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PAPER

Reduced chromatic discrimination in children with autism spectrum disorders

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Abstract

Atypical perception in Autism Spectrum Disorders (ASD) is well documented (Dakin & Frith, 2005). However, relatively little is known about colour perception in ASD. Less accurate performance on certain colour tasks has led some to argue that chromatic discrimination is reduced in ASD relative to typical development (Franklin, Sowden, Burley, Notman & Alder, 2008). The current investigation assessed chromatic discrimination in children with high-functioning autism (HFA) and typically developing (TD) children matched on age and non-verbal cognitive ability, using the Farnsworth-Munsell 100 hue test (Experiment 1) and a threshold discrimination task (Experiment 2). In Experiment 1, more errors on the chromatic discrimination task were made by the HFA than the TD group. Comparison with test norms revealed that performance for the HFA group was at a similar level to typically developing children around 3 years younger. In Experiment 2, chromatic thresholds were elevated for the HFA group relative to the TD group. For both experiments, reduced chromatic discrimination in ASD was due to a general reduction in chromatic sensitivity rather than a specific difficulty with either red–green or blue–yellow subsystems of colour vision. The absence of group differences on control tasks ruled out an explanation in terms of general task ability rather than chromatic sensitivity. Theories to account for the reduction in chromatic discrimination in HFA are discussed, and findings are related to cortical models of perceptual processing in ASD.

Introduction

Autism Spectrum Disorders (ASD) are pervasive neurodevelopmental disorders that are defined by impairments in social interaction, non-verbal and verbal communication and imagination (American Psychological Association, 1994). In addition to these behavioural and cognitive characteristics, there is also converging evidence for atypical perceptual processing (see Dakin & Frith, 2005, for review). Some perceptual processes appear to be enhanced in ASD, such as visual search (O'Riordan, 2004; O'Riordan, Plaisted, Driver & Baron-Cohen, 2001; Plaisted, O'Riordan & Baron-Cohen, 1998a); auditory processing (Bonnel, Mottron, Peretz, Trudel, Gallun & Bonnel, 2003; Heaton, Hermelin & Pring, 1998; Mottron, Peretz & Ménard, 2000), visuo-spatial perception (Caron, Mottron, Rainville & Chouinard, 2004; Caron, Mottron, Berthiuame & Dawson, 2006; Mitchell & Ropar, 2004); and perceptual learning (Plaisted, O'Riordan & Baron-Cohen, 1988b). However, there is also evidence for perceptual deficits in ASD, such as reduced sensitivity to global, coherent motion (Milne, Swettenham, Hansen, Campbell, Jeffries & Plaisted, 2002; Spencer, O'Brien, Riggs, Braddick, Atkinson & Wattam-Bell, 2000; Bertone, Mottron, Jelenic & Faubert, 2005; Pellicano, Gibson, Maybery, Durkin & Badcock, 2005). Investigation of perceptual phenomena in ASD has led to theories on cognitive and perceptual processing styles in ASD such as 'Enhanced Perceptual Functioning' (Mottron, Dawson, Soulières, Hubert & Burack, 2006) and 'Weak Central Coherence' theories (Happé & Frith, 2006). Physiological accounts of atypical processing in ASD have also been provided (e.g. Dakin & Frith, 2005).

Despite the surge of interest in perceptual functioning in ASD, it remains poorly understood for many perceptual domains. One domain which requires further investigation is that of colour. There are several indicators that colour perception may be atypical in ASD. Brian, Tipper, Weaver and Bryson (2003), in a study that investigated inhibitory mechanisms in ASD, unexpectedly found that colour produced a facilitation effect on a negative priming task for those with ASD but not for a control group. Brian *et al*. speculate that 'in autism, stimulus features such as color may be encoded too readily, and thus are detected more easily than is typically the case' (p. 558).

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Heightened sensitivity to colour could explain the strong colour obsessions that many of those with ASD are frequently reported to have (Moore, 2004), and could also account for reports that colour naming is enhanced in ASD (Schafer & Williams, 2008). However, direct investigations of colour perception in ASD (Heaton, Ludlow & Roberson, 2008; Franklin *et al*., 2008) have not supported claims that sensitivity to colour is enhanced in ASD.

Heaton *et al*. (2008) investigated colour perception in ASD by comparing a sample of low-functioning children with autism with an age matched typically developing (TD) control group and a group of children with moderate learning disabilities (MLD) matched for non-verbal cognitive ability. In Experiment 1, both the ASD group and the MLD group were less accurate at identifying the colour that was the most different out of a set of three colours than the TD group. Although this was interpreted as evidence for poorer colour discrimination in ASD, alternative explanations cannot be ruled out. First, the accuracy of the ASD and MLD groups did not significantly differ and so poor performance could be attributed to general low non-verbal cognitive ability rather than attributed to autism. Second, the lack of an identical control task that draws on a domain other than colour means that it is difficult to disentangle poor task performance (such as difficulty selecting the 'most different') from a specific difficulty with colour.

Experiment 2 in Heaton *et al*.'s study investigated colour memory using an animal–colour association task. Children were familiarized to animal–colour pairings (e.g. picture of dog paired with red patch; picture of cat paired with blue patch), and then, during the test phases, were presented with the picture of the animal and asked to select the correct colour patch. In phase 1, the correct colour patch had to be selected from a set of four colour patches – all different in colour category (red, green, blue, yellow). In phase 2, the correct colour patch had to be selected from a set of three colour patches that were all from the same category (e.g. red1, red2, red3) and that were additionally more chromatically similar. All groups performed above chance on phase 1 of the task (with highest accuracy for the TD group), although only the ASD group performed above chance on phase 2. The researchers reasoned that in phase 1, as the correct colour patch had to be selected from a set of colours that differed in colour name and that were greatly different perceptually, a child could remember the colour–animal association on the basis of the colour name or on the basis of the perceptual characteristics of the colour, whereas in phase 2, as the colour patches were all the same colour name, only the perceptual characteristics could be relied on. The above-chance performance of the ASD group and below-chance performance of the TD and MLD groups was therefore taken as evidence that the ASD group relied on the perceptual characteristics of the colours to a greater extent and verbal codes to a lesser extent than the TD or MLD groups.

The intriguing pattern of results in Experiment 2 of Heaton *et al*.'s study clearly suggests that there is something atypical in colour perception in ASD. However, an account that argues that children with autism 'remember the exact shades … rather than relying on the category name' (p. 7) does not account for all the findings. For example, if children were to rely on remembering the exact shades of colour, we would expect performance to be significantly higher for phase 1 (where the colour patches are most perceptually dissimilar) than for phase 2, whereas this does not appear to be the case for the ASD group. Providing an explanation that accounts for the findings of both Experiment 1 and Experiment 2 is difficult.

Franklin *et al*. (2008) also directly investigated colour perception in children with ASD, although they tested high-functioning children with autism (HFA) and a control group of typically developing children matched on age and non-verbal cognitive ability. In Experiment 1, accuracy of colour perception was assessed using recognition memory and a search task. The HFA group were less accurate at remembering a coloured target or identifying a coloured target out of a grid of coloured distractors than the TD group. However, accuracy was not significantly different for the TD and HFA groups on identical tasks, where stimuli differed in form and not colour. In Experiment 2, a target detection task was used to seek converging evidence for reduced accuracy on colour perception tasks and also to assess the strength of categorical perception of colour in HFA. Coloured targets were shown on coloured backgrounds and the colours of the targets and the backgrounds were either from different colour categories or the same colour category, with equivalent hue separations for both conditions (see Franklin, Pilling & Davies, 2005; Drivonikou, Kay, Regier, Ivry, Gilbert, Franklin & Davies, 2007). Categorical perception of colour – where different category colours are discriminated faster or more accurately than same category colours of equal hue difference (Harnad, 1987) – was equally strong in the HFA and the TD groups. As for Experiment 1, overall accuracy of detection of coloured targets for the HFA group was reduced compared to the TD group. Therefore, although the influence of categorization on discrimination was typical for the ASD group, there was an overall reduction in chromatic sensitivity relative to the TD group. On the basis of the findings from these two experiments, Franklin *et al*. (2008) concluded that, contrary to what the findings of Brian *et al*. (2003) may seem to indicate, those with ASD actually have reduced sensitivity to colour differences.

The current investigation further explored the hypothesis that those with ASD have reduced sensitivity to colour differences, using two tasks that are traditionally used for direct measurement of

chromatic discrimination.[1] Experiment 1 used a colour vision test that is widely used in clinical practice to identify disorders of colour vision – the Farnsworth-Munsell 100 hue test (Farnsworth, 1943). Experiment 2 used a psychophysical task to estimate chromatic thresholds. In both experiments, a group of high-functioning children with autism (HFA) and a group of typically developing children (TD) matched on age and non-verbal cognitive ability were tested. Additionally, in both experiments, an identical control task where stimuli differ in luminance and not chromaticity was included to ensure that any differences between the two groups are due to colour discrimination rather than the general task ability.

The Farnsworth-Munsell 100 hue test and the threshold discrimination task were used in the current study to seek converging evidence that chromatic discrimination is reduced in ASD and to quantify any reduction in discrimination. Additionally, the tasks allow an assessment of whether differences in discrimination are restricted to certain regions of the colour spectrum or certain subsystems of colour vision. Colour vision derives from two physiologically distinct subsystems that correspond to two 'cardinal directions' in colour space (Krauskopf, Williams & Heeley, 1982). One subsystem, the red–green cardinal direction, involves the comparison of signals from long- (L-) and medium- (M-)wavelength sensitive cone photoreceptors in the retina while the signal from short- (S-)wavelength sensitive cone photoreceptors is constant. The other subsystem, the yellow–blue cardinal direction, involves the comparison of signals from short-wavelength sensitive cone photoreceptors with the combined signals from long- and medium-wavelength cones.[2] The pathways from the retina to the cortex also code for these two subsystems. Deficits in colour vision can arise from deficits in either of these subsystems. For example, some individuals have a 'red–green' colour deficiency arising from an inherited defect in either long or medium wavelength cone photoreceptors. Colour vision deficiency can also be acquired; for example, acquired deficits in the blue–yellow system can arise due to the effect of certain drugs such as chloroquine (e.g. Lagerlöf, 1980), and are also found in various neurological disorders such as Parkinsons (Haug, Kolle, Trenkwalder, Oertel & Paulus, 1995) and Attention Deficit Hyperactivity Disorder (ADHD) (Banaschewski, Ruppert, Tannock, Albrecht, Becker, Uebel, Sergeant & Rothenberger, 2006). If children with ASD have reduced chromatic discrimination, as the findings of Franklin *et al.*'s study suggest, this could arise from a selective deficit in one of these subsystems or alternatively from a general reduction in sensitivity across the hue spectrum. Both of the tasks used in the current investigation allowed an assessment of this issue.

[1] Colour varies psychologically on three dimensions: hue (the perceptual property of colour corresponding to the physical property of dominant wavelength); saturation (depth of hue with respect to white); lightness / luminance (relative quantity of light). Chromatic discrimination is discrimination of either a hue or saturation difference. Achromatic stimuli have no chromaticity (black, grey, white). Lightness / luminance differences between either chromatic stimuli or achromatic stimuli do not involve chromatic discrimination.

[2] Although these subsystems are called 'red–green' and 'blue–yellow', the appearance of colours along the cardinal directions actually varies from cherry to teal and from violet to chartreuse (Jameson & D'Andrade, 1997).

Experiment 1: Chromatic discrimination on the Farnsworth-Munsell 100 hue test

Experiment 1 compared a group of high-functioning children with autism with a group of typically developing children matched on age and non-verbal cognitive ability on the Farnsworth-Munsell 100 hue test (F-M 100 hue test) (e.g. Banaschewski *et al.*, 2006). The F-M 100 hue test is commonly used both in clinical practice and in vision research to assess accuracy of chromatic discrimination and to identify the nature of any deficit. Simple task instructions and low task demands allow the test to be used to assess children's colour vision (e.g. Mäntyjärvi, 2001; Roy, Podgor, Collier & Gunkel, 1991; Verriest, Van Laetham & Uvijls, 1982), in some cases for children as young as 5 years old (e.g. Kinnear & Sahraie, 2002), and the task has even been used with children with ADHD (Banaschewski *et al.*, 2006). Developmental changes in performance on the task are also consistent with developmental changes in chromatic sensitivity as assessed by threshold measures and electrophysiological measures of chromatic sensitivity (e.g. Knoblauch, Vital-Durand & Barbur, 2001; Crognale, 2002), revealing the test to be a reliable and valid measure of chromatic discrimination. The test consists of a series of coloured caps which span the complete hue circle when placed in order, with small incremental hue variation between adjacent caps. The participant's task is to put the caps in order of hue, and accuracy of chromatic discrimination is assessed by quantifying the amount of error the participant makes in ordering the hue series. In addition, the error on red–green and blue–yellow axes of colour vision can be computed (Smith, Pokorny & Pass, 1985), giving an indication of the underlying nature of any deficit. The distribution of errors across the hue spectrum can also be displayed visually for individuals and for groups. Finally, norms for the test across development exist (e.g. Kinnear & Sahraie, 2002), so performance of an individual can be compared with what would typically be expected for their age group. The current experiment also included a control task which involved ordering an achromatic series of stimuli that varied in luminance from black to white. This control task was included to ensure that any differences between the HFA and TD groups could be attributed to

differences in chromatic discrimination, rather than an inability to order visual stimuli.

Method

Participants

Twenty-eight children (mean age 14 years) took part in the study, 14 with ASD and 14 typically developing children (all males). Children were screened for the most common form of inherited colour vision deficiency (red–green) using the Ishihara Color Vision Test (Ishihara, 1987). Genetic L-, M- and S-cone deficiencies can also be diagnosed with the F-M 100 hue test, and later analysis of F-M 100 hue data revealed that no children showed a pattern of errors consistent with these diagnoses. All children with ASD were high functioning, attended schools for children with ASD, and on entrance to their school had been diagnosed by a trained clinician according to the criteria of DSM-IV (American Psychological Association, 1994). None of the children in either group had received a diagnosis of Attention Deficit Hyperactivity Disorder (ADHD). The TD and HFA groups did not significantly differ in non-verbal cognitive ability as assessed by Raven's Standard Progressive Matrices (Sets A, B, C, D, E; Raven, Court & Raven, 1992), ($t(26) = 0.44$, $p = 0.67$), or in chronological age ($t(26) = 0.84$, $p = 0.41$) (see Table 1). Parental consent was obtained and ethical approval was granted by the Faculty of Arts and Human Sciences Ethics Committee at the University of Surrey.

Tasks and procedure

Farnsworth-Munsell 100 hue test: The test consists of 85 black plastic caps with coloured centres; these caps are distributed across four trays (with 21 caps in three trays and 22 in the fourth tray). Participants were given one tray of caps at a time, with only the first and last cap of the hue series in position. All other caps for that tray were placed in a random arrangement on a surface in front of the participant. Participants were required to return the caps to the tray, arranging them in order so they complete the hue series between the first and last cap. Participants were asked 'Can you put these back into the tray in order?' and were then given the prompt, 'So which one looks most like this', while pointing to the first cap in the tray.

Achromatic control: An achromatic series of stimuli was printed with a colour printer (Hewlett Packard Designjet 800PS). Stimuli were then measured with a colorimeter (Avantes SpectroCam 75RE) to verify that stimuli varied only in luminance. The series consisted of 23 stimuli (CIE, 1931, x = 0.33, y = 0.33), with the first stimulus in the series having a black appearance (Y = 2.48) and the last stimulus in the series having a white appearance (Y = 80.52). The average incremental variation in luminance was Y = 3.55 ($SD = 2.67$). Stimuli were of the same size and shape as the coloured centre of an F-M 100 hue cap, and were backed on black cardboard disks that were the same size as the black plastic surround of an F-M 100 hue cap. The procedure and instructions were identical to the F-M 100 hue test.

All participants completed the Ishihara colour vision test first (Ishihara, 1987). The achromatic control series and the four trays of the F-M 100 hue test were then completed in a randomized order, with binocular viewing. Participants were tested individually, in a dark room, with the test area illuminated with a Gretag Macbeth lamp that simulated natural daylight (D65, 6500K).

Table 1 *The mean, standard deviation (SD) and range for age and Raven's Standard Progressive Matrices scores, for HFA and TD groups, Experiment 1*

	Age			Raven's		
	Mean	*SD*	Range	Mean	*SD*	Range
HFA ($n = 14$)	13.71	1.27	12–16	45	5.60	34–52
TD ($n = 14$)	13.93	1.33	12–16	43	6.89	32–55

Results

Farnsworth-Munsell 100 hue test

Error scores on the F-M 100 hue test were calculated using scoring software provided with the test. Each cap was allocated a partial error score that represents the accuracy of the placement of the cap in the sequence. Error plots were drawn by the scoring software for each participant. These error plots give the partial error score for each cap and visually represent the magnitude and distribution of errors across the hue spectrum. The Total Error Score (TES), representing the total error in ordering the hue series, was calculated by summing the partial error scores of each cap. The error score for the red–green axis was calculated by summing the partial error scores of caps 13–33 and 55–75, and for the blue–yellow axis by summing the partial error scores of caps 1–12, 34–54 and 76–85 (Smith *et al.*, 1985). Figure 1 gives the average error plot for HFA and TD groups.

Visual inspection of the error plots indicates greater error for the HFA group than the TD group. The mean TES for the HFA group was 130.37 ($SD = 61.56$) and the mean TES for the TD group was 76.29 ($SD = 33.26$). Figure 2 gives the mean error score for blue–yellow and red–green axes separately, for the two groups of children.

To assess whether there was a significant difference in error for TD and HFA groups, and to assess whether the distribution of errors on red–green and blue–yellow axes

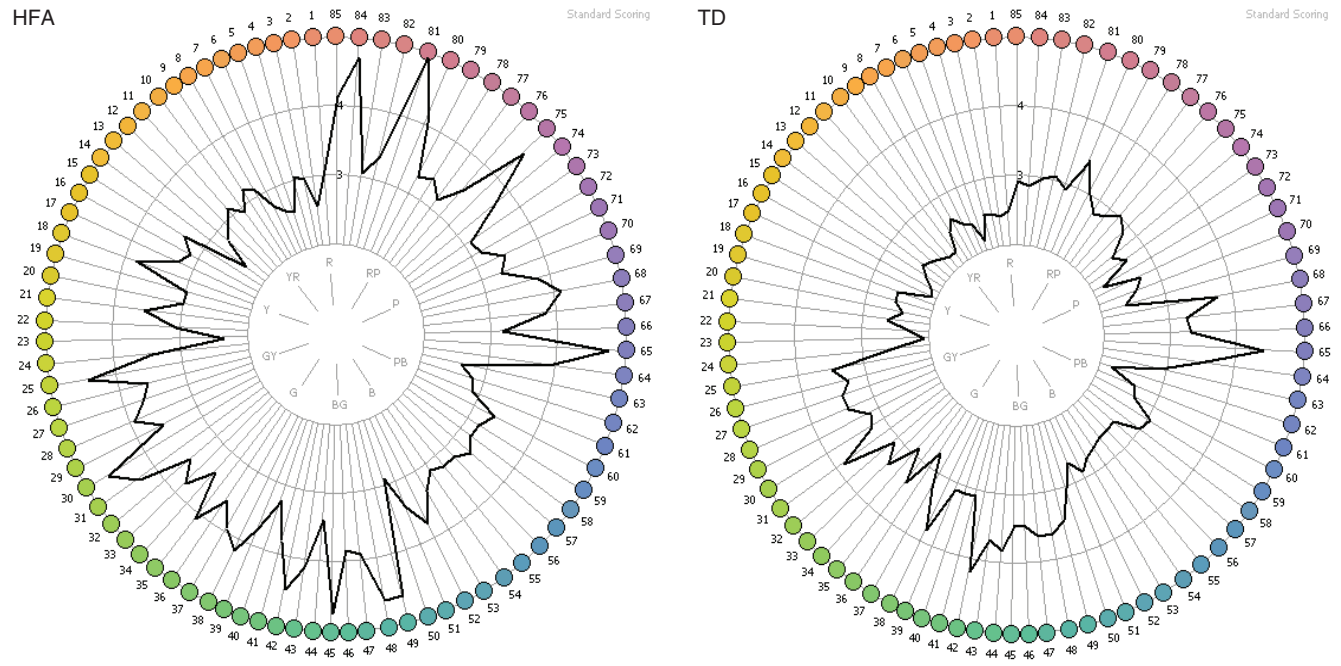

Figure 1 *Error plots on the F-M 100 Hue test averaged separately for the HFA and TD groups, scaled to a partial error score of 5. Each shaded and numbered circle represents a cap in the series. The ten lines in the inner circle represent the general area of the hue spectrum: R = red; RP = red-purple; P = purple; PB = purple-blue; B = blue; BG = blue-green; G = Green; GY = green-yellow; Y = yellow; YR = yellow-red. The thick black line represents the average error score for each cap and greater amplitude from the centre indicates greater error.*

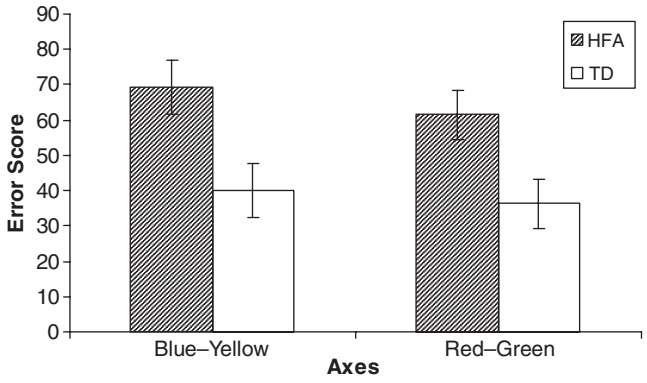

Figure 2 *Mean error scores for the blue–yellow and red–green axes of the F-M 100 hue test, for the HFA and TD groups.*

was different for HFA and TD groups, an ANOVA was conducted on error scores for each axis (red–green / blue–yellow), with Axis as a repeated measures factor and Group (HFA / TD) as a between-groups factor.[3] There was a main effect of Group, with more errors for the HFA group (mean = 65.29, SD = 30.78) than the TD group (mean = 38.13, SD = 16.63), $F(1, 26) = 8.43$, $MSE = 1224$, $p < .01$. There was no significant main effect of Axis or interaction of Axis and Group (largest $F = 1.63$, smallest $p = 0.21$).

The TES were compared to the test norms for children of different ages (Kinnear & Sahraie, 2002). For each participant, the difference between their TES and the average TES norm for their age was calculated. The mean deviation from the TES norm was 2.78 (35.84) for the TD group and 55.21 (61.86) for the HFA group. One sample t-tests conducted against a value of 0 revealed a significant deviation from the test norms for the HFA group, $t(13) = 3.34$, $p < .01$, but not for the TD group, $t(13) = 0.29$, $p = 0.78$. The mean TES for the TD group was in line with what is expected for the mean age of the group (mean TES for TD group = 76; TES norm for 13-year-olds = 74). However, the mean TES for the HFA group was closer to the test norm for an age group 3 years younger (mean TES for HFA group = 130; TES norm for 10-year-olds = 125).

Achromatic control

Error scores were calculated for the achromatic control task using the same method as the F-M 100 hue test. Error score per cap was then calculated for hue and luminance versions of the task and an ANOVA with Group (HFA/TD) as a between-groups factor and Task

[3] There is debate about whether the square root of error scores should be used for statistical analysis (Kinnear, 1970; Dain, 1998). An equivalent analysis on the square root of error scores revealed the same pattern of findings, with a significant main effect of Group, $F(1, 26) = 7.73$, $p < .05$, $\eta_p^2 = .23$, but no significant main effect of Axis or interaction of Axis and Group (largest $F = 1.69$, smallest $p = .21$).

(Hue / Luminance) was conducted on the error scores. There was a main effect of Group, with more errors per cap for the HFA group (mean = 0.99, *SD* = 0.41) than the TD group (mean = 0.65, *SD* = 0.30), $F(1, 26) = 6.49$, $MSE = 0.26$, $p < .05$. There was a main effect of Task, with more errors per cap for the Hue (mean = 1.22, SD = 0.66) than the Luminance task (mean = 0.42, *SD* = 0.24) task, $F(1, 26) = 61.39$, $MSE = 0.14$, $p < .001$. There was also a significant interaction of Task and Group, $F(1, 26) = 8.44$, $MSE = 0.14$, $p < .01$. Post hoc *t*-tests identified a significant difference in error for the TD and ASD groups on the hue task (ASD mean = 1.54, *SD* = 0.72; TD mean = 0.89, *SD* = 0.39), $t(26) = 2.9$, $p < .01$, but not on the luminance task (ASD mean = 0.45, *SD* = 0.20; TD mean = 0.40, *SD* = 0.28), $t(26) = 0.53$, $p = 0.60$. Error scores were significantly below ceiling (0) for both hue and luminance tasks for both groups (all *p*s < .001).

Discussion

Children with high-functioning autism made more errors on the F-M 100 hue test than typically developing children matched on age and non-verbal cognitive ability. Visual inspection of error plots revealed that errors were distributed throughout the hue spectrum for both groups. An analysis of error scores for red–green and blue–yellow axes of colour vision confirmed that although the HFA group made significantly more errors than the TD group, the distribution of errors on red–green and blue–yellow axes did not significantly differ for the two groups. This suggests a general reduction in chromatic sensitivity rather than a difficulty with a specific subsystem of colour vision. The total error score for the TD group was in line with what is expected according to test norms (Kinnear & Sahraie, 2002). However, the total error scores for the HFA group significantly deviated from the test norms for their ages. The mean TES for the HFA group was closest to the test norm for 10-year-olds – around 3 years younger than the average age of the HFA group. The number of errors on the achromatic control task were not significantly different for the two groups, indicating that the HFA group could do the task equally as well as the TD group when chromatic discrimination was not involved. This control task rules out the possibility that the high error score for the HFA group was due to a specific verbal difficulty in understanding task instructions or a general difficulty with ordering stimuli. However, the hue task appears to be harder than the luminance task as more errors per cap were made even by TD children. Therefore, this luminance task does not adequately control for task difficulty. Therefore, in Experiment 2 we resolve this issue by using an adaptive psychophysical procedure that ensures that task difficulty is equated for chromatic and luminance conditions. In both conditions stimulus difficulty is continuously adjusted to estimate thresholds at 82% correct performance, ensuring that task difficulty is held constant across hue and luminance conditions for the HFA and TD children.

Experiment 2: Chromatic discrimination on a threshold discrimination task

Experiment 2 tested HFA and TD groups' chromatic discrimination using a psychophysical threshold discrimination task. The first aim of the experiment was to provide evidence that the reduced ability of those with ASD on tasks of chromatic discrimination is due to reduced chromatic sensitivity rather than the effect of general task demands. The second aim was to provide converging evidence that there is a general reduction in chromatic sensitivity for those with ASD that is not selective for one or other of the subsystems of colour vision (red–green or blue–yellow). The third aim was to quantify the difference in chromatic sensitivity according to a standardized perceptual colour metric (CIE, L*u*v*, 1976).[4]

Threshold discrimination tasks have proved useful for investigation of other perceptual domains in ASD, such as motion perception (e.g. Milne *et al.*, 2002). Such tasks allow an estimation of the point at which a stimulus difference is just detectable (just-noticeable difference). Here we used a version of a threshold task that has proved to provide a sensitive and reliable measure of chromatic discrimination thresholds (Notman, Sowden, Davies, Alexander & Özgen, 2008). Participants were shown a circle with the two halves of the circle coloured differently. This created a colour-defined boundary and the participant's task was to make a simple judgment of the direction of boundary tilt (left or right). Initially, the chromatic difference of the two halves of the circle was large, and on subsequent trials the chromatic difference was reduced or increased on the basis of the accuracy of the participant's response. The just-noticeable difference (jnd) was estimated using a Zippy Estimate of Sequential Testing (ZEST) algorithm (King-Smith, Grigsby, Vingrys, Benes & Supowit, 1994). This is a Bayesian adaptive threshold estimation procedure that continuously modifies an assumed *a priori* probability density (pdf) function, which represents the probability that threshold is at each of a range of levels of stimulus intensity, on the basis of the preceding response, and sets the difficulty of the next trial to be the mean of the current pdf function. In this way all of an observer's previous responses are taken into account in setting the

[4] The CIE (Committee International D'Éclairage) has several systems for describing colour (see Hunt, 1987). CIE (L*u*v*, 1976) is a colour space that is appropriate for describing differences in colour appearance, where equal distances in the space are intended to correspond with equal perceptual distances. CIE (Y,x,y, 1931) is appropriate for measuring chromaticity and luminance co-ordinates of a colour.

difficulty of the next trial. The procedure homes in on threshold at some predefined point on the psychometric function, which here was set to be the point at which performance was approximately 82% correct. After some number of trials (here set to be 32 trials per run) the procedure terminates and the final estimate of threshold is equal to the mean of the *a posteriori* pdf. The ZEST algorithm provides a particularly efficient and less biased estimate of threshold compared to other threshold estimation methods (King-Smith *et al.*, 1994) and has been used to estimate thresholds in children as young as 5 (e.g. Quinn, Gardiner, Wheeler, Newkirk & Johnson, 2006). The low number of trials required make it particularly suited to testing with children. While the mechanics behind the ZEST algorithm may sound complicated, from the point of view of the observer the testing procedure is much like any other where an adaptive method is used to estimate threshold; the difficulty of the next trial in a given run varies as a function of the observer's preceding response(s). This is just like the staircase methods that have been previously used to test infant and childhood vision (e.g. Atkinson, Wattam-Bell, Pimm-Smith, Evans & Braddick, 1986). Therefore, we consider the threshold task used in the current investigation to be suitable for estimating thresholds in children and those with developmental disorders, both due to the speed and efficiency of the ZEST algorithm, and due to the simplicity of the tilt discrimination task.

Chromatic stimuli were defined according to the axes in the MacLeod-Boynton (1979) colour space, at equiluminance for the average observer. The two axes of this colour space are intended to correspond to the two cardinal directions of colour vision – the y axis (s) corresponds to variation in the S-cone signal, and the x axis (l–m) corresponds to variation in the ratio of L- and M-cone signals. In the current study, chromatic thresholds were estimated for two different types of chromatic variation. First, for stimulus variation along the 's' axis of the MacLeod-Boynton colour space (variation in the S-cone signal), at a constant value on the 'l and m' axis (constant ratio of L- and M-cone signals) – the blue–yellow mechanism. Second, for stimulus variation along the 'l and m' axis of the MacLeod-Boynton colour space (variation in ratio of L- and M-cone signals), at a constant value along the 's' axis (constant S-cone signal) – the red–green mechanism.

Estimating jnds for these two chromatic conditions therefore allows a further investigation of whether reduced chromatic discrimination in ASD is due to a general reduction in sensitivity rather than a difficulty with just one of the subsystems of colour vision. In addition to estimating chromatic thresholds, there was also a control task where luminance thresholds were estimated around the same points in colour space. Stimuli were chromatic, yet varied only in luminance. This control task was included to ensure that any differences between the HFA and TD groups could be attributed to differences in chromatic discrimination rather than differences in general task ability such as the ability to judge the orientation of a line during rapid presentation. Because, as described above, a ZEST procedure was used to estimate both chromatic and luminance thresholds at 82% correct performance, the difficulty of the chromatic and luminance tasks was kept the same. Thus, explanations that posit variation in task difficulty as the source of any difference in between-group performance across the two tasks are eliminated in the present experiment.

Method

Participants

Seventy children (mean age 13 years) took part in the study, 37 with high-functioning autism and 33 typically developing children (all males). Three HFA children failed to complete the experimental session and were excluded from the study, resulting in a final HFA sample of 34 children. All children passed a colour vision test that screens for major colour vision deficiencies (City Colour Vision Test, 2nd edn.; Fletcher, 1981). All HFA children attended schools for children with ASD and on entry to the school had been diagnosed by a trained clinician as having high-functioning autism according to criteria such as those of DSM-IV (APA, 1994). None of the children had a diagnosis of ADHD. The TD and HFA groups were not significantly different in non-verbal cognitive ability as assessed by Raven's Standard Progressive Matrices (Sets A, B, C, D, E; Raven *et al.*, 1992), ($t(65) = 0.72$, $p = 0.47$), or in chronological age ($t(65) = 1.26$, $p = 0.21$), (see Table 2). Parental consent was obtained and ethical approval was granted by the Faculty of Arts and Human Sciences Ethics Committee at the University of Surrey.

Experimental set-up and apparatus

Participants sat 57 cm away from and at eye-level to a 21-inch Eizo Flexscan F980 CRT monitor (CIE, 1931, x,y phosphor co-ordinates: $x_{red} = 0.614$ $y_{red} = 0.335$; $x_{green} = 0.277$ $y_{green} = 0.599$; $x_{blue} = 0.155$ $y_{blue} = 0.072$).

Table 2 *The mean, standard deviation (SD) and range for age and Raven's Standard Progressive Matrices scores, for HFA and TD groups, Experiment 2*

	Age			Raven's		
	Mean	*SD*	Range	Mean	*SD*	Range
HFA ($n = 34$)	12.74	0.79	11–14	38.03	5.62	24–52
TD ($n = 33$)	12.48	0.83	11–14	38.91	4.27	31–54

Stimuli were generated by a Cambridge Research Systems (CRS; Rochester, UK) Visual Stimulus Generator (VSG) 2/3 graphics card. This uses a 12-bit per gun resolution palette-based graphics system to generate colour stimuli with high precision. The monitor and VSG system were calibrated using proprietory CRS software in combination with a CRS ColorCal colorimeter. Calibration involved measuring (in CIE, 1931, Yxy co-ordinates) the response of the red, green and blue monitor guns in isolation and in combination throughout their response range, thereby providing information on the monitor phosphor co-ordinates (in CIE, 1931, xy co-ordinates as listed above), the dark point for each gun and allowing calculation of the gamma function for each gun in isolation and their combination. This calibration information was used to define the monitor gamut (the region of colour space that the monitor can reproduce) and to ensure accurate and high resolution reproduction of the desired colours. The chromaticity and luminance co-ordinates (CIE, 1931, Y,x,y) of the resultant stimuli were then verified using the ColorCal colorimeter. Participants' responses were made with a game pad.

Stimuli

Chromatic thresholds were estimated around two points in colour space. Around one point, stimuli varied along the 's' axis of the MacLeod-Boynton colour space, at a constant value on the 'l and m' axis (variation around s = 0.350 with l constant at 0.700) – referred to as 'variation in s' hereafter. Around another point, stimuli varied along the 'l and m' axis of the colour space, at a constant value on the 's' axis (l = 0.673, with s constant at 0.512) – referred to as 'variation in l and m' hereafter (MacLeod & Boynton, 1979; formula taken from Golz & MacLeod, 2003). Table 3 gives the CIE, 1931, x,y chromaticity co-ordinates of the stimuli around which chromatic thresholds were estimated and for another stimulus on the chromatic line.

For chromatic thresholds, all stimuli were constant in luminance (Y = 36.5 cd/m^2), and were therefore at isoluminance for the average observer. The initial chromatic difference between stimuli was 20ΔE units.[5] As a control task, thresholds were also estimated around the same two points in colour space (see midpoints in Table 3), but with stimulus variation in luminance. The initial luminance difference was 5 ΔE units.

Table 3 *CIE, 1931, x,y chromaticity co-ordinates for the point around which thresholds were estimated and another stimulus on the line, for conditions where stimuli vary in s or where stimuli vary in l and m (MacLeod & Boynton, 1979). The white point of the monitor was Y = 63.49 cd/m^2, x = 0.286, y = 0.305*

	Midpoint		Other stimulus on line	
	x	y	x	y
Variation in s	0.385	0.448	0.289	0.239
Variation in l and m	0.315	0.447	0.656	0.223

Design

The technique for estimating thresholds was taken from a study by Notman *et al*. (2008). A chromatic circle (visual angle = 8.5°) was shown on an achromatic grey background (CIE, 1931, co-ordinates: Y = 28.57, x = 0.286, y = 0.385) for 150 ms. The two halves of the circle were different colours, with the sharp-edged (square-wave) colour defined boundary at an oblique angle of 45°. For chromatic thresholds, the two halves of the circle varied in chromaticity and were at constant luminance. For luminance thresholds, the two halves of the circle varied in luminance and were at constant chromaticity. Just noticeable differences (jnd) were estimated in CIE (1976, L*u*v*) ΔE units, using a ZEST algorithm (King-Smith *et al*., 1994). In order to satisfy the assumption of independence of trials made by the ZEST algorithm for each condition, there were two random interleaved runs of 32 trials, giving two jnds per condition. The order of condition was randomized across participants.

Each participant completed two conditions – a chromatic condition (either variation in l and m or variation in s), and the corresponding luminance condition (variation in luminance around the same midpoint as the chromatic condition). Thresholds for variation in l and m were estimated for 20 HFA children and 15 TD children. Thresholds for variation in s were estimated for 14 HFA children and 18 TD children. Two-way ANOVAs with Type of Variation (l and m/s) and Group (HFA/TD) as between-groups factors, revealed no significant interaction between Type of Variation and Group for either age, $F(1, 67) = 0.24$, $MSE = 0.63$, $p = 0.62$, or Raven's matrices scores, $F(1, 67) = 0.87$, $MSE = 25.22$, $p = 0.35$, confirming that the lack of significant difference in HFA and TD age and Raven's matrices scores was maintained for both types of chromatic variation.

Procedure

All participants completed the City Colour Vision test first (Fletcher, 1981). Participants were given a set of instructions for the threshold task where they were told 'for every trial please indicate whether the line is sloping left or right, by pressing the left or right joy-stick button'. Prior to trial onset, a central fixation point was shown on an achromatic background. The onset of each trial was

[5] ΔE is the euclidean distance between two points in the CIE (L*u*v*, 1976) colour space.

controlled by the participant pressing the space bar on the keyboard. Participants were given a set of 16 practice trials and if it was clear that the participant had understood the task instructions, the experimental session began. Participants were given feedback in the form of two different computer generated noises for correct (a high 'ping' sound) and incorrect responses (a low 'doh' sound).

Results

Chromatic thresholds

Figure 3 gives the lowest jnd estimate for each participant, averaged for HFA and TD groups, for variation in s and variation in l and m.

An ANOVA with the between-groups factors of Group (HFA/TD) and Chromatic Variation (variation in s / variation in l and m) was conducted on the jnds. Jnds were significantly larger for the HFA group (mean jnd = 7.56 ΔE, SD = 5.08) than the TD group (mean jnd = 5.34 ΔE, SD = 3.14), $F(1, 67) = 7.22$, MSE = 15.70, $p < .01$. Jnds were significantly larger for variation in s (mean jnd = 8.11 ΔE, SD = 3.99), than for variation in l and m (mean jnd = 4.85 ΔE, SD = 3.96), $F(1, 67) = 11.08$, MSE = 15.70, $p < .001$. However, there was no significant interaction between Group and Chromatic Variation, $F = 0.34$, $p = 0.57$.

Chromatic and luminance thresholds

An ANOVA with the repeated measures factor of Task (Chromatic / Luminance) and the between-groups factor of Group (TD / ASD) was conducted on the jnds. Jnds were significantly larger for the ASD group (mean = 4.56 ΔE, SD = 2.91) than the TD group (mean = 3.33 ΔE, SD = 1.94), $F(1, 65) = 4.10$, MSE = 12.31, $p < .05$. Jnds were significantly larger for chromaticity (mean =6.45 ΔE, SD = 4.35) than luminance (mean = 1.45 ΔE, SD = 1.18), $F(1, 67) = 118.53$, MSE = 7.10, $p < .001$. There was a significant interaction between Task and Group, $F(1, 67) = 4.63$, MSE = 7.07, $p < .05$ (see Figure 4). Post-hoc t-tests revealed a significant difference between HFA and TD groups in chromatic jnd, $t(65) = 2.13$, $p < .05$, but not in luminance jnd, $t(65) = 0.83$, $p = 0.41$.

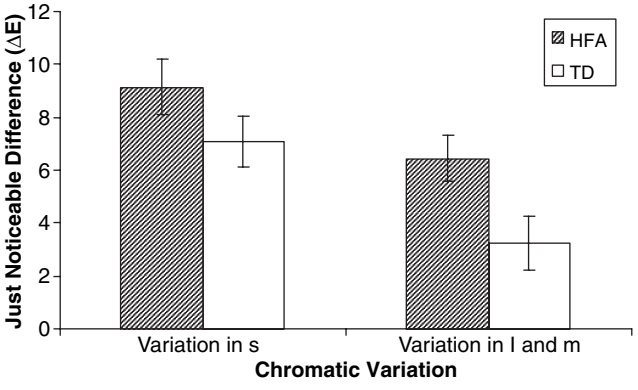

Figure 3 *Mean estimated jnd in ΔE units (CIE, L*u*v*, 1976) (±1 SE), for chromatic varation in s (constant l and m) or chromatic variation in l and m (constant s) (MacLeod & Boynton, 1979), for HFA and TD groups. NB: Larger jnd indicates less sensitive chromatic discrimination.*

Discussion

Children with high-functioning autism had elevated thresholds for orientation discrimination of a chromatic but not a luminance boundary relative to a group of typically developing children that were not significantly different in age or non-verbal cognitive ability. On average the chromatic difference needed to be 2.64 ΔE (CIE, L*u*v*, 1976) larger to facilitate discrimination by the HFA group compared to the TD group. Therefore, further evidence is provided for reduced chromatic discrimination in ASD and the difference in chromatic sensitivity has also been quantified according to a perceptual colour metric. Chromatic thresholds were elevated for the HFA group relative to the TD group, equally for the two cardinal directions in colour vision, as defined by the 's' and 'l and m' axes in the MacLeod and Boynton (1979) colour space. This provides further evidence that the reduced chromatic discrimination in ASD is due to a general reduction in sensitivity, rather than a specific difficulty with one of the subsystems of colour vision. Importantly, no significant difference was found between the HFA and TD groups' luminance thresholds around the same points in colour space. This indicates that the elevated thresholds for the HFA group were due to a difficulty discriminating chromatic difference rather than a difficulty with the general task.

In Experiment 1, the luminance control task was easier for both groups and this might have been the reason that there was no performance difference between the groups on the luminance control, while there was a difference on the more difficult F-M 100 hue test. However, in Experiment 2 task difficulty was held constant through the use of an adaptive threshold estimation procedure (ZEST) that estimated threshold at 82% correct

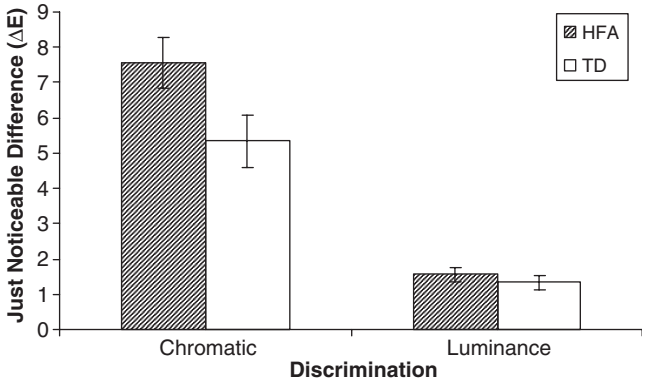

Figure 4 *Mean estimated jnd in ΔE units (CIE, L*u*v, 1976) for chromatic and luminance variation, for HFA and TD groups.*

performance. Despite the fact that the luminance control in Experiment 2 had the same difficulty as the chromatic threshold task there was still no difference between the groups on this luminance control, but the HFA group had larger thresholds on the chromatic task. This pattern of findings agrees well with those from Experiment 1 and validates the interpretation that the HFA group have a specific deficit in chromatic discrimination rather than an explanation based on a difference in task demands between the F-M 100 hue and the control task.

General discussion

On both the F-M 100 hue test (Experiment 1) and a chromatic threshold discrimination task (Experiment 2) children with high-functioning autism had poorer performance than typically developing children that were not significantly different in age or non-verbal cognitive ability. On both of these tasks, the distribution of errors across red–green and blue–yellow subsystems of colour vision did not significantly differ for the children with ASD compared to the controls. Therefore, we provide converging evidence for reduced chromatic sensitivity in ASD that is due to a general reduction in sensitivity rather than a selective deficit in one of the subsystems. Comparison of ASD performance on the F-M 100 hue test with developmental test norms revealed performance at the level of typically developing children around 3 years younger. The size of chromatic difference that is required for orientation discrimination was also quantified for the two groups, allowing for the reduction in chromatic sensitivity for those with ASD to be quantified according to a perceptual colour metric. It is worth noting that discrimination of large orientation differences produces equivalent measures of threshold to detection responses (Thomas & Gille, 1979), supporting a fundamental deficit in chromatic sensitivity in the HFA group. The current investigation therefore provides support to Franklin *et al.*'s (2008) claims that sensitivity to chromatic difference is reduced in those with high-functioning autism, and also provides further information about the nature of this deficit.

Reduced chromatic sensitivity has previously been found for another neurodevelopmental disorder: ADHD (Banaschewski *et al.*, 2006). However, when children with ADHD and typically developing children were tested on the F-M 100 hue test, the deficit for the ADHD group was found for the blue–yellow rather than the red–green subsystem of colour vision. Colour discrimination deficiency on the blue–yellow subsystem can also occur due to the effects of drugs (Largerlöf, 1980) and in other neurological disorders (Haug *et al.*, 1995). As blue–yellow defects are also common in disorders involving atypical dopamainergic transmission (e.g. Haug *et al.*, 1995), Banaschweksi *et al.* argued that reduced sensitivity to colour in ADHD is due to a retinal effect of dopamine affecting the blue–yellow subsystem of colour vision. However, the deficiency in chromatic discrimination in ASD appears to affect both red–green and blue–yellow colour vision, so, despite claims that dopamine levels are also atypical in ASD (Gillberg & Svennerholm, 1987), this is unlikely to account for the general reduction in sensitivity found here.

The precise areas that are involved in colour processing are controversial, and how the brain processes colour is not completely understood (Engel & Furmanski, 2001). However, a basic account is that activation of cones sensitive to either short, medium or long wavelengths of light leads to the red–green and blue–yellow subsystems (Krauskopf *et al.*, 1982). Then, Lateral Geniculate Nucleus parvocellular and koniocellular code for chromaticity, and magnocellular cells for luminance, leading to distinct red–green, blue–yellow and luminance pathways to the visual cortex (e.g. Lee, Porkorny, Smith, Martin & Valberg, 1990; Livingstone & Hubel, 1998; although see Schiller & Logothetis, 1990). Various areas of the visual cortex are involved in colour vision, with colour-selective neurons in areas V1 and V2 (e.g. Livingstone & Hubel, 1984) and V4 (e.g. Zeki, Watson, Lueck, Friston, Kennard & Frackowiak, 1991) / V8 (Hadjikhani, Liu, Dale, Cavanagh & Tootell, 1998). After the visual cortex, a network of brain areas is thought to be involved (e.g. Gulyas & Roland, 1994), predominantly in the ventral occipito-temporal cortex (e.g. Beauchamp, Haxby, Jennings & De Yoe, 1999), yet some have argued for dorsal involvement as well (Claeys, Duport, Cornette, Sunaert, Van Heche, De Schutter & Orban, 2004).

Reduced chromatic discrimination could theoretically occur due to atypical processing at any of these stages. General changes in chromatic sensitivity are found across typical development, with a peak in sensitivity around adolescence, and a slow decline of sensitivity thereafter (Kinnear & Sahraie, 2002; Knoblauch *et al.*, 2001). One explanation for the decline in chromatic sensitivity seen in typical ageing is that neural noise increases or that cone photoreceptors become less sensitive (Knoblauch *et al.*, 2001). Similar retinal accounts could be provided to account for the reduced chromatic discrimination shown by those with ASD. Alternatively, reduced chromatic discrimination could arise from atypical processing at later stages in discrimination. Based on previous research into perceptual processing in ASD, we can further hypothesize about the locus of the deficit in chromatic discrimination. For example, as parvocellular processing in ASD appears typical (Bertone *et al.*, 2005; Pellicano *et al.*, 2005), reduced chromatic sensitivity in ASD is unlikely to be due to a general deficit in the parvocellular pathway. As those with ASD outperform typically developing children on some ventral tasks (e.g. Bertone *et al.*, 2005), reduced chromatic sensitivity in ASD is also unlikely to be due to a general deficit in the ventral stream. Over-functioning of neurons in V1 and reduced synchrony of V1 with other cortical areas (Caron *et al.*, 2006; Villalobos, Mizuno, Dahl,

Kemmotsu & Muller, 2005) could account for reduced chromatic discrimination in ASD, as chromatic discrimination relies on the synchrony of V1 and later cortical areas such as V2, V4 and the infero-temporal cortex. However, neurophysiological research, such as fMRI of chromatic discrimination in ASD, is essential to test the plausibility of this hypothesis and to fully understand the neural basis of the effect.

Reduced discrimination in children with ASD has now been demonstrated on a series of chromatic tasks: colour memory; colour search; colour target detection tasks (Franklin *et al*., 2008); the F-M 100 hue test and a threshold chromatic discrimination task (the current investigation). The findings of the current investigation suggest that reduced chromatic discrimination in ASD is due to a general reduction in chromatic sensitivity rather than a specific difficulty with either red–green or blue–yellow subsystems of colour vision. For the children tested, performance on a chromatic discrimination task, for those with ASD, was at the level of typically developing children around 3 years younger. The size of the reduction of chromatic sensitivity was also quantified according to a perceptual colour metric. Reduced chromatic sensitivity in HFA may occur at the retinal level, although cortical models of perceptual processing in ASD, such as over-functioning of V1 and reduced cortical integration (e.g. Caron *et al*., 2006), could also account for the findings.

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