Cognition 159 (2017) 127–138

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

Eye movements reveal a dissociation between memory encoding and retrieval in adults with autism

Rose A. Cooper[a], Kate C. Plaisted-Grant[a], Simon Baron-Cohen[b], Jon S. Simons[a,*]

[a] Department of Psychology, University of Cambridge, Cambridge CB2 3EB, UK
[b] Autism Research Centre, Department of Psychiatry, University of Cambridge, Cambridge CB2 8AH, UK

ARTICLE INFO

Article history:
Received 5 July 2016
Revised 23 November 2016
Accepted 28 November 2016

Keywords:
Autism
Eye-tracking
Attention
Recollection
Encoding

ABSTRACT

People with Autism Spectrum Disorder (ASD) exhibit subtle deficits in recollection, which have been proposed to arise from encoding impairments, though a direct link has yet to be demonstrated. In the current study, we used eye-tracking to obtain trial-specific measures of encoding (eye movement patterns) during incidental (natural viewing) and intentional (strategic) encoding conditions in adults with ASD and typical controls. Using this approach, we tested the degree to which differences in encoding might contribute to recollection impairments, or whether group differences in memory primarily emerge at retrieval. Following encoding of scenes, participants were asked to distinguish between old and similar lure scenes and provide 'remember'/'familiar' responses. Intentional encoding increased eye movements and subsequent recollection in both groups to a similar degree, but the ASD group were impaired overall at the memory task and used recollection less frequently. In controls, eye movements at encoding predicted subsequent correct responses and subsequent recollection on a trial-by-trial basis, as expected. In contrast, despite a similar pattern of eye movements during encoding in the two groups, eye movements did not predict trial-by-trial subsequent memory in ASD. Furthermore, recollection was associated with lower similarity between encoding- and retrieval-related eye movements in the ASD group compared to the control group. The eye-tracking results therefore provide novel evidence for a dissociation between encoding and recollection-based retrieval in ASD.

1. Introduction

Autism Spectrum Disorder (ASD) is primarily associated with social interaction and communication difficulties as well as restrictive and repetitive behaviours, although the presence of memory deficits in people with ASD has also been widely observed in recent years, particularly affecting the recollection of previous experiences (see Boucher, Mayes, & Bigham, 2012 for a review). Recollection is defined by a threshold process of recalling the specific details and spatial-temporal context of a particular stimulus whereas familiarity is defined by a feeling of knowing a stimulus has been encountered before without accompanying recollection of the event details (Yonelinas, 2002). Deficits in recollection have been observed across a range of tasks in ASD, including reduced memory for an item's original context (e.g. Bowler, Gaigg, & Gardiner, 2014; Bowler, Gardiner, & Berthollier, 2004; Cooper, Plaisted-Grant, Baron-Cohen, & Simons, 2016; Lind & Bowler, 2009; Ring, Gaigg, & Bowler, 2015) and a reduction in subjective reports of recollection during recognition memory (Bowler, Gardiner, & Gaigg, 2007; Cooper et al., 2015; Gaigg, Bowler, Ecker, Calvo-Merino, & Murphy, 2015; Meyer, Gardiner, & Bowler, 2014), despite typical familiarity-based recognition memory.

Most theories aiming to account for the pattern of memory performance in ASD focus on encoding as the potential basis of recollection deficits (cf. Boucher et al., 2012), but the relative contributions of encoding and retrieval dysfunction remain underspecified. This is because determining whether an item has been encoded can often only be achieved by testing memory for that item later on, meaning that encoding and retrieval processes are difficult to tease apart. For instance, impairments characterised by theories focused on encoding, such as deficits in complex information processing (Minshew & Goldstein, 2001) and relational binding (Bowler, Gaigg, & Gardiner, 2008; Bowler et al., 2014), could easily arise due to deficits in strategic retrieval (cf. Cooper et al., 2015; Solomon, McCauley, Iosif, Carter, & Ragland, 2016). Similarly, the task support effect (Bowler et al., 2004), highlighting that retrieval cues (reducing strategic retrieval demands) ameliorate

---

* Corresponding author at: Department of Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, UK.

E-mail address: jss30@cam.ac.uk (J.S. Simons).

http://dx.doi.org/10.1016/j.cognition.2016.11.013

recollection deficits in ASD, could arise due to deficient encoding (cf. Meyer et al., 2014). Hence, encoding and retrieval explanations of recollection deficits in ASD that have been proposed to date have not been sufficiently distinguished from one another.

In order to dissociate these two stages of memory, it is important to manipulate and measure aspects of encoding independently of retrieval. One recent suggestion is that recollection deficits in ASD can be attributed to a difficulty engaging elaborative encoding (Meyer et al., 2014), known to disproportionately benefit subsequent recollection over and above familiarity (Yonelinas, 2002). Of note, adults with ASD show more pronounced recollection deficits under instructions to 'learn' rather than to 'forget' when these trial types are inter-mixed (Meyer et al., 2014), possibly suggesting a difficulty in engaging effective encoding strategies. Furthermore, subjects with ASD can show reduced recall of semantically-related words compared to unrelated words (e.g. Gaigg, Gardiner, & Bowler, 2008), and atypical inferior frontal gyrus function during memory encoding (Gaigg et al., 2015), a region that is involved in semantic and elaborative encoding (Otten, Henson, & Rugg, 2001). However, in the study by Meyer et al. (2014), it is unclear whether low levels of recollection of to-be-forgotten words in the control group as well as potential issues of cognitive and behavioural flexibility when switching between trial types may have contributed to the apparent reduction in elaborative encoding in ASD. The relationship between elaborative encoding and recollection deficits in ASD is therefore somewhat unclear.

Incidental encoding *versus* intentional encoding would provide an informative alternative test of an elaborative encoding deficit in ASD, having been used to test strategic encoding in older adults (e.g. Naveh-Benjamin et al., 2009). This task has the advantage of providing a direct comparison between a more 'natural' encoding situation (engaging bottom-up processes), which is rarely employed when investigating memory in ASD, and strategic learning (engaging more top-down control processes). Only one study to date has compared the effect of incidental and intentional encoding on recollection (source memory) in adolescents with ASD and, in contrast to Meyer et al. (2014), observed that both groups benefitted similarly from intentional encoding (Souchay, Wojcik, Williams, Crathern, & Clarke, 2013). However, there was no overall deficit in source memory in ASD and different source contexts were used for the two encoding tasks, meaning that one type of information could have simply been easier to remember. The current study thus aimed to test intentional encoding in comparison to incidental encoding using the same type of stimuli and test for both conditions to improve our understanding of elaborative encoding in ASD.

While the aforementioned evidence focuses on potential deficits in top-down control of memory encoding, there is also evidence in ASD that bottom-up processes might also function atypically, potentially revealed by investigating incidental encoding. Research has suggested that differences in natural patterns of attention (Ames & Fletcher-Watson, 2010) and perception (Happé & Frith, 2006; Mottron, Dawson, Soulières, Hubert, & Burack, 2006) exist in ASD and that such differences could contribute to memory deficits by altering the quality of memory experiences and limiting information that can be subsequently recollected (Loth, Carlos Gómez, & Happé, 2011). Specifically, some evidence suggests that people with ASD have enhanced perception of local features (Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; Smith & Milne, 2009), and make fewer fixations that are more biased towards salient lower-level features than central objects or semantic features when viewing scenes (Heaton & Freeth, 2016; Wang et al., 2015). Conversely, other studies have revealed minimal differences between subjects with ASD and typical controls in their fixation patterns to complex scenes (Au-Yeung, Benson, Castelhano, & Rayner, 2011; Freeth, Foulsham, & Chapman, 2011). Furthermore, others have observed a similar or even an impaired ability to discriminate between stimuli varying in local features, including scenes (Au-Yeung et al., 2011; Fletcher-Watson et al., 2012; Loth, Carlos Gómez, & Happé, 2008) and objects (O'Hearn et al., 2014; Peiker et al., 2015). It therefore remains possible that differences in bottom-up attention and perception might contribute to memory impairments in ASD, but exactly what differences are present and how these might influence memory representations are unclear. Only one study to date has linked eye movements and memory in ASD, observing that these individuals were less likely to fixate objects related to the semantic context when viewing scenes, which was accompanied by reduced recall of these objects later on (Loth et al., 2011). This suggests that differences in fixation patterns at encoding in ASD might affect how well visual information can be recollected.

In the neurotypical population, research has increasingly used eye movements as a measure of encoding and an indirect measure of memory retrieval due to the additional information that cannot be ascertained from explicit memory responses (cf. Hannula et al., 2010). For instance, a greater number of fixations to visual stimuli during encoding is predictive of subsequent retrieval success on a trial-by-trial basis (Molitor, Ko, Hussey, & Ally, 2014; Pertzov, Avidan, & Zohary, 2009), suggesting that encoding-related fixations reflect an accumulation of evidence and a more deeply encoded memory representation. Similarly, with regard to recollection specifically, there is evidence that the degree to which fixations cluster (distance between fixations) during encoding can predict subsequent recollection success, compared to familiarity (Kafkas & Montaldi, 2011; Sharot, Davidson, Carson, & Phelps, 2008). However, whether more clustered or less clustered fixations predict recollection is likely dependent on the type of visual stimuli and task used; i.e. whether memory for a couple of specific details or many details of the image would improve memory. Measuring eye movements during encoding can also prove informative about the strategies participants are adopting and, thus, are well suited for identifying differences between incidental and intentional encoding (e.g. Shih, Meadmore, & Liversedge, 2012).

Eye movements during retrieval can also reveal a substantial amount of information about memory processes. A greater number of fixations during retrieval is thought to be indicative of identification of the correct response or novelty even when an incorrect explicit memory decision is made (Hannula & Ranganath, 2009; Molitor et al., 2014). In the study by Molitor and colleagues, participants made more fixations to a novel stimulus compared to a familiar stimulus even when they incorrectly identified the novel stimulus as familiar. Recollection has been observed to be associated with more distributed fixations during retrieval compared to familiarity (Kafkas & Montaldi, 2012) and there is also evidence that greater encoding-retrieval similarity in fixations, in terms of the proportion of retrieval eye movements that are directed towards areas attended to during encoding, predicts recollection rather than familiarity judgements (Holm & Mantyla, 2007). It is thought that this fixation 'reinstatement' possibly reflects configural memory of the studied stimulus (Ryals, Wang, Polnaszek, & Voss, 2015). Importantly, disrupting this perceptual reconstruction during retrieval has been shown to selectively impair recollection without affecting familiarity (Mantyla & Holm, 2006), suggesting that this process is directly associated with the likelihood of recollection success. Similarly, greater fixation reinstatement has been associated with more accurate memory and disrupting reinstatement reduces memory accuracy (Laeng, Bloem, D'ASDenzo, & Tommasi, 2014; Olsen, Chiew, Buchsbaum, & Ryan, 2014). Fixation reinstatement has been interpreted as a reconstruction of the memory representation (Laeng et al., 2014) and, thus, may shed light on the efficiency and quality of recollection in ASD and the relationship between encoding and retrieval.

Memory research in ASD has so far not directly investigated the link between encoding processes and recollection success, and measuring eye movement patterns during encoding and retrieval in ASD could provide valuable insight into processes that might underlie memory deficits. In the current eye-tracking study, we assessed participants' performance on a long-term memory task and recorded their eye movements while participants encoded a series of scenes and again during a recognition memory test. Participants were asked to discriminate between studied scenes (targets) and perceptually similar lures, and to report whether their memory judgement was based on recollection or familiarity. A recognition memory test involving perceptually similar targets and lures (as opposed to dissimilar, as is standard) is considered to largely depend on recollection for successful performance (e.g., Migo, Montaldi, Norman, Quamme, & Mayes, 2009) and is, therefore, ideal for investigating eye movements and recollection impairments in ASD. An incidental/intentional encoding manipulation additionally allowed us to assess how effectively subjects with ASD engaged in strategic encoding. We also assessed participants' performance on a separate control perceptual discrimination task, where participants were asked to distinguish between simultaneously presented visual stimuli, to measure and control for any baseline differences in perceptual specificity that might contribute to performance on the memory task. It was hypothesised that the ASD group would show an impairment in memory accuracy, accompanied by a selective reduction in recollection, and a reduced benefit of intentional encoding on memory if strategic encoding deficits are present in this population.

Measuring eye movements on a trial-by-trial basis allowed us to study differences in eye movements at encoding, to investigate how encoding-related eye movements predict subsequent memory, and to examine how eye movements during retrieval characterise memory success. Specifically, we first investigated whether natural eye movement patterns differ between ASD and control participants, such as potentially fewer fixations made by ASD participants, and whether eye movements change more in the control group compared to the ASD group following intentional encoding instructions. Secondly, we investigated whether encoding-related eye movements predict subsequent retrieval success and recollection or whether retrieval in ASD is independent of eye movements at encoding. To investigate retrieval-related eye movements, we first tested whether eye movements indirectly reflect memory accuracy even during an incorrect response in ASD, suggesting an 'intact' memory representation and a failure of explicit recollection. Lastly, we tested if recollection is associated with the same level of fixation reinstatement in ASD participants as in controls to investigate whether recollected memories are reconstructed in the same way in the two groups.

2. Materials and methods

2.1. Participants

Forty-one volunteers aged between 18 and 45 took part, including 20 adults with ASD (14 males, 6 females) and 21 healthy control participants (13 males, 8 females). Participants had normal or corrected-to-normal vision and hearing and none of the control participants had diagnoses of any psychiatric, neurological, or developmental disorder or learning difficulty. All participants in the ASD group had a formal diagnosis of autism according to DSM-5 or ICD-10 criteria, and received their diagnosis following specialist assessment by a qualified clinician. All participants completed the Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), as well Raven's Advanced progressive matrices (short-form) (Arthur & Day, 1994) and the National Adult Reading Test (NART) (Nelson, 1982) as indices of non-verbal and verbal ability, respectively. Participants were matched at the group level for age, education, verbal and non-verbal ability (see Table 1). One additional male participant in the ASD group was excluded due to a computer error during the experiment and one female control participant was excluded from analyses of eye movement data due to poor data quality (majority of eye movement data was invalid on both an encoding and a retrieval task phase) as a result of peripheral factors (reflection from glasses).

Participants with ASD were recruited via participant databases at the Cambridge Laboratory for Research into Autism and the Autism Research Centre, Cambridge. Control participants were recruited via participant databases at the Behavioural and Clinical Neuroscience Institute (BCNI) and Memory Laboratory, Cambridge University, as well as social media adverts. Ethical approval was obtained from the Cambridge Psychology Research Ethics Committee. Participants gave written informed consent prior to taking part and were paid a standard honorarium for their time.

2.2. Apparatus

We programmed the computer tasks using MATLAB Cogent 2000 toolbox and a Tobii T120 eye tracker was used to record eye movements at a sampling rate of 120 Hz, with a screen resolution of 1024 × 768 pixels. Participants sat approximately 60 cm from the screen, but distance was recorded continuously throughout the experiment. We did not use a chin rest in order to maximise comfort throughout the task. The eye-tracker was built into the monitor and so no head-mounted equipment was required. We collected gaze data for every trial of the experiment and participants were instructed that they should keep their head as still as possible and to try not to blink while the stimuli were on the screen. Data were collected using the Tobii SDK Matlab toolbox and a standard 9-point calibration was carried out before each task phase.

2.3. Design and procedure

The stimuli for the memory task included 320 naturalistic scene pictures (size 600 × 412 pixels), subtending a visual angle of $\sim 19^{\circ} \times 14^{\circ}$. The stimulus set comprised 160 pairs of perceptually similar scenes, such as places of a similar overall appearance or the same location from different viewpoints or times, which we collated from Google image searches as well as from existing stimulus databases. Scenes within each pair were highly similar in overall appearance but differed on a number of features, not just the presence or absence of a single item, for example. Half of the scenes were indoor locations and half were outdoor locations. The task comprised two blocks, one for the incidental learning condition and one for the intentional learning condition, and each block contained one encoding phase and one retrieval phase. Participants viewed 80 scenes in each encoding phase and each retrieval phase, which included one scene from each pair.

In preparation for the incidental encoding phase, participants were told only that their eye movements would be monitored while they viewed a series of scenes and no mention was made of the subsequent memory test. Participants were told to look at the scenes 'naturally', without guidance as to particular parts of the scene they should focus on. Participants viewed 4 example scenes before the first encoding phase and each scene was viewed for 3 s (see Fig. 1). Eye movements were recorded during each 3 s presentation of the scenes. After the incidental encoding phase, the researcher timed a break of 10 min before the memory retrieval

Table 1
Mean (SD) demographic information for the ASD and control groups.

	Control (N = 21)	ASD (N = 20)	*p* value	Cohen's d
Age	30.52 (6.32)	31.70 (7.89)	*p* = 0.59	0.17
Education	16.52 (2.36)	15.60 (1.79)	*p* = 0.17	0.44
Raven's	10.33 (1.65)	10.50 (1.61)	*p* = 0.75	0.10
NART	34.48 (5.89)	33.90 (6.21)	*p* = 0.76	0.10
AQ	14.52 (6.18)	35.85 (7.24)	*p* < 0.001	3.13

Note: The maximum score on the Raven's matrices is 12 and the maximum score on the NART and AQ is 50.

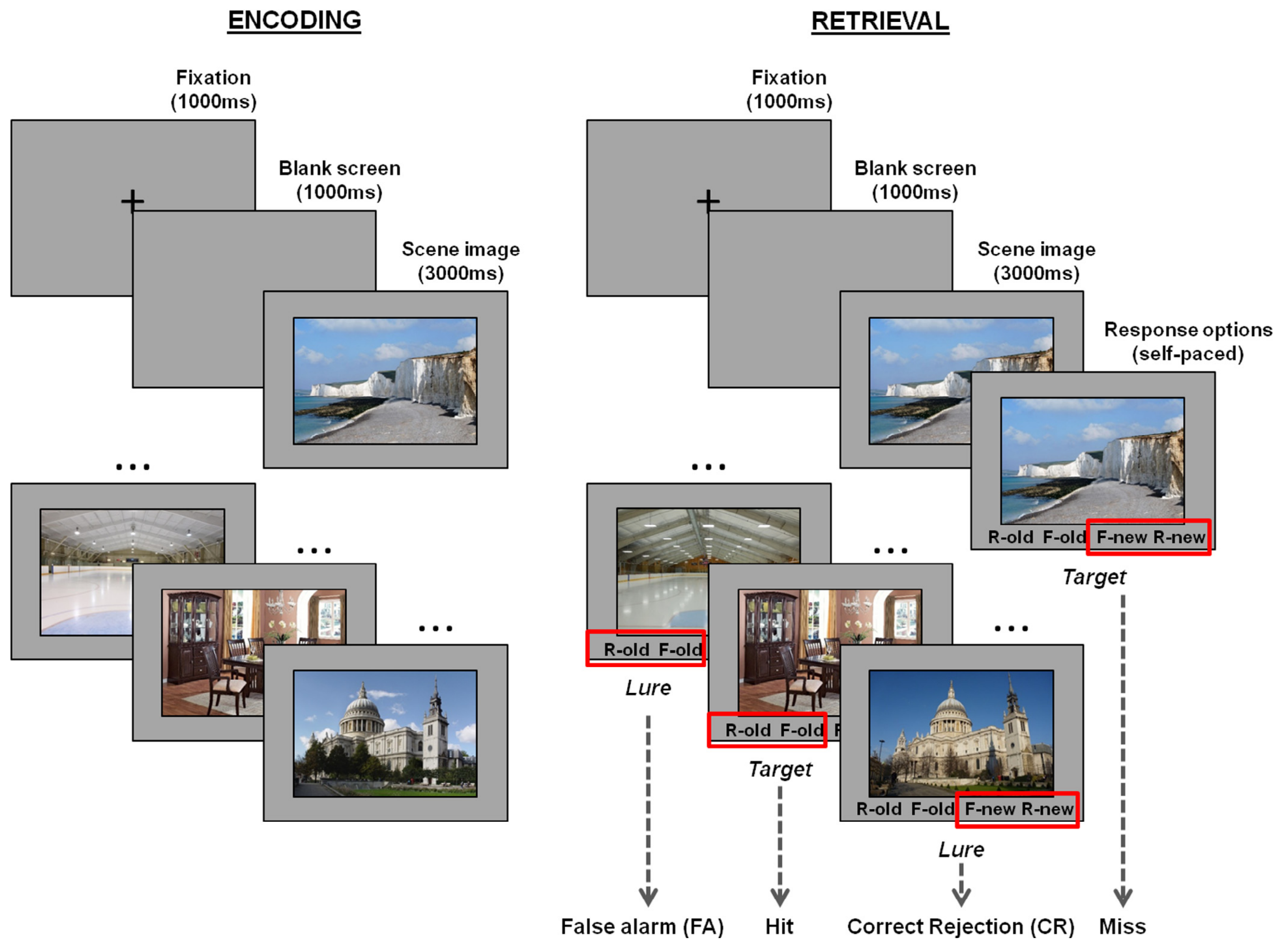

Fig. 1. The structure of the memory task during the encoding and retrieval phases. An example of an individual trial is shown at the top of both the encoding and retrieval sections and further example stimuli are presented below. Each type of response (FA, Hit, CR, Miss) is illustrated during the retrieval phase (bottom of figure) based on a participant responding with one of the options highlighted in red. All types of response can be accompanied by either a recollection (R) or familiarity (F) judgement. Eye movements were analysed from the 3 s the scene image was presented alone during both the encoding and retrieval phases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phase, which was filled by either the Raven's or NART, the selection of which was counterbalanced across participants, and the instructions for the memory test.

Half of the scenes viewed during the retrieval phase were exactly the same scenes that had been studied (target/'Old' scenes), and half of the scenes were the perceptually similar versions of the other studied scenes (lure/'New' scenes). Participants were asked to identify whether each scene was old or new as well as to report whether their judgement was based on recollection or familiarity (see Fig. 1). Participants were instructed that:

- Remember-Old responses should reflect recognition of the scene and memory for additional details from the time the scene was studied, such as various thoughts or feelings about specific details of the scene's appearance.
- Familiar-Old responses should reflect recognition of the scene but an inability to recall any additional specific details from the time the scene was originally studied.
- Unfamiliar-New responses to should reflect a failure to recognise a scene without memory for any additional information about the original studied scene's appearance.

- Remember-New responses should reflect memory for specific details of the original studied scene's appearance that are different from the new scene being tested.

We adapted the instructions for recollection and familiarity from previous studies that have measured recollection for both target and lure stimuli (e.g. Kim & Yassa, 2013; Migo et al., 2009). After the instructions for the memory test had been explained, participants completed a practice memory test using the 4 example studied scenes. For each retrieval trial, participants viewed the scene for 3 s and then the 4 response options appeared below the scene. Responses, made via a choice of four response buttons (numbers 1–4), were self-paced and participants were instructed to take their time to arrive the best possible answer. Eye movements were only analysed from the first 3 s of each retrieval trial (while the response options were not present) to match the duration of the encoding trials and to ensure that data were not affected by back and forth eye movements between the scene and response options.

In preparation for the intentional encoding phase, we told participants that they should now try their best to learn the appearance of each scene, focusing on specific details that would likely help them to discriminate between similar scenes later on. Other than the encoding instruction, the procedure for the intentional block was identical to that of the incidental block. In the 10 min break in between the intentional encoding and retrieval phases, participants completed whichever of the Raven's or NART they had not undertaken earlier. Scenes were presented in a random order for both encoding phases and a pseudo-random order for the retrieval phases, where no more than 3 target scenes or 3 lure scenes were presented in a row. The presentation of the scenes in the incidental or intentional blocks as well as presentation of the target or lure scene from each pair was counterbalanced across participants.

After the memory task, participants completed a post-experiment questionnaire to verify that they had not actively tried to memorise the scenes in the incidental encoding phase and that they had understood the difference between Old and New scenes, as well as between recollection and familiarity. We confirmed that all participants had performed the task according to the instructions. At the end of the session, participants also completed a control perceptual discrimination task (using stimuli and a task design from a previous study; Erez, Lee, & Barense, 2013; see Supplementary Materials). This task was self-paced and required participants to discriminate between perceptually similar stimuli (via an appropriate button press) that were viewed simultaneously. It was administered to assess participants' ability to identify subtle differences in features between visual stimuli, and we included this control task because of the possibility that differences in baseline perceptual specificity could affect performance on the current memory task (due to the perceptually similar nature of the scene pairs) and could contribute to memory impairments in ASD.

2.4. Eye movement data processing

Eye movement data were averaged between the left and right eyes and samples were marked as invalid where no data were recorded, due to large head movements, blinks, or reflection from glasses, or when gaze fell outside the stimulus boundary. We added 0.5° of visual angle to the scene boundary to account for potential eye-tracker measurement error. The data were smoothed to reduce noise using the median of a 5 sample window and each participant's average distance from the monitor per trial was used to calculate visual angle. We calculated fixations per trial using the criteria that fixation samples should not be further apart than 1° of visual angle and the duration should be at least 100 ms (cf. Hannula et al., 2010). Fixations that were extremely close spatially, having centres closer than 0.5° of visual angle, and temporally, 75 ms or less apart in time, were merged into a single fixation because it is unlikely these fixations were separated by a blink or saccade-fixation sequence. The mean x and y coordinates as well as duration in ms were calculated for each fixation.

Trials were not subsequently analysed if the percentage of invalid samples was greater than 40% (cf. Kafkas & Montaldi, 2011, 2012) and/or if no valid fixations were recorded. 2.1% of trials (range across subjects: 0–9.69%) were excluded across all participants and the mean percentage of gaze data excluded per trial (including invalid trials) was only 5.7% (range: 0.46–20.45%), which did not differ between the ASD and control groups ($p > 0.6$). As mentioned in the Participants section, we removed one control participant from all analyses of gaze data due to both a high percentage of invalid trials and data lost per trial (>25%). Participants were not included in specific analyses if they had fewer than 4 trials of a particular response type (cf. Hannula et al., 2010; Molitor et al., 2014), resulting in 2 ASD participants being removed from analyses including FAs and 4 participants (2 ASD and 2 control) being removed from analyses including familiarity responses. Of note, the groups remained matched on all demographic variables where analyses did not include the full sample.

2.5. Eye movement measures

To investigate eye movements during the memory encoding and retrieval phases, we calculated two commonly used eye movement measures that have been associated with memory processes to assess both the quantity and distribution of fixations: number of fixations and inter-fixation distance. Number of fixations simply reflected the number of times participants fixated on the scene image within the 3 s time window and inter-fixation distance was calculated as the mean degrees of visual angle from every fixation to all other fixations made to a scene.

We also calculated an additional measure to directly compare fixations made during encoding and retrieval of scenes. This measure, termed 'fixation reinstatement', was calculated using a method adapted from those of Ryals et al. (2015) and Holm and Mantyla (2007) to assess how much time participants spent during the retrieval phase viewing the same regions they viewed in the encoding phase. Specifically, the proportion of total fixation duration (measured in ms) to a scene in the retrieval phase that was spent fixating areas within 75 pixels (~2.5° of visual angle) of any fixation to the same scene during the encoding phase was calculated for each target scene. Because a greater number of encoding fixations would artificially inflate reinstatement values (due to a higher probability of a retrieval fixation falling near any encoding fixation), values were converted to z scores using the mean and standard deviation derived from all non-matching encoding-retrieval scene pairs with the same number of encoding fixations (as reinstatement for these non-matching pairs should be due to chance). Therefore, reinstatement reflected the similarity of encoding and retrieval fixations, independent of the number of encoding fixations.

2.6. Behavioural and eye movement data analyses

We first compared recognition memory performance (Hits - FAs) in the incidental and intentional encoding conditions between groups to assess the degree to which participants were able to improve their memory following the intentional encoding instructions. We then analysed whether the contribution of recollection to successful memory also differed between the encoding conditions and whether changes in recollection differed between groups.

Lastly, we assessed participants' performance on the perceptual control task and tested the degree to which recognition memory and recollection correlated with perceptual discrimination ability in each group.

With regard to the eye movement data, we first analysed overall group differences in encoding eye movements across all trials as well as changes associated with intentional encoding. Trials were then divided into response types to investigate how eye movements at encoding and retrieval varied according to memory, on the basis of previous studies in typical subjects observing differences in the number of and distribution of fixations depending on memory success and recollection (e.g. Kafkas & Montaldi, 2012; Molitor et al., 2014). Analyses investigating eye movements associated with distinguishing targets and lures tested differences between subsequent Hits, CRs, and FAs (consistent with the analysis by Molitor et al. (2014)). Note that we did not analyse Misses as they do not tell us about the degree to which a participant could distinguish between perceptually similar stimuli in memory (as reflected in eye movements and/or explicit judgements). An analysis investigating encoding-related eye movements associated with recollection and familiarity focused on targets and lures that had been correctly judged as recollected or familiar. To investigate reconstruction of encoding eye movements during retrieval, fixation reinstatement during retrieval of targets correctly judged as recollected *versus* targets judged to be familiar or new (combined as non-recollected targets) was analysed. Note that this analysis could only be conducted on targets and not lures as reinstatement involves comparing the similarity of regions in the same image. Targets judged as familiar and those missed (judged as new) were combined to avoid losing multiple participants from this analysis (participants who had too few familiar trials *or* too few misses) and were compared to correctly recollected targets to control for participants having a general tendency to revisit or to avoid previously viewed regions.

3. Results

3.1. Behaviour

3.1.1. Memory task performance

To test overall performance on the memory task (see Table 2) and whether memory accuracy was affected by the type of encoding, we conducted a 2 (group: ASD, control) × 2 (encoding condition: incidental, intentional) ANOVA on corrected recognition (Hits – FAs). A main effect of group indicated that the ASD group exhibited significantly reduced performance on the memory task, on average, relative to the control group ($F(1,39) = 6.34$, $p = 0.016$, $\eta^2 = 0.14$). Performance was significantly better following intentional encoding relative to incidental encoding, $F(1,39) = 40.35$, $p < 0.001$, $\eta^2 = 0.51$, and this increase was equally apparent ($F(1,39) < 0.4$, $p > 0.5$, $\eta^2 < 0.01$) in both the control group ($t(20) = 5.19$, $p < 0.001$, $d = 1.13$) and the ASD group ($t(19) = 3.87$, $p = 0.001$, $d = 0.87$), suggesting that both groups engaged effective encoding strategies to improve their performance. Of note, when analysing Hits and CRs separately, the ASD group showed a significant reduction in CRs (so an increase in FAs) relative to the control group ($t(39) = 2.07$, $p = 0.045$, $d = 0.65$), but the group difference in Hits did not reach significance ($t(39) = 1.44$, $p = 0.16$, $d = 0.45$).

To investigate the relative contribution of recollection and familiarity to correct memory decisions (see Table 2), we compared the proportion of correct responses (Hits and CRs) that were accompanied by recollection between groups and encoding conditions. Note that recollection here is conditional upon a correct response and so is independent of corrected recognition and is mutually exclusive with familiarity. A 2 (group: ASD, control) × 2 (encoding condition: incidental, intentional) ANOVA revealed that correct responses in the ASD group were less likely to be accompanied by recollection than correct responses in the control group ($F(1,39) = 3.92$, $p = 0.05$, $\eta^2 = 0.09$). A main effect of encoding condition, $F(1,39) = 23.83$, $p < 0.001$, $\eta^2 = 0.37$, indicated that a greater proportion of correct responses were accompanied by recollection following intentional relative to incidental encoding. This increase did not differ between groups, $F(1,39) < 1$, $p = 0.37$, $\eta^2 < 0.02$, and was present in both the control ($t(20) = 3.51$, $p = 0.002$, $d = 0.77$) and the ASD ($t(19) = 3.47$, $p = 0.003$, $d = 0.78$) groups separately. Interestingly, across both encoding conditions, recollection correlated with corrected recognition in both the control ($r = 0.47$, $p = 0.03$) and the ASD ($r = 0.50$, $p = 0.02$) groups, highlighting that participants who could recollect the scenes more often performed better on the task than participants who relied more on familiarity.

3.1.2. Perceptual control task

We assessed the ability to discriminate between perceptually similar stimuli using an independent samples *t*-test on the proportion correct in each group, and the groups did not perform significantly differently on this control task (control mean = 0.91 (0.05); ASD mean = 0.90 (0.07); $t(39) = 0.7$, $p = 0.5$, $d < 0.3$). Perceptual accuracy correlated significantly with corrected recognition (Hits - FAs) in both the control group ($r = 0.46$, $p = 0.03$) and the ASD group ($r = 0.51$, $p = 0.02$). Importantly, when perceptual accuracy was entered as a covariate, the ASD group still showed significantly reduced corrected recognition, $F(1,38) = 6.06$, $p = 0.018$, $\eta^2 = 0.11$. Interestingly, perceptual accuracy only correlated with correct recollection (proportion of recollection-based Hits and CRs) in the control group ($r = 0.67$, $p < 0.001$) and not in the ASD group ($r = -0.12$, $p = 0.61$), with the correlation in the control group being significantly larger than that in the ASD group ($Z = 2.75$, $p < 0.01$). Therefore, while perceptual accuracy predicted recollection ability in the control group, there was no such relationship in the ASD group (see Fig. 2).

3.2. Eye movements

3.2.1. Encoding

3.2.1.1. Eye movements during incidental and intentional encoding. To analyse eye movements during encoding and how eye

Table 2
Mean (SD) proportion of target and lure trials responded to correctly (Hits and CRs, respectively) and incorrectly (Misses and FAs, respectively), and the mean proportion of correct responses given a recollection or familiarity judgement in the incidental and intentional encoding conditions for the control and ASD groups.

	Control		ASD	
	Incidental	Intentional	Incidental	Intentional
Hits	0.79 (0.10)	0.90 (0.08)	0.74 (0.15)	0.86 (0.12)
Misses	0.21 (0.10)	0.10 (0.08)	0.26 (0.15)	0.14 (0.12)
CRs	0.79 (0.11)	0.84 (0.10)	0.72 (0.18)	0.73 (0.21)
FAs	0.21 (0.11)	0.16 (0.10)	0.28 (0.18)	0.27 (0.21)
Recollection	0.72 (0.15)	0.79 (0.12)	0.62 (0.17)	0.72 (0.16)
Familiarity	0.28 (0.15)	0.21 (0.12)	0.38 (0.17)	0.28 (0.16)

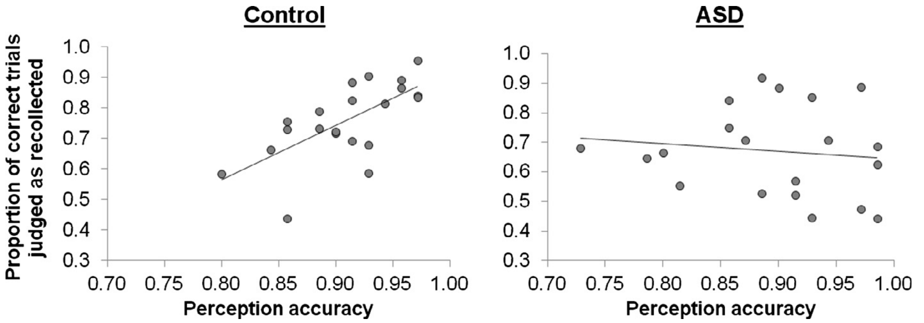

Fig. 2. Scatter plots illustrating the relationship between performance on the perceptual discrimination task and correct recollection within each group.

movements changed following intentional encoding instructions (see Table 3), we conducted 2 (group: ASD, control) × 2 (encoding condition) ANOVAs. Eye movements in both groups changed significantly from the incidental to the intentional encoding phase, including an increase in the number of fixations, $F(1,38) = 19.85$, $p < 0.001$, $\eta^2 = 0.34$, and an increase in inter-fixation distance, $F(1,38) = 14.46$, $p = 0.001$, $\eta^2 = 0.27$. Neither analysis of eye movements revealed a significant interaction between encoding condition and group ($Fs < 0.6$, $ps > 0.44$, $\eta^2s < 0.02$), and the groups did not significantly differ overall on either number of fixations or inter-fixation distance during encoding ($Fs < 0.7$, $ps > 0.41$, $\eta^2s < 0.02$). Other eye movement measures (see Supplementary Materials) also suggested that the groups were largely fixating on similar regions of the scenes (see Fig. 3). Subsequent analyses of eye movements are collapsed across incidental and intentional encoding conditions due to the similarity of eye movement changes between these conditions across the ASD and control groups.

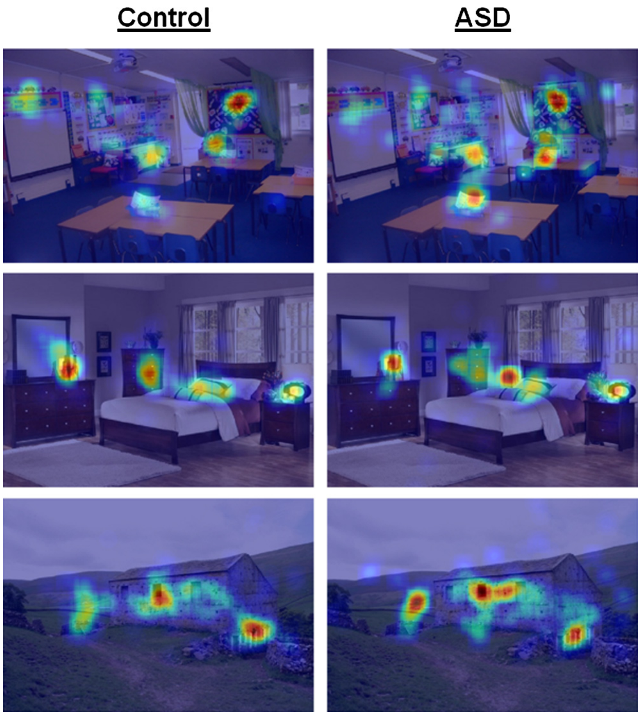

Fig. 3. Fixation heat maps. All fixations from participants in the control group and ASD groups are plotted for three trials during the memory encoding phase, illustrating the general similarity between the groups' fixation patterns during memory encoding.

3.2.1.2. Eye movements associated with distinguishing subsequent targets and lures. To investigate the influence of encoding-related eye movements on participants' ability to subsequently distinguish between target and lure scenes (see Fig. 4), we conducted 2 (group: ASD, control) × 3 (trial type: Hit, CR, FA) ANOVAs. Two participants with ASD were removed from this analysis due to low trial numbers (resulting in 20 control and 18 ASD participants). Consistent with the previous analysis, the groups did not differ on number of fixations ($F(1,36) = 0.4$, $p = 0.5$, $\eta^2 < 0.02$) or inter-fixation distance ($F(1,36) = 1.1$, $p = 0.3$, $\eta^2 < 0.03$). The difference in number of fixations between the trial types was marginally significant, $F(2,72) = 2.65$, $p = 0.08$, $\eta^2 = 0.06$; however, this was influenced by a significant group × trial type interaction, $F(2,72) = 3.96$, $p = 0.023$, $\eta^2 = 0.09$, driven by the difference between FAs and Hits/CRs, $F(1,36) = 6.81$, $p = 0.01$, $\eta^2 = 0.16$, and not between Hits and CRs ($F(1,36) = 1$, $p = 0.3$, $\eta^2 < 0.03$). Subsequent FAs in the control group were associated with fewer encoding fixations than both subsequent Hits ($t(19) = 3.14$, $p < 0.01$, $d = 0.70$) and CRs ($t(19) = 2.31$, $p = 0.03$, $d = 0.52$). However, number of fixations for subsequent FAs did not differ significantly from fixations to subsequent Hits ($t(17) < 0.5$, $p > 0.6$, $d < 0.1$) or CRs ($t(17) = 1.2$, $p = 0.25$, $d = 0.28$) in the ASD group. Note that no between-group differences in number of fixations for individual trial types reached significance ($ts(36) < 1.17$, $ps > 0.25$, $ds < 0.38$). No effects were significant in the analysis of inter-fixation distance ($Fs < 2$, $ps > 0.15$, $\eta^2s < 0.06$). Therefore, we observed that number of encoding fixations predicted subsequent FAs (compared to Hits and CRs) in the control group but not in the ASD group.

3.2.1.3. Eye movements associated with subsequent recollection and familiarity. In order to investigate encoding-related eye movements associated with subsequent recollection (R) and familiarity (F) during memory retrieval for both Hits and CRs, we conducted 2 (group: ASD, control) × 2 (trial type: Hit, CR) × 2 (response type: recollection, familiarity) ANOVAs (see Fig. 4). Two controls and two

Table 3
Mean (SD) number of fixations and inter-fixation distance across all trials during the incidental and intentional encoding phases for the ASD and control groups.

	Control		ASD	
	Num. fixations	Inter-fix dist.	Num. fixations	Inter-fix dist.
Incidental	9.13 (1.13)	5.24 (0.80)	8.87 (1.22)	5.02 (0.95)
Intentional	9.63 (0.77)	5.51 (0.72)	9.35 (1.17)	5.42 (0.92)

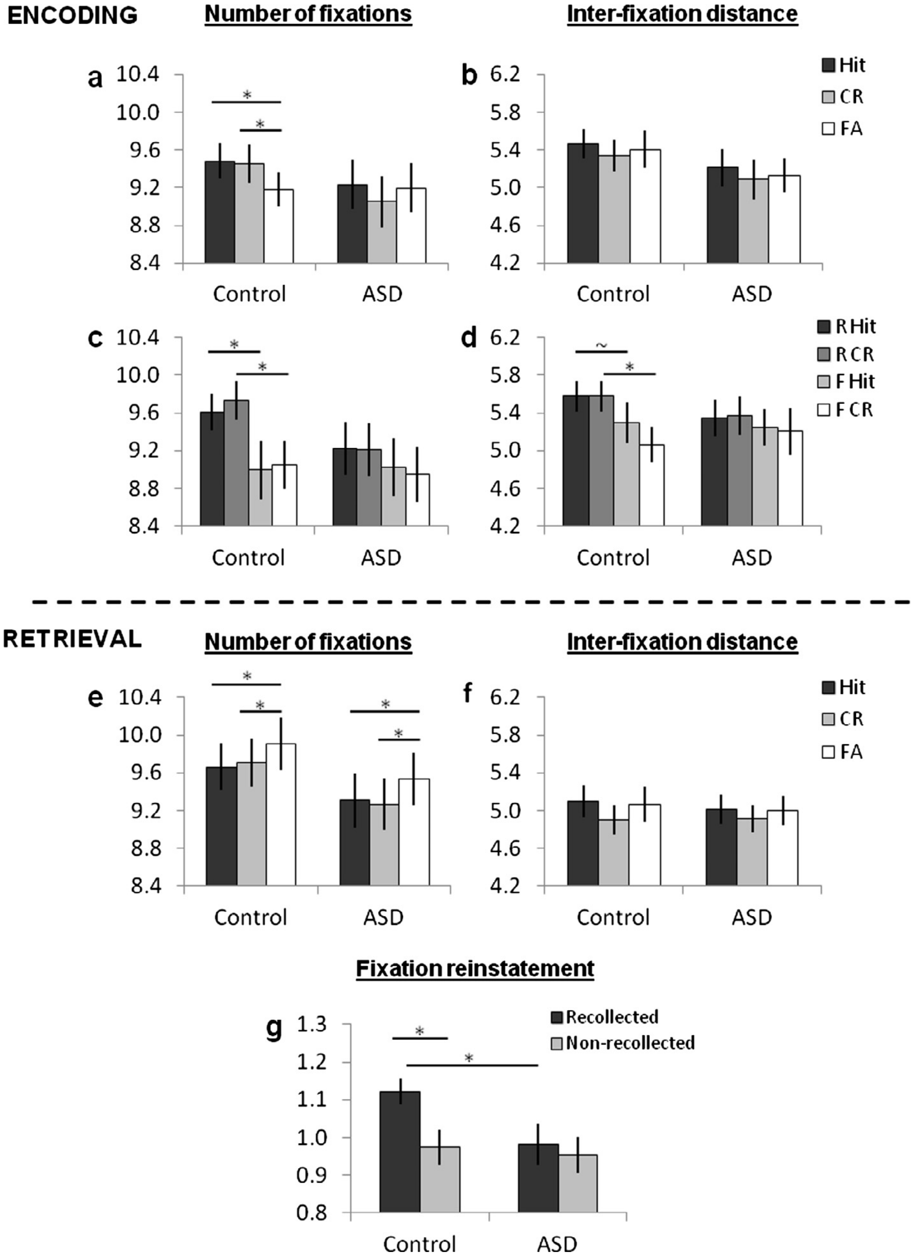

Fig. 4. Mean eye movements during encoding and retrieval in the control and ASD groups. Trials are divided into different types of memory response, including number of fixations and inter-fixation distance for Hits, CRs, and FAs during encoding (a and b) and retrieval (e and f), number of fixations and inter-fixation distance during encoding of Recollection (R) Hits and CRs, and Familiarity (F) Hits and CRs (c and d), and fixation reinstatement z values during retrieval of targets based on recollection or not (g). Significant differences are indicated with *. Error bars represent standard error of the mean.

ASD participants had low numbers of familiarity responses and so 18 participants per group were included. Subsequent recollection was associated with more encoding fixations than subsequent familiarity, $F(1,34) = 17.39$, $p < 0.001$, $\eta^2 = 0.32$. Interestingly, an interaction between response and group, $F(1,34) = 3.91$, $p = 0.05$, $\eta^2 = 0.07$, reflected that subsequent recollection was associated with more fixations than familiarity for both Hits ($t(17) = 2.76$, $p = 0.01$, $d = 0.65$) and CRs ($t(17) = 4.53$, $p < 0.001$, $d = 1.07$) in the control group, but this difference was smaller and not significant in the ASD group for both Hits ($t(17) = 1.68$, $p = 0.11$, $d = 0.39$) and CRs ($t(17) = 1.40$, $p = 0.18$, $d = 0.33$). No other effects were significant ($Fs < 0.6$, $ps > 0.4$, $\eta^2s < 0.02$). Note that, despite a numerical reduction, the group difference in number of fixations for correctly recollected trials did not reach significance ($t(34) = 1.35$, $p = 0.19$, $d = 0.45$). Subsequent recollection was also associated with more spatially distributed fixations than familiarity, $F(1,34) = 21.53$, $p < 0.001$, $\eta^2 = 0.35$. A significant interaction between response and group, $F(1,34) = 5.25$, $p = 0.03$, $\eta^2 = 0.09$, reflected that subsequent recollection was associated with more distributed fixations at encoding than familiarity for both Hits ($t(17) = 2.03$, $p = 0.06$, $d = 0.48$) and CRs ($t(17) = 4.87$, $p < 0.001$, $d = 1.15$) in the control group, but again there was no difference for both Hits ($t(17) = 0.97$, $p = 0.36$, $d = 0.23$) and CRs ($t(17) = 1.33$, $p = 0.20$, $d = 0.31$) in the ASD group. No other effects were significant ($Fs < 1.4$, $ps > 0.24$, $\eta^2s < 0.04$). Therefore, number of encoding fixations and inter-fixation distance predicted subsequent recollection (compared to familiarity) in the control group, but not in the ASD group.

3.2.2. Retrieval

3.2.2.1. Eye movements associated with distinguishing targets and lures. We conducted 2 (group: ASD, control) × 3 (trial type: Hit, CR, FA) ANOVAs to investigate retrieval-related eye movements associated with distinguishing target and lure scenes (see Fig. 4). Two participants with ASD were removed from this analysis due to low trial numbers, resulting in 20 control and 18 ASD participants. The groups did not differ significantly on the mean number of fixations during retrieval ($F(1,36) = 1.0$, $p = 0.31$, $\eta^2 < 0.03$). The trial types differed significantly in the number of retrieval fixations, $F(2,72) = 8.35$, $p = 0.001$, $\eta^2 = 0.19$, as FAs were found to be accompanied by significantly more fixations during retrieval than both Hits ($t(37) = 3.74$, $p = 0.001$, $d = 0.61$) and CRs ($t(37) = 3.54$, $p = 0.001$, $d = 0.57$). The number of fixations for Hits and CRs did not differ ($t(37) < 0.1$, $p > 0.9$, $d < 0.01$), and the differences between trial types did not vary between the groups ($F(2,72) < 0.3$, $p > 0.7$, $\eta^2 < 0.01$). For inter-fixation distance, there was no overall difference between the groups ($F(1,36) < 0.1$, $p > 0.8$, $\eta^2 < 0.01$), differences across trials did not reach significance ($F(2,72) = 2.60$, $p = 0.08$, $\eta^2 < 0.07$) and this did not vary between the groups ($F(2,72) < 0.3$, $p > 0.7$, $\eta^2 < 0.01$). Therefore, we observed that both groups increased their rate of eye movements during FAs compared to Hits and CRs.

3.2.2.2. Recollection-related fixation reinstatement. To investigate fixation reinstatement during retrieval for recollected and non-recollected target scenes, we used a 2 (group: ASD, control) × 2 (trial type: recollected vs. non-recollected target) ANOVA to analyse reinstatement z scores. Participants showed greater fixation reinstatement when viewing recollected compared to non-recollected target scenes, $F(1,38) = 8.74$, $p = 0.005$, $\eta^2 = 0.17$, and there was no overall difference in reinstatement between the groups, $F(1,38) = 1.9$, $p = 0.18$, $\eta^2 = 0.05$. However, an interaction between group and trial type, $F(1,38) = 4.03$, $p = 0.05$, $\eta^2 = 0.08$, was attributable to a significantly greater proportion of reinstated fixations for recollected (mean $z = 1.12$, $SD = 0.15$) compared to non-recollected scenes (mean $z = 0.97$, $SD = 0.1$) in the control group ($t(19) = 3.35$, $p < 0.01$, $d = 0.75$), but no difference between recollected (mean $z = 0.98$, $SD = 0.24$) and non-recollected scenes (mean $z = 0.95$, $SD = 0.21$) in the ASD group ($t(19) < 1$, $p > 0.4$, $d < 0.16$). Reinstatement associated with recollected scenes was also significantly higher in the control group compared to the ASD group ($t(38) = 2.19$, $p = 0.03$, $d = 0.69$), but there was no difference in reinstatement for non-recollected scenes ($t(38) < 0.5$, $p > 0.7$, $d < 0.1$), highlighting that subjects with ASD did not simply have a propensity to avoid previously viewed locations. Therefore, subjects with ASD showed a selective reduction in the similarity between regions viewed during encoding and retrieval during recollection (see Fig. 5).

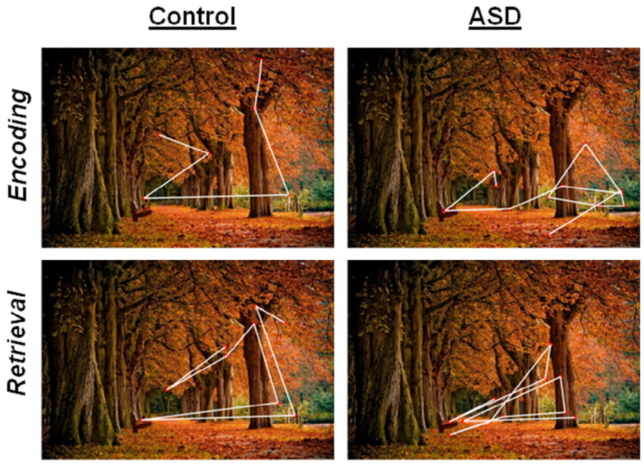

Fig. 5. Recollection-related fixation reinstatement. An example of the difference in recollection-related fixation reinstatement between a control and an ASD participant, showing that the control participant spends more time fixating areas they viewed during the encoding phase compared to the ASD participant during a recollection-based Hit.

4. Discussion

Many theories of memory dysfunction in ASD focus on encoding-related deficits, with few theories considering the potential for distinct retrieval contributions to recollection impairments (see Boucher et al., 2012). In the current study, we used behavioural and eye movement measures to investigate the relationship between encoding, including top-down strategic and bottom-up attentional and perceptual processes, and memory retrieval in ASD. As predicted, the ASD group exhibited impaired discrimination of previously encountered target and novel lure scenes, with a specific reduction in recollection-based correct responses. This recollection impairment replicates the results of previous studies that have observed a reduction in remember responses in ASD (Bowler et al., 2007; Cooper et al., 2015; Gaigg et al., 2015; Meyer et al., 2014), as well as studies that have reported an impairment in discriminating between similar target and lure stimuli in memory (Bowler et al., 2014; Cooper et al., 2015; Ring, Gaigg, & Bowler, 2016). Having supported the existence of a recollection impairment in ASD, it is necessary to consider the processes that might be driving this difference in performance between the two groups.

It has been suggested that people with ASD do not engage elaborative encoding strategies as effectively as controls, contributing to their recollection impairment (Meyer et al., 2014). In contrast to Meyer et al., we found that intentional encoding substantially improved performance over and above incidental learning similarly in both control and ASD groups. One possibility is that the task used by Meyer and colleagues may have been confounded by demands on task-switching abilities involved in interleaving trials to 'learn' and to 'forget'. Another possible explanation is that, in the current design, participants always completed intentional encoding after incidental encoding and so improvements could be due to familiarity with the memory test. However, intentional encoding disproportionately improved recollection in both groups, consistent with the commonly observed effects of elaborative encoding (Yonelinas, 2002). Moreover, we would expect both familiarity with the memory test and intentional encoding instructions to encourage the same strategic control over encoding processes and attention in the second encoding phase. In addition to the comparable behavioural effects, both groups also displayed a similar change in eye movements from incidental to intentional encoding, with participants apparently aiming to encode more features of the scenes in the latter condition. Therefore, the ability to engage elaborative encoding strategies may be relatively intact in ASD, as has been previously observed in a source memory task (Souchay et al., 2013), consistent with memory deficits that persist across different types of encoding condition in ASD (Cooper et al., 2016; Smith, Gardiner, & Bowler, 2007). However, even if the strategies invoked were comparably successful, an incidental/intentional manipulation cannot tell us whether each group's strategies were the same. Nonetheless, it is important to emphasise that the memory impairment was present across both encoding conditions in ASD, suggesting that whatever is disrupting recollection seems to be somewhat independent of strategic encoding.

Other potential influences on memory in ASD during both encoding conditions could include differences in bottom-up processes such as attention and perception. For instance, if people with ASD exhibit altered fixation patterns (e.g., Heaton & Freeth, 2016; Wang et al., 2015) and impaired discrimination of similar complex stimuli (e.g., Fletcher-Watson et al., 2012; O'Hearn et al., 2014) then this might impact how well memories are represented and subsequently recollected. However, on our control task, we found no evidence for a difference in perceptual discrimination ability between the groups, consistent with some previous research (Au-Yeung et al., 2011; Burack et al., 2009; Loth et al., 2008), and the memory impairment observed in ASD remained after controlling for perceptual accuracy. Furthermore, analyses of eye movements during encoding revealed no evidence that the pattern of attention at encoding differed between the ASD and control groups in terms of quantity and spatial distribution of fixations. It is possible that the previous approaches used were more sensitive to reveal differences in attending to specific regions of interest, or that, perhaps, eye movements of high-functioning adults with ASD do not substantially differ from controls during perception and memory tasks (e.g. Freeth et al., 2011; Hedley, Young, & Brewer, 2012). Interestingly, we found a direct dissociation between perception and retrieval in ASD, such that perceptual accuracy did not predict recollection in ASD, unlike in controls. Adding to the results showing a lack of influence of encoding instructions on the memory retrieval deficit in ASD, this finding suggests that recollection is not well predicted by perceptual specificity in ASD.

The analyses of the trial-by-trial relationship between encoding-related eye movements and memory retrieval further supports the notion of a disparity between encoding and retrieval in ASD and adds to previous findings by demonstrating this disparity *within* individual participants. In the control group only, trialwise discrimination of scene targets and lures was related to the number of fixations at encoding, as has been previously reported (Molitor et al., 2014), suggesting that a greater number of fixations likely resulted in a more detailed memory representation (Pertzov et al., 2009) and an increased probability of a scene being successfully retrieved. We also found that number of fixations was related to subsequent recollection in controls, as has been previously shown (Kafkas & Montaldi, 2011); however, unlike previous studies (Kafkas & Montaldi, 2011; Sharot et al., 2008), subsequent recollection was related to more dispersed, rather than clustered, fixations. It is likely that this disparity is a function of the task demands: in our study, memory for many specific details of the scenes would be beneficial due to the large overlap of features between old and lure scenes, whereas memory for a small, specific detail of a scene may often be sufficient to facilitate correct recollection. Even so, the current findings support previous studies in demonstrating that discrimination of target and lure items and recollection success are influenced by eye movements during encoding in typical individuals.

Conversely, the number of fixations exhibited by participants with ASD did not predict subsequent retrieval success and did not relate to correct recollection or familiarity, which also was not predicted by the spatial distribution of encoding fixations. These findings demonstrate that encoding eye movements have a reduced influence on trial-by-trial retrieval success in ASD. Notably though, we observed that the ASD group increased their eye movements following intentional encoding, which was accompanied by an overall increase in recollection, suggesting that a greater number of encoding fixations did indeed lead to better memory representations in these subjects (cf. Pertzov et al., 2009). In light of this observation, the dissociation between trial-specific encoding eye movements and retrieval success in ASD subjects thus suggests that the recollection deficits observed may at least be partly influenced by deficits during retrieval, independent of encoding. Interestingly, our findings are somewhat consistent with the results of the only fMRI study of long-term memory in ASD to date (Gaigg et al., 2015), which found that activity in inferior frontal gyrus during encoding differentiated subsequent recollection and familiarity in the control group, as expected, but not in the ASD group. Deficits after encoding may also have contributed to the recollection deficit in ASD observed by Gaigg et al., leading to a dissociation between neural measures of 'successful' encoding and retrieval success.

Evidence for memory deficits arising at retrieval in ASD may explain a number of findings in the literature, including the disproportionate benefit ASD participants gain from task support and retrieval cues (Bowler et al., 2004). This effect has previously been interpreted as resulting from encoding deficits (Bowler et al., 2014; Meyer et al., 2014), but the current results demonstrating no evidence for encoding differences as well as a lack of relationship between encoding and retrieval in ASD suggest that these theories may not capture the basis of recollection deficits in this population. Evidence for the benefit of task support on recollection in ASD has been found across a range of tasks, from source memory (Bowler et al., 2004; Maras, Memon, Lambrechts, & Bowler, 2013), to autobiographical recall (Crane, Lind, & Bowler, 2013) and eye-witness testimony (Maras & Bowler, 2012), where subjects with ASD can recall as much information as typical controls when sufficient cues are provided. The results of the current study suggest that retrieval cues likely ameliorate deficits at retrieval rather than encoding, possibly by minimising the monitoring demands involved in recollection. For instance, retrieval cues narrow the search for information in memory and reduce the amount of information to be held in working memory, which is thought to be impaired under high memory loads in ASD (Barendse et al., 2013; Williams, Goldstein, Carpenter, & Minshew, 2005). Similarly, Solomon et al. (2016) recently observed that cognitive control demands have a substantial influence on episodic memory success in ASD, emphasising the impact that retrieval demands can have on memory task performance.

In line with a retrieval deficit account, evidence suggests that while explicit memory judgements can be impaired in ASD, implicit memory (memory reflected indirectly and independently of an explicit judgement) appears to be intact, possibly indicating that information is successfully encoded but cannot be explicitly retrieved. Adults with ASD have been shown to exhibit impaired explicit memory but intact implicit memory for object location (Ring et al., 2015) and, during discrimination of old and similar lure faces in a memory test, ASD participants made more fixations to lures than targets, as do typical participants, despite impaired explicit memory discrimination (Hedley et al., 2012). Similarly, the present eye movement data at retrieval showing greater fixations during FAs compared to Hits might suggest that implicit memory for the scenes is somewhat intact in ASD. The possibility of a deficit in explicit recollection that cannot easily be explained by encoding is also supported by studies of metamemory in ASD. Evidence of a lack of relationship between feeling-of-knowing judgements at encoding and subsequent memory (Grainger, Williams, & Lind, 2014; Wojcik, Moulin, & Souchay, 2013) again suggests a disparity between encoding and retrieval success in ASD, and a reduced relationship between retrieval confidence and memory accuracy (Cooper et al., 2016; Wilkinson, Best, Minshew, & Strauss, 2010) suggests impaired monitoring during retrieval.

Our finding of reduced fixation reinstatement during recollection, evidenced by less correspondence between regions viewed during encoding and retrieval, adds further weight to the proposal of a reduced relationship between these two stages of memory in ASD. This eye movement measure provides what may be the first objective evidence that recollected memories appear to be reconstructed in a different way in people with ASD. One possibility is that reduced reinstatement of encoding fixations reflects a difficulty engaging strategic retrieval processes, as previously discussed, meaning that recollection is less efficient. Alternatively, a reduction in the reconstruction of a memory representation could reflect a reduced level of detail accompanying successfully recollected memories. The only main strand of evidence in ASD to suggest that recollection may possibly be less detailed as well as less frequent comes from autobiographical memory studies and subjective reports, showing that people with ASD recall fewer specific details (Maister, Simons, & Plaisted-Grant, 2013), fewer correct details (Maras & Bowler, 2012), and report their memories as being less salient than typical subjects do (Lind, Williams, Bowler, Peel, & Raber, 2014), although it is unclear from these verbal report-based methods and from fixation reinstatement exactly how recollected memories are qualitatively different in ASD. Moreover, it is acknowledged that fixation reinstatement is only calculated from the first three seconds of each retrieval trial and it is therefore unclear the extent to which participants' viewing may have changed following onset of the response options.

Of course there are a number of important processes that operate at retrieval, from pre-retrieval cue specification, to maintaining information in working memory, and post retrieval monitoring of recollected content, and further research will be needed to tease apart which processes are most affected in ASD. It is also important to emphasise that there may be aspects of encoding that are affected in ASD and which impact on retrieval success depending on the nature of the task. Rather than highlighting that encoding is 'intact', the current data demonstrate that measures of encoding do not always map on to recollection in ASD in the same way as they do in typical controls, which raises the possibility that retrieval processes, independent of encoding, contribute to memory impairments in ASD. To this end, it is important to note that the measures and conditions implemented here – such as memory improvements following intentional encoding, number of fixations as reflective of better encoding, and reinstatement as reflective of memory reconstruction – are based on evidence from the neurotypical population. It may not be appropriate to directly apply such findings to the study of memory deficits in ASD (cf. Mottron, Dawson, & Soulieres, 2008). For instance, eye movements may not be as representative a measure of successful encoding in ASD as in controls, and may reflect a different process altogether, meaning that a relationship between trial-specific encoding eye movements and retrieval might not be expected. While it is unclear why this would be the case based on the current literature and our data, group differences should of course be treated with caution.

In conclusion, the current study found that both top-down and bottom-up encoding processes did not moderate the recollection deficit observed in ASD. It is proposed that one explanation for the reduced relationship observed between encoding eye movements and subsequent memory in the ASD group could be that disruptions to memory occur at least in part during memory retrieval, which seems likely given that retrieval is a cognitively demanding task that relies substantially on working memory and monitoring processes. By analysing eye movements, this is the first study to provide direct evidence for a dissociation between encoding and recollection success in ASD as well as evidence of reduced memory reconstruction during recollection, suggesting that recollection may not only occur less frequently but may also be qualitatively reduced in people with ASD.

Acknowledgements

This research was supported by a James S. McDonnell Scholar Award to J.S.S., and an Economic and Social Research Council Award to R.A.C. We would like to thank all the participants who gave their time for this experiment, as well as the Autism Research Centre, Cambridge for helping with participant recruitment and providing access to the eye-tracking equipment used for this study.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.11.013.

References

Ames, C., & Fletcher-Watson, S. (2010). A review of methods in the study of attention in autism. *Developmental Review, 30*, 52–73.

Arthur, W. J. R., & Day, D. V. (1994). Development of a short form for the Raven advanced progressive matrices test. *Educational and Psychological Measurement, 54*(2), 394–403.

Au-Yeung, S. K., Benson, V., Castelhano, M., & Rayner, K. (2011). Eye movement sequences during simple versus complex information processing of scenes in autism spectrum disorder. *Autism Research and Treatment* 657383.

Barendse, E. M., Hendriks, M. P. H., Jansen, J. F. A., Backes, W. H., Hofman, P. A. M., Thoonen, G., ... Aldenkamp, A. P. (2013). Working memory deficits in high-functioning adolescents with autism spectrum disorders: Neuropsychological and neuroimaging correlates. *Journal of Neurodevelopmental Disorders, 5*(1), 14.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *Journal of Autism and Developmental Disorders, 31*(1), 5–17.

Boucher, J., Mayes, A., & Bigham, S. (2012). Memory in autistic spectrum disorder. *Psychological Bulletin, 138*(3), 458–496.

Bowler, D. M., Gaigg, S. B., & Gardiner, J. M. (2008). Effects of related and unrelated context on recall and recognition by adults with high-functioning autism spectrum disorder. *Neuropsychologia, 46*(4), 993–999.

Bowler, D. M., Gaigg, S. B., & Gardiner, J. M. (2014). Binding of multiple features in memory by high-functioning adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 44*(9), 2355–2362.

Bowler, D. M., Gardiner, J. M., & Berthollier, N. (2004). Source memory in adolescents and adults with Asperger's syndrome. *Journal of Autism and Developmental Disorders, 34*(5), 533–542.

Bowler, D. M., Gardiner, J. M., & Gaigg, S. B. (2007). Factors affecting conscious awareness in the recollective experience of adults with Asperger's syndrome. *Consciousness and Cognition, 16*(1), 124–143.

Burack, J. A., Joseph, S., Russo, N., Shore, D. I., Porporino, M., & Enns, J. T. (2009). Change detection in naturalistic pictures among children with autism. *Journal of Autism and Developmental Disorders, 39*, 471–479.

Cooper, R. A., Plaisted-Grant, K. C., Baron-Cohen, S., & Simons, J. S. (2016). Reality monitoring and metamemory in adults with autism spectrum conditions. *Journal of Autism and Developmental Disorders, 46*, 2186–2198.

Cooper, R. A., Plaisted-Grant, K. C., Hannula, D. E., Ranganath, C., Baron-Cohen, S., & Simons, J. S. (2015). Impaired recollection of visual scene details in adults with autism spectrum conditions. *Journal of Abnormal Psychology, 124*(3), 565–575.

Crane, L., Lind, S. E., & Bowler, D. M. (2013). Remembering the past and imaging the future in autism spectrum disorder. *Memory, 21*(2), 157–166.

Erez, J., Lee, A. C. H., & Barense, M. D. (2013). It does not look odd to me: Perceptual impairments and eye movements in amnesic patients with medial temporal lobe damage. *Neuropsychologia, 51*, 168–180.

Fletcher-Watson, S., Leekam, S. R., Connolly, B., Collis, J. M., Findlay, J. M., McConachie, H., & Rodgers, J. (2012). Attenuation of change blindness in children with autism spectrum disorders. *British Journal of Developmental Psychology, 30*, 446–458.

Freeth, M., Foulsham, T., & Chapman, P. (2011). The influence of visual salience on fixation patterns in individuals with autism spectrum disorders. *Neuropsychologia, 49*, 156–160.

Gaigg, S. B., Bowler, D. M., Ecker, C., Calvo-Merino, B., & Murphy, D. G. (2015). Episodic recollection difficulties in ASD result from atypical relational encoding: Behavioral and neural evidence. *Autism Research, 8*(3), 317–327.

Gaigg, S. B., Gardiner, J. M., & Bowler, D. M. (2008). Free recall in autism spectrum disorder: The role of relational and item-specific encoding. *Neuropsychologia, 46*(4), 983–992.

Grainger, C., Williams, D. M., & Lind, S. E. (2014). Metacognition in highfunctioning adults with autism spectrum disorder: Diminished feelings of knowing and mindreading ability. *Journal of Abnormal Psychology, 123*(3), 650–659.

Hannula, D. E., Althoff, R. R., Warren, D. E., Riggs, L., Cohen, N. J., & Ryan, J. D. (2010). Worth a glance: Using eye movements to investigate the cognitive neuroscience of memory. *Frontiers in Human Neuroscience, 4*(166), 1–16.

Hannula, D. E., & Ranganath, C. (2009). The eyes have it: Hippocampal activity predicts expression of memory in eye movements. *Neuron, 63*, 1–8.

Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36*(1), 5–25.

Heaton, T. J., & Freeth, M. (2016). Reduced visual exploration when viewing photographic scenes in individuals with autism spectrum disorder. *Journal of Abnormal Psychology, 125*(3), 399–411.

Hedley, D., Young, R., & Brewer, N. (2012). Using eye movements as an index of implicit face recognition in autism spectrum disorder. *Autism Research, 5*, 363–379.

Holm, L., & Mantyla, T. (2007). Memory for scenes: Refixations reflect retrieval. *Memory & Cognition, 35*(7), 1664–1674.

Joseph, R. M., Keehn, B., Connolly, C., Wolfe, J. M., & Horowitz, T. S. (2009). Why is visual search superior in autism spectrum disorder? *Developmental Science, 12*(6), 1083–1096.

Kafkas, A., & Montaldi, D. (2011). Recognition memory strength is predicted by pupillary responses at encoding while fixation patterns distinguish recollection from familiarity. *Quarterly Journal of Experimental Psychology, 64*(10), 1971–1989.

Kafkas, A., & Montaldi, D. (2012). Familiarity and recollection produce distinct eye movement, pupil and medial temporal lobe responses when memory strength is matched. *Neuropsychologia, 50*, 3080–3093.

Kim, J., & Yassa, M. A. (2013). Assessing recollection and familiarity of similar lures in a behavioral pattern separation task. *Hippocampus, 23*(4), 287–294.

Laeng, B., Bloem, I. M., D'ASDenzo, S., & Tommasi, L. (2014). Scrutinizing visual images: The role of gaze in mental imagery and memory. *Cognition, 131*, 263–283.

Lind, S. E., & Bowler, D. M. (2009). Recognition memory, self-other source memory, and theory-of-mind in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 39*(9), 1231–1239.

Lind, S. E., Williams, D. M., Bowler, D. M., Peel, A., & Raber, J. (2014). Episodic memory and episodic future thinking impairments in high-functioning autism spectrum disorder: An underlying difficulty with scene construction or self-projection? *Neuropsychology, 28*(1), 55–67.

Loth, E., Carlos Gómez, J., & Happé, F. (2008). Detecting changes in naturalistic scenes: Contextual inconsistency does not influence spontaneous attention in high-functioning people with autism spectrum disorder. *Autism Research: Official Journal of the International Society for Autism Research, 1*(3), 179–188.

Loth, E., Carlos Gómez, J., & Happé, F. (2011). Do high-functioning people with autism spectrum disorder spontaneously use event knowledge to selectively attend to and remember context-relevant aspects in scenes? *Journal of Autism and Developmental Disorders, 41*, 945–961.

Maister, L., Simons, J. S., & Plaisted-Grant, K. (2013). Executive functions are employed to process episodic and relational memories in children with autism spectrum disorders. *Neuropsychology, 27*(6), 615–627.

Mantyla, T., & Holm, L. (2006). Gaze control and recollective experience in face recognition. *Visual Cognition, 14*(3), 365–386.

Maras, K. L., & Bowler, D. M. (2012). Context reinstatement effects on eyewitness memory in autism spectrum disorder. *British Journal of Psychology, 103*(3), 330–342.

Maras, K. L., Memon, A., Lambrechts, A., & Bowler, D. M. (2013). Recall of a live and personally experienced eyewitness event by adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 43*(8), 1798–1810.

Meyer, B. J., Gardiner, J. M., & Bowler, D. M. (2014). Directed forgetting in high-functioning adults with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 44*(10), 2514–2524.

Migo, E., Montaldi, D., Norman, K. A., Quamme, J., & Mayes, A. (2009). The contribution of familiarity to recognition memory is a function of test format when using similar foils. *Quarterly Journal of Experimental Psychology, 62*(6), 1198–1215.

Minshew, N. J., & Goldstein, G. (2001). The pattern of intact and impaired memory functions in autism. *Journal of Child Psychology and Psychiatry, 42*(8), 1095–1101.

Molitor, R. J., Ko, P. C., Hussey, E. P., & Ally, B. A. (2014). Memory-related eye movements challenge behavioral measures of pattern completion and pattern separation. *Hippocampus, 24*, 666–672.

Mottron, L., Dawson, M., Soulières, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: An update, and eight principles of autistic perception. *Journal of Autism and Developmental Disorders, 36*(1), 27–43.

Mottron, L., Soulières, I., & Dawson, M. (2008). How useful are distinctions built for non autistic in describing autistic memory? In J. Boucher & D. Bowler (Eds.), *Memory in autism*. Cambridge University Press.

Naveh-Benjamin, M., Shing, Y. L., Kilb, A., Werkle-Bergner, M., Lindenberger, U., & Li, S.-C. (2009). Adult age differences in memory for name–face associations: The effects of intentional and incidental learning. *Memory, 17*(2), 220–232.

Nelson, H. E. (1982). *National adult reading test (NART): For the assessment of premorbid intelligence in patients with dementia: Test manual*. Windsor, UK: NFER-Nelson.

O'Hearn, K., Tanaka, J., Lynn, A., Fedor, J., Minshew, N., & Luna, B. (2014). Developmental plateau in visual object processing from adolescence to adulthood in autism. *Brain and Cognition, 50*, 124–134.

Olsen, R. K., Chiew, M., Buchsbaum, B. R., & Ryan, J. D. (2014). The relationship between delay period eye movements and visuospatial memory. *Journal of Vision, 14*(1), 1–11.

Otten, L. J., Henson, R. N. A., & Rugg, M. D. (2001). Depth of processing effects on neural correlates of memory encoding: Relationship between findings from across- and within-task comparisons. *Brain, 124*(2), 399–412.

Peiker, I., David, N., Schneider, T. R., Nolte, G., Schottle, D., & Engel, A. K. (2015). Perceptual integration deficits in autism spectrum disorders are associated with reduced interhemispheric gamma-band coherence. *The Journal of Neuroscience, 35*(50), 16352–16361.

Pertzov, Y., Avidan, G., & Zohary, E. (2009). Accumulation of visual information across multiple fixations. *Journal of Vision, 9*(10), 1–12.

Ring, M., Gaigg, S. B., & Bowler, D. M. (2015). Object-location memory in adults with autism spectrum disorder. *Autism Research, 8*(5), 609–619.

Ring, M., Gaigg, S. B., & Bowler, D. M. (2016). Relational memory processes in adults with autism spectrum disorder. *Autism Research, 9*(1), 97–106.

Ryals, A. J., Wang, J. X., Polnaszek, K. L., & Voss, J. L. (2015). Hippocampal contribution to implicit configuration memory expressed via eye movements during scene exploration. *Hippocampus, 25*, 1028–1041.

Sharot, T., Davidson, M. L., Carson, M. M., & Phelps, E. A. (2008). Eye movements predict recollective experience. *PLoS One, 3*(8), e2884.

Shih, S.-I., Meadmore, K. L., & Liversedge, S. P. (2012). Aging, eye movements, and object-location memory. *PLoS One, 7*(3), e33485.

Smith, B. J., Gardiner, J. M., & Bowler, D. M. (2007). Deficits in free recall persist in Asperger's syndrome despite training in the use of list-appropriate learning strategies. *Journal of Autism and Developmental Disorders, 37*, 445–454.

Smith, H., & Milne, E. (2009). Reduced change blindness suggests enhanced attention to detail in individuals with autism. *Journal of Child Psychology and Psychiatry, 50*(3), 300–306.

Solomon, M., McCauley, J. B., Iosif, A. M., Carter, C. S., & Ragland, J. D. (2016). Cognitive control and episodic memory in adolescents with autism spectrum disorders. *Neuropsychologia, 89*, 31–41.

Souchay, C., Wojcik, D. Z., Williams, H. L., Crathern, S., & Clarke, P. (2013). Recollection in adolescents with autism spectrum disorder. *Cortex, 49*(6), 1598–1609.

Wang, S., Jiang, M., Duchesne, X. M., Laugeson, E. A., Kennedy, D. P., Adolphs, R., & Zhao, Q. (2015). Atypical visual salience in autism spectrum disorder quantified through model-based eye tracking. *Neuron, 88*, 604–616.

Wilkinson, D. A., Best, C. A., Minshew, N. J., & Strauss, M. S. (2010). Memory awareness for faces in individuals with autism. *Journal of Autism and Developmental Disorders, 40*, 1371–1377.

Williams, D. L., Goldstein, G., Carpenter, P. A., & Minshew, N. J. (2005). Verbal and spatial working memory in autism. *Journal of Autism and Developmental Disorders, 35*(6), 747–756.

Wojcik, D. Z., Moulin, C. J. A., & Souchay, C. (2013). Metamemory in children with autism: Exploring "feeling-of-knowing" in episodic and semantic memory. *Neuropsychology, 27*(1), 19–27.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441–517.