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Reduced visual exploration when viewing photographic scenes in individuals with Autism Spectrum Disorder

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Abstract

Individuals with Autism Spectrum Disorder (ASD) often display enhanced attention to detail and exhibit restricted behaviour. However, due to a lack of comprehensive eye-movement modelling techniques, it is currently unknown whether these behavioural effects are also evident during scene viewing (i.e. detailed visual inspection and restricted visual exploration). Free viewing eye-tracking data from observation of everyday photographic scenes were recorded during two experiments involving high functioning adolescents with ASD and matched typically developing (TD) controls (Experiment 1 ASD n=14; TD n=22; Experiment 2 ASD n=16; TD n=23). Data from both experiments were combined and analysed using five novel methods of eye-tracking time-course analysis, enabling detailed characterisation of viewing strategies. Participants' verbal descriptions of scenes were also assessed. Scenes either contained a centrally positioned person whose face was in full view or contained no centrally positioned face. For both types of scene, ASD participants displayed significantly less exploration of new areas over time compared to their TD peers. Analyses of scanpath length and recursion suggested a greater tendency to explore areas close to the current fixation in the ASD group, termed visual persistence. Differences were not accounted for by fixation rate. Significantly more areas within the scenes were also missing from the verbal descriptions in the ASD group. Differences were observed for both scene types suggesting a domain-general difference rather than a specific impairment related to face processing. The observed characteristic viewing patterns may explain relative superior processing of local level information in individuals with ASD.

General Scientific Summary: Using new analytic approaches to eye-tracking data, we demonstrate that eye movements when free-viewing visually complex scenes made by individuals with autism are fundamentally different compared to those of their typically developing peers. We observed reduced visual exploration in those with autism and a greater tendency to explore areas close to the current fixation. This will result in the visual information received by the perceptual system being systematically different between those who have autism and those who do not.

Keywords: Visual exploration; autism; eye tracking; complex scenes; convex hull; linear model with random effects.

1 Introduction

The world around us contains a vast array of visually complex information. Although certain aspects of gist can be extracted from a brief glance at a scene (Fei-Fei et al. 2004; Dobel et al. 2007), during longer scene viewing fixations tend to be directed towards important and informative regions enabling more detailed information to be extracted. This is due to high quality visual information only being available from a limited spatial region surrounding the centre of gaze (the fovea) (Henderson 2003). When viewing our environment, we tend to fixate only on a small portion of the available information and from this we construct an internal representation of reality. Therefore, how we visually explore our environment has a fundamental impact on our perception and understanding of that environment. Klin (2003) termed this process the “enactive mind”. Recently interest in characterising the temporal dynamics of eye movement scanpaths during free-viewing of scenes has begun to emerge (Anderson et al. 2013; Wu et al. 2014), although the current range of methods available to researchers is limited and all work in this area to date has been conducted on data collected from the neurotypical population.

Many aspects of attention are known to be atypical in individuals with Autism Spectrum Disorder (ASD), see Ames and Fletcher-Watson (2010); Landry and Parker (2013); Guillon et al. (2014) for reviews. Hence it is possible that general temporal properties of eye movement scanpaths are also different in this population. However, currently available methods for characterising temporal aspects are not sufficiently developed to enable such assessment, in particular the likelihood to fixate new areas over time; tendency to remain close to previous fixations, or to revert to areas previously viewed. There is therefore a need for new approaches to characterising eye movement scanpaths that can improve our insight into these aspects of visual exploration.

Individuals with ASD generally display heightened attention to detail. The revised theory of Weak Central Coherence (Happé and Frith 2006) suggests a processing bias for local over global levels of information in ASD, resulting in local details being relatively more salient and a processing bias towards features. This relative local salience has been linked to enhanced perceptual functioning in ASD (Mottron et al. 2006). It has also been proposed that individuals with ASD have enhanced perceptual capacity (Remington et al. 2009, 2012) resulting in distractor information being suppressed to a lesser extent and making more information available for perceptual processing. This is supported by the finding that those with ASD have difficulty ignoring distracting visual information (Burack 1994), and that high levels of autistic traits are associated with a neural correlate of increased attention to task-irrelevant features of the visual array (Milne et al. 2013).

Those with ASD have also been described as having sticky attention. They can have difficulty disengaging from an initial point of fixation (Kikuchi et al. 2011; Landry and Bryson 2004) and in demanding tasks tend to display reduced saccadic activity (Kemner et al. 1998; Goldberg et al. 2002). In line with this Vabalas and Freeth (2015) recently found that during a face-to-face interaction individuals who were high in autistic displayed restricted eye-movements (shorter and less frequent saccades) compared to peers who were low in autistic traits. Visual inspection of objects is also often prolonged or unusual in infants who later develop ASD (Ozonoff et al. 2008). When children with ASD viewed picture arrays they tended to view fewer objects overall, look at individual objects for longer and make more fixations per object inspected (Sasson et al. 2008). Similar findings were observed in younger children (2–5yr olds) with ASD (Sasson et al. 2011) though the most pronounced differences were observed in adolescence (Elison et al. 2012). However, it is currently unclear whether these circumscribed viewing strategies would also be employed when viewing more naturalistic, visually complex stimuli, such as visual scenes. It is also unclear whether any temporal differences exist and can be characterised.

Restricted behaviour is another core feature of ASD. This can apply to a range of domains, such as having special interests or performing repetitive actions (South et al. 2005). Pierce and Courchesne (2001) found that children with autism displayed restricted exploration of their environments in a free-play situation and propose that this type of behaviour could cause those with autism to miss learning opportunities that fall outside their scope of interest. Pellicano et al. (2011) also observed reduced exploratory behaviour in a large scale behavioural search task, finding that children with autism had a greater tendency to re-visit areas previously searched than their typically developing peers. It is possible that restricted exploration is a domain-general feature of ASD, also applying to eye movements during free-viewing. This hypothesis is tested by the current investigation. However, in relation to free-viewing of visual scenes, restricting fixations to smaller regions within scenes may not necessarily have a negative outcome. This could, perhaps, increase information gained from those regions compared to those who take more cursory glances at such regions, resulting in increased knowledge or understanding of those regions more carefully inspected.

In this paper, we develop five highly sensitive, novel, robust measures of visual exploration assessing different aspects of eye movement behaviour: spread of fixations; scanpath length progression; fixation rate; visual persistence (the tendency to remain in the same area of viewing); and reversion to areas previously viewed. We also analyse verbal scene descriptions, noting regions omitted, to indicate how widely interest has been captured. These methods were applied to data previously collected from adolescents with ASD and matched typically developing (TD) adolescents for other studies, sub-sets of which were published presenting area of interest analyses in relation to social aspects of scene content (Freeth et al. 2010, 2011b) and analyses of eye movements in relation to visual saliency properties of images (Freeth et al. 2011a). In the current work however the interest was in characterising the nature of visual exploration of scenes during free-viewing and the progression of exploration over time. The presented methodologies are not however only applicable to our study group and we hope will have broader appeal to those interested in temporal analysis of scanpaths and who wish to obtain more detailed characterisations than have been previously available. All analysis was performed in the R programming language (R Core Team 2015) and code is available from the authors on request.

Adolescents with and without ASD viewed a series of photographic scenes for 5 (Expt1) or 15 seconds (Expt2) each. In Expt2, following the free-viewing phase, participants were asked to look at each scene again and provide a verbal description of the scene. No time limit was applied in this phase. Data from these two experiments were combined and used to model the progression of visual exploration over time. We analysed scenes both with and without a centrally positioned face to investigate whether any differences in exploration would be observed in response to all scenes or merely those containing prominent faces. Based on the findings of picture array viewing (Sasson et al. 2008, 2011; Elison et al. 2012), together with general observations of detail focussed processing in ASD (Happé and Frith 2006; Mottron et al. 2006) and restricted behaviour (South et al. 2005) we predicted that while viewing these complex photographic scenes individuals with ASD would display reduced visual exploration, as indicated by our fixation spread model. If found to be correct, our tailored models would enable us to establish whether differences were more likely a result of persistence within an area (South et al. 2005; Pierce and Courchesne 2001) or reversion to previously explored areas (Pellicano et al. 2011). Additionally, we were able to establish whether individuals with ASD generally moved their eyes over a shorter distance, as indicated by scanpath length, and whether there was a reduced fixation rate overall, which would support suggestions of individuals with ASD exhibiting delayed disengagement from the current fixation (Kikuchi et al. 2011; Landry and Bryson 2004). We were also interested in the potential implications of more restricted viewing on perception and specifically whether verbal descriptions would also be more restricted. We therefore predicted that significantly more areas within the scenes would be omitted from the descriptions of ASD participants.

2 Methods and Materials

2.1 Data Collection

Participants Twenty three 11–16 year old intellectually able (Full-Scale IQ $>$ 70) adolescents (21 males and 2 females) with ASD and 24 matched TD adolescents participated in Expt1. Twenty four 11-16 year old intellectually able (Full-Scale IQ $>$ 70) adolescents (21 males and 3 females) with ASD and 23 matched TD adolescents participated in Expt2. Of the individuals who took part in Expt2, twelve of the ASD participants and 17 of the TD participants had also completed Expt1 within a larger testing battery reported elsewhere

(Freeth et al. 2011a,b, 2010). Each participant had a break of at least 6 months between testing sessions.

All participants with ASD had been formally diagnosed by a UK mental health professional and had a statement of Special Educational Needs for Autism or ASD. An Autism Spectrum Screening Questionnaire (ASSQ) (Ehlers and Gillberg 1993; Ehlers et al. 1999) was completed by a parent or teacher of each participant. The ASSQ is a 27-item screening questionnaire which provides an indication of current level of autistic features. Possible score range is 0 to 54 and it has a suggested cut-off of 11 indicating clinical relevance when completed by teachers (a cut-off of 13 is suggested when completed by parents) (Ehlers et al. 1999). Higher scores indicate more autistic features. Participants were excluded from all analyses reported here if scores fell outside the suggested cut-offs for each group, resulting in a final sample of data from 14 ASD participants in Expt1 and 16 ASD participants in Expt2; 22 TD participants in Expt 1 and 23 TD participants in Expt2. See Tables 1 and 2 for further details of the final sample. All participants plus a parent or individual in loco parentis gave informed consent to participate prior to participation. Ethical procedures were in accordance with the Declaration of Helsinki.

Stimuli Twenty four photographs (1024×512 pixels) of everyday indoor and outdoor scenes, created by the second author, were viewed by each participant in Expt1; sixteen photographs from the same image set were viewed by each participant in Expt2. Within both Expt1 and Expt2, images were presented in the same order to each participant to reduce the potential for additional variation. Each scene contained at least one person (see Figure 1 for examples) and was partitioned into two categories: 1 — those containing a centrally positioned person whose face was in full view (panels A and D); and 2 — those without a centrally positioned face (panels B and C). Scenes in category 1 (central faces) accounted for 80% of the images presented while those in category 2 (no central faces) accounted for 20%. The stimuli from the two categories were dispersed throughout presentation of scenes in a standard order. Differences in contrast and luminance between images were controlled for via the random effects terms in our analysis model which allow each image to have a conditionally independent and data adaptive exploration rate. See Section 2.2 for further details.

Apparatus Eye movements were recorded using a remote Tobii 1750 eye-tracker system. Images were displayed at a distance of approximately 60cms and subtended a visual angle of approximately 32° horizontally and 24° vertically. A fixation was recorded if eye-tracking points were within 1.5° of visual angle for 80ms or more.

Procedure Following a calibration and head position check, participants viewed a series of photographs for 5 seconds each (Expt1) or 15 seconds each (Expt2). For Expt1, participants were told that all they needed to do was to look at the photos. For Expt2 participants were told that they needed to view and then verbally describe each photo. In Expt2, following each 15 second viewing phase, a screen prompt requested the participant give a "short" description of the scene. The scene was still visible in this phase in order that participants did not need to rely on memory to produce these descriptions, and also that in the viewing phase participants would genuinely be free-viewing rather than attempting to encode information from the image. No time limit was administered in the verbal description phase.

2.2 Analysis Approach

We modelled five aspects of exploration strategy, 1) evolution of fixation spread, 2) scanpath progression, 3) fixation rate, 4) visual persistence within an area, and 5) reversion to previous fixation locations. Group differences were investigated by fitting, over the time-course, linear models with random effects accounting for repeated images and individuals. Our novel measures provide an overview of an individual's tendency to view new regions of an image as opposed to remaining in or returning to previously explored areas. For our exploration analysis, the entire 5s of Expt 1 was combined with the initial 5s of viewing in Expt 2 and used together to assess potential differences between the two groups (ASD and TD).

We also explored whether scene perception was more restricted via analysis of the verbal descriptions generated in Expt2. For each image and individual, the spread of the items mentioned by participants was quantified as a measure of scene perception. Between group differences were assessed via a randomisation test to observe the potential implications of differences in visual exploratory behaviour on global understanding.

2.2.1 Comparison of spread and scanpath progression

Measuring Spread — Convex Hull The area of the fixations' convex hull provides a proxy for the area of scene explored. While this approach to measuring spread has been used previously for eye-tracking analysis (Goldberg and Kotval 1999; Sullivan et al. 2005), our novelty involves studying its rate of increase over time.

The convex hull of any set of fixations $\mathcal{X}$ is defined as the smallest convex set containing them. Intuitively, this hull can be imagined by stretching an elastic band around the outer bounds of all fixations before allowing it to contract (Figure 2). A set of fixations with a large convex hull indicates a propensity to move to new, previously unexplored areas of the image rather than remain in (or return to) locations previously viewed. Larger hulls are also obtained if saccades explore new "orthogonal" directions as opposed to scanpaths lying along straight lines.

We believe the convex hull to be the most suitable measure of visual exploration, though a range of alternatives were considered (see next section for discussion). While any measure of spread based on covering the entire scanpath has the potential to be significantly influenced by single, distant fixations (even if these fixations occur for only a short time) this is dealt with by our methodology. Our linear model combines repeat measurements over multiple images and individuals meaning no single distant excursion can overly influence group comparisons. If distant excursions occur more frequently in one group, this in itself would indicate a difference in exploration strategy.

It is however important not to suggest exploration is equivalent to comprehension. An individual fixating on all four corners of a scene without directing any attention towards the centre would result in a maximal convex hull but probable poor overall scene comprehension. While we cannot say an individual has necessarily comprehended everything within the convex hull, a larger hull does suggest a tendency to explore new areas rather than remain viewing the same regions.

Consideration of alternatives to the convex hull It would be feasible to measure exploration area by covering the fixations with other shapes, however the convex hull is the canonical choice and also robust to small changes in fixation locations. For example, a single circumscribed circle will provide greatly differing areas with only minor variations in fixation locations (for an illustration, see Goldberg and Kotval 1999). Scanpaths lying only along a single straight line will also be allocated larger circles than those where fixations lie two-dimensionally.

An alternative could be the bivariate contour ellipse area (BCEA) approach (Holmqvist et al. 2011). However this measure is based upon an assumption that fixation locations fall independently according to an identically distributed bivariate normal distribution. This is unlikely to be justified for fixation locations in a general scene. Such a measure is also highly dependent upon the classification and overall number of fixations. If a single fixation is instead classed as two separate fixations at near identical locations (perhaps separated by a microsaccade), the BCEA will decrease simply due to this reclassification. An individual who evenly explores an image with a large overall number of fixations will therefore be estimated to have lesser exploration than an individual who covers the identical overall area but with fewer fixations. This is an undesirable feature in a measure of exploration. Additionally, this dependence means that a BCEA based measure of exploration can decrease with viewing time. The convex hull is invariant to such classification of fixation number and is monotonically increasing with time as more of the image is, by definition, explored.

Finally, building an attention map by placing Gaussian kernels around each fixation and measuring the proportion of image with attention above a certain threshold (Holmqvist et al. 2011; Wooding 2002) requires an arbitrary but critical selection of both kernel spread parameters and attention cut-off threshold. Dependent upon this choice, it can also suffer from a similar lack of invariance to fixation number classification as the BCEA. Such a measure is more suited to assess image coverage than exploration. Once outside the cut-off distance from previous kernels, it does not distinguish between fixations which are still relatively close within the image and those which are truly distant from one another.

Creating a time-dependent measure of spread To quantify spread at time t we calculated, for each individual i and image j, the area $A_{ij}(t)$ of the convex hull of those fixations occurring before t (see Figure 3). With each new fixation, the hull will either remain unchanged (if this fixation falls within the existing hull) or increase (if outside). As such $A_{ij}(t)$ increases monotonically over time.

Measuring Scanpath Progression We also measured evolution of the total length of scanpath. For individual i, viewing image j, let $D_{ij}(t)$ be the summed length of the saccades in the scanpath occurring before time t. Larger values of $D_{ij}(t)$ will correspond to individuals exploring the image at a faster rate as measured in terms of saccadic movement.

While distance alone cannot distinguish between an individual exploring entirely new areas and one who simply alternates between previously viewed regions, when combined with assessment of fixation spread more insight can be gained. If individual A has a larger hull area but equivalent scanpath length to B, this suggests A is continuously moving to new image regions while B is moving away initially but then returning to previously viewed areas.

Linear modeling with random effects Using our image exploration measures, we investigated potential differences between the ASD and TD groups using a mixed effects model. For illustration, we refer to $A_{ij}(t)$, our measure of fixation spread. An identical procedure was followed for the path lengths $D_{ij}(t)$. At any time of interest, we consider

$$A_{ij}(t) = \begin{cases} \mu(t) + \alpha(t) + \lambda_i(t) + \mu_j(t) + \epsilon_{ij}(t) & \text{if } i \text{ non-ASD} \\ \mu(t) + \lambda_i(t) + \mu_j(t) + \epsilon_{ij}(t) & \text{if } i \text{ ASD} \end{cases} \tag{1}$$

Of specific interest is $\alpha(t)$, the additional mean area viewed by a TD individual by time t (a negative value indicates reduced mean area). Of the other terms, $\mu(t)$ denotes the mean area viewed by those with ASD at time t; $\lambda_i(t) \sim N(0, \tau^2)$ the random effect of individual i; $\mu_j(t) \sim N(0, \zeta^2)$ the random effect of image j; and $\epsilon_{ij}(t) \sim N(0, \sigma^2)$ the additional noise independent of image and individual.

A mixed effects model is required since, in any population, there may be some individuals who tend to explore an image more quickly than others. Similarly some images may be explored more rapidly. To enable conclusions to be generalised outside the specific population of study, to new images or individuals, these factors must be modeled as random effects.

2.2.2 Comparison of Fixation Rate

Modeling fixation occurrence as a time-inhomogeneous Poisson Process (Diggle 2003; Barthelmé et al. 2013), we counted, for individual i and stimulus j, the number of new fixations $N_{ij}(t)$ falling in the interval $[t - w_{size}/2, t + w_{size}/2]$. A random effects Poisson regression was used to assess differences in rate between groups over the viewing period where $N_{ij}(t) \sim Po(\nu_{ij}(t)w_{size})$ and

$$\log \nu_{ij}(t) = \begin{cases} \mu(t) + \alpha(t) + \lambda_i(t) + \mu_j(t) + \epsilon_{ij}(t) & i \text{ non-ASD} \\ \mu(t) + \lambda_i(t) + \mu_j(t) + \epsilon_{ij}(t) & i \text{ ASD} \end{cases}$$

Here $\nu_{ij}(t)$ is the instantaneous rate of new fixations at time t. Other model terms are analogous to the hull model. To obtain robust estimates, a window w_{size} of 200ms was chosen.

2.2.3 Comparison of Persistence and Reversion

In the context of visual scene exploration, we define persistence as the tendency of an individual to remain viewing a location close to the current fixation into the future. Alternatively, reversion is the relative tendency of an individual to return towards previous fixations having moved away. Considering the scanpath as a time series $\mathbf{X}_t$ we quantify both these aspects of exploration through the (scaled) expected distance

$$L(\tau) = \mathbb{E}\left[\frac{||\mathbf{X}_t - \mathbf{X}_{t+\tau)}||_2}{S(t, t+\tau)}\right].$$

Here $||.||_2$ denotes Euclidean distance. The indices t and τ can either denote continuous time if interest is in the expected distance at future time τ; or discrete fixation number if interest is in the distance to the τ^{th} future fixation.

Selection of different denominator scalings tailors this measure towards either persistence or reversion. Using $S(t, t+\tau) = 1$, $L(\tau)$ simply measures the expected distance from the location of the current fixation to that at future time (or fixation) τ. Individuals exhibiting persistence will have small such values due to their tendency to remain viewing regions near the current fixation. Reversion requires a finer measure to control for how far the individual has moved during the interim period from t to $t+\tau$. This can be achieved if we rescale by $S(t, t+\tau) = D(t+\tau) - D(\tau)$, the length of the interim scanpath. Small values of $L(\tau)$ will then be obtained if this is large in relation to the numerator. This can only occur if an individual has continued to explore the image before reverting towards the previous location. Rescaling by the root of the convex hull area would provide a similar reversion measure.

We believe our two measures offer an improvement over current recursion approaches e.g. RQA (Anderson et al. 2013). Explicit incorporation of the lag τ provides clearer and stronger insight into the time scales on which recurrence might occur and does not require selection of an arbitrary threshold. The ability to rescale also makes them more adaptable. Having estimated $L(\tau)$ another random effects linear model assesses potential group differences at all lags τ.

2.2.4 Associations between eye-tracking outcomes and ASD symptom severity

We were also interested in potential links between our various eye-tracking measures and the symptom severity of those individuals with ASD (as measured by their ASSQ scores). To investigate such differences, for each of our five measures, separate sub-analyses on the ASD group alone were run including the ASSQ score as a potential predictor in the model. The significance of the ASSQ score was then assessed using generalised likelihood ratio tests. Since it is only possible to measure the significance of any term in the model at fixed time points (i.e. not for the entire course of the experiment) we chose to perform this subanalysis either at 5000ms (the end of the experiment) or when the differences between the ASD and TD groups appeared largest.

2.2.5 Verbal description analysis

To investigate whether scene processing was more restricted in area in the ASD group, a potential consequence of visual exploratory strategy, we considered the quality of the verbal descriptions provided by the participants in Expt2. Analogously to our scanpath analysis, interest was in the ability to capture the entirety of the scene as assessed by the spread of items described. Each image was partitioned into five regions of equal area - a central area plus the four corner quadrants. Every individual item in the scene was allocated to one of these regions; where an item covered more than one area, this item was allocated to a single region for coding purposes, see Figure S1. The number of regions lacking a mention of any items was recorded to give a *missingness* score between 0 and 5.

Let M_{ij} denote the missingness score for individual i and image j. To test for a reduction in the spread of the verbal descriptors amongst those with ASD, we used a cumulative t-based statistic summed over the image set

$$T = \sum_j t_j,$$

where

$$t_j = \frac{\bar{M}^j_{\text{ASD}} - \bar{M}^j_{\text{Typ}}}{s^j_{\bar{M}^j_{\text{ASD}} - \bar{M}^j_{\text{Typ}}}} \tag{2}$$

is the standard signed t-statistic to compare the missingness scores of the two groups on image j. A positive value of t_j suggests more areas were absent from descriptors in the ASD group for image j. Use of cumulative *signed* t-statistics guaranteed we assessed uniformity in the direction of differences in missingness between groups e.g. that the ASD missingness scores were constantly higher over all images. The significance of any reduction in descriptor spread between groups was assessed using a randomisation test based on 10,000 reallocations of the participants. Analyses of this form were also conducted on mean length of utterance data and the number of nouns in each description in order to establish whether these measures could account for any differences between groups in missingness scores. N.B. For a contents analysis of these data, please see Freeth et al. (2011b).

2.2.6 Data cleaning and pre-processing

Before analysis, off screen fixations were removed. It was also decided that any individual who was seen to fixate on-screen for less than an average of 90% of the time analysed over the images would be discarded i.e. fixated off screen for more than 500ms of the 5000ms. No individuals fell into this category. One image, depicting the second author, was also removed (Figure 1, panel D). This image was not felt to be comparable to the other images due to the author's involvement in administration of the experiment. After cleaning, for each individual within the ASD group, the average time (of the 5000ms analysed) spent looking off screen was 80ms. Within the TD group it was 44ms.

Data from Expt1 and Expt2 contributed to all five models: all data from Expt1 and the first 5s of data from Expt2. Models contained data from 36 distinct ASD participants and 30 TD participants once accounting for those individuals participating in both experiments. Analysis was performed using the R programming language (R Core Team 2015). Code is available from the authors on request.

3 Results

Group comparison of eye-tracking data The (generalised) linear model results of our area, distance, and rate comparisons can be seen in Figure 4. The estimated values for each group at time t are shown in the left hand plots while the right hand plots show $\alpha(t)$, the additional area/distance/fixation rate for the TD adolescents compared to the ASD group, together with 95% confidence intervals. Estimates are calculated pointwise over time with statistical significance indicated by confidence intervals which do not overlap zero. However, one should recognise that tests at neighbouring time points are not independent but instead borrow strength from one another. If differences are seen consistently over a period of time (as is mainly the case in our analysis) then a pointwise approach to significance will give a conservative assessment of group differences. Similarly one must not to read too much into individual significant time points when there is little evidence for a trend at surrounding times. As we will see, this is somewhat less of a concern in our study since most measures show consistent trends whereby once differences are observed between the groups they tend to remain for future times.

The fixation spread, as measured by the convex hull, is consistently greater in the TD group. This becomes particularly clear from 2500ms when a gradient change can be seen in $\alpha(t)$ suggesting a point at which the ASD individuals slow their exploration. Beyond this time, the mean hull area of the TD group is uniformly larger than that of the ASD group. Analysis of scanpath length also suggests a trend that the TD group travel further although, unlike the hull area, the pointwise 95% confidence intervals still overlap zero and no corresponding gradient change at 2500ms is seen. This suggests the ASD group are continuing to make eye movements but the location of gaze is less likely to be in an entirely new area. Importantly, there is no evidence for a difference in the rate of new fixations between the two groups at any time. This indicates that the above differences are not simply due to a decrease in the number of new fixations but rather a more structural disparity in viewing strategy between the two groups.

Figure 5 shows our measure of persistence (top) and reversion (bottom). Persistence was measured with a continuous time lag τ so long dwells on the same location are considered evidence of persistence. At all lags τ, the TD individuals are expected to be further from previous fixations than those with ASD clearly demonstrating increased persistence in ASD. Similar results were seen with a fixation number lag. Reversion was measured with a fixation number lag so $L(\tau)$ was still defined if the individual had not moved in the period from t to $t + \tau$. As shown by a mean level consistently above zero, there is some evidence for increased reversion amongst the ASD group. This reversion seems to occur predominantly in those images with a centrally located face, see Figure S4 indicating lesser reversion for general scenes.

Analysis by stimuli type Our stimuli fall into two general categories: 1. Prominent face scenes - containing a centrally positioned person whose face was in full view (80% of all images) ; 2. Non-prominent face scenes - containing no centrally positioned face (20% of all images). To demonstrate our results are not just due to atypical attention to faces in ASD, all analyses were repeated on only the scenes containing no centrally positioned face. All effects, except for reduced levels of reversion (discussed above) and scanpath length (where the observed mean path length for the ASD group was actually larger than the TD group between 1000 and 3000ms), were replicated (see Figures S3 and S4).

Importance of ASSQ score on eye-tracking outcome measures within ASD group Our sub-analysis amongst the ASD group indicated little or no evidence that symptom severity (as assessed by ASSQ score) played a significant role in any of our exploration measures. As explained in Section 2.2.4, it is only possible to assess such importance at single time-points. Hull area (p-value 0.58) and scanpath length (p-value 0.18) were both assessed at 5000ms; fixation rate (p-value 0.58) at 3000ms when the difference between the ASD and TD groups appeared largest and rates still reasonably high; persistence/lagged distance by time (p-value 0.77) at 2000ms and reversion/scaled lagged distance by fixation (p-value 0.2) at lag 20 where again the observed TD to ASD group differences were towards their largest. The fact no evidence for the importance of ASSQ score was seen even at these time points suggests that, beyond being diagnosed with ASD, an individual's symptom severity was not a significant factor for our exploration outcomes — although it may be that ASSQ score is not a suitable linear measure of such severity.

Verbal description analysis Analysis of verbal description data indicated strong evidence for a uniform increase in the number of areas missed from the ASD participants descriptions across the entire image set (two-sided p-value 0.035) supporting our hypothesis that the descriptions of participants with ASD would be significantly more restricted in area than those of TD participants. Figure 6 presents the mean additional number of areas missed in verbal descriptions (together with approximate 95% confidence intervals based on individual t-tests) for each image. As can be seen, for all of the 16 images, the mean number of areas lacking description is higher amongst the ASD group. This adds further support to our hypothesis that scene processing was more restricted in area amongst the ASD group. As for analyses of the eye-tracking data, no relation was found between symptom severity and number of areas missed - a Pearson's correlation found no significant correlation between ASSQ scores and overall number of areas missing from participant descriptions, r=.01, p=.96. The difference between groups in the number of areas described was not simply due to variations in length of the descriptions or the number of nouns used between groups. An analogous randomisation test analysis on the total length of utterance indicated no strong evidence of a decrease in length in the ASD descriptions compared to the TD group (p-value 0.16); similarly there was no strong evidence that the number of nouns used in the descriptions was different between the groups (p-value 0.11). 10% of data were blind second coded. Inter-rater reliability was assessed via intra class correlation. There was excellent agreement for both the missingness coding, r=.99, $p < .001$, and the number of nouns coding, r=.95, $p < .001$.

Consistency amongst individuals and range of exploration speeds One may also be interested in whether, separately from any ASD effect, individuals are consistent in their rate of exploration over images or if they vary. Specifically, does an individual in either the TD or ASD group who explores one image at a faster rate than the rest of their group also explore the other images at this same increased rate or do they vary their speed from image to image. This consistency, along with the range of exploration speeds in both groups, can be assessed via the λ_i random effect terms of Equation 1 which correspond to the various individuals i. We assessed consistency for both our area and distance exploration measures on the complete scanpath data at 5000ms. A generalised likelihood ratio test was used to compare the full models of Equation 1 with reduced models which did not include the λ_i individual random effect terms. In both cases there was overwhelming evidence ($p < 2 \times 10^{-16}$) to support inclusion of the individual random effect term corresponding to individual exploration consistency across images. For more details and histograms of the estimated random effects, see Section A.4 in Supplementary Information.

4 General Discussion

We report five novel methods of eye-tracking analysis applied to data collected during free-viewing of scenes completed by adolescents with and without ASD plus analysis of participants' verbal descriptions of these scenes. Analyses enabled characterisation of the time-course of various eye-tracking measures revealing clearly different visual exploration strategies between groups. This suggests fundamentally different perceptual experiences for individuals belonging to each group. Analysis of fixation spread, as measured by progression of the area of the convex hull of fixation points, revealed that adolescents with ASD had a slower rate of increase in area viewed when compared to TD adolescents. This finding demonstrates a detailed focussed processing style of visual exploration, replicating findings reported in other domains (Happé and Frith 2006; Mottron et al. 2006). This became particularly clear from 2500ms after stimulus onset. Study of scanpath progression found somewhat shorter scanpaths for the ASD participants, suggesting a tendency to explore areas closer to the current fixation than their TD peers. Investigation of fixation rate via a Poisson regression model indicated both the above differences were not simply due to a reduction in the rate of new fixations but rather fundamentally differing strategies adopted by each group, therefore we found no evidence of sticky attention, or delayed disengagement at the level of fixation, in our current dataset (Kikuchi et al. 2011; Landry and Bryson 2004). Our data also reveal that interest in a more restricted area within scenes was not only found in the eye-tracking data but also in the verbal description data as participants with ASD missed significantly more areas within the scenes from their verbal descriptions than did the TD participants. We found no evidence to suggest that the extent of reduced visual exploration was related to ASD symptomatology, as indicated by scores on the ASSQ (Ehlers et al. 1999). However, further investigation using a more robust assessment and symptomatology tool, such as ADOS (Lord et al. 2000) or ADI (Le Couteur et al. 2003), would be necessary to draw firmer conclusions in this regard and should be a focus of future investigation.

A recursion analysis found evidence of increased visual persistence in the ASD group as individuals with ASD tended to view locations significantly closer to previous locations for all lags τ, extending findings of behavioural persistence often observed in ASD (South et al. 2005; Pierce and Courchesne 2001) to the visual domain. This trend was observed across the whole dataset, and independently in our two stimulus categories - images depicting a centrally positioned person whose face was in full-view and in scenes where there was no centrally positioned face - indicating that this finding was independent of scene content. This is important as it demonstrates that increased visual persistence is domain general rather than being driven by atypical face processing. In addition, for scenes containing a centrally positioned face, there was also a tendency for ASD participants to return towards previous locations after having moved away suggesting a propensity to revisit areas previously viewed. However, differences were not as marked on this measure as for visual persistence.

Previous work has suggested that individuals with ASD exhibit circumscribed viewing patterns when looking at picture arrays and tend to view fewer items than TD individuals (Sasson et al. 2008, 2011; Elison et al. 2012). Our visual exploration models support this work and extend the findings to everyday scenes. It appears that for individuals with ASD, attention was captured by aspects of the visual scene that were close to the current fixation to a greater extent than was the case for TD individuals. This is in accordance with the observation that individuals with ASD can be disproportionally affected by distracter items close to a current fixation (Burack 1994). It has been proposed that those with ASD have an enhanced perceptual capacity and spontaneously process surrounding information as well as central information (Remington et al. 2009, 2012). It is possible that, in the current study, this enhanced perceptual capacity resulted in ASD participants taking in more information surrounding the current fixation and hence exploring this in greater detail at certain points in their visual exploration. Conversely, the mechanism could operate in the opposite direction in that reduced visual exploration *results* in enhanced perceptual capacity. Regardless of the causative direction, a naturally different sampling method, such as observed here, will likely have a profound effect on visual perception and other aspects of processing.

If the systematic differences in visual exploration and processing observed here generalise to everyday life, this could help explain why those with ASD display a local processing bias. The evidence presented here suggests many aspects of the environment will likely not be sampled during natural visual exploration by individuals with ASD. Restricted or persistent behaviour is commonly reported in individuals with ASD (South et al. 2005). It had previously been proposed that individuals with ASD may exhibit visual persistence (Pierce and Courchesne 2001). Here we demonstrate clear evidence in support of this theory.

There are a number of future directions that we see as particularly important in relation to the current work. The stimuli presented to participants in the current experiment represented a range of scenes that could be viewed in everyday life. Our scenes fell into two categories: 1. Prominent face scenes — containing a single centrally positioned person whose face was in full view; 2. Non-prominent face scenes — containing no centrally positioned face, in which individuals could be small and/or in the background. However, none of our scenes were entirely non-social. An interesting future question will be whether the same effects (i.e. restricted visual exploration and visual persistence in those with ASD) would be observed when viewing scenes completely absent of all social elements. Additionally, it would be of interest to investigate whether, as suggested in the convex hull analysis of Figure 4, there is a step change in exploration rate at around 2500ms where those with ASD being to slow relative to their TD peers.

Future work could also investigate individual differences in exploration strategy and strategy consistency over time, i.e. the degree of exploration strategy consistency over multiple testing sessions. A particular further question of importance in relation to individual differences is the relationship between restricted and repetitive behaviours and visual exploration strategy in both the general population and in those with ASD. This could be assessed using the Repetitive Behaviours sub-scale of the ADI-R (Le Couteur et al. 2003), the RBS-R (Bodfish et al. 2003) or the RBQ/RBI (Turner 1995)). An association between "repetitive sensory and motor behaviours" or "insistence on sameness" (two sub-scales of the ADI-R (Szatmari et al. 2006)) and visual exploration strategy could facilitate understanding of these aspects of the autistic profile.

To conclude, this paper aims to provides a two-fold contribution to the literature: to investigate differences between the exploration strategies of ASD and TD individuals; and also present a new set of analysis tools for the temporal analysis of scanpaths. The novel visual fixation modelling methods presented here provide a clearer insight into visual exploration behaviour than was previously possible. This significantly improves our understanding of the perceptual experience of the individual and provides a more holistic overview of this experience. For the data analysed in the current study our novel eye-tracking data analysis methods found fundamentally different viewing strategies in individuals with ASD compared to TD individuals, demonstrating reduced visual exploration by adolescents with ASD. Our verbal description data also suggested that visual processing was more restricted in ASD. However, it is not necessarily the case that one strategy is better than another, or that one strategy represents a deficit. Rather it is valuable to consider the implications of each strategy. Although exploring less of the visual scene overall will lead to certain information being missed, one potential benefit of the observed viewing strategies exhibited by individuals with ASD could be improved attention to detail within a small area. It could be that the individuals with ASD, as a result of their more restricted viewing strategy, were able to more effectively process the available information within the areas viewed. In the future, it will be important to investigate potential consequences of reduced visual exploration for individuals with ASD.

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	ASD participants	Typically developing participants
N	14	22
Age (years;months)		
Mean	13;6	14;3
SD	1.0	1.3
Range	11;6 – 15;1	11;8 – 16;5
Full-scale IQ		
Mean	96.6	96.3
SD	16.2	8.3
Range	70 – 129	79 – 109
ASSQ		
Mean	28.9**	2.2**
SD	13.1	2.8
Range	18 – 45	0 – 9

Table 1: *Participant Characteristics — Experiment 1. The double starred ** entries indicate a p-value* $p < 0.001$ *i.e. participants with ASD scored significantly higher on the ASSQ than TD participants.*

	ASD participants	Typically developing participants
N	16	23
Age (years;months)		
Mean	14;8	14;9
SD	1.4	1.3
Range	12;4 – 16;6	12;4 – 17;1
Full-scale IQ		
Mean	102.5	97.9
SD	13.3	7.3
Range	74 – 126	83 – 112
ASSQ		
Mean	26.4**	2.2**
SD	8.5	2.8
Range	17 – 43	0 – 9

Table 2: *Participant Characteristics — Experiment 2. The double starred ** entries indicate a p-value* $p < 0.001$ *i.e. participants with ASD scored significantly higher on the ASSQ than TD participants.*

Figure 1: Example stimuli: Scene category 1. Prominent face scenes - panel A and D (contain a centrally positioned person whose face was in full view), Scene category 2. Non-prominent face scenes - panel B and C (contain no centrally positioned face)

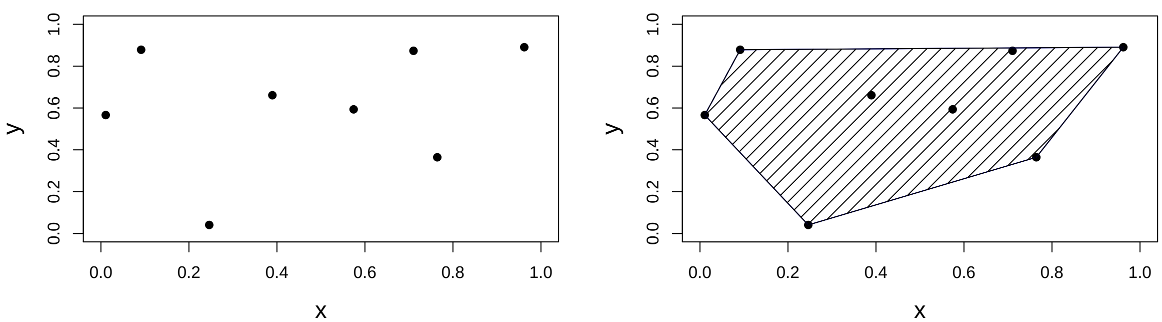


Figure 2: *Illustration of a convex hull. The left plot shows a hypothetical set of fixations; the right plot shades their convex hull.*

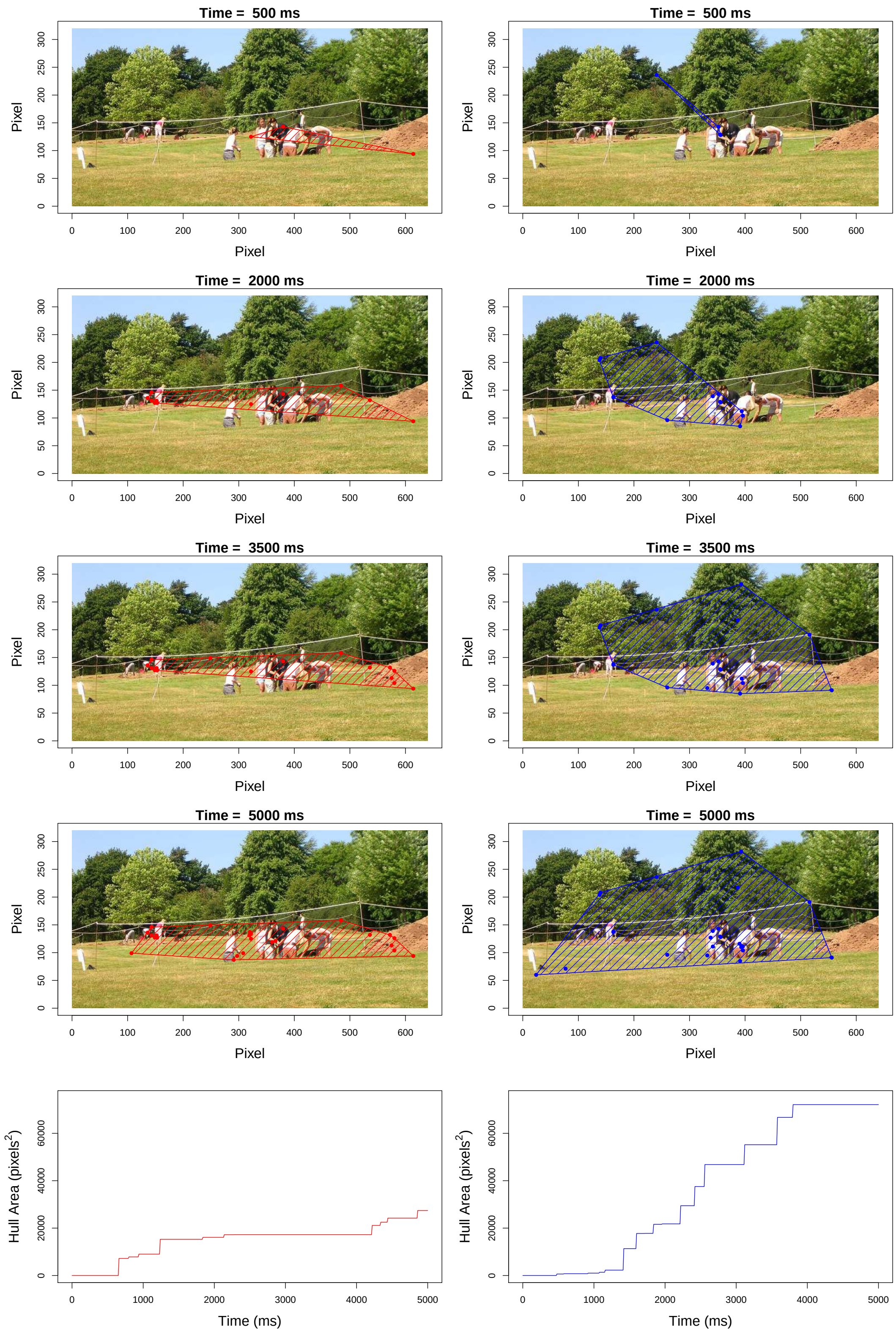


Figure 3: *Convex Hull Evolution. The fixations for two individuals at a series of increasing times (t = 500, 2000, 3500, 5000 ms) for an image of an archaeological dig. The left hand red plots show the fixations of an ASD adolescent while the right hand blue plots a TD adolescent. At each time point we draw the increasing convex hull of the fixations and calculate its shaded area. The bottom two plots show the evolution of the convex hull between $t = 0$ and 5000ms.*

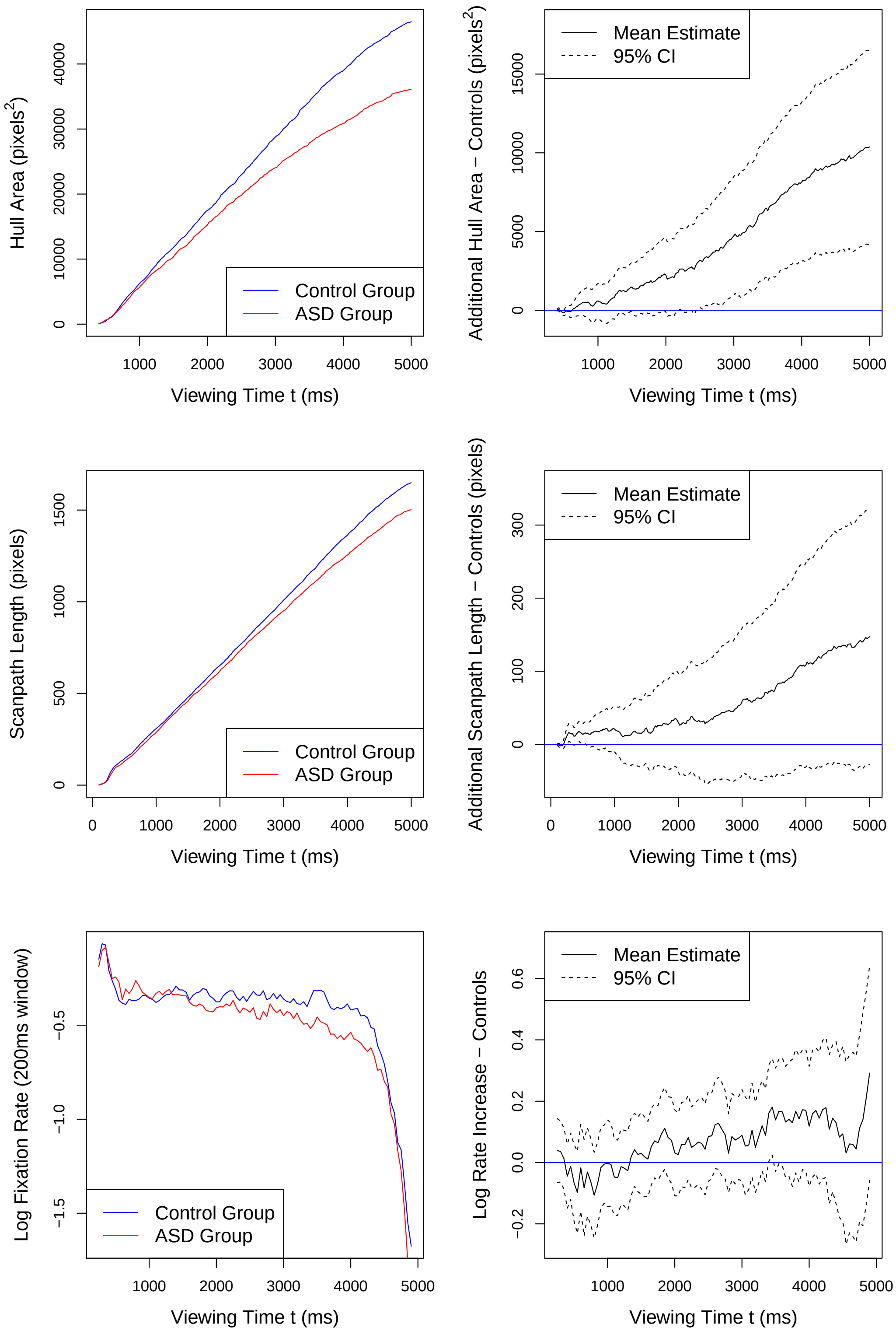


Figure 4: *Linear model results for evolution of area, scanpath distance and fixation rate. The left hand plots show the estimates for each group. The right hands plots show $\alpha(t)$ — the additional area, distance and rate of the TD group compared to the ASD group — together with their pointwise 95% confidence intervals. Positive values of $\alpha(t)$ indicate that the TD group have a larger hull area/scanpath length/fixation rate respectively.*

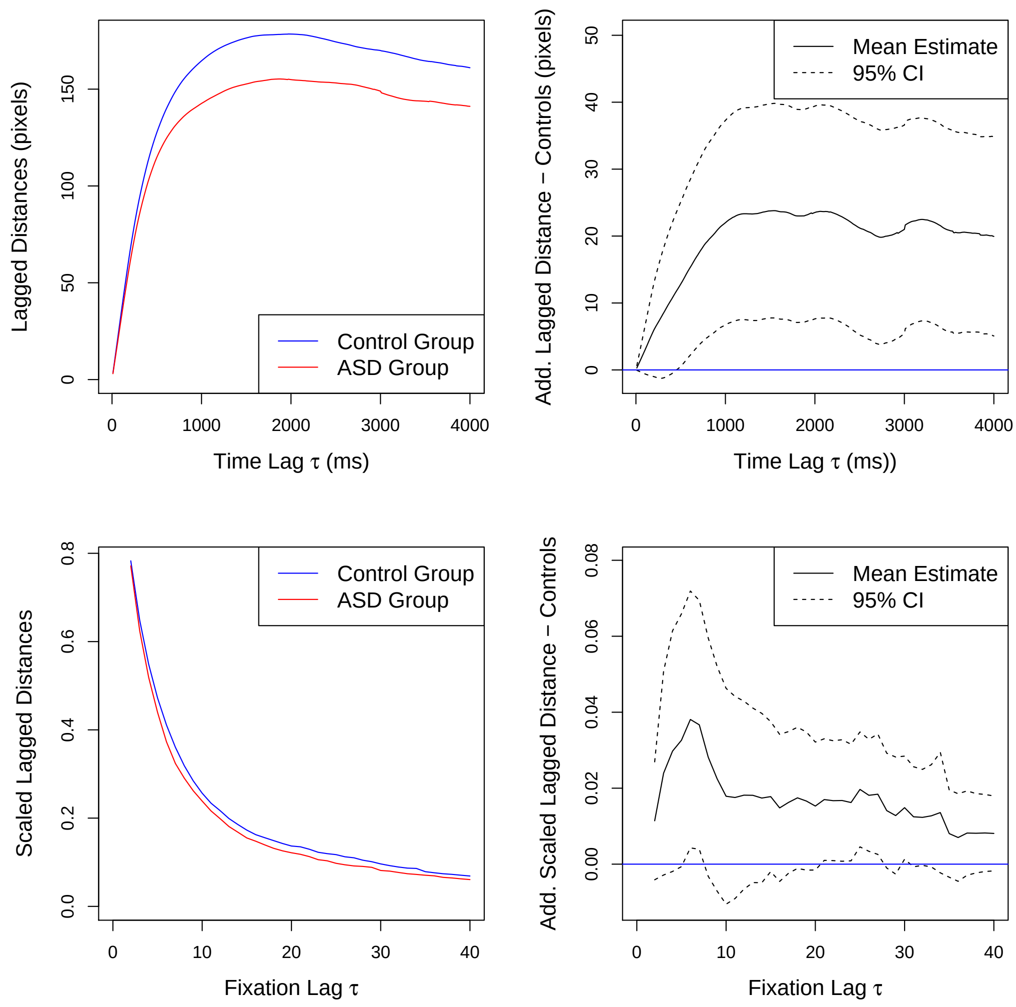


Figure 5: *Linear model results for lagged distance (persistence, top) and scanpath scaled distance (reversion, bottom). The left plots show the mean for each group. The right hands plots show, for each measure, the additional distance as a function of lag τ within the TD group compared to the ASD group, again with pointwise 95% confidence intervals. Positive values indicate greater persistence/reversion amongst the ASD group.*

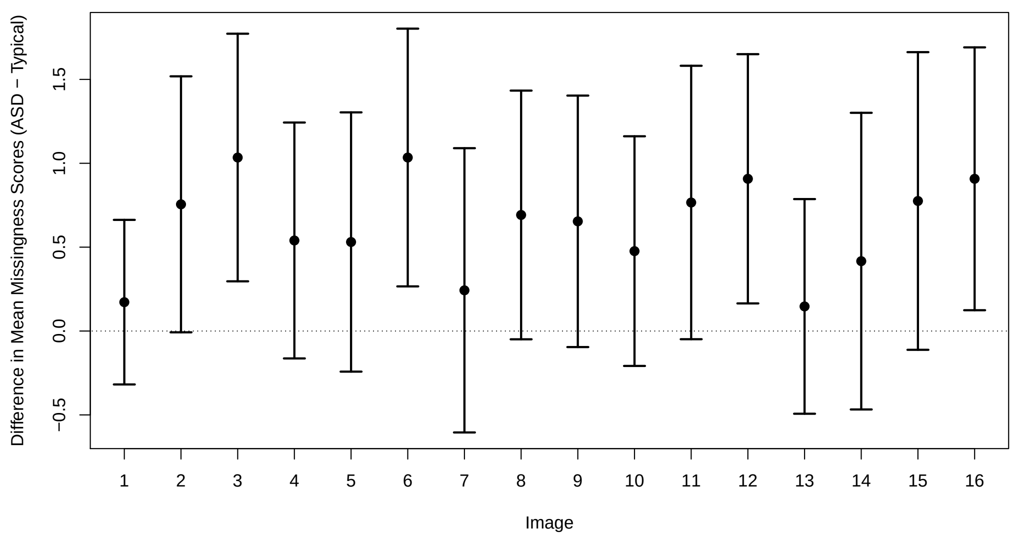


Figure 6: *The difference in means between ASD and TD individuals (with 95% approximate CIs based on t-test) for the verbal descriptor missingness scores calculated by image. A positive difference indicates more areas were missed by the ASD group.*

A Supplementary Information

A.1 Assessment of global processing quality

In Figure S1 we illustrate the partitioning of a sample image into five regions. From the verbal descriptions given by the participants of Expt2, each item in the scene was coded and identified. The number of regions which were not mentioned by the participant was recorded and used as a proxy for the quality of global processing.

A.2 Illustrative Example - Change in exploration rate amongst ASD adolescents

Figure S2 presents the mean area and scanpath evolution for a single stimulus. The path lengths increase at a fairly constant rate for both groups throughout the experiment. However, in keeping with the findings of our linear model, the rate of increase in hull area for the ASD group undergoes a change around 2500ms. At this point the ASD individuals appear to slow new exploration and fixate on points already within their convex hull. Since a similar change is not seen in scanpath length, this indicates the start of a tendency to return to/remain in previously viewed areas.

A.3 Analysis by Stimuli Type

To evidence that our results were not only found on a single type of stimulus, analysis was repeated on only those images without a centrally prominent face. Plots of the extra distance travelled, area explored and rate of new fixations with viewing time for these scenes are shown in Figure S3. The overall findings agree with the analysis of the full image set in both direction and magnitude — a consistently reduced hull area for ASD individuals (showing pointwise signficance beyond about 3000ms) which is not explained by a difference in the rate of new fixations. This suggests robustness to stimuli type. Interestingly however, differences in scanpath length between the two groups are reduced. Figure S4 plots the lagged distance (perseveration measure) and scanpath scaled distance (reversion measure). Again results agree with analysis of the complete stimuli set. Even on images without a centrally prominent face, ASD individuals are expected to be viewing a location significantly closer to the current fixation location at future times τ. There is however less evidence of a tendency to revert to previous fixations having moved away.

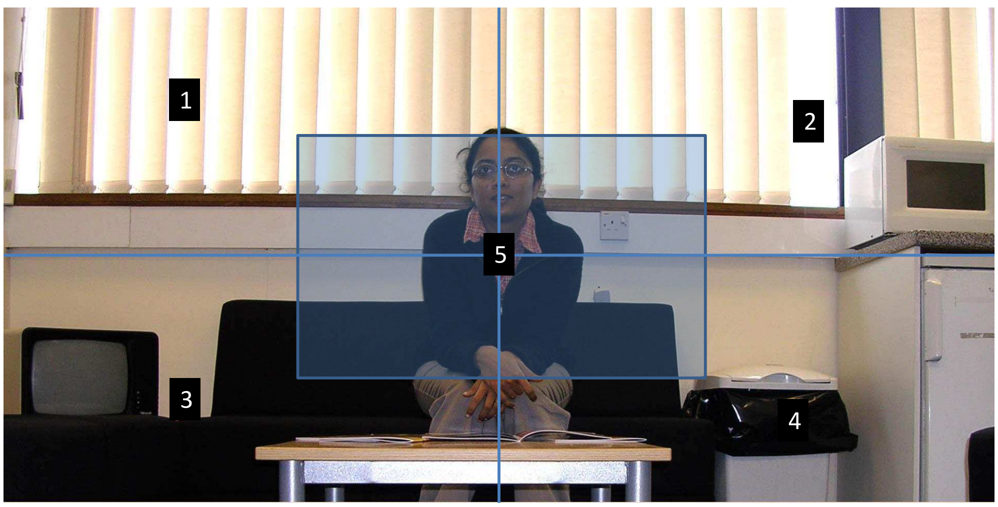
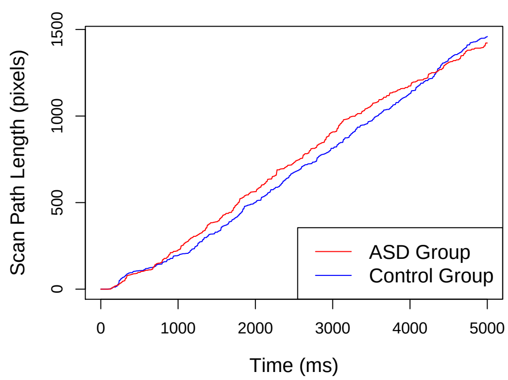


Figure S1: Partitioning of a sample image into five disjoint regions to assess spread of the verbal description data. Each item in the image was allocated to the most representative region. For this particular image, items were coded to the following regions: Area 1: window, blinds, Area 2:microwave, worktop, kitchen surface Area 3: TV, magazine, desk, books, grey trousers Area 4: bin, fridge Area 5: woman, girl, glasses, black cardigan, plug socket, she, person

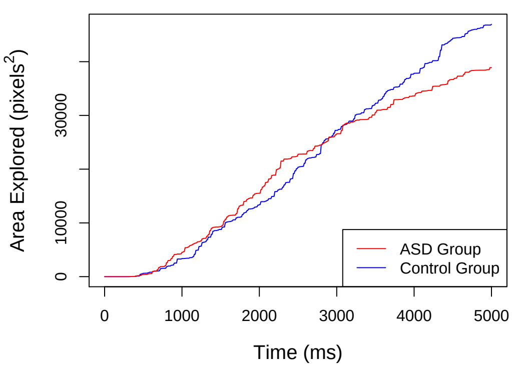
A.4 Size of random effects

Figure S5 shows histograms, stratified into ASD and TD groups, of the estimated random effects for individuals in both hull area and scanpath length after 5000ms stratified. They represent the range of individual variation in exploration rate, shown consistently across the images and in addition to the fixd ASD effect, within both groups i.e. the random effects for the ASD individuals relate to only their variation in exploration relative to other ASD individuals and likewise for the TD individuals. To allow some idea of their relative sizes, the plots legends show the area/path length that an average ASD/TD individual would have at this time.

As can be seen, there is considerable support for variation in individual exploration rates exhibited consistently across images within the groups. A fast/slow explorer can consistently explore a hull area of 10,000-20,000 more/fewer pixels^2 than the average for their group. Similarly, within each group, individuals can have a consistent scanpath length of up to 500 pixels longer/shorter than the group average across the images. We also note that one individual in the ASD group appears to have explored very little, as shown by the single large negative random effects for both area and scanpath length. Our earlier results on ASD/TD group differences are robust to this one individual since, as we see, their reduced exploration has been accounted for by their large personalised λ_i random effects within our model and hence not the *between group* parameter α of primary interest.



width=0.22



width=0.22

Figure S2: A sample illustration of the mean area viewed and scanpath length.

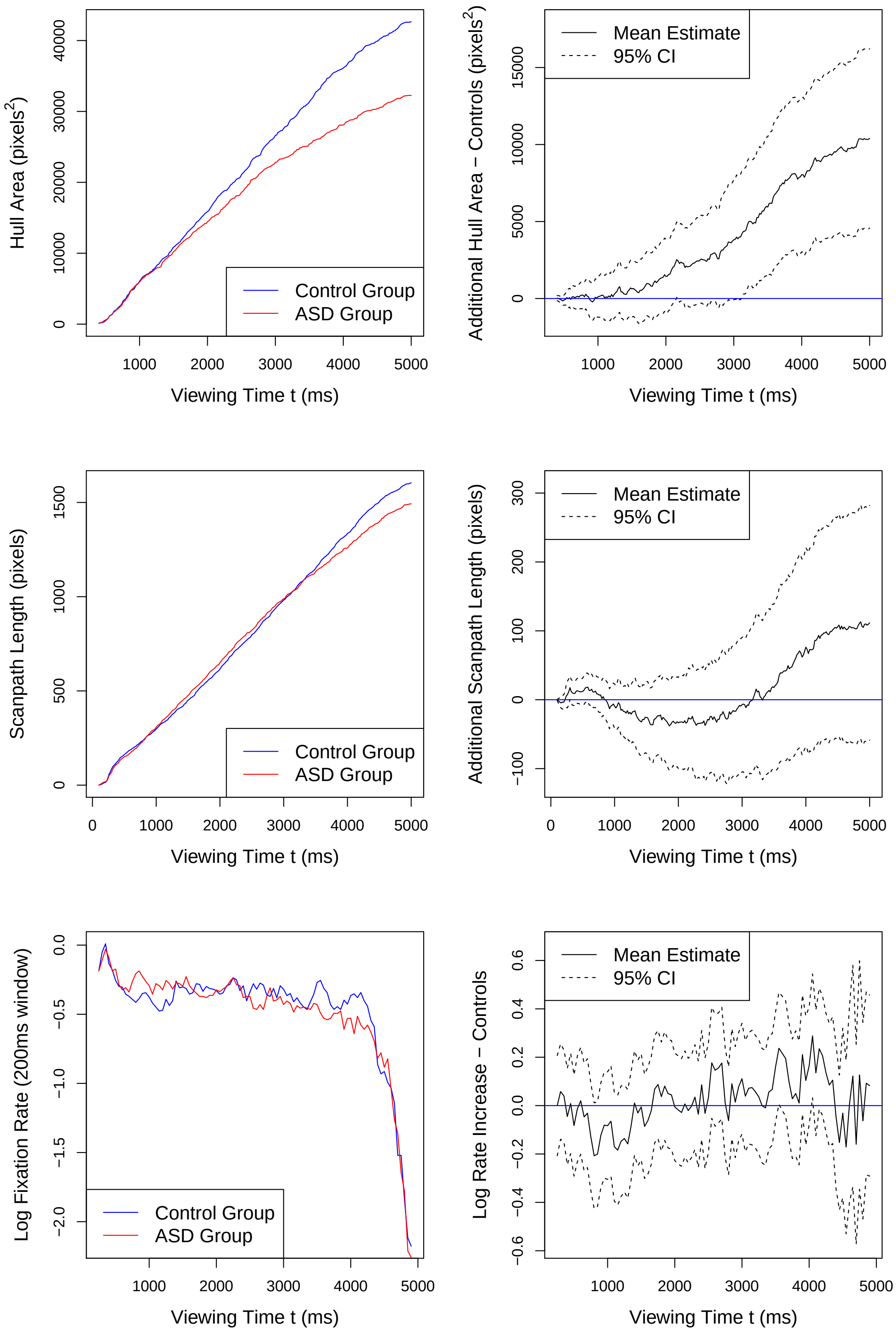


Figure S3: *Linear model results for evolution of area, scanpath distance and fixation rate using only those images without a prominent centrally positioned face. The left hand plots show the estimates for each group. The right hands plots show* $\alpha(t)$ *— the additional area, distance and rate of the TD group compared to the ASD group — together with their pointwise 95% confidence intervals. Positive values of* $\alpha(t)$ *indicate that the TD group have a larger hull area/scanpath length/fixation rate respectively.*

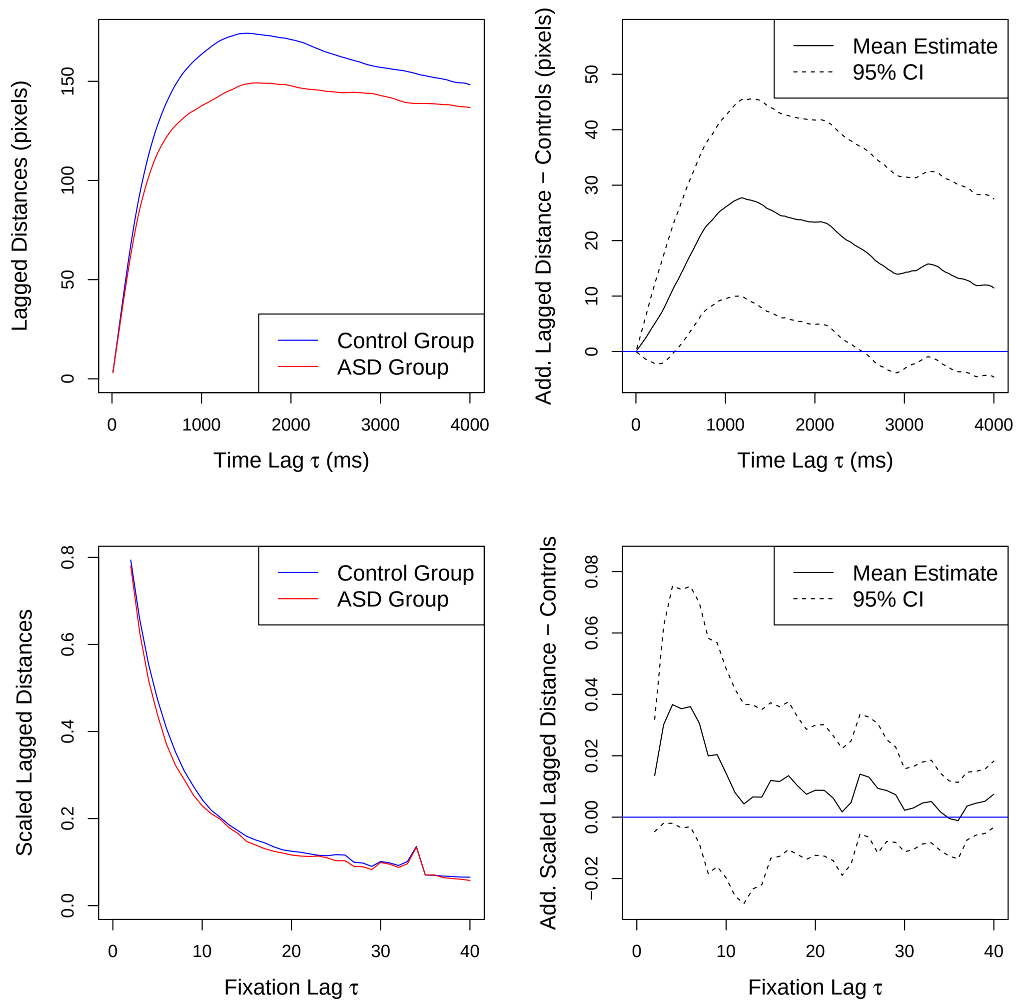


Figure S4: *Linear model results for lagged distance (persistence) and scanpath scaled distance (reversion) using only those images without a prominent centrally positioned face. The left plots show the mean for each group. The right hands plots show, for each measure, the additional distance as a function of lag τ within the TD group compared to the ASD group, again with pointwise 95% confidence intervals. Positive values indicate greater persistence/reversion amongst the ASD group.*

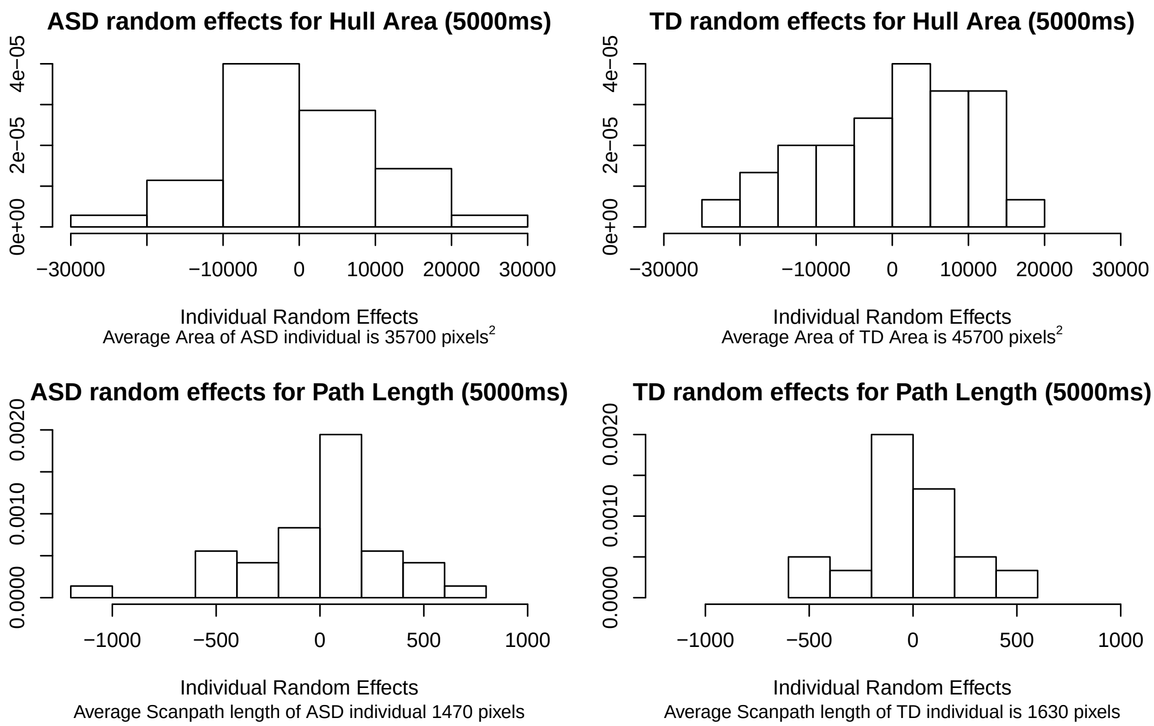


Figure S5: *Histograms of estimated random effect terms for each individual for the area explored and scanpath length at 5000ms. These can be contrasted with the expected values for a TD/ASD individual at this time.*