec (< 1% of ASD and TD trials), and the number of excluded trials was similar between the groups ($P = 0.3$). As the focus of interest is the efficiency with which the eyes were directed to the target object region, trials in which a participant did not fixate the target region prior to response were eliminated (3% of ASD trials and 2.3% of TD trials), and again, the number of excluded trials was similar between the groups ($P = 0.8$). For repeated measures analyses, Mauchly's [1940] test was inspected, and departure from sphericity was corrected using the Greenhouse–Geisser epsilon [Greenhouse & Geisser, 1959]. Corrected degrees of freedom are reported to one decimal place. Figure 2 represents the mean RT (msec) across blocks on learning (left panel) and transfer phase (right panel). Consistent with other studies (e.g. Chun & Jiang, 1998; Olson & Chun, 2002), we averaged the reaction time of two successive blocks to create an epoch as a means to increase the statistical power.

Learning. In the first block of the experiment, there were no reaction time differences between the WholeCxt and LocalCxt conditions, $F < 1$, suggesting that any differences between conditions later in the experiment were due to learning. The mean RT for all correct trials was analysed using an Epoch (1–5) \times Context (Whole, Local) \times Group (ASD, TD) mixed analysis of variance (ANOVA). The main effect of group was significant, $F(1,31) = 4.7, P < 0.05, \eta_p^2 = 0.13$, as the ASD group was slower in both WholeCxt and LocalCxt trials compared with the TD group by 195 msec on average. Both groups exhibited perceptual/skill learning [Chun & Phelps, 1999; Schneider & Shiffrin, 1977] because search times became significantly faster as the experiment progressed (main effect of epoch), $F(2.8,86.6) = 30.5, P < 0.00001, \epsilon = 0.69, \eta_p^2 = 0.50$. None of the other main ($F < 1$) or interaction effects (all $P \geq 0.13$) reached significance.

Transfer. The mean RT for all correct trials was analysed using a Context (Whole, Local, Novel) \times Group (ASD, TD) mixed ANOVA. The main effect of trial type was significant, $F(1.6,49.6) = 8.52, \epsilon = 0.8, P = 0.001, \eta_p^2 = 0.22$, and pairwise comparisons showed that both groups detected targets faster in whole ($m = 97$ msec, $P < 0.0005$) and local context trials ($m = 82$ msec, $P < 0.005$) compared with novel trials, and this benefit in search time shows *contextual cueing*. In addition, the main effect of group was significant, $F(1,31) = 4.22, P = 0.05, \eta_p^2 = 0.12$, as the ASD group was slower by 138 msec on average. The interaction of group with trial type was not significant ($P = 0.35$) indicating that the overall magnitude of contextual cueing was not greater in one of the groups.

Analysis of covariance. Although the two groups are well matched on IQ, there is always the possibility that

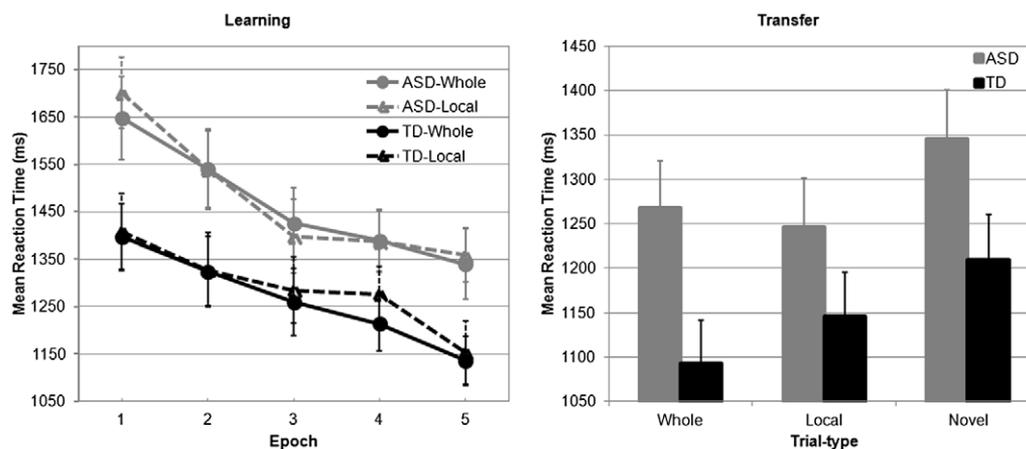


Figure 2. Mean manual reaction time (in msec) across the whole context and the local context conditions as a function of group and epoch (one epoch = two blocks). ASD, autism spectrum disorder; TD, typically developing.

because reaction time is related to IQ that slower search may be carried by a few participants with ASD who are at the lower end of IQ. To test this possibility, in the aforementioned mixed ANOVA, full-scale IQ was entered as a covariate. Findings showed no significant IQ effects, while the group effect persisted both in learning and in transfer phases (both $P < 0.05$).

Recognition phase. Replicating previous research, we established that participants showed implicit memory of the repeated displays. We compared the hit rate (correct recognition of the repeated displays as previously seen) with the false-alarm rate (incorrect recognition of the novel displays as previously seen). Chance levels were at 50%. There was one participant from the ASD group who did not carry out the recognition task, reducing the number of ASD participants to 14. A mixed ANOVA with Rate (Hit, False Alarm) \times Condition (WholeCxt, LocalCxt) \times Group (ASD, TD) was performed. Findings showed that the main effect of rate was not significant ($F < 1$), as hit rate (TD 46%, ASD 53%) did not significantly differ from false-alarm rate (TD 42%, ASD 62%). This result indicated that memory representations of context were implicit for both groups.

Eye Movement Analysis

A fixation was counted as landing on the target region if it fell within a rectangular area that encompassed three items (the target and two distractors). The target region represents 25% of the total display. We defined the target region following recent research on contextual cueing [Brady & Chun, 2007] that has shown that learning in the contextual cueing task may be restricted to target quadrant (the target and two local distractors) even when the entire configuration is repeated.

To test the *temporal hypothesis* according to which slower search derives from a greater fixation duration and saccade duration, we explored (a) time from the start of the search display to the initiation of the first saccade, (b) duration of the initial fixation, (c) time interval from movement away from the initial fixation until the first fixation that entered the target region (scan time), (d) time spent from the first fixation that entered the target region to making a response (gaze duration). From these oculomotor parameters, the duration of initial fixation, scan time and gaze duration are three measures that are independent of each other, and together, they make up the total reaction time in a trial [Hidalgo-Sotelo, Oliva, & Torralba, 2005]. Figure 3 represents the decomposition of RT into these three different stages. To test the *spatial hypothesis* according to which slower search results from a greater number of fixations, we explored the fixation frequency within a trial and within the target region.

Temporal hypothesis: do longer duration of fixations and saccades contribute to slower search in ASD?

Time to initiate first saccade. Time to initiate the first saccade is defined as the time from the start of the search display to the occurrence of the first saccade. This measure examines the influence of contextual learning in the pre-attentive processing of visual information that guides attention before the first saccade is initiated. In the learning phase, ASD participants were slower to initiate their first saccade ($m = 198$ msec) than participants in the TD group ($m = 173$ msec), $F(1,31) = 4.96$, $P < 0.05$, $\eta_p^2 = 0.14$. No other main (all $P > 0.25$) or interaction effects (all $P > 0.20$) reached significance.

In the transfer phase, there was a main effect of trial type, $F(2,62) = 5.70$, $P = 0.005$, $\eta_p^2 = 0.15$, described by a reliable quadratic trend, $F(1,31) = 11.74$, $P < 0.005$, $\eta_p^2 = 0.275$, because the latency of the first saccade was smaller in LocalCxt trials compared with WholeCxt and Novel trials. A main effect of group, $F(1,31) = 6.57$, $P = 0.01$, $\eta_p^2 = 0.175$, revealed that ASD participants were slower to initiate their first saccade ($m = 204$ msec) compared with participants in the TD group ($m = 173$ msec), while the interaction between group and trial type was not significant ($P = 0.070$). These findings suggest that latency of the first saccade may change as a result of learning and it is longer in the ASD group.

Duration of initial fixation. The initial fixation is the first fixation that observers perform following trial onset. This measure examines whether contextual learning directs attention as soon as the initial fixation. In the learning phase, the ASD group showed on average a greater duration of the initial fixation of 23 msec compared with the TD group, $F(1,31) = 4.24$, $P = 0.05$, $\eta_p^2 = 0.12$, and this was true for both WholeCxt and LocalCxt trials. No other main or interaction effects reached significance (all $P > 0.14$).

In the transfer phase, the ASD group showed on average about 26 msec greater duration in the initial fixation than the TD group, $F(1,31) = 4.64$, $P < 0.05$, $\eta_p^2 = 0.13$. There was a main effect of trial type, $F(2,62) = 3.60$, $P < 0.05$, $\eta_p^2 = 0.10$, described by a reliable quadratic trend because similarly to the initial saccade latency, initial duration in LocalCxt trials was smaller than in WholeCxt trials and Novel trials, $F(1,31) = 6.57$, $P = 0.01$, $\eta_p^2 = 0.17$.

Scan time. Scan time is defined as the time from moving away from the first fixation until the first entry to the target region. This measure examines whether contextual learning directs attention faster by reducing the time it takes to process the distractor items. In the learning phase, scan time to enter the target region was reduced with time, $F(4,124) = 7.19$, $P < 0.00005$, $\eta_p^2 = 0.19$. The

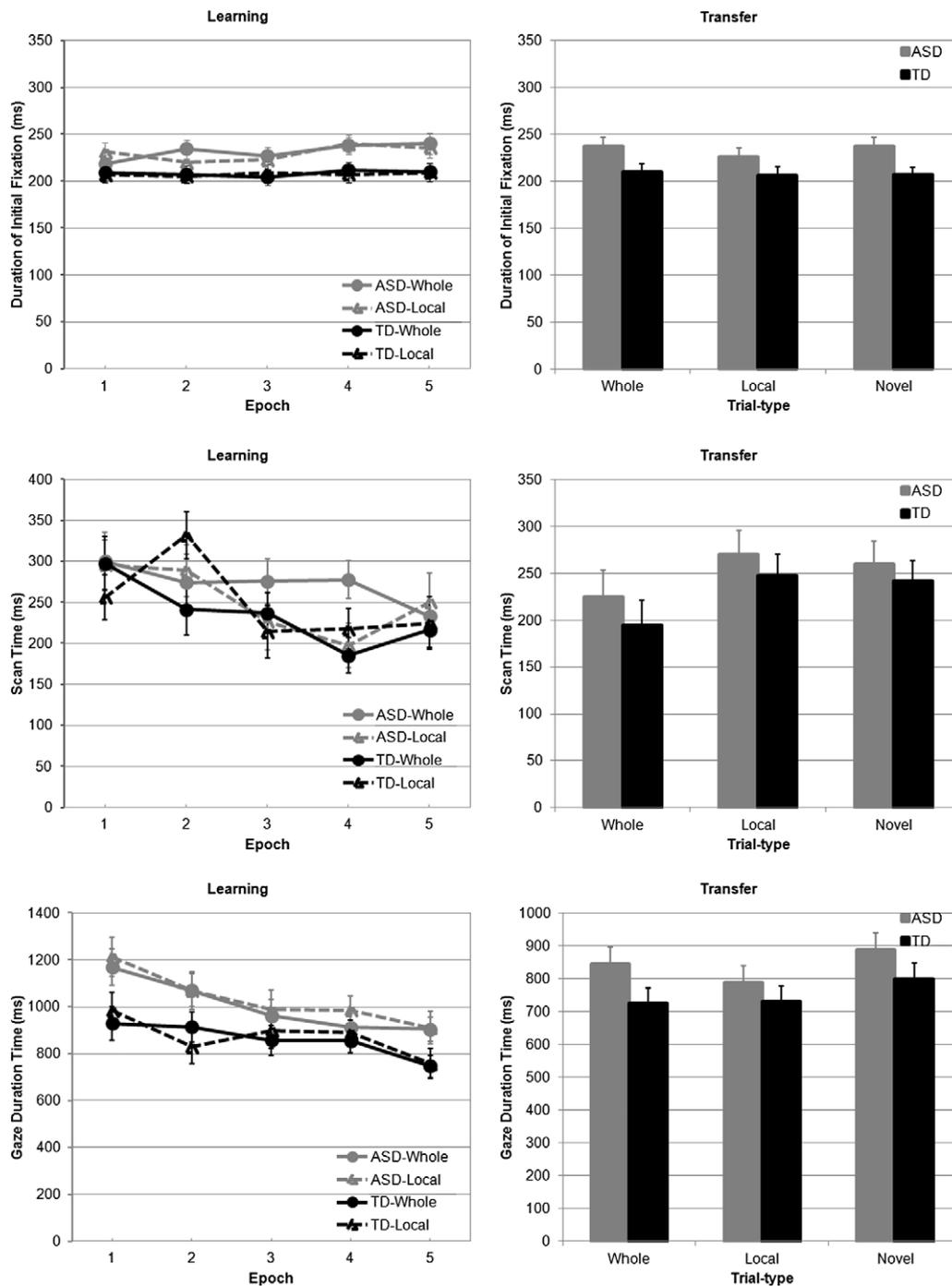


Figure 3. Decomposition of reaction time into initial fixation, scan time, and gaze duration in the whole context and local context. ASD, autism spectrum disorder; TD, typically developing.

main effect of group was not significant, as the ASD group was slower compared with the TD group by only 20 msec. The effect of condition was not significant ($F < 1$), and none of the interaction effects reached significance (all $P > 0.09$).

In the transfer phase, scan time to enter the target region was shorter in WholeCxt trials compared with LocalCxt and novel trials, $F(2,62) = 3.1$, $P = 0.05$,

$\eta_p^2 = 0.09$. The main effect of group was not significant as the ASD group was slower compared with the TD group only by 24 msec, and the interaction effect also did not reach significance (all $F < 1$).

Gaze duration. Gaze duration is defined as the time spent from entry in the target region to making a response. This measure encompasses both the time to explore the items

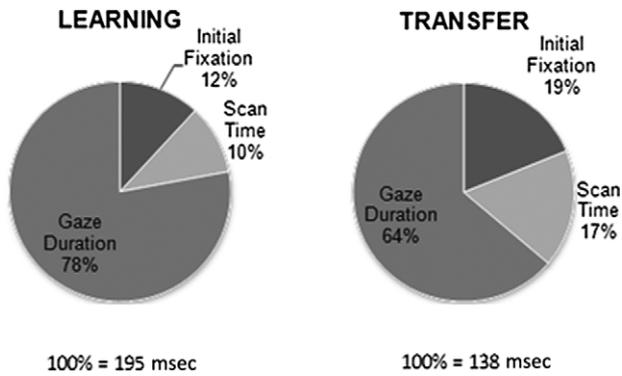


Figure 4. Summary of how the total reaction time cost of the autism spectrum disorder (ASD) group compared with the typically developing (TD) group is distributed during the search process. The pie charts represent how much longer—expressed as a percentage—the fixations of the ASD group were in comparison with TD individuals across the different stages. In the learning phase, the ASD group was slower compared with the TD group by 195 msec and in the transfer phase by 138 msec. The overall reaction time cost is explained entirely by the initial fixation, scan time, and gaze duration of the target region. The breakdown of percentage of the reaction time cost in ASD shows that its majority is accumulated in the gaze duration stage.

in the target region but also outside of it because the eyes may have entered the target region and move outside the target region before they made the response. In addition, gaze duration encompasses the decision time to make a motor response. In the learning phase, gaze duration of the target region was reduced with time, $F(4,124) = 15.58$, $P < 0.00001$, $\eta_p^2 = 0.33$, and the ASD group was slower, albeit not significantly, by 152 msec, $F(1,31) = 3.43$, $P = 0.07$, $\eta_p^2 = 0.10$. All other effects did not reach significance (all $P > 0.08$).

In the transfer phase, there was a main effect of trial type, $F(2,62) = 5.91$, $P < 0.005$, $\eta_p^2 = 0.16$, because gaze duration was shorter in WholeCxt and LocalCxt trials compared with novel trials by 60 and 84 msec, respectively. This finding of similar magnitude of learning in the two conditions is consistent with the hypothesis that the contextual cueing task is associated with learning of the local context of the target. The main effect of group was not significant although the ASD group was slower compared with the TD group by 88 msec ($P = 0.17$). The interaction effect did not reach significance ($F < 1$).

In sum, the ASD group was slower compared with the TD group, and this reaction time cost was 195 msec in the learning phase and 138 msec in the transfer phase because of the longer fixation durations, particularly at the gaze duration stage. Figure 4 illustrates how the reaction time cost is distributed in the three different stages that make up the total reaction time. In regards to the gaze duration stage, the ASD group shows 78% longer

fixation duration compared with the TD group in the learning phase, and this percentage reduces to 64% in the transfer phase. Thus, the initial fixation and scan time contribute less to the slower search in ASD.

Spatial hypothesis: over time, do people with ASD demonstrate slower search by making a greater number of fixations?

Trial fixation frequency. Fixation frequency is defined as the number of fixations that occurred in a trial. This measure examines whether contextual learning results in fewer fixations. In the learning phase, the number of fixations that occurred in a trial decreased from seven to six over the course of five epochs, $F(3.0,93.54) = 41.34$, $P < 0.00001$, $\epsilon = 0.75$, $\eta_p^2 = 0.50$, which suggests that participants became more efficient over time in locating the target in a display. None of the other effects reached significance (all $P < 0.21$).

In the transfer phase, there was a main effect of trial type, $F(2,62) = 6.95$, $P < 0.005$, $\eta_p^2 = 0.18$, and as planned comparisons showed, a smaller number of fixations were needed to localise a target in repeated (WholeCxt: $m = 5.5$, $P = 0.001$; LocalCxt: $m = 5.5$, $P = 0.002$) compared with novel trials ($m = 6$). None of the other effects reached significance (all $P < 0.14$).

Target region fixation frequency. Target fixation frequency is defined as the number of fixations that occurred within the target region. In the learning phase, the number of fixations that occurred within the target region decreased from 3.2 to 2.7 over the course of five epochs, $F(3.4,93.04) = 22.605$, $P < 0.00001$, $\epsilon = 0.75$, $\eta_p^2 = 0.42$, which suggests that participants became more efficient over time in locating the target after entering the target region. None of the other effects reached significance (all $P < 0.15$).

In the transfer phase, there was a main effect of trial type, $F(1.7,51.9) = 5.16$, $\epsilon = 0.84$, $P = 0.01$, $\eta_p^2 = 0.14$, and pairwise comparison showed that compared with novel trials ($m = 2.75$), a decrease in fixation frequency was found for LocalCxt trials ($m = 2.5$, $P = 0.004$) rather than for WholeCxt trials ($m = 2.7$, $P = 0.18$). The effect of group was not significant ($F < 1$) and neither the interaction of trial type with group ($P > 0.05$).

General Discussion

The present study used eye movement measures to contrast two hypotheses about how repeated displays may facilitate search times in ASD: the spatial hypothesis and the temporal hypothesis. We used a visual search task that included trials in which the target and its arrangement of distractors remained constant throughout the

experiment (repeated trials) and trials in which the target and distractors changed (novel trials). Our findings can be summarised as follows: in repeated trials, manual response times were faster compared with novel trials, indicating that both groups memorised the repeated context and used this information to facilitate visual search. Moreover, as participants failed to recognise these items on a subsequent memory test, we can conclude that this facilitation was due to implicit knowledge. Importantly, individuals with ASD were significantly slower to find the target, and slower search in ASD was driven by prolonged duration of fixations, which supports the temporal hypothesis.

Longer fixation durations are typically associated with decreased discriminability during visual search and processing difficulties at the fixated region [Hooge & Erkelens, 1998; Liversedge & Findlay, 2000]. This finding goes against the bulk of research presented in the introduction, according to which people with ASD show superior visual search because they have enhanced discrimination abilities. One reason for this discrepancy may be related to the differences in task demands that exist between the tasks. Briefly, in tasks where superior or equal search has been noted, attention is driven solely from visual factors relating to the visual discriminability of the target with its distractors, while in the present, task search may be slower because people direct their attention using previous experience. Slowing of search in a task involving the use of prior experience has also been reported in other research [Pellicano et al., 2010]. It is unlikely that factors such as age and IQ account for the discrepancy because superior search has been noted in adults too [e.g. O’Riordan, 2004] and although the IQ level of the samples used is often much above average (above 100), there is an IQ match with control groups.

A more thorough analysis of how fixation time is distributed across the search stages gives us a plausible explanation for the slower search in ASD. Group differences in fixation duration were found in the third stage of “gaze duration in the target region” that encompasses a perceptual component, i.e. the time taken to recognise the stimuli in and outside of the region, and a decision-making component, i.e. the time it takes from detecting the target to making a motor response. Recently, it has been argued that the decision component is most important in speeding search in the contextual cueing task because previous experience works by making the decision to respond faster rather than by guiding one’s attention to the target [Hout & Goldinger, 2012; Kunar et al., 2007, 2008]. In other words, it is argued that as it is easier to find an object when you know its location, similarly in the contextual cueing task faster search is driven by a higher level mechanism [Hout & Goldinger, 2012], whereby repeated exposure gives participants greater confidence about the location target resulting in faster

recognition and/or response. Thus, if participants’ performance on this later stage of the task is driven by what participants have seen before (i.e. prior experience), then slower search in ASD could indicate that prior experience does not bias search behaviour as much as it does for those with TD people as recently proposed by Pellicano and Burr [2012].

The search cost of the ASD group compared with the TD group was mostly accounted by the longer fixation duration in the gaze duration stage (78% in the learning phase and 64% in the transfer phase). This finding suggests that slower search in ASD maybe because contextual cueing does not speed visual search by lowering the decision-response thresholds as it does for TD individuals. It is not easy to determine whether the reason behind slower search in ASD is that the response thresholds do not lower as much as the TD group’s because as mentioned earlier, this stage also involves the time it takes to process the distractor items. However, as the differences were only significant in this stage and not in the other two of initial duration and scan time, it is likely that the decision component associated with this stage may have at least partly delayed search times.

The finding that the time to initiate the first saccade is also slower boosts the argument of decision-making difficulties in ASD. Saccadic eye movements involve a higher level decision that the brain has to make to determine “when” to initiate a saccade [Findlay & Walker, 1999; Ludwig, Gilchrist, McSorley, & Baddeley, 2005]. Recent studies have also shown that people with ASD show a delay in initiating the first saccade [Fletcher-Watson et al., 2009; Goldberg et al., 2002; Kuhn et al., 2010] giving insights on which aspects of a scene receive attentional priority. The decision to release a saccade and the decision of making a response rely on different modalities but seem to share the same neural basis [Ho, Brown, & Serences, 2009], and so it is logical to link them here conceptually too on the basis that they involve higher level mechanisms that influence the control of decisions.

The findings of the present study have implications on implicit learning abilities in ASD. First, it seems that people with ASD do not show a local processing bias in learning because they show learning both when only a few items are repeated (local context) and also when all the items are repeated (global context). This finding is corroborated in a recent study [Kourkoulou et al., 2012] that also found inefficient transfer to novel contexts in adults with autism, especially when they were biased towards attending to local parts of the display. This finding of significantly slower novel trial responding in ASD was not found in the present study. However, the discrepancy of findings could be due to the methodological differences that exist between the two tasks such as the smaller number of trials included in the present study

compared with Kourkoulou et al.'s [2012] study and also the use of eye tracking that makes this study unique. Second, individuals with ASD who took part in both studies were adolescents and adults, but given that autism is a developmental condition, it is possible that their atypical performance in the contextual cueing task may be masked by alternative more explicit-based strategies that are developed at these later ages. If this is true, then the deficits of implicit and automatic processes may remain even in adulthood as seen for example in studies of implicit mentalising [Abell, Happé, & Frith, 2000; Senju, Southgate, White, & Frith, 2009]. Therefore, it is important to study implicit learning developmentally and using tasks that assess different types of learning strategies.

Atypical learning strategies have been proposed to underlie performance in other type of implicit learning tasks in ASD. For example, in a category learning task [Soulières, Mottron, Giguère, & Laroche, 2010], participants were tested on their ability to distinguish between two categories of animals. Findings showed that participants with ASD needed more training to learn the categories, but eventually, they did categorise in the same way as the comparison group. Soulières et al. [2010] concluded that slower acquisition was accompanied by an atypical learning strategy. They proposed that participants with ASD took longer to adopt a definite strategy during training and relied more on implicit learning at the beginning of the task, while they used more explicit learning later on. It is indeed possible that participants in our study may have generated an explicit learning strategy, but if this was true, one might have expected that during the recognition test, participants would recognise the repeated displays at above chance rate.

The findings of the present study may also be relevant to the literature of disengagement difficulties in ASD using the gap overlap task. Disengagement of attention is typically examined by one's ability to disengage attention from a fixated central cue and shift attention to a target stimulus by making a saccade. One recent study [Kikuchi et al., 2011], which points to the inconsistent findings on this area of research, found that for TD individuals, faces rather than objects retained the attention of observers and the disengagement from a face stimulus to an object stimulus was delayed. These findings were not seen in children with ASD under a free-viewing condition. Other studies too using non-face stimuli show difficulties in disengagement because children with ASD remained fixated on the stimulus and did not make an eye movement towards the other stimulus that appeared [Landry & Bryson, 2004]. In the same sense, longer fixation duration and delay in initiating the first saccade may well point to difficulties in disengaging attention, while the finding of equal fixation frequency between the two groups shows no difficulties in shifting attention.

Although problems in attention shifting have been reported in ASD, it is unlikely that slower search is due to difficulties in changing the spatial focus of attention. The spatial hypothesis predicts slower search if memory does not bias the visual system away from visiting previously viewed locations [Hout & Goldinger, 2012]. Because the number of fixations in the entire trial as well as in the target region did not differ significantly between the two groups, we found little support for the spatial hypothesis. Although it is difficult to make definitive inferences from null effects, there were no group differences in fixation frequency for any of the conditions and neither within or outside the target region. It is unlikely that the earlier result has to do with reduced power because as expected, contextual cueing resulted in fewer fixations for repeated than novel trials, and this was true for both groups. Thus, it seems unlikely that increased fixation frequency is responsible for the slower search in ASD.

Whether slower search in ASD derives from differences in the neural network that controls visual search and saccades remains to be resolved. Oculomotor studies are a useful approach for studying cognitive and neurophysiological aspects of disorders such as autism because they are heavily dependent upon the integration of neural systems that are well characterised [Sweeney, Takarae, Macmillan, Luna, & Minshew, 2004]. Sweeney et al.'s [2004] review of oculomotor studies in autism indicates abnormalities in executive control of behaviour that is mediated by prefrontal systems. Although this conclusion was based on studies that have used oculomotor paradigms different to the ones used here, one could infer that the slower search in ASD in the contextual cueing task is due to oculomotor dysfunction [cf. Barnes et al., 2008]. A recent review of functional imaging studies in autism using a wide range of visual tasks in which ASD performance is enhanced finds less activity in the frontal cortex [Samson, Mottron, Soulières, & Zeffiro, 2012]. According to Samson et al. [2012], this abnormal pattern of brain activity between ASD and control groups is not associated with differences in oculomotor behaviour but with a greater degree of reliance from ASD groups on visual processing mechanisms regardless of the stimuli employed. Samson et al. focused on studies of enhanced visual functioning in ASD rather than in tasks such as the contextual cueing in which visual search performance is not enhanced. However, it is possible that slower search in ASD in the contextual cueing task in particular could be related to the neural network responsible for oculomotor functioning. Visual search in the contextual cueing task relies on the effective use of prior experience, which might be less optimal for those with ASD as a means of guiding search [Pellicano & Burr, 2012]. Similarly, a greater degree of reliance on visual processing mechanisms in ASD as Samson et al. suggest should have an

impact on the way that the brain predicts incoming information—and therefore on the making of anticipatory eye movements [Pellicano & Burr, 2012].

An important limitation of the current study that needs to be considered is the small sample size. Indeed some of the interactions between group and condition that were approaching significance may have been significant if the sample size was larger. For instance, the manual RT data during the transfer of learning suggest that while learning in TD individuals is modulated by the context of initial learning (whole, local, novel), this seems to be less the case for individuals with ASD who show little difference in reaction times for learning in local and whole contexts.¹ Future research is needed to follow this up with larger samples because of what we might be missing in the current result. If learning in ASD is not modulated by the size of repeated context, such finding would suggest either difficulties with processing of the whole context or enhanced processing of the local context. Such findings would contribute to our understanding of how people with ASD learn.

In summary, there were three main findings: (a) both groups made fewer fixations for repeated than novel stimuli as a result of learning; (b) the ASD group made as many fixations as the TD group before finding the target, which suggests that the two groups fixated on an equal number of components; and (c) the ASD group made longer fixations and took longer to initiate the first saccade than the TD group resulting in overall slower search times. It is concluded that slower search in tasks where experience drives attention is accounted for not by a spatial shifting deficit but by a temporal processing delay that is related to preparing eye movements and the decision of making a response. This finding means that protocols of training attention need to explore the role of temporal processes in ASD beyond processes that relate to how attention shifts from one spatial location to another. Future studies will need to elucidate these findings further and dissociate perceptual from decision-making processes.

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¹We thank one of the reviewers for raising this point.

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