J Autism Dev Disord (2010) 40:978–987
DOI 10.1007/s10803-010-0953-7

ORIGINAL PAPER

Spatial Contrast Sensitivity in Adolescents with Autism Spectrum Disorders

Hwan Cui Koh · Elizabeth Milne · Karen Dobkins

Published online: 6 March 2010

Abstract Adolescents with autism spectrum disorders (ASD) and typically developing (TD) controls underwent a rigorous psychophysical assessment that measured contrast sensitivity to seven spatial frequencies (0.5–20 cycles/degree). A contrast sensitivity function (CSF) was then fitted for each participant, from which four measures were obtained: visual acuity, peak spatial frequency, peak contrast sensitivity, and contrast sensitivity at a low spatial frequency. There were no group differences on any of the four CSF measures, indicating no differential spatial frequency processing in ASD. Although it has been suggested that detail-oriented visual perception in individuals with ASD may be a result of differential sensitivities to low versus high spatial frequencies, the current study finds no evidence to support this hypothesis.

Keywords Autism spectrum disorders · Spatial frequency · Contrast sensitivity · Visual acuity · Perception · Visual psychophysics

Introduction

Over the last several years, there have been numerous studies demonstrating atypical visual processing in individuals with autism spectrum disorders (ASD). Relevant to the current study, individuals with ASD show superior performance on visual tasks that require attention to local details and deficits in holistic-oriented tasks (e.g., Brosnan et al. 2004; Jarrold et al. 2005, see Happé and Frith 2006 for review). Because detail-oriented and holistic-oriented tasks require the use of high and low spatial frequency information, respectively (Badcock et al. 1990; Boeschoten et al. 2005; Hughes et al. 1996), the "spatial frequency hypothesis" in ASD proposes that the detail-oriented bias in ASD reflects enhanced sensitivity to high spatial frequencies and/or a reduced sensitivity to low spatial frequencies (Behrmann et al. 2006; Kemner and van Engeland 2006; Milne et al. 2002).

Several studies have attempted to investigate the spatial frequency hypothesis in ASD, however, the results have been mixed, and there are a number of methodological limitations that make it difficult to compare results across studies. One approach has been to measure *visual acuity*. Visual acuity refers to the finest detail (i.e., the highest spatial frequency) the visual system can perceive, and is measured by asking participants to detect stimuli of decreasing size. Two studies that measured visual acuity using clinical screening charts have reported no differences between participants with ASD and typically developing (TD) controls. One study employed the Landholt-C gap stimulus, where participants reported the position of the gap (up, down, left or right) for various gap sizes, as a way to determine the smallest perceivable gap size (de Jonge et al. 2007). The other study employed the Crowded LogMAR test (Keeler Ophthalmic Instruments), where participants named letters that decreased in size (Milne et al. 2009). However, because these clinical screening tests of visual acuity are considered quick assessments and are therefore not very rigorous, subtle group differences might have been missed. In support of this possibility, a different study that employed the Landholt-C gap stimulus/task to test visual acuity, yet used a more thorough

H. C. Koh · E. Milne
Department of Psychology, The University of Sheffield, Sheffield, UK

K. Dobkins (✉)
Department of Psychology, University of California, Mail Code 0109, San Diego, La Jolla, CA 92093-0109, USA
e-mail: kdobkins@ucsd.edu

staircase procedure (i.e., the Freiburg Visual Acuity and Contrast Test, FrACT), did report that participants with ASD had significantly higher visual acuity than TD controls (Ashwin et al. 2009). These results, which suggest enhanced sensitivity to high spatial frequencies in individuals with ASD, have been challenged, however, as the spatial resolution of the visual display at the reported viewing distance in this study may not have been sufficient to enable measurement of the reported visual acuity values (Bach and Dakin 2009). Another concern about all the above-mentioned studies is that none tested for refractive errors (i.e., with a retinoscope), which could confound the findings if the authors were not careful to ensure that participants with refractive errors were corrected to normal (via glasses/contact lenses), especially as refractive errors may be common in individuals with ASD (Scharre and Creedon 1992).

Another approach that has been used to investigate the spatial frequency hypothesis is to measure "contrast sensitivity" across a range of spatial frequencies. Contrast sensitivity refers to how sensitive the visual system is to small luminance variations in a sinusoidal grating stimulus, which consists of a pattern that alternates sinusoidally between light and dark stripes. The higher the spatial frequency of the grating, the narrower the individual stripes. Contrast sensitivity is measured by asking participants to indicate the presence/absence of a grating or its orientation. Two studies that measured contrast sensitivity across a range of spatial frequencies using clinical screening charts have reported no differences between participants with ASD and TD controls. One study employed the Vistech wall chart, where participants indicated the orientation of gratings that decreased in contrast, at the following spatial frequencies: 1.5, 3, 6, 12 and 18 cycles/degree (cpd) (de Jonge et al. 2007). The other study employed the CSV-1000, where participants indicated which of two patches contained a grating stimulus across a range of contrasts, at the following spatial frequencies: 3, 6, 12 and 18 cpd (Milne et al. 2009). However, as mentioned above for clinical screening charts that measure visual acuity, those measuring contrast sensitivity are considered to be quick assessments, developed for monitoring contrast sensitivity of clinical patients whose conditions (e.g., glaucoma, cataracts) result in large deterioration of visual abilities. As such, they are blunt instruments when comparing contrast sensitivity between individuals with ASD and TD controls, given that both groups likely possess visual abilities within the normal range.

There is one study to date that has used a more rigorous research-based approach to measure contrast sensitivity across a range of spatial frequencies. Specifically, Behrmann et al. (2006) compared contrast sensitivity between individuals with ASD and TD controls (at 0.13, 0.42, 1.26, 4.19 and 12.6 cpd) by using a staircase procedure. In line with results from the aforementioned clinical screening tests, this staircase procedure revealed no group differences at any spatial frequency tested. There are, however, a couple of limitations to their protocol, which could have led to negative findings. First, they used relatively few (i.e., 20) total trials per spatial frequency, and their staircase procedure used a fixed and somewhat large step size of contrast (i.e., 0.2 log units, which is a 1.58-fold change). These conditions can lead to rather noisy estimates of contrast threshold, making it difficult to notice small group differences. Second, because the maximum spatial frequency they tested (12.6 cpd) was well below visual acuity for humans (which is about 30–40 cpd, see Kelly 1977; Ridder 2004; Robson 1966; Virsu and Rovamo 1979), their data could not address differences between groups in visual acuity.

A further approach to investigate the spatial frequency hypothesis in ASD has been to conduct electrophysiological studies. Two studies to date have reported greater differential neural response to low versus high spatial frequencies in typical individuals than individuals with ASD (Boeschoten et al. 2007a; Milne et al. 2009), suggesting some atypical spatial frequency processing in ASD, leaving open the question of whether perceptual sensitivity to different spatial frequencies is atypical in ASD.

Given the mixed results across, and methodological limitations of, previous studies, the objective of the current study was to investigate the spatial frequency hypothesis of ASD as rigorously and thoroughly as possible. This was achieved by (1) measuring contrast sensitivity using a staircase procedure that employed a *variable* step size, and presenting 60 trials per spatial frequency, which allows for more precision than previous studies, (2) obtaining contrast sensitivity over a larger range of spatial frequencies (0.5–20 cpd) than previous studies, and (3) fitting a contrast sensitivity function (CSF) for each participant, which allowed us to obtain four measures of spatial frequency processing: visual acuity (i.e., the highest perceivable spatial frequency), contrast sensitivity at a very low spatial frequency, the spatial frequency producing the peak contrast sensitivity, and the contrast sensitivity at that peak. If enhanced detail processing and/or reduced holistic processing reported in ASD arises from differential spatial frequency processing, participants with ASD are expected to show higher visual acuity and peak spatial frequency, and/or reduced contrast sensitivity at low spatial frequency.

Methods

Participants

A total of 13 adolescents with ASD and 29 TD adolescents participated in the study. The participants were recruited from the San Diego Unified School District and community

resources in San Diego. The adolescents with ASD had an external diagnosis by a licensed clinical psychologist or medical doctor not associated with this research, based on DSM-IV-TR criteria (APA 2004). The diagnosis was confirmed through research methods in our laboratory (see *Psychometric Assessments*, below). The participants with ASD had no known specific neurological or genetic conditions (e.g., Fragile X, Rett Syndrome) that could account for their diagnosis. Informed consent was obtained from all participants, as well as from their parents. The study took 2–3 h to complete, and participants were paid USD10 per hour. All protocols were approved by the UCSD Human Research Protection Program.

Data from three participants with ASD and four TD participants were excluded because their contrast sensitivity data were too noisy to be fitted with a function (see below). This resulted in a final sample of 10 participants with ASD and 25 TD participants. The external diagnoses of the 10 ASD participants were as follows: one with Autistic Disorder, seven with Asperger's Syndrome, and two with Pervasive Developmental Disorder Not Otherwise Specified (PDD-NOS). The mean age of the participants with ASD and TD participants was 15 years 1 month (SD = 1 year, 9 months) and 15 years 7 months (SD = 1 year, 2 months), respectively, and there were no significant age difference between the two groups ($p = 0.33$, 2-tailed t-test). Note that the reason for having more participants in the control group was to maximize the accuracy of our measures in typical individuals. Additional analyses with the two groups matched in numbers yielded the same results, as did other analyses that took gender, colour deficiencies, and use of corrective lenses into account.[1] Participant information (including ages, gender, corrective lenses, assessment scores) is presented in Table 1.

[1] Several addition analyses were conducted to ensure that a group difference, or a lack of group difference, was not due to other uncontrolled factors. (1) Because there were more girls in the TD group (11 out of 25) than the ASD group (0 out of 10), we made sure that there were no group differences between boys and girls in our TD sample. Accordingly, for all visual measures, gender differences were insignificant (all p values >0.31), and for this reason it is justified to use a mixture of boys and girls in the TD sample. (2) Because there were more participants in the TD group (25) than the ASD group (10), we conducted an additional analysis that equated the number of participants (10 in each group, using 10 TD participants well matched to the participants with ASD). The results using 10 TD participants were the same as using all 25. (3) Two ASD and two TD participants had some colour deficiencies, however, because colour vision is not relevant to the current study (which tested only light/dark visual sensitivity), and because analyses with their data included/excluded yielded no differences in results, their data were kept in our analyses. (4) Three ASD and eight TD participants required corrective lenses and wore them during the experimental sessions. The statistical results were also no different if their data were included/excluded, so their data were kept in our analyses.

Psychometric Assessments

For each participant, three psychometric assessments were conducted. (1) The Lifetime version of the Social Communication Questionnaire (SCQ) consists of 40 "Yes/No" questions asking parents if their child currently displays specific autism-related behaviors or whether those behaviors were present between the ages of 4–5 years (Rutter et al. 2003). The SCQ cut-off score for ASD is 15. (2) The Social Responsiveness Scales (SRS) required parents to rate (on a five point scale) the frequency of 65 autism-related behaviors in their child in the past six months (Constantino et al. 2000). There is no cut-off score for the SRS, but the published mean score for participants with PDD-NOS is 101.5, with a SD of 23.6. Both the SCQ and SRS aim to obtain information on social communication and interaction difficulties. (3) The Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler 1999) is an experimenter administered (by author HCK or by a trained research associate) test that measures cognitive abilities. It is comprised of four standardized subtests that assess expressive language, perceptual organization, abstract verbal reasoning and nonverbal fluid reasoning abilities. The two verbal sub-test scores can be converted into a "verbal IQ" score, and the two non-verbal sub-test scores can be converted into a "performance IQ" score. The four sub-tests when considered together yield a "full scale IQ" that provides a composite measure of the participant's intelligence.

In addition, for each participant with ASD, the diagnosis was verified by author HCK using the autism diagnostic observation schedule (ADOS) (Modules Three or Four), which is a play-based experimenter-administrated assessment designed to elicit behaviors (or lack of behaviors) associated with a diagnosis of ASD (Lord et al. 2000). The ADOS cut-off score for ASD is seven, and for Autistic Disorder is ten. (Note that the ADOS does not distinguish Asperger's Syndrome, and that the specific diagnosis determined from the ADOS does not always conform to that of the external diagnosis, see Risi et al. 2006). By these criteria, six participants met the criteria for ASD[2] and three for Autistic Disorder. One participant, who received an external diagnosis of Asperger's Syndrome, obtained an ADOS score below seven. However, by our other psychometric assessments (SCQ and SRS), he scored as having ASD, and for this reason, his data were included in our analyses. As expected, the results of independent sample t-tests revealed significant differences between participants with ASD and TD controls on the SCQ ($p < 0.001$, 2-tailed t-test) and the SRS ($p < 0.001$, 2-tailed t-test). However,

[2] Note, however, that throughout the paper we use the general term ASD to refer to all participants with an external diagnosis of Autistic Disorder, Asperger's syndrome or PDD-NOS.

Table 1 Participant information: gender, chronological age, IQ scores, SCQ scores, SRS scores

	ASD ($N = 10$)	TD ($N = 25$)	t & p values
Sex	10 boys	14 boys, 11 girls	
Chronological age (years: months)			
M	15: 1	15: 7	$t(df = 33) = 0.985$, $p = 0.332$
SD	1: 9	1: 2	
Range	13: 1–17: 9	14: 0–17: 8	
Verbal IQ			
M	101	108	$t(df = 33) = 1.06$, $p = 0.295$
SD	22	15	
Range	64–133	77–133	
Performance IQ			
M	104	108	$t(df = 33) = 0.94$, $p = 0.352$
SD	13	13	
Range	76–121	74–127	
Full Scale IQ			
M	103	109	$t(df = 33) = 1.21$, $p = 0.233$
SD	16	14	
Range	75–125	79–133	
SCQ score[a]			
M	25	3	$t(df = 30) = 13.7$, $p < 0.001$
SD	6	4	
Range	18–33	0–13	
SRS score[a]			
M	104	52	$t(df = 30) = 11.2$, $p < 0.001$
SD	21	5	
Range	77–133	39–64	
ADOS total[b]			
M	8.5		
SD	3		
Range	4–14		

ADOS scores were obtained only for participants with ASD

[a] Parents of three TD participants did not return the SCQ and SRS

[b] One ASD participant who had an external diagnosis of Asperger's Syndrome scored below the ADOS cut-off for ASD (total score = 4). He was nonetheless considered ASD, and his data were included in our analyses, because he both scored above the cut-off for ASD on the SCQ (score = 22), and scored one SD below the SRS published mean for PDD-NOS (score = 94)

the two groups did not differ in verbal IQ ($p = 0.295$, 2-tailed t-test), performance IQ ($p = 0.352$, 2-tailed t-test), or full-scale IQ ($p = 0.233$, 2-tailed t-test).

Visual Apparatus

The visual stimuli were presented on a high resolution RGB monitor (19.8" SONY GDM-F520 monitor, 100 Hz frame rate, 1024 × 768 pixels at dot pitch of 0.22 mm). The monitor was driven by a Microsoft Windows XP computer with Intel Pentium 4 processor. The Cambridge Research System's toolbox for MATLAB was used to create the visual stimuli and run the experimental paradigm, driven by a VSG2/3F digital video board. The 14-bit video board allowed for 16,384 discrete luminance levels. Gamma correction was performed to linearize the voltage/luminance relationship for the monitor display, using a PR-650 SpectraColorimeter (Photoresearch). At a viewing distance of 100 cm, the viewable portion of the monitor subtended 23.1 × 16.7° visual angle.

Stimuli

The stimuli in this experiment were luminance (light/dark) static Gabor patches (mean luminance = 23 cd/m^2, chromaticity (CIE) coordinates = 0.489 0.453) presented on a background with the same luminance/chromaticity. Gabor patches were created by convolving horizontally oriented sinusoidal gratings that subtended 3.1° with a Gaussian circular envelope (SD = 0.5°). The contrast (i.e., the luminance difference between the light and dark stripes of the grating) is calculated as: $100 \times (\text{Luminance}_{\max} - \text{Luminance}_{\min})/(\text{Luminancemax} + \text{Luminance}_{\min})$. Zero percent contrast refers to a uniform field, which is indistinguishable from the background. To obtain a full "contrast sensitivity function" (see below), the gratings were

presented at seven different spatial frequencies, i.e., 0.5, 2, 4, 8, 12, 16, and 20 cycles/degree (cpd).

Psychophysical Paradigm

Participants were tested in a dark room and viewed the video monitor binocularly from a chin rest situated 100 cm away. Participants were instructed to maintain fixation on a small cross (length and width = 0.2°) in the center of the monitor. Fixation was not monitored because the stimuli were centrally located, thus there was no reason for subjects to move their eyes i.e. break fixation to detect the stimulus. Participants began each trial with a key press, after which a Gabor stimulus appeared at the center of the monitor in one of two 250 ms intervals, separated by a 500 ms gap. The beginning of each of the two time intervals was accompanied by a beep. After each trial, participants reported whether the visual stimulus appeared during the first or second beep via key press, i.e., in a standard two-alternative forced choice manner. Feedback was provided in the form of a beep (different pitch from the beeps during stimulus presentation) indicating a correct response. The seven different spatial frequencies were presented in a random fashion across trials, with 60 trials obtained for each spatial frequency. The total number of trials was 420 (60 trials × 7 spatial frequencies).

Adaptive Staircase Procedure

Contrast varied across trials in an adaptive staircase procedure. Specifically, on the first trial a given spatial frequency was presented, its contrast was 90%. The contrast for subsequent trials of that spatial frequency varied in a 1 down/2 up procedure, based on the parameter estimation and sequential testing (PEST) method (Taylor and Creelman 1967). Contrast was decreased by one step size after a correct response, and was increased by two step sizes after an incorrect response. The maximum step size was 0.14 log units (1.38-fold change in contrast). The value of the step size was determined by an acceleration factor (AC) of 1.2 and a reversal factor (RF) of 1.1. The step size was multiplied by AC, following either two correct or two incorrect responses, and was multiplied by $(1/\mathrm{AC})^{\mathrm{RF}}$, following a reversal in correctness. The use of a variable step size allowed more precision than a fixed step size.

Obtaining Contrast Sensitivity Functions

For each participant, at the end of the experiment, the 60 trials obtained for each spatial frequency were used to obtain a contrast threshold for that spatial frequency. This was performed by fitting a psychometric Gumbel function (Gumbel 1958) to "percent correct vs. contrast" data, using maximum likelihood method (Johnson et al. 1995; Watson 1979). Contrast *threshold* was defined as the contrast value yielding 75% correct performance. Contrast *sensitivity* was calculated as the inverse of contrast threshold. Contrast sensitivity was then logged, since logarithmic, but not linear, contrast sensitivity data conform to normal distributions.

The log contrast sensitivities derived for the seven different spatial frequencies were fitted with a double exponential function to create a contrast sensitivity function (CSF), using an iterative minimization process as previously described (Dobkins et al. 1999; Movshon and Kiorpes 1988). The function is described as:

$$f(x) = -A + a(\varpi b)^{d} e^{-c\varpi b}$$

where ω is the spatial frequency, a allows vertical shifts of sensitivity, b allows lateral shifts in spatial frequency, c affects the high frequency fall-off and d affects the low frequency fall-off. $-A$ is set to an arbitrarily large number so that the function extrapolates to the x-axis.

Deriving Measures of Spatial Frequency Processing

For each participant, four measures of spatial frequency processing were derived from the CSF: (1) The maximum perceivable spatial frequency (maxSF), i.e., where the curve extrapolates to the x-axis, which is considered *visual acuity*, (2) The contrast sensitivity at a relatively low SF, i.e., 0.1 cpd (lsfCS). Note that although the lsfCS is an arbitrary low-end limit, it should suffice to capture contrast sensitivity to low spatial frequencies. (3) The spatial frequency yielding the peak contrast sensitivity (peakSF), and (4) The peak contrast sensitivity at that peak (peakCS). An example double exponential fit from a participant with ASD is presented in Fig. 1.

Mean best error estimates for participants with ASD (mean = 0.16, SD = 0.07) and TD participants (0.12, SD = 0.06) did not differ from one another ($t(df = 33) = 1.51$, $p = 0.142$). And, the four measures and best error values for all participants were within 3 SDs of the group means.

Data Analysis

For each of the four measures derived from the CSF, group differences were investigated using independent sample t-tests (2-tailed). A multivariate analysis of variance (MANOVA) was also used to analyze the group difference in the combined effect of the four CSF measures, with the CSF measures entered as the dependent variables and group as the between subjects factor. For all four CSF measures, data satisfied Kolmogorov–Smirnov tests for

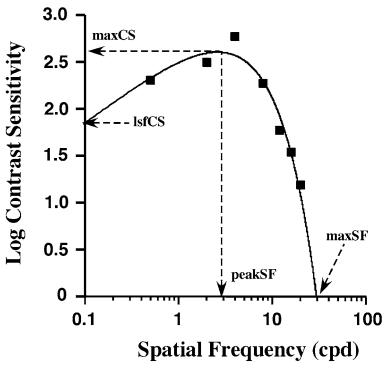

Fig. 1 Example CSF Fit for an ASD participant. The CSF was obtained with a double exponential fit to contrast sensitivity obtained for seven different spatial frequencies (*filled squares*). The value of the four measures of the CSF (maxSF, lsfCS, peakSF, peakCS) are presented. The data show the expected bandpass shape of the CSF with a peak near 3 cpd

normality and Levene's tests of homogeneity of variances between the two participant groups. In addition, for each spatial frequency tested, group differences in mean log contrast sensitivity were investigated. Because here the log contrast sensitivity data did not conform to normality (as is usually the case, see Gunther and Dobkins 2002), non-parametric Mann–Whitney tests were used for this analysis.

Results

CSF Measures

Group means and SDs for the four measures of spatial frequency processing derived from the CSF (maxSF, lsfCS, peakSF, peakCS) are presented in Table 2. These values are very similar to those reported in previous studies of typical individuals, including a peak in contrast sensitivity (peakSF) near 3 cpd and visual acuity (maxSF) near 40 cpd (e.g., Gwiazda et al. 1997; Kelly 1977; Movshon and Kiorpes 1988; Ridder 2004; Robson 1966; Virsu and Rovamo 1979). Independent sample *t*-tests revealed no group difference in any of the four CSF measures. And, the MANOVA indicated no significant group difference in the combined effect of the measures (Wilk's $\Lambda = 0.948$, $F(4,30) = 0.415$, $p = 0.796$).

Power analyses were computed (Faul et al. 2007) to calculate the sample size required to detect a significant group difference given the effect sizes based on means and SDs reported in Table 2. These analyses revealed that more than 156 participants in each group would be required to see a significant group difference in any of the four CSF measures.

Group Mean CSF

To further demonstrate that there were no group differences, group mean CSF for the ASD and the TD group are presented in Fig. 2. These were created by first, averaging log contrast sensitivity values across participants for each of the seven spatial frequencies tested, and then fitting the double exponential function to these mean sensitivity values. Error bars denote SEs of the means. The CSF for both groups show the expected band-pass shape, and the functions for the two groups overlap one another. Also, at each of the seven spatial frequencies tested, non-parametric Mann–Whitney tests yielded no significant group difference in contrast sensitivity ($U > 79.0$, $p > 0.097$ in all cases).

ASD Subgroups and Correlational Analyses

It is possible that the lack of group difference is due to heterogeneity of diagnosis in the ASD group. That is, the participants with ASD had varying external diagnoses (i.e., Autistic Disorder, Asperger's Syndrome or PDD-NOS) as well as varying severity of ASD based on their ADOS scores (see "Methods"). Although the relatively low sample size of the current study makes it difficult to analyze the effects of heterogeneity, visual inspection of our data revealed no obvious differences in CSF measures across the subgroups.

To further investigate heterogeneity in our data, correlations between CSF measures (maxSF, lsfCS, peakSF, peakCS) and assessment scores were analyzed. The assessment scores included the total ADOS score, the SCQ and SRS scores, verbal IQ, performance IQ and full scale IQ. For the TD group, there was a significant correlation between peakCS and performance IQ ($r(20) = 0.472$, $p = 0.020$), with higher performance IQ being associated with higher peak contrast sensitivity.[3] For the ASD group, there was a significant correlation between lsfCS and total ADOS score ($r(7) = 0.757$, $p = 0.018$), with higher, i.e., more severe, ADOS scores correlated with higher contrast sensitivity to low spatial frequency.[4] In addition, there were also two significant negative correlations in the ASD group: between verbal IQ and maxSF ($r(8) = -0.784$, $p = 0.007$) and between full scale IQ and maxSF ($r(8) = -0.642$, $p = 0.045$), the direction of the

[3] For three TD participants, Performance IQ scores were outlying data points (i.e. more than two standard deviations from the group mean). Data from these participants were removed from the correlational analyses.

[4] For one participant with ASD, the ADOS total score was an outlying data point (i.e. more than two standard deviations from the group mean). Data from this participant were removed from the correlational analyses.

Table 2 Means and SDs (in parentheses) for four CSF measures

	ASD ($N = 10$)	TD ($N = 25$)	t- and p-values
Maximum perceivable spatial frequency (cpd)	37 (11)	39 (8)	$t(df = 33) = 0.749$, $p = 0.459$
Contrast sensitivity at a low spatial frequency	1.7 (0.28)	1.6 (0.30)	$t(df = 33) = 0.683$, $p = 0.500$
Peak spatial frequency (cpd)	2.8 (1.1)	3.2 (0.9)	$t(df = 33) = 1.08$, $p = 0.286$
Peak contrast sensitivity	2.4 (0.23)	2.4 (0.27)	$t(df = 33) = 0.211$, $p = 0.834$

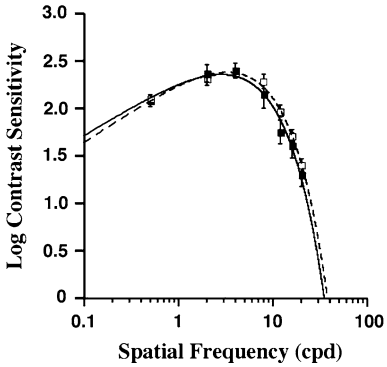

Fig. 2 Group mean CSF, for the ASD group (*bold line*) and the TD group (*dashed line*). *Squares* denote the group mean sensitivities for the seven different spatial frequencies (ASD = *filled squares,* TD = *open squares*), and *error bars* denote SEs of the means

correlations indicating that better cognitive functioning correlated with lower visual acuity. These preliminary results, while intriguing, should be viewed with extreme caution, however, given the low sample size and multiple comparisons.

Discussion

The current study investigated the "spatial frequency processing" hypothesis in ASD using a rigorous approach, being the first to investigate the entire contrast sensitivity function (CSF) in individuals with ASD. The results show no evidence for group differences on any CSF measure: visual acuity (i.e., the highest perceivable spatial frequency), contrast sensitivity at a very low spatial frequency, the spatial frequency producing the peak contrast sensitivity, and the contrast sensitivity at that peak. Thus, we conclude that individuals with ASD do not show atypical spatial frequency processing, and suggest that previously reported perceptual biases in terms of enhanced detail processing/reduced holistic processing in ASD are unlikely to be driven by an imbalance of high versus low spatial frequency sensitivity.

The failure to find any difference in spatial frequency processing between individuals with and without ASD is in line with the majority of studies as reviewed in the "Introduction". The exception is a recent study reporting significantly enhanced visual acuity in individuals with ASD (Ashwin et al. 2009). There are several potential reasons for the discrepancy between the positive visual acuity results of the Ashwin study and the negative results of the current study. First, there could be a difference between studies in power, based on differences in number of participants. This is an unlikely explanation, however, since total numbers were roughly equal between the two studies: Ashwin et al. compared 15 ASD to 15 TD participants, and the current study compared 10 ASD to 25 TD participants. Also, note that the effect size of $d = 4.22$ reported by Ashwin et al. indicates that a significant group difference should be seen with just three participants in each group (Faul et al. 2007), suggesting that the participant numbers in the current study should be sufficient to reveal differences in visual acuity. Second, the makeup of the participants with ASD was different between the two studies: Ashwin et al. tested eight with Autistic Disorder and seven with Asperger's syndrome, whereas the external diagnoses of the participants in the current study were: one with Autistic Disorder, seven with Asperger's Syndrome and two with PDD-NOS. At first glance, one might conjecture that the discrepancy between studies could be due to enhanced visual acuity being more predominant in Autistic Disorder (and was thus missed in the current study because of there being only one participant in this subgroup). This is unlikely to be the case, however, since Ashwin, et al.'s data revealed that both their participants with Autistic Disorder and with Asperger's Syndrome showed enhanced visual acuity. Visual inspection of our data also did not reveal any obvious differences across subgroups. A final, most likely, reason for the discrepancy between studies is the different manner in which visual acuity was measured: Ashwin et al. employed a Landholt-C gap task, whereas the current study obtained visual acuity as a measure derived from the CSF. Perhaps the two different measures of visual acuity tap different neural resources and/or require different strategies, and thus individuals with and without ASD may differ on neural resources/strategies employed in the Landholt-C gap task.

In addition to the contrast sensitivity studies reviewed in the "Introduction", a number of other perceptual studies, while not addressing the spatial frequency hypothesis in ASD per se, have measured luminance contrast sensitivity

in individuals with ASD at various spatial and temporal frequencies. These studies report no difference in contrast sensitivity between ASD and typical individuals over a range of spatial frequencies (0.5–6 cpd) and temporal frequencies (1–12.5 Hz) (Bertone et al. 2005; Davis et al. 2006; Koh, Milne and Dobkins, in prep; Pellicano et al. 2005), in line with results from the current study and those reviewed in the Introduction. One exception is contrast sensitivity at a relatively high spatial frequency (13.4 cpd/2 Hz), which has been reported to be *reduced* in individuals with ASD compared to controls (Davis et al. 2006). Interestingly, this reduced sensitivity at high spatial frequency would, if anything, predict *poorer* acuity in ASD, which contradicts the results from Ashwin et al. (2009).

Given that the results of the current and previous perceptual studies do not tend to support the spatial frequency hypothesis in ASD, it is important to address what then could underlie enhanced detail processing/reduced holistic processing reported in ASD. We suggest that while individuals with ASD may not possess differential spatial frequency processing per se, they may differentially *use* spatial frequency for higher-level visual tasks. In line with this hypothesis are results from perceptual studies that investigated which spatial frequencies are most critical for face processing in individuals with ASD, addressed by filtering out different ranges of spatial frequencies. Two studies have measured perceptual discrimination of facial identity and emotion for "low" and "high" spatial frequency faces, and showed that while TD individuals rely more on low, than high, spatial frequencies, individuals with ASD exhibit the reverse pattern (Deruelle et al. 2004; Deruelle et al. 2008, and see Boeschoten et al. 2007b for similar and relevant results obtained from EEG studies). In line with these findings, another study showed that while individuals with ASD have no trouble discriminating facial emotions in unfiltered faces, they underperform TD individuals when the faces contain only low spatial frequencies (Katsyri et al. 2008).

The finding that individuals with ASD tend to be biased towards using high spatial frequencies for these face tasks is consistent with other lines of evidence that they are more detailed-oriented (with details containing high spatial frequency) and less holistic-oriented (with global information containing low spatial frequency). Along these lines, the well documented deficits in discriminating facial identity and facial expressions of emotion seen in ASD (see Jemel et al. 2006 for review) have been attributed to their use of a detail-oriented, rather than a holistic approach, to face processing (e.g. Behrmann et al. 2006; Lahaie et al. 2006). In sum, the combined results from the current and previous studies suggest that ASD may be associated with differential *use* of spatial frequencies for face, and perhaps other types of visual, processing, rather than differential spatial frequency processing per se. This notion is consistent with the conceptualization of detail-oriented bias in ASD as a cognitive preference for details/high spatial frequency information, which can be used to explain the apparent deficit in holistic/low spatial frequency information in ASD (Happé and Frith 2006; Mottron et al. 2006).

In conclusion, the general consensus from the current and previous studies is that processing of different spatial frequencies appears normal in ASD, although there are some noted discrepancies across studies. It is possible that differences across studies are driven by sampling biases, which is a reasonable concern given that atypicalities in ASD are much more heterogeneous than originally believed (see Happé et al. 2006 for review). For example, it is now accepted that there are different subgroups in ASD, in terms of genetics (Abrahams and Geschwind 2008; Liu et al. 2008) and cognitive/language behaviors (Beglinger and Smith 2001; Tadevosyan-Leyfer et al. 2003; Tager-Flusberg and Joseph 2005). Given the relatively small sample size of the current study, one cannot rule out the possibility that our sample was biased to consist of individuals with ASD who do not exhibit enhanced detail processing/reduced holistic processing, in which case, any link between enhanced detail processing/reduced holistic processing and differential spatial frequency processing would necessarily be missed. Future studies that obtain performance on detail- versus holistic-oriented tasks, as well as measurements of spatial frequency processing (as in the current study), will be needed to address whether individuals with ASD who exhibit enhanced detail processing/reduced holistic processing are the ones who show atypical spatial frequency processing.

Acknowledgments This research was supported by NIH grant R01 HD052804-01A2 (KD), and a WUN Research mobility award (HCK). We would like to thank all of the families who generously participated in this study, and the schools who helped with participant recruitment. We also acknowledge Ms Beth Hannaman, the Program Manager of Resources for Students with Autism, and the Research Review committee with the Research and Reporting Department, at the San Diego Unified School District for their valuable input and assistance in participant recruitment. We would also like to thank Sarah Song for her assistance with data collection, and Katie Wagner and Hao Ye for technical advice.

References

Abrahams, B. S., & Geschwind, D. H. (2008). Advances in autism genetics: On the threshold of a new neurobiology. *Nat Rev Genet, 9*(5), 341–355.

APA. (2004). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.

Ashwin, E., Ashwin, C., Rhydderch, D., Howells, J., & Baron-Cohen, S. (2009). Eagle-eyed visual acuity: An experimental investigation of enhanced perception in autism. *Biological Psychiatry, 65*(1), 17–21.

Bach, M., & Dakin, S. (2009). Commentary on "Eagle-eyed visual acuity: An experimental investigation of enhanced perception in autism". *Biological Psychiatry, 66*(10), e19–e20.

Badcock, J. C., Whitworth, F. A., Badcock, D. R., & Lovegrove, W. J. (1990). Low-frequency filtering and the processing of local—global stimuli. *Perception, 19*(5), 617–629.

Beglinger, L., & Smith, T. (2001). A review of subtyping in autism and proposed dimensional classification model. *Journal of Autism and Developmental Disorders, 31*(4), 411–422.

Behrmann, M., Avidan, G., Leonard, G. L., Kimchi, R., Luna, B., Humphreys, K., et al. (2006a). Configural processing in autism and its relationship to face processing. *Neuropsychologia, 44*(1), 110–129.

Behrmann, M., Thomas, C., & Humphreys, K. (2006b). Seeing it differently: Visual processing in autism. *Trends in Cognitive Sciences, 10*(6), 258–264.

Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain, 128*(10), 2430–2441.

Boeschoten, M. A., Kemner, C., Kenemans, J. L., & van Engeland, H. (2005). The relationship between local and global processing and the processing of high and low spatial frequencies studied by event-related potentials and source modeling. *Cognitive Brain Research, 24*(2), 228–236.

Boeschoten, M. A., Kenemans, J. L., van Engeland, H., & Kemner, C. (2007a). Abnormal spatial frequency processing in high-functioning children with pervasive developmental disorder (PDD). *Clinical Neurophysiology, 118*(9), 2076–2088.

Boeschoten, M. A., Kenemans, J. L., van Engeland, H., & Kemner, C. (2007b). Face processing in pervasive developmental disorder (PDD): The roles of expertise and spatial frequency. *Journal of Neural Transmission, 114*(12), 1619–1629.

Brosnan, M. J., Scott, F. J., Fox, S., & Pye, J. (2004). Gestalt processing in autism: Failure to process perceptual relationships and the implications for contextual understanding. *Journal of Child Psychology and Psychiatry, 45*(3), 459–469.

Constantino, J. N., Przybeck, T., Friesen, D., & Todd, R. D. (2000). Reciprocal social behavior in children with and without pervasive developmental disorders. *Journal of Developmental and Behavioral Pediatrics, 21*(1), 2–11.

Davis, R., Bockbrader, M., Murphy, R., Hetrick, W., & O'Donnell, B. (2006). Subjective perceptual distortions and visual dysfunction in children with autism. *Journal of Autism and Developmental Disorders, 36*(2), 199–210.

de Jonge, M. V., Kemner, C., de Haan, E. H., Coppens, J. E., van den Berg, T., & van Engeland, H. (2007). Visual information processing in high-functioning individuals with autism spectrum disorders and their parents. *Neuropsychology, 21*(1), 65–73.

Deruelle, C., Rondan, C., Gepner, B., & Tardif, C. (2004). Spatial frequency and face processing in children with autism and asperger syndrome. *Journal of Autism and Developmental Disorders, 34*(2), 199–210.

Deruelle, C., Rondan, C., Salle-Collemiche, X., Bastard-Rosset, D., & Da Fonseca, D. (2008). Attention to low- and high-spatial frequencies in categorizing facial identities, emotions and gender in children with autism. *Brain and Cognition, 66*(2), 115–123.

Dobkins, K. R., Anderson, C. M., & Lia, B. (1999). Infant temporal contrast sensitivity functions (tCSFs) mature earlier for luminance than for chromatic stimuli: Evidence for precocious magnocellular development? *Vision Research, 39*(19), 3223–3239.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Gumbel, E. J. (1958). *Statistics of extremes*. New York: Columbia University Press.

Gunther, K. L., & Dobkins, K. R. (2002). Individual differences in chromatic (red/green) contrast sensitivity are constrained by the relative number of L- versus M-cones in the eye. *Vision Research, 42*(11), 1367–1378.

Gwiazda, J., Bauer, J., Thorn, F., & Held, R. (1997). Development of spatial contrast sensitivity from infancy to adulthood: Psychophysical data. *Optometry and Vision Science, 74*(10), 785–789.

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

Happé, F., Ronald, A., & Plomin, R. (2006). Time to give up on a single explanation for autism. *Nature Neuroscience, 9*(10), 1218–1220.

Hughes, H. C., Nozawa, G., & Kitterle, F. (1996). Global precedence, spatial frequency channels, and the statistics of natural images. *Journal of Cognitive Neuroscience, 8*(3), 197–230.

Jarrold, C., Gilchrist, I. D., & Bender, A. (2005). Embedded figures detection in autism and typical development: Preliminary evidence of a double dissociation in relationships with visual search. *Developmental Science, 8*(4), 344–351.

Jemel, B., Mottron, L., & Dawson, M. (2006). Impaired face processing in autism: Fact or artifact? *Journal of Autism and Developmental Disorders, 36*(1), 91–106.

Johnson, N. L., Kotz, S., & Balakrisnan, N. (1995). *Continuous univariate distributions* (Vol. 2). New York: Wiley.

Katsyri, J., Saalasti, S., Tiippana, K., von Wendt, L., & Sams, M. (2008). Impaired recognition of facial emotions from low-spatial frequencies in Asperger syndrome. *Neuropsychologia, 46*(7), 1888–1897.

Kelly, D. H. (1977). Visual contrast sensitivity. *Journal of Modern Optics, 24*(2), 107–129.

Kemner, C., & van Engeland, H. (2006). ERPs and eye movements reflect atypical visual perception in pervasive developmental disorder. *Journal of Autism and Developmental Disorders, 36*(1), 45–54.

Koh, H. C., Milne, E., & Dobkins, K. R. (in prep). Magnocellular and parvocellular pathway functioning and their contribution to motion processing in adolescents with ASD and their siblings.

Lahaie, A., Mottron, L., Arguin, M., Berthiaume, C., Jemel, B., & Saumier, D. (2006). Face perception in high-functioning autistic adults: Evidence for superior processing of face parts, not for a configural face-processing deficit. *Neuropsychology, 20*(1), 30–41.

Liu, X. Q., Paterson, A. D., & Szatmari, P. (2008). Genome-wide linkage analyses of quantitative and categorical autism subphenotypes. *Biological Psychiatry, 64*(7), 561–570.

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Leventhal, B. L., DiLavore, P. C., et al. (2000). The autism diagnostic observation schedule—generic: A standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30*(3), 205–223.

Milne, E., Griffiths, H., Buckley, D., & Scope, A. (2009a). Vision in children and adolescents with autistic spectrum disorder: Evidence for reduced convergence. *Journal of Autism and Developmental Disorders, 39*(7), 965–975.

Milne, E., Scope, A., Pascalis, O., Buckley, D., & Makeig, S. (2009b). Independent component analysis reveals atypical electroencephalographic activity during visual perception in individuals with autism. *Biological Psychiatry, 65*(1), 22–30.

Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. *Journal of Child Psychology and Psychiatry, 43*(2), 255–263.

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

Movshon, J. A., & Kiorpes, L. (1988). Analysis of the development of spatial contrast sensitivity in monkey and human infants. *Journal of the Optical Society of America Association, 5*(12), 2166–2172.

Pellicano, E., Gibson, L., Mayberry, M., Durkin, K., & Badcock, D. R. (2005). Abnormal global processing along the dorsal visual pathway in autism: A possible mechanism for weak visuospatial coherence? *Neuropsychologia, 43*(7), 1044–1053.

Ridder, W. H. (2004). Methods of visual acuity determination with the spatial frequency sweep visual evoked potential. *Documenta Ophthalmologica, 109*(3), 239–247.

Risi, S., Lord, C., Gotham, K., Corsello, C., Chrysler, C., Szatmari, P., et al. (2006). Combining information from multiple sources in the diagnosis of autism spectrum disorders. *Journal of Amer Academy of Child & Adolescent Psychiatry, 45*(9), 1094–1103.

Robson, J. G. (1966). Spatial and temporal contrast-sensitivity functions of the visual system. *Journal of Optical Society America, 56*(8), 1141–1142.

Rutter, M., Bailey, A., Lord, C., & Berument, S. K. (2003). *Social communication questionnaire*. Los Angeles, CA: Western Psychological Services.

Scharre, J. E., & Creedon, M. P. (1992). Assessment of visual function in autistic children. *Optometry and Vision Science, 69*(6), 433–439.

Tadevosyan-Leyfer, O., Dowd, M., Mankoski, R., Winklosky, B., Putnam, S., McGrath, L., et al. (2003). A principal components analysis of the autism diagnostic interview-revised. *Journal of American Academy of Child and Adolescent Psychiatry, 42*(7), 864–872.

Tager-Flusberg, H., & Joseph, R. M. (2005). Identifying neurocognitive phenotypes in autism. *Philisophical Transactions of the Royal Society London B Biological Science, 358*(1430), 303–314.

Taylor, M. M., & Creelman, C. D. (1967). PEST: Efficient estimates on probability functions. *Journal of the Acoustical Society of America, 41*(4A), 782–787.

Virsu, V., & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research, 37*(3), 475–494.

Watson, A. B. (1979). Probability summation over time. *Vision Research, 19*(5), 515–522.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence (WASI)*. San Antonio, TX: Harcourt Assessment.