SPATIAL FREQUENCY PROCESSING IN AUTISM SPECTRUM DISORDER

by

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**ABSTRACT**

Autism Spectrum Disorder (ASD) is a developmental disorder characterized by deficits in social-communication and interaction in addition to restricted and repetitive behaviours and interests (American Psychiatric Association, 2013). Despite these deficits, a few studies have reported superior performance in various detail-oriented visual tasks, such as visual search (O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001) and embedded figures (Shah & Frith, 1983). It has been suggested that these atypicalities can be attributed to enhanced perceptual functioning (EPF) in the ASD population (Mottron, Dawson, Soulières, Hubert, & Burack, 2006). In the present study we examined basic visual processing of spatial frequency (SF) as a potential source for EPF. We employed three experiments to assess three distinct aspects of SF perception: sensitivity, precision, and accuracy. In Experiment 1, using a 2-interval forced choice (2-IFC) detection paradigm, we measured contrast sensitivity at eight SFs. In Experiment 2, we assessed precision as a function of spatial frequency via a 2-IFC discrimination paradigm. In Experiment 3, we examined accuracy of SF perception (i.e., veridical perception) via a method-of-adjustment paradigm. Finally, in Experiment 4 we implemented a visual search paradigm that has previously demonstrated superior performance in people with ASD (Kemner, van Ewijk, van Engeland, & Hooge, 2007; O'Riordan et al., 2001). No evidence for enhanced perceptual functioning was found in any of our three experiments examining sensitivity, precision, or accuracy of SF perception in ASD (N = 20) compared to age-, gender-, non-verbal IQ-matched controls (N = 20). In addition, in the visual search task we found faster reaction times in our control group, the opposite of previous studies that found superior performance in ASD. These findings are consistent with previous research on visual orientation perception (Shafai, Armstrong, Iarocci, & Oruc, 2015) suggesting that enhanced low-level visual processing is not a source of EPF in ASD,
as well as meta-analyses suggesting that EPF is not a characteristic of the overall population with ASD (Muth, Hönekopp, & Falter, 2014; Van der Hallen, Evers, Brewaey, Van den Noortgate, & Wagemans, 2015).
LAY SUMMARY

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder defined by deficits in social communication and social interaction in addition to restricted and repetitive behaviours and interests. While exploring various aspects of the disorder, researchers have discovered that people with autism have superior abilities in several visual tasks such as searching for objects in a cluttered environment. The Enhanced Perceptual Functioning (EPF) theory attributes these superior abilities to over functioning of low-level visual cortical processes. My research examined spatial frequency processing as a source for this enhancement, and assessed performance in a visual search task for our sample. Our comprehensive investigation of spatial frequency processing did not uncover any superior abilities for our group with ASD, suggesting that enhanced low-level visual processing is not a source of EPF in autism.
PREFACE

All experiments are based on work conducted in UBC’s Neuroscience of Vision and Action (NOVA) Laboratory (ICORD, Vancouver General Hospital), supervised by Dr. Ipek Oruc.

I was responsible for aiding in designing the experiments, recruiting subjects, and running the experiments. I was responsible for coding the procedures for Experiments 1-3 by implementing modifications to existing code in the NOVA lab to adapt them to the present study with guidance and assistance of my supervisor Dr. Oruc. Dr. Grace Iarocci and the Developmental Disorders laboratory at Simon Fraser University completed the Autism Diagnostic Observation Schedule (ADOS) with participants from the group with ASD. I was solely responsible for coding the search experiment (Experiment 4). Dr. Oruc and I worked on data processing and data analysis. I wrote the thesis in full with guidance and minor edits from my supervisor Dr. Oruc. Parts of this work have been presented in poster form at the 2018 Canadian Association for Neuroscience CAPNet Satellite, and at the 2018 Annual Meeting of Vision Sciences Society (Kamensek, Shafai, Iarocci, & Oruc, 2018).

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To my parents
CHAPTER 1 – INTRODUCTION

1.1 Autism spectrum disorder

Autism spectrum disorder (ASD) is a developmental disorder characterized by social and communication difficulties, often marked with stereotyped and repetitive movements or behaviours (American Psychiatric Association, 2013). Early diagnostic criteria for autism (prior to the 1980s) were associated with more qualitatively severe forms of the autistic behavioural phenotype, but have gradually included less severe forms of autism (Buxbaum & Hof, 2012). It is important to note the distinction between autism and intellectual disability. While early reports may have overestimated the prevalence of individuals with autism and intellectual disorder (70%), more current estimates place the association around 30% (Lyall et al., 2017). Current consensus based on the fifth revision of the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) combines previously separate categories of disorders including Autism, Asperger’s syndrome, and Pervasive development disorder- not otherwise specified (PDD-NOS) under the umbrella diagnosis of ASD. Autism is typically diagnosed in early childhood through parental questionnaires such as the Autism Diagnostic Interview (ADI-R) or through observational means such as the Autism Diagnostic Observational Schedule (ADOS) (Lord et al., 2000). Early behavioural manifestations include delayed communication and lack of social responsiveness. Children diagnosed with autism tend to be less interested in peers, less likely to make eye contact, respond appropriately to smiles, or look at the faces of others (Buxbaum & Hof, 2013). Restricted and repetitive behaviours associated with children diagnosed with autism include unusual sensory interests, repetitive use of objects, complex mannerisms often involving the hands and fingers, unusual preoccupations, abnormal responses and difficulties with changes in routines, as well as unusual attachments (Richler, Bishop, Kleinke, & Lord, 2007). A hallmark
feature of the disorder is marked clinical heterogeneity (Uljarević et al., 2017). This heterogeneity not only creates challenges in treatment, but in investigation. Uljarević et al. (2017) state that understanding sensory features associated with ASD can help constrain this clinical heterogeneity.

Developmental trajectories are quite variable in ASD and depend on the severity of autistic traits, difficulties in social and communication functioning, and repetitive behaviours, as well as general level of functioning including adaptive behaviours and intellectual functioning (Buxbaum & Hof, 2013). McGovern and Sigman (2005) found that although the diagnosis of autism shows very strong stability over time, individuals with ASD overall demonstrate improvements in adaptive behaviour skills, emotional responsiveness with reductions in repetitive behaviours and stereotyped interests.

1.1.1 Prevalence

Current reports from The National Autism Spectrum Disorder Surveillance System (NASS) estimate approximately 1 in 66 children and youth aged 5-17 are diagnosed with autism in Canada (Ofner et al., 2018). In the United States, the Autism and Developing Disabilities Monitoring Network of the Center for Disease Control and Prevention found similar numbers, with prevalence estimates of 1 in 63 children diagnosed by 8 years of age (Christensen et al., 2016). All reports have indicated an increasing trend for prevalence estimates that has been attributed to better education, diagnostic tools, and reporting practices, as well as the style in which questions are posed in the national survey (Buxbaum & Hof, 2013; Hansen, Schendel, & Parner, 2015; Zablotsky, Black, Maenner, Schieve, & Blumberg, 2015).

Consistently, males are identified about four times more frequently than females (Christensen et al., 2016; Fombonne, 2005; Ofner et al., 2018). Male to female gender ratios
decrease in lower functioning individuals to 1.95:1, and increase in those with average IQs to 5.5:1 (Fombonne, 2005). There are several theories as to why such a gender ratio exists, especially in higher functioning individuals with ASD, including biased diagnostic criteria favouring male diagnosis, and the development of compensatory social-communication ability specific to females that makes ASD harder to recognize (Bargiela, Steward, & Mandy, 2016; Dworzynski, Ronald, Bolton, & Happé, 2012; Frazier, Georgiades, Bishop, & Hardan, 2014; Frazier & Hardan, 2017; Head, McGillivray, & Stokes, 2014; Lai et al., 2011). Studies also suggest that cognitively able females with ASD have substantially lower levels of restricted and repetitive behaviours or interests (Frazier et al., 2014; Frazier & Hardan, 2017; Harrop, Gulsrud, & Kasari, 2015).

1.1.2 Etiology

Research findings of high concordance rates among monozygotic twins (47-90%) and low concordance rates among dizygotic twins (0-37%) has lead to an abundance of literature exploring genetic causes of ASD (Bailey et al., 1995; Folstein & Rutter, 1977; Kim & Leventhal, 2015; Lichtenstein et al., 2010; Ronald et al., 2006). These studies, indicating high heritability of the disorder, estimated that genetic factors were accounting for up to 80 percent of variation in liability for ASD (Lichtenstein et al., 2010). More recently however, heritability estimates have decreased substantially with analysis of much larger cohorts of twins (Hallmayer, Cleveland, Torres, & et al., 2011; Sandin et al., 2014). With a sample of twins born between 1987 and 2006 in California, Hallmayer et al. (2011) found that 58 percent of variance in liability for ASD could be attributed to shared environmental factors, in addition to moderate genetic heritability (38%). Sandin et al. (2014) who assessed a population cohort of 2,049,973 unique siblings or cousins, born between 1982 and 2006 in Sweden, found heritability to be about 50 percent, with the risk
of recurrence increasing with genetic relatedness. Interestingly, in a country where children undergo mandatory developmental assessments (motor, language, social and cognitive development) at age 4, the male:female ratios for ASD diagnosis were 2.7:1 (Sandin et al., 2014). In sum, while early findings indicated a large genetic contribution to the disorder, further investigation is warranted regarding environmental factors and genetic-environment interactions in ASD.

1.2 Theories of Perception in ASD

Visual atypicalities have long been associated with people with autism, such as enhanced performance in detail-oriented tasks including visual search (Kemner et al., 2007; O'Riordan, 2004), locating simple shapes embedded in complex figures (Jarrold, Gilchrist, & Bender, 2005; Shah & Frith, 1983), and block design subtest of the Wechsler Abbreviated scale of Intelligence (WASI) IQ test (Shah & Frith, 1993). These findings led researchers to believe that people with autism have superior visuo-spatial ability when it comes to detail-oriented or feature-based tasks. Thus, two frameworks have been proposed for explaining altered perception in the ASD population: the Weak Central Coherence theory (WCC) (Frith, 1989), which attributes feature-based perception to a lack of ability in global or whole-picture perception, and Enhanced Perceptual Functioning (EPF) (Mottron & Burack, 2001; Mottron et al., 2006), which attributes a detail-oriented perceptual style to superior low-level visual processing.

Since the proposal of these theories, several meta-analyses have challenged the repeatability of the studies fueling them (Kaldy, Giserman, Carter, & Blaser, 2016; Van der Hallen, Evers, Brewaeyis, Van den Noortgate, & Wagemans, 2015, Muth et al. 2014). For example, Muth et al. (2014) found substantial heterogeneity between studies investigating figure disembedding in autism. The results from Shah and Frith (1983) suggesting superior
performance in ASD, was an outlier compared to other studies, and when removed from statistical analysis, made the small advantage for ASD disappear. In addition, Van der Hallen et al.’s (2015) meta-analysis found that the ASD group was not superior in search, embedded figures, or block design.

Despite these challenges there has been agreement among some studies assessing visuo-spatial ability in autism. One particular visual search task where participants locate a vertical line among titled distractors has demonstrated superior performance in ASD consistently (Kemner, van Ewijk, van Engeland, & Hooge, 2008; O’Riordan, Plaisted, Driver, & Baron-Cohen, 2001). In addition, researchers agree that people with ASD demonstrate a local preference in Navon letters (Plaisted, Swettenham, & Rees, 1999, Muth et al. 2014) and hierarchical figures tasks (Stevenson et al., 2016; Wang, Mottron, Peng, Berthiaume, & Dawson, 2007). In these tasks, a larger character is made up of the spatial combination of several smaller characters. For example, in the Navon letters task several small S’s would be combined to create the shape of a large H. Participants are instructed to identify either the smaller character (local level) or larger character (global level). Typically, the identity of the small characters has no effect on recognition of the large ones, however when global cues conflicted with the local ones, responses are inhibited to the local level (global-to-local interference)(Navon, 1977). People with autism tend to demonstrate the opposite trend, where global identification is slower than local identification when the characters do not match, demonstrating local-to-global interference (Behrmann et al., 2006). In addition, people with ASD are more accurate than neurotypicals when having to attend to the local level, and ignore the incongruent global level character (Van der Hallen et al., 2015). Performance in these tasks indicates a more spontaneous or default perceptual processing style that focuses on local aspects of the environment (Happé & Frith, 2006; Mottron et al., 2006;
Plaisted, Swettenham, & Rees, 1999; Stevenson et al., 2016; Van der Hallen et al., 2015).

Researchers have also demonstrated that when primed, or properly instructed, people with ASD are just as able to perceive global information from the environment as controls, but they coordinate their attention between global and local information differently (Iarocci, Burack, Shore, Mottron, & Enns, 2006; Wang et al., 2007). This notion is reflected in the most current account of the WCC theory that has moved emphasis to superiority in local processing rather than a deficit in global processing in ASD (Happe and Frith 2006). Similarly, the first tenet of the EPF model states that “the default setting of perception in individuals with autism is more locally oriented than that of typical individuals” (Mottron et al. 2006). This difference could give people with ASD an advantage in certain tasks, and lead to impairments in others (Iarocci et al., 2006; Marco et al. 2011). Marco et al. (2011) suggest that differences in sensory processing could contribute to visual difficulties associated with ASD, such as face and emotion perception, while Happe and Frith (2006) call for a better understanding of the potential relationships between a detail-focused processing bias, and real-life abilities and difficulties.

EPF theory suggests that perceptual atypicalities in autism are due to superior lower level visual processing, however a neural source for this enhanced functioning has yet to be determined.

1.3 Early Vision in Autism

1.3.1 Visual Acuity

Super-normal acuity was suggested by Ashwin et al. (2009) as the source of enhanced perceptual functioning. However, these results were found to be spurious due to methodological issues (Crewther & Sutherland, 2009). No differences in visual acuity were found between people with ASD and neurotypical controls when these methodological issues were corrected.
(Tavassoli, Latham, Bach, Dakin, & Baron-Cohen, 2011), consistent with other reports of visual acuity in autism (Falkmer et al., 2011; Kéïta, Mottron, & Bertone, 2010).

1.3.2 Orientation Processing

Low-level basic visual processing of orientation, likely a function of the primary visual cortex, which contains receptive fields tuned for orientation and spatial frequency (Campbell & Robson, 1968; Hubel & Wiesel, 1959; Movshon, Thompson, & Tolhurst, 1978; Nauhaus, Nielsen, Disney, & Callaway, 2012) is another area of investigation for enhanced low-level processing.

Our lab has systematically examined visual orientation processing using psychophysical methods in adults with and without ASD and found no qualitative or quantitative differences between the two groups (Shafai et al., 2015). Shafai et al. (2015) implemented three experiments to assess three distinct aspects of orientation perception. In their first experiment Shafai et al. (2015), assessed precision of orientation perception in adults with and without ASD with an orientation discrimination task. Orientation discrimination thresholds were measured as a function of base orientation spanning a 180-degree range starting at the horizontal position. No differences were found between groups at any of the tested base orientations (Shafai et al., 2015). These results were in line with the findings of Brock, Xu and Brooks (2011), who reported that orientation discrimination ability was similar between those with high and low Autism Spectrum Quotient (AQ) (a self reported measure of autistic-like characteristics in the general population) scores in the general population. Second, Shafai et al. (2015) assessed veridicality of orientation perception with a method of adjustment task. The central tendency of repeated settings of a 3-cpd Gabor patch to target orientations provided an estimate of accuracy of orientation processing. Again, no differences between groups were observed. Finally, Shafai et al (2015) assessed
sensitivity of orientation perception via a 2-interval forced choice contrast detection task. Contrast detection thresholds were measured as a function of stimulus orientation, and again, no quantitative or qualitative differences were observed between ASD and control groups. Across all three conditions both groups displayed the oblique effect, where sensitivity, accuracy, and precision were greater around cardinal orientations (vertical and horizontal) (Shafai et al., 2015). These findings differed from those of Bertone et al. (2005), who assessed orientation perception in young adults with and without ASD via an orientation identification task. The group with ASD outperformed the control group at labelling vertical or horizontal sine wave gratings in noise (Bertone et al., 2005). These findings however, were not replicated years later with a different ASD participant group (Meilleur, Berthiaume, Bertone, & Mottron, 2014). Shafai et al. (2015) suggested that the difference in results could be due to important differences in the characteristics of the clinical group who participated in the study by Bertone et al. (2005).

Specifically 83% of the ASD participant group in Bertone et al.’s study had a relative block design test peak (BDT-peak) as indicated by Caron et al. (2006). The block design test is a subtest of the WASI II that contributes to an individual’s non-verbal or performance IQ score, and involves manually rearranging blocks to reproduce a spatial pattern. An individual has a BDT-peak when their performance in the block design subtest is superior to the other subtests. The incidence of BDT-peak in the ASD population with average intelligence has been shown to be 22% (Siegel, Minshew, & Goldstein, 1996). These observations suggest that superior low-level processing could be related to a specific subgroup of the ASD population who demonstrate peak performance in the block design test compared to the other subtests of the WASI-II. Post hoc analysis by Shafai et al. (2015) did hint at the possibility that the presence of a BDT-peak may be a critical factor in whether enhanced perceptual processing is observed in individuals
with ASD, based on results from their first two experiments. However, as they were not specifically addressing BDT-peak within the population of ASD, and thus only a small subsample of the participant group happened to have a BDT-peak, they could not provide conclusive evidence of this (Shafai et al., 2015). In sum, research assessing orientation processing in ASD suggests that enhanced perceptual functioning may be a characteristic of a specific subset of individuals with ASD, and reflects the importance of testing a well characterized clinical population.

1.4 Spatial Frequency processing

Our present study examined spatial frequency (SF) processing as a potential source for the detail oriented perception style and superior visuo-spatial abilities in adults with ASD. The luminance variation in any image can be decomposed into sinusoidal components by Fourier analysis. The spatial frequency in an image represents the rate of change of the degree of variation in luminance. High spatial frequencies represent abrupt spatial changes in luminance corresponding to fine detail, while low spatial frequencies represent smoother and more gradual changes in luminance corresponding to coarser information (Bar, 2004). Neurons within the primary visual cortex are organized into receptive fields tuned for spatial frequency and orientation (Hubel & Wiesel, 1959; Nauhaus et al., 2012; Swindale, 2000). Campbell and Robson (1968) describe a visual system of channels, each selectively sensitive to a narrow band of spatial frequencies. A system better tuned to perceive high spatial frequency information may account for some of the visual atypicalities observed in ASD, such as increased accuracy in local conditions of the Navon letters task (Stevenson et al., 2016), or impairments in everyday visual exploration (Iarocci et al., 2006). Over three experiments, we systematically examined three distinct aspects of spatial frequency perception in ASD: sensitivity, precision and accuracy.
All three tasks used Gabor patches as experimental stimuli, commonly used in studies of low-level spatial vision for their localization in both spatial frequency and spatial domains and their resemblance to visual receptive fields in V1 (Jones & Palmer, 1987; Torreão, Victer, & Amaral, 2014). A 2-dimensional Gabor filter can be described as the product of a sinusoidal plane wave and a bivariate elliptic gaussian (Jones & Palmer, 1987). The number of repeated light and dark gratings (cycles) that occur within unit space, e.g., one degree of visual angle, represents the spatial frequency. Woods and Wood (1995) define low spatial frequencies as less than 0.5 cycles per degree (cpd), mid range frequencies between 2 and 6 cpd and high spatial frequencies above 10 cpd. This definition leaves some grey area, with different labs labelling low, medium and high SFs slightly different than others, often based on the range of spatial frequencies being tested. For example, Keita et al. (2009) labelled 8 cpd as high, Deruelle et al. (2004, 2008) labelled high spatial frequency as above 6 cpd, while others labelled high spatial frequencies as 18 cpd (Nomura et al. 2003; Sia et al. 2013). We examined eight spatial frequencies: 1, 2, 4, 8, 12, 16, 20, and 24 cpd. Over our set of spatial frequencies, we consider 1-2 cpd to be low, 4-8 cpd to be medium, and 12-24 to be high spatial frequencies.

1.4.1 Contrast Detection

Human observers’ ability to see different features of a visual scene is dependent on the relative size and contrast of the features present (Campbell and Robson, 1968). Contrast sensitivity can be measured with gratings whose luminance is modulated sinusoidally about a fixed mean. The contrast necessary for detection varies with spatial frequency. Typically, peak sensitivities can be found at mid-range spatial frequencies between two and four cycles per degree, and sensitivity decreases for both lower and higher spatial frequencies (Campbell & Robson, 1968; Woods & Wood, 1995).
In a review of visual perception in ASD, Simmons et al (2009) concluded that no study with well-matched controls had demonstrated a difference in contrast sensitivity at any spatial frequency when the stimuli were defined by luminance contrast. These findings are based on results using static contrast sensitivity measures (Behrmann et al., 2006; Jonge et al., 2007). Jonge et al. (2007), used Vistech contrast sensitivity charts to test their child, adolescent and adult participants at SFs from 1.5 to 18 cpd and found small differences at intermediate and high spatial frequencies, showing a trend for increased sensitivity for their ASD group. However, these differences did not reach statistical significance. Behrmann et al., (2006) measured contrast thresholds with horizontal Gabor stimuli of spatial frequencies ranging from 0.3 – 30 cycles per inch. Based on the viewing distance reported, these corresponded to approximately 1.2-12.5 cpd. Using a two-interval (200 ms stimulus presentation) forced choice (2-IFC) paradigm, they did not find any differences between groups. However, results from this experiment have been criticized for using too few trials (20) per SF and for using fixed and large steps of contrast in their staircase procedure (0.2 log units per step; 1.58-fold change each step) (Koh et al., 2010).

Koh et al (2010) assessed contrast sensitivity in adolescents with and without ASD across 7 spatial frequencies from 0.5 to 20 cpd, with a standard 2-IFC detection paradigm. They implemented an adaptive staircase procedure with variable step sizes that allowed for a more precise assessment of contrast sensitivity than a fixed step size (Koh et al., 2010). No differences between groups were observed, leading the authors to conclude that individuals with ASD do not show atypical spatial frequency processing, suggesting a detail oriented perceptual bias is unlikely to be driven by an imbalance of high versus low spatial frequency sensitivity (Koh et al., 2010).
More recently, Keita et al. (2014), measured contrast thresholds with luminance defined vertical sine wave gratings at 0.5, 1, 2, 4, and 8 cpd. Their 2-IFC paradigm with 500 ms stimulus intervals, found increased sensitivity for the 8 cpd condition in young adults with ASD compared to neurotypical controls. Unfortunately, they did not measure thresholds beyond 8 cpd to investigate if this enhanced sensitivity extended into higher spatial frequencies.

In a follow up study, Guy et al. (2016) measured contrast sensitivities in children and youth (ages 6-16) with and without ASD (ASD N:34, Control N:55). Their results supported previous findings from Koh et al. (2010) who found no differences in contrast sensitivities between neurotypical and adolescents with autism. However, unlike Koh et al. who had a relatively small and unbalanced sample (ASD N:10; Control N:25), Guy et al. (2016) could explore relationships between age and sensitivity, to create developmental trajectories. Guy et al. found that sensitivity for 8 cpd was significantly lower in late childhood (10 years) in ASD compared to the typically developing (TD) group, however the difference diminished in adolescence. The ASD group demonstrated a positive linear relationship between age and sensitivity at 8 cpd, whereas sensitivity for the typically developing group remained relatively constant across age. Guy et al. (2016) suggest that this positive relationship between age and sensitivity at 8 cpd in ASD indicates that development may continue beyond the ages tested. Therefore, these results were in line with the lack of difference between groups in Koh et al.’s (2010) adolescents and the difference observed in adulthood at 8 cpd by Keita et al. (2014). These findings may also explain why Jonge et al. (2007) who used a sample of people aged 7-33 years did not find any difference in their study on spatial contrast sensitivity using Vistech contrast sensitivity charts. Should there be a developmental relationship between age and
sensitivity in people with ASD compared to neurotypical controls, these differences would be lost in a sample with such a wide range of ages.

Our study aims to extend the investigation of spatial frequency processing in adults with autism with a larger range of spatial frequencies, utilizing a well-characterized ASD cohort and a well-matched control group.

1.4.2 Spatial Frequency Discrimination

Spatial frequency discrimination tasks examine the minimum difference in spatial frequency a participant requires to tell two apart. This difference is referred to as the just-noticeable difference (JND) or just-noticeable frequency ratio (JNFR). Discrimination tasks provide an indication of precision of spatial frequency processing. Precision refers to the closeness of two or more measurements to each other. The ability to detect small differences between two similar stimuli therefore reflects an individual’s precision of perception. Spatial frequency discrimination has never been assessed in the ASD population. Initial assessment of spatial frequency in the general population indicated that across spatial frequencies ranging from 1-16 cpd, discrimination thresholds vary by no more than a factor of two (6-12%) (Campbell, Nachmias, & Jukes, 1970). Another study measured discrimination thresholds at 0.5 and 4 cpd, and found JNDs of 2.4-4.2% respectively (Webster, De Valois, & Switkes, 1990). The reason for lower JNDs measured by Webster et al., compared to Campbell et al. could be a result of a simultaneous stimulus presentation by Webster et al. compared to Campbell et al.’s sequential stimulus presentation paradigm. A study by Yehuda and Ahissar (2004) demonstrated that under sequential and simultaneous stimulus presentation, JNDs were 6.9% and 11.9% respectively, with 250 ms view times, around a 0.5 cpd reference grating.
1.4.3 Spatial Frequency Adjustment

The central tendency of repeated settings to specific target spatial frequency gives an indication of accuracy of spatial frequency processing. Accuracy refers to the closeness of a measured value to standard or known value. The closeness of a participant’s mean setting to a specified target, therefore, gives an estimate of their accuracy of spatial frequency perception. Shafai et al. (2015) have used an adjustment paradigm to assess orientation processing in ASD, however accuracy of spatial frequency processing has not been assessed in the ASD population. With this paradigm, we will be able to examine any biases towards low, medium or high spatial frequencies that may be present in the ASD or neurotypical population.
CHAPTER 2 – METHODS

2.1 Participants

Twenty participants with ASD (mean age = 23.8 years; SD = 6.36; 6 females) and 20 controls (mean age = 27.9; SD = 6.96; 7 females) participated in the study. All participants had their verbal and non-verbal IQs assessed using the Wechsler Abbreviated Scale of Intelligence II (WASI-II; Wechsler, 2011). WASI-II full-scale scores in ASD ranged from 82 to 137 (M = 109.45; SD = 14.6) and from 98-129 in controls (M = 109.85; SD = 7.18). Participants with a full-scale IQ score of less than 75 were excluded from the study. Participants were matched on all aspects of IQ, and did not differ significantly in age (p = 0.06) or gender (p = 0.65 with chi-square test) (Table 1). The controls did tend to be slightly older than our participants with ASD, which could be argued to give our group with ASD an advantage, however this advantage did not result in superior performance in any of our experiments. The protocol was approved by the ethics review boards of the University of British Columbia, Simon Fraser University, and Vancouver General Hospital. Informed consent was obtained in accordance with the declaration of Helsinki. All participants were naïve with respect to the purpose of the experiment.

Table 1. Descriptive statistics for Control and ASD groups

Descriptive statistics for Control and ASD groups including age, Wechsler’s Abbreviated Scale of Intelligence II IQ (full scale, non-verbal, and verbal) scores, and Autism Quotient scores.

<table>
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<tr>
<th></th>
<th>Control</th>
<th>ASD</th>
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<tbody>
<tr>
<td></td>
<td>14 males, 6 females</td>
<td>13 males, 7 females</td>
</tr>
<tr>
<td>Age</td>
<td>Mean: 27.9, SD: 6.96, Range: 18-44</td>
<td>Mean: 23.8, SD: 6.36, Range: 18-46</td>
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<tr>
<td></td>
<td>Mean: 112.2, SD: 12.96, Range: 92-140</td>
<td>Mean: 112.05, SD: 22.24, Range: 79-154</td>
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<td></td>
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<td>p = 0.06</td>
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<td>p = 0.97</td>
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<td>p = 0.98</td>
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<td>p = 0.79</td>
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All participants completed an eye exam by a licensed optometrist including tests for visual acuity at 3 meters, cover test to determine any pre-existing strabismus, and stereopsis to assess the degree of depth perception. Visual acuity was assessed using a LogMAR chart and was recorded in Snellen acuity. A cover test was performed to determine if the subject had any ocular deviations or strabismus. Stereo acuity was measured using Wirt circles and was recorded in seconds of arc. Subjects with a pre-existing prescription had their lenses neutralized with a lensometer and monocular habitual acuities were recorded and measured to rule out amblyopia. Those who did not achieve 20/20 vision at 3 meters unaided or with their own prescription glasses were refracted to the best corrected visual acuity by the optometrist. These participants were asked to wear the trial lenses that provide their best corrected acuity for the duration of the experiment. Three participants with ASD and two neurotypical controls were aided with trial lenses.

All participants completed the Autism Spectrum Quotient (AQ) test (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), a fifty-item, self-administered questionnaire, used to assess traits associated with the autism spectrum. Participants can receive a score between 0-50, with higher scores representing more severe autistic traits. A score of 32 represents the cut-off for distinguishing individuals who have clinically significant levels of autistic traits (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). We used a score of 20 as an exclusion criterion for controls as it allows for individuals who tend to have higher scores, such as those in mathematics and sciences, while still maintaining the greatest separation between adults with and without ASD (Baron-Cohen et al., 2001).
All participants with ASD (N=20) were previously diagnosed by a clinician according to the criteria set by the revision of the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (American Psychiatric Association, 2000). Six participants also had their diagnoses confirmed with the Autism Diagnostic Observation Schedule (Lord et al., 2000), completed by trained researchers from the Autism and Developmental Disorders Lab. Comorbid disorders diagnosed included anxiety (3), depression (2), attention hyperactive deficit disorder (ADHD) (2), obsessive compulsive disorder (OCD) (1). Medications reported being taken consisted of prescription antidepressants (1), antipsychotics (1) and stimulants (1). In our control sample, diagnoses included OCD (3), anxiety (3), ADHD (1) and depression (1). Reported prescription medication being taken included antidepressants (1) and depressants (1).

2.2 Experimental setup

Experiments 1, 2 and 3 were programmed in Matlab, and were run on a Dell Precision 11700 computer equipped with a ViSaGe system (Cambridge Research Systems) and a HP p1230 Cathode Ray Tube (CRT) monitor. The monitor was set to a resolution of 1600 x 1200 pixels with a frame rate of 60 Hz. Gamma correction was done with a ColorCAL II colorimeter and ViSaGe software. Participants were seated at 298 cm from the screen.
Figure 1. Schematic illustrations of a typical trial in Experiments 1, 2 and 3.

(A) Experiment 1: Sensitivity (task = detection)

(B) Experiment 2: Precision (task = discrimination)

(C) Experiment 3: Accuracy (task = adjustment)

(A) Experiment 1: Protocol for measuring contrast sensitivity as a function of spatial frequency using a detection task. Participants were shown a Gabor stimulus (in one of 8 spatial frequencies) in one of two intervals and a blank screen in the other and asked to indicate which interval contained the stimulus. The contrast of the Gabor stimulus was controlled via a psychophysical staircase, allowing estimation of
detection contrast thresholds at each spatial frequency. (B) Experiment 2: Protocol for measuring
precision of spatial frequency perception using a spatial frequency discrimination task. Participants were
shown a reference spatial frequency followed by a test spatial frequency, then asked if the test spatial
frequency was lower or higher than the reference spatial frequency. Discrimination thresholds were
measured for 3 reference spatial frequencies (low: 1 cpd, medium: 4 cpd, and high: 16 cpd). (C)
Experiment 3: Protocol for measuring accuracy of perceived spatial frequency using an adjustment task.
Participants were required to manually (via keypress) adjust a Gabor of random spatial frequency to a
specified target spatial frequency (low: 1 cpd, medium: 4 cpd and high: 16 cpd).

2.2 Experiment 1: Contrast detection

Contrast thresholds for detecting Gabor patches at eight spatial frequencies, 1, 2, 4, 8, 12,
16, 20, and 24 cpd were measured for each participant. Detection thresholds allow us to infer
sensitivity (defined as reciprocal of contrast threshold) for a wide range of spatial frequencies.
Typically, human observers are most sensitive to medium spatial frequencies (2-4 cpd) with
sensitivities dropping at higher and lower frequencies (Campbell & Robson 1968; Woods &
Wood 1995). A total of four thresholds were collected per participant at each spatial frequency.

2.2.1 Stimuli and procedure

Stimuli were 1, 2, 4, 8, 12, 16, 20, 24 cpd sine-phase Gabors at vertical orientation. The
Gaussian aperture varied with spatial frequency such that a fixed number of cycles were
presented at each spatial frequency condition. Stimuli were presented in one of two intervals in a
2-IFC paradigm. First, a fixation cross was presented for 200 ms to orient the subjects’ gaze,
then a 200-ms blank screen, followed by interval 1 for 200 ms, another 200-ms blank screen, a
second fixation cross for 200 ms, a 200-ms blank screen, then interval 2 for 200 ms, and finally a
blank screen that remained until the participant entered a response. Participants indicated in
which interval they saw the stimuli by pressing the 1 or 2 key, for interval 1 or 2 respectively.
Auditory stimuli were used to mark each interval, and to provide feedback for correct and incorrect responses. The next trial started immediately after each participant response.

Contrast sensitivity in Experiments 1 was assessed with two different test durations: short (200 ms) and long (1000 ms). Trials were blocked by spatial frequency and split into two sets. The “low-SF” set included blocks of 1, 2, 4, and 8 cpd conditions and the “high SF” set included blocks of 12, 16, 20 and 24 cpd conditions. The 200-ms test duration was tested at all spatial frequencies. On day one of testing, participants completed the low SF blocks first, and high SF second. On day two, participants repeated all blocks, this time completing high SFs first, and then low SFs, for a total of 4 thresholds at each SF. SF blocks within each set were presented in a random order. Participants completed two blocks at each spatial frequency tested in long and short test durations. Two randomly-interleaved staircases were used to estimate contrast thresholds at each block, producing 2 threshold estimates per block. Staircases were implemented using the QUEST procedure (Watson & Pelli, 1983) with the Psychophysics toolbox for MATLAB (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). If threshold estimates were more than double each other, they were deemed inconsistent and blocks were repeated until reliable thresholds were obtained. In the 200-ms viewing condition, two thresholds estimates were collected on day 1, and two threshold estimates were collected on day 2. If thresholds were inconsistent across days, a third block was completed on day 2. Three of forty participants demonstrated a learning curve, with thresholds from the second and third blocks collected on day 2 (for 1 of 7 spatial frequencies each), substantially lower than day one, and all within double each other. In this case, day one thresholds were excluded and data analysis was based on the consistent (maximum and minimum of the four thresholds from two blocks were within double of each other) data. In cases where there was overlap between thresholds across days (out of the
four threshold values, some within double, some more than double) a third block was completed, minimum and maximum threshold values were removed and the middle four threshold values were retained. The long (1000-ms) test duration condition was only tested at “high-SF” blocks as the stimuli in these blocks were harder to detect than the “low” spatial frequencies. We did not want to miss any superior processing in ASD that may have been masked due to short stimulus durations. Van der Hallen et al. (2012) show in their meta analysis that in some tasks people with ASD can perform as accurately as controls when given adequate processing time.

2.3 Experiment 2: Spatial frequency discrimination

Spatial frequency discrimination thresholds were measured across three base (reference) spatial frequencies: 1 cpd, 4 cpd, and 16 cpd, representing low, medium, and high spatial frequencies, respectively. Discrimination thresholds provide a measure of precision around each reference spatial frequency. While most previous studies of SF processing in ASD have focused on contrast sensitivity, no prior study has examined spatial frequency discrimination in this population.

2.3.1 Stimuli and Procedure

Gabor patches at a fixed supra-threshold contrast of 0.5 were presented on a uniform gray background at a viewing distance of 298 cm with a fixed Gaussian aperture, such that the full width of the Gabor at half height was 2.2 degrees, and random phase. With a random phase, the vertical bars of the Gabor would appear in random locations with respect to the horizontal axis of the screen. This way, participants were not able to use the screen’s border as a reference while completing the task. Trials were blocked by base spatial frequency resulting in three experimental blocks completed in random order. Each block began with eight warm-up trials. A psychophysical staircase controlled spatial frequency increments or decrements presented in each
trial using two randomly interleaved staircases of 40 trials each. Psychophysical staircases were implemented using the QUEST procedure (Watson & Pelli, 1983) in Psychophysics toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Participants repeated each experimental block three times, producing 6 threshold estimates per base spatial frequency.

Trials began with a 200-ms fixation cross, followed by the reference stimulus for 200 ms, another 200-ms fixation cross, then the test stimulus for 200 ms, and finally a blank screen until the participant made a response. Participants pressed the 1 key to indicate the test stimulus was a lower spatial frequency than the reference, or the 2 key to indicate the test stimulus was a higher spatial frequency than the reference (see Figure 1b for an illustration of the procedure).

Participants were instructed that as spatial frequency decreases, the bars of the Gabor patch would become fatter, and that as spatial frequency increases, the bars would become thinner. During the experiment, participants were instructed to press 1 if the test Gabor was fatter, or 2 if the test Gabor was thinner, compared to the reference.

Blocks where thresholds estimates were deemed inconsistent (one estimate more than double the other) were repeated until reliable estimates were collected.

Auditory feedback was used to mark test and reference intervals, as well as provide response feedback (1 click for correct, 2 clicks for incorrect).

2.3.2 Data analysis

Each block utilised two randomly-interleaved staircases to estimate spatial frequency discrimination thresholds at 82% criterion accuracy. Each block was repeated three times for a total of six independent threshold estimates, from which maximum and minimum values were
removed. The average of the remaining four estimates represented the overall threshold estimate for each base SF.

2.4 Experiment 3: Spatial frequency adjustment

Experiment 3 assessed participants’ veridicality of perception of low, medium and high spatial frequencies. While Experiment 2 measured precision around three base spatial frequencies, this on its own does not provide a measure of any implicit bias of each spatial frequency. In this experiment, we familiarized subjects with three target spatial frequencies (low, medium, and high - same as the base spatial frequencies used in Experiment 2). Then, participants were asked to manually adjust a Gabor of random spatial frequency to one of the targets (not visible to the participant during the adjustment). The central tendency of repeated settings across trials was used as a measure of accuracy of spatial frequency perception. We examined possible biases away from veridical perception, which would be indicated with central tendency estimates that deviated from the true spatial frequency of the target. Variability of settings across trials allowed us to infer a second estimate of precision (in addition to the discrimination thresholds of Experiment 2) of perception around low, medium, and high spatial frequencies.

2.4.1 Stimuli and Procedure

Vertical sine-phase Gabors at fixed supra-threshold Michelson contrast of 0.5, on a uniform gray background at a viewing distance of 298 cm with a fixed Gaussian aperture were presented to participants. Participants were asked to manually adjust the spatial frequency of the Gabor patch (of random initial spatial frequency) to a specified target spatial frequency. Target spatial frequencies were identical to the base spatial frequencies used in Experiment 2 (low: 1 cpd, medium: 4 cpd, high: 16 cpd).
Participants were familiarized with the targets in an identification quiz, in which low, medium, and high targets were presented in random order over 30 trials. Participants indicated which target was presented by pressing the L key for low, M key for medium, and H key for high. After participants met an identification accuracy criterion of 93% they could move on to the adjustment task. If participants did not meet the criterion for identification they repeated the quiz until reaching criterion. The identification quiz was competed before each experimental block to refresh the participants’ memory of each target.

Each trial began with a brief fixation cross, followed by a Gabor of random spatial frequency and phase. Trials were blocked by target spatial frequency and each block lasted 40 trials. Blocks were presented in random order and subjects were verbally informed of the target spatial frequency at the start of each block. One block was completed at each target SF. Within each trial, pressing the 1-key reduced the spatial frequency of the Gabor, and pressing the 2-key increased the spatial frequency. Gabors were adjusted in increments of 5 percent of the base/target spatial frequency, and each new Gabor was presented in random phase so that subjects could not use the location of bars on the screen as a cue for their final setting. Pressing the enter key indicated the participant was done adjusting. The following trial began immediately and no feedback was given between trials.

2.4.2 Data analysis

Bias was defined as the difference between the arithmetic average of the 40 settings at each target spatial frequency and the true target spatial frequency. Absolute value of bias was used to assess the magnitude of deviation from veridical perception.
2.5 Experiment 4: Visual search

In this experiment we employed a visual search task that has been used in previous studies to demonstrate enhanced performance in participants with ASD compared to controls (Kemner et al., 2007; O’Riordan et al., 2001).

2.5.1 Experimental setup

Experiment 4 was programmed in Open Sesame 3, and run on a Dell Precision 11700 computer equipped with a Dell P2314H (DP) screen. Participants were seated 80 cm from the screen.

2.5.2 Procedure and Stimuli

A single light grey vertical target (0 degrees) was presented among tilted distractor lines (17 degrees clockwise), on a dark grey background screen in set sizes of 4, 16, and 25 lines. At the viewing distance of 80 cm each line subtended 1 degree of visual angle. The target was present in half the trials. Each trial began with a screen instructing the participant to press the spacebar to begin, followed by a 500-ms fixation dot and then the test screen. The test screen was one of six unique combinations of target probe (absent or present) and set size (4, 16, 25 lines). Each combination of target probe and set size was presented 30 times in random order for a total of 180 trials. Subjects responded by pressing the left key for target present and the right key for target absent. Response feedback was given in the form of a green or red fixation dot for correct or incorrect, respectively. Each block began with a six-trial warm-up to ensure participants understood the task.
2.5.3 Data analysis

Reaction time and accuracy scores were collected for each trial. Reaction times of correct trials were averaged at each set size and target probe combination for comparison. A repeated measures ANOVA with Set-size (4, 16, 25) and Target presence (absent, present) as the within-subject factors and group (ASD, Control) as the between-subjects factor was carried out to examine main effects and interactions of experimental conditions.

2.6 Experimental Hypotheses

**Hypothesis one**: The group with ASD will demonstrate greater sensitivity to spatial frequencies from 8-24 cpd than the control group.

Group mean contrast thresholds will be compared between groups for the 200ms and 1000ms test durations.

**Hypothesis two**: Discrimination thresholds will be the same between groups at the low and medium spatial frequency conditions, and the group with ASD will have an advantage in the high spatial frequency condition.
ASD group mean discrimination thresholds will be compared to control group mean discrimination thresholds across the three spatial frequencies tested.

**Hypothesis three:** *The group with ASD will demonstrate a superior perception of higher spatial frequencies, evidenced by more accurate settings of the high spatial frequency target.*

The central tendency of repeated settings (i.e., arithmetic average in the present context) and its distance from the physical spatial frequency of the target stimulus gives a measure of accuracy, or veridicality, of spatial frequency perception. Mean settings will be compared between groups to examine any differences in veridical perception of low, medium and high spatial frequencies.

**Hypothesis four:** *Our group with ASD will demonstrate superior search ability through faster average reaction times than the control group.*
CHAPTER 3 – RESULTS

3.1 Experiment 1 – Contrast Sensitivity

Figure 3 shows log transformed contrast energy values for detecting a Gabor stimulus as a function of spatial frequency in the 200 ms test duration for the group with ASD (red curve) and the control group (blue curve). Threshold signal energy at each spatial frequency was computed as squared contrast integrated over the stimulus area. Five participants’ data from each group was omitted from statistical analysis, as these participants were unable to reach a threshold at our highest spatial frequency (24 cpd). Contrast energy thresholds were submitted to a repeated-measures ANOVA with spatial frequency as a within-subject factor and group (ASD, Control) as a between-subjects factor. This revealed a significant main effect of SF (F(7, 196)=19.06, p << 0.001), but no main effect of group (F(1, 28) = 2.89, p =0.10) and no interaction between the two (F(7, 196) = 1.51, p = 0.63). Both groups demonstrated the characteristic trend of peak sensitivities at around 4 cpd, with sensitivity dropping at high and low spatial frequencies.
Figure 3. Results of Experiment 1, 200 ms test screen duration. Detection contrast energy thresholds plotted as a function of spatial frequency. Data from the group with ASD (red curve) do not differ significantly from that of the control group (blue curve).

Figure 4 shows log transformed contrast energy values for detecting a Gabor stimulus as a function of spatial frequency in the high SF range (12-24 cpd) and the 1000ms test duration for the group with ASD (red curve) and the control group (blue curve). Again, five participants from each group were unable to reach threshold at 24 cpd. Their data was excluded from analysis. Contrast energy thresholds were submitted to a repeated-measures ANOVA with spatial frequency as a within-subject factor and group (ASD, Control) as a between-subjects factor. This revealed a significant main effect of SF ($F(3, 84) = 8.23, p << 0.001$), no main effect of group, ($F(1, 28) = 1.22, p = 0.28$) and no interaction between the two ($F(3, 84) = 1.24, p = 0.30$). Given the extra exposure time, the group with ASD still did not outperform the control group, performing numerically, but not significantly, worse at each of the higher spatial frequencies.
Figure 4. Results of Experiment 1, 1000ms test duration. Detection contrast energy thresholds are plotted as a function of spatial frequency. Data from the group with ASD (red curve) do not differ significantly from that of the control group (blue curve).

3.2 Experiment 2 – Spatial Frequency Discrimination

Figure 5A shows JND as a function of spatial frequency for individuals from the group with ASD (red squares) and individuals from the control group (blue squares). Two participants’ data from the group with ASD were omitted as they did not complete the task. Figure 5B shows mean group JND values as a function of spatial frequency. There was a highly significant main effect of SF (F(2,68) = 23.74, p<<0.001), but no main effect of group (F(1,34)=0.24, p=0.63) and no interaction between the two (F(2,68) = 1.14, p = 0.33). Thresholds were significantly higher at the high (16 cpd) compared to both medium (4cpd) and low (1cpd) SFs (both p’s<0.05, Tukey-Kramer Multiple Comparison test). Thresholds at the medium and low SFs did not differ from each other (p’s>0.05). Importantly, no difference between the ASD (M=9.3%) and Control
(M=8.7%) groups were observed (p=0.63). Thresholds did not differ between the two groups any of the three SFs tested.

**Figure 5. Results of Experiment 2, spatial frequency discrimination.** (A) Just noticeable difference percentages are plotted as a function of spatial frequency for individuals from the group with ASD (red squares) and individuals from the control group (blue squares). (B) Mean just noticeable difference percentages plotted as a function of spatial frequency for the group with ASD (red line) and controls (blue line). Data from the group with ASD do not differ significantly from that of the control group.

**3.3 Experiment 3 – Spatial frequency adjustment**

Figure 6A shows percent bias as a function of spatial frequency for individuals with ASD (red circles) and individuals from the control group (blue squares). Figure 6B shows the absolute magnitude of error, or mean absolute bias percentage, as a function of spatial frequency for the group with ASD (red curve) and the control group (blue curve). Magnitude of the errors (absolute percent bias) differed significantly (F(1,35) = 6.87, p = 0.01) between the two groups, with larger errors in the ASD group (20% bias) compared to the Controls (13%). Error magnitude did not differ across spatial frequencies (F(2, 70) = 1.69, p = 0.19) and there was no interaction between group and SF (F(2,70) = 0.11, p = 0.90). Figure 6C shows mean bias percent, or signed average group bias, as a function of spatial frequency for the group with ASD.
(red curve) and the control group (blue curve). Both groups tended to underestimate spatial frequencies with no statistical differences in the average signed group bias ($F(1,35) = 0.53, p = 0.47$), ASD bias $= -7.4\%$; Control bias $-10.5\%$). No main effect of SF ($F(2,70) = 1.14, p = 0.24$) or an interaction between group and SF ($F(2,70) = 0.06, p = 0.95$) were found.

Figure 6. Results from Experiment 3, spatial frequency adjustment. (A) Individual percent bias plotted as a function of spatial frequency. Individuals with ASD are represented by red circles and control individuals are represented by blue squares. (B) Absolute percent bias or Absolute magnitude of error...
plotted as a function spatial frequency for the group with ASD (red curve) and control group (blue curve). The group with ASD had significantly larger errors than the control group. (C) Mean percent bias plotted as a function of spatial frequency. Both groups tended to underestimate the target spatial frequency, with no difference between the average signed group bias.

3.4 Experiment 4 – Visual Search

Figure 7 shows group mean reaction times (RTs) as a function of set size. Only correct responses were counted towards the reaction time averages for each participant and both groups had above 95% accuracy across all search conditions. RTs did not differ significantly between the ASD and Control groups as indicated by a lack of main effect of Group (F(1,38) = 1.82, p=0.19). There was a trend for longer reaction times in the ASD group (1150.8 ms) compared to the Control group (984.6 ms). There was a highly significant main effects of Set size (F(2,76) = 40.93, p<<0.001) and Target presence (F(1,38) = 31.23, p<<0.001) and a highly significant interaction between the two (F(2, 76) = 24.93, p<<0.001). To examine the source of this interaction, we analyzed the Target absent and Target present conditions separately. In the Target absent condition this analysis revealed a significant main effect of set size (F(2,76) = 36.17, p << 0.001), no main effect of group (F(1,38) = 0.90, p =0.35) and no interaction between the two (F(2,76) = 0.14, p = 0.87). However, in the Target present condition, in addition to a significant main effect of set size (F(2,76) = 16.62, p << 0.001), there was also a significant main effect of group (F(1,38) = 4.43, p = 0.04) and no interaction between the two (F(2,76) = 0.63, p = 0.54). Posthoc multiple comparisons showed that RTs for Controls (819.10 ms) were significantly faster than those for the group with ASD (983.32 ms) in the target present condition (Tukey Kramer, p < 0.05). This difference was significant at each of the three set sizes (Tukey Kramer, all p’s < 0.05).
Figure 7. Results of Experiment 4, Search. Group mean reaction times are plotted as a function of set size for the group with ASD (red curves) and the control group (blue curves) for target absent (dotted lines) and target present (solid line) conditions.
CHAPTER 4 - DISCUSSION

This study represents the second leg of a systematic line of research aimed at conclusively determining whether the earliest stages of visual cortical processing are enhanced for individuals with ASD. The first leg, completed by Shafai et al. (2015), investigated orientation processing in ASD via three distinct psychophysical experiments designed to assess three distinct aspects of perception: sensitivity, precision, and accuracy. Their three experiments, orientation detection, discrimination and adjustment did not yield any evidence for enhanced orientation processing in ASD, however post hoc analysis hinted at enhanced processing in a specific subset of ASD individuals, specifically those with a BDT-peak (Shafai et al., 2015). Our experiments followed the same research design as Shafai et al., with three experiments to assess three distinct aspects of perception, this time focused on spatial frequency processing. Both orientation and spatial frequency processing are presumed to be functions of the primary visual cortex (Campbell, Cooper, & Enroth-Cugell, 1969; Hubel & Wiesel, 1959; Nauhaus et al., 2012; Swindale, 2000). We also added a fourth experiment to assess the replicability of a search paradigm that has previously demonstrated superior performance in ASD (Hessels, Hooge, Snijders, & Kemner, 2013; Kemner et al., 2007; O’Riordan et al., 2001).

We employed robust psychophysical methodologies to study a well-characterized ASD participant group, matched on gender, IQ, and age to our controls. Each participant was screened by an optometrist prior to participation to ensure they had normal or corrected-to-normal visual acuity at our viewing distance. All participants completed all four experiments, which facilitated qualitative comparisons of results across experiments.

We hypothesized that a system tuned for higher spatial frequencies could contribute to a perceptual style that focuses on, or is biased towards, more detailed information in a scene.
However, none of our three experiments assessing SF processing in ASD indicated this to be the case. First, our group with ASD did not display greater sensitivity for detecting any of the tested spatial frequencies than our control group. Contrast threshold energies from both groups matches previous research assessing contrast sensitivity in the general population (Oruc & Landy, 2009), as well as the majority of prior research that has assessed contrast sensitivity as a function of spatial frequency in the ASD population (Behrmann et al., 2006; Guy et al., 2016; Jonge et al., 2007; Koh et al., 2010; Simmons et al., 2009). However, our results do not agree with recent findings of enhanced sensitivity at 8 cpd by Keita et al. (2014). One possible explanation is that Keita et al. used a single adaptive staircase procedure and used one threshold per participant for luminance defined gratings at each spatial frequency. We used two interleaved staircases to collect two threshold estimates per block, and had participants complete two blocks per spatial frequency. This gave us a total of 4 threshold estimates per spatial frequency per participant. This exhaustive method of measuring contrast thresholds eliminates the opportunity for ‘one off’ data points where participants could produce either an extra low, or extra high threshold estimate through a series of good or bad guesses. Keita et al (2014) could have also found increased sensitivity in ASD because they used a longer interval time (500 ms) compared to ours (200 ms). However, to ensure that our faster interval time (200 ms) was not impeding our ASD participants from producing lower thresholds than our controls, we measured contrast sensitivity of the higher spatial frequencies (12-24 cpd) with a longer (1000 ms) interval time. Even with the longer interval time, we did not observe greater sensitivity in our group with ASD, eliminating the argument that Keita et al. (2014) found greater sensitivity in their group with ASD at high spatial frequency because of a longer (500 ms) interval time.
Second, our discrimination experiment found that precision of SF perception was similar in people with ASD and neurotypical controls. If people with autism had a perceptual style that focused on detailed aspects of a visual scene, it could be assumed that more time would be spent focusing on higher SF information. This could be caused by, or lead to, a system that is more precise at perceiving higher SFs. However, this was not the case. My study is the first to assess spatial frequency discrimination in people with ASD. We measured discrimination thresholds around three reference spatial frequencies, low (1 cpd), medium (4 cpd), and high (16 cpd). Our just noticeable spatial frequency differences, ranging from 7.87% to 13.88% from 1-16 cpd were consistent with previous literature (Ben-Yehudah & Ahissar, 2004; Campbell et al., 1970; Patel, Maurer, & Lewis, 2010) and are similar in people with ASD and neurotypical controls. These results did not support our hypothesis that people with ASD would have an advantage in the high spatial frequency condition.

In perhaps our most intuitive hypothesis, we suggested that if people with ASD are biased towards more detailed, higher spatial frequency aspects of an image, they would demonstrate a superior accuracy for perception of higher spatial frequencies. Our adjustment paradigm, designed to assess accuracy of SF perception, revealed that people with ASD and controls demonstrate similar accuracy in perception of low, medium and high spatial frequencies. These results do not support our hypothesis that people with ASD would demonstrate enhanced accuracy of spatial frequency perception at high spatial frequencies. Like our discrimination experiment, this is the first-time accuracy of SF perception has been examined in ASD.

Participants were briefly introduced to the three targets, low (1 cpd), medium (4 cpd), and high (16 cpd), with a labelling quiz before being asked to adjust Gabors of random phase and SF to a target SF. Both groups tended to underestimate all SF targets, with the magnitude of error
remaining constant across SFs. The signed mean bias did not differ significantly between groups; however, the absolute magnitude of error was greater in the group with ASD than controls. These results demonstrate that accuracy of spatial frequency perception is not superior in ASD.

In our fourth experiment, we assessed the replicability of an experimental paradigm that has previously demonstrated superior performance in ASD, via faster reaction times (Hessels et al., 2013; Kemner et al., 2007; O’Riordan et al., 2001). First O’Riordan et al. (2001) reported that children with ASD could find the presence or absence of a vertical line among tilted distractors faster than controls. Second, Kemner et al. (2007) found similar results in adults with ASD, however, their cohort had faster reaction times with vertical distractors (which they named the “easy” condition) as well as tilted distractors (“hard” condition). Finally Hessels et al. (2013) showed that their ASD cohort was significantly faster in the “easy” condition, but not in the “hard” condition. Results from experiments such as these have contributed to the assertions made by models such as EPF or the WCC theory that people with ASD have certain perceptual superiorities, as well as a perceptual system focused on detailed aspects of a visual scene. We hypothesized that our group with autism would demonstrate faster reaction times in search. Our results, however, indicate that controls are faster than people with ASD in search suggesting that people with ASD are not perceptually superior in this context. These results agree with research from Iarocci and Armstrong (2014), who found no evidence for enhanced search in a large sample of children with ASD (N = 34) with well matched typically-developing controls.

One possible explanation for the superior performance observed in previous literature could be relatively high IQs in the ASD cohorts used by other research groups. Kemner et al.’s (2007) ASD group had an average total IQ of 121.1, average verbal IQ of 124.0 and average performance IQ of 114.0, compared to control scores of 115.3, 119.1, and 106.6 respectively.
investigate this possible explanation, we decided to explore the relationship between IQ and performance in visual search in our sample. We used a hierarchical correlation approach, first analyzing the correlation between average search reaction time and full-scale IQ. We found a significant negative correlation in our group with ASD ($r = -0.64$, $p = 0.002$), but not our control group ($r = -0.16$, $p = 0.50$) (see Figure 8), indicating that search time decreases as IQ increases in ASD, but not in neurotypical controls. Since a significant correlation was found in the ASD group we continued the hierarchical approach to investigate if there were significant correlations between verbal IQ and reaction time, or non-verbal/performance IQ scores and reaction time in ASD. Our analysis revealed significant negative correlation between verbal IQ and reaction time ($r = -0.47$, $p = 0.03$) as well as non-verbal IQ and reaction time ($r = -0.58$, $p = 0.008$) (Figure 9). Following these significant correlations in both IQ sub-scores, we extended our hierarchical analysis into each subtests of the WASI-II, which consisted of the block design, vocabulary, matrix reasoning, and similarities subtests. Significant correlations were found in all subsections, except vocabulary (Figure 10).
**Figure 8.** Correlation analysis of average reaction time in search and full-scale IQ scores. Control (blue) IQ did not correlate significantly with reaction time, however significant negative correlation was found for reaction time and IQ in our group with ASD (red).

**Figure 9.** Correlation analysis of average reaction time (RT) in search and verbal/non-verbal IQ in ASD. Significant negative correlations between RT and verbal IQ (left) as well as non-verbal IQ (right) in ASD.
**Figure 10. Correlation analysis of reaction time and each WASI-II subtest.** Significant correlations were found between RT and block design (upper left), matrix reasoning (upper right), and similarities (lower left). A non-significant relationship was found between RT and vocabulary (lower right).

These correlations suggest that if a cohort of participants with ASD have exceptional IQ scores, this may lead to faster reaction times in visual search. This provides a potential explanation why Kemner et al. (2007), whose results were based on a group of 6 individuals with ASD characterized by high IQ, had significantly faster reaction times than controls. The effect is reduced in Hessels et al.’s (2013) cohort, which included 13 ASD participants, with a mean total IQ score of 116.1. While their group with ASD performed numerically faster than the control
group in both “easy” and “hard” conditions of their search tasks, these results did not reach significance for the “hard” condition, which is the format of the test that we used.

It has also been shown that superior low-level processing interacts with a locally oriented bias in a subgroup of individual with autism to produce outstanding block design performance (Caron et al., 2006). In their study, their ASD group with BDT-peak performed with consistent superiority in multiple visuospatial tasks compared to full scale IQ matched participants and equivalent performance to controls with BDT-peak (Caron et al., 2006). Shafai et al. (2015) demonstrated a similar trend with greater precision and accuracy of orientation processing for their block design peak group with ASD. Of our 40 participants, 3 participants with ASD and 5 controls had a BDT-peak (peak score in block design subtest of WASI-II). Of the 3 participants with ASD, 1 participant was unable to provide consistent scores for our discrimination task and sensitivity task so their data is excluded from the following analysis. In Figure 11 we have plotted contrast sensitivity functions for the BDT-peak individuals from the group with ASD (A) and the control group (B). While we do not have enough participants from each group with BDT-peak to allow for statistical analysis we can see that the BDT-peak ASD participants demonstrated greater sensitivity across all spatial frequencies, except 20 and 24 cycles per degree, and the BDT-peak controls had great sensitivity across all spatial frequencies. When comparing performance between BDT-peak participants from both groups, individuals with ASD performed slightly better from 1 – 8 cpd, and equivalent or slightly worse from 12 – 24 cpd. This trend of superior performance compared to full scale IQ matched participants and equivalent performance to BDT-peak participants agrees with the claims of Caron et al. (2006).
We also compared the performance of BDT-peak individuals in our discrimination task (Figure 12). Here, we see superior performance at medium and high spatial frequencies for our BDT-peak ASD individuals (A) and at high SF for our control BDT-peak participants. Our ASD BDT-peak participants also had superior performance compared to BDT-peak controls at medium and high SF, and inferior performance at low SFs.
Figure 12. BDT-peak data for Experiment 2. BDT-peak data (black asterisk) plotted from our discrimination task for ASD (A), controls (B) and both (C).

Figure 11 shows BDT-peak data plotted as a function of absolute magnitude of error from our adjustment task for BDT-peak participants from the ASD group (A), the control group (B), and from both groups (C). Both ASD and Controls with BDT-peak demonstrate superior accuracy at low and high SFs compared non-BDT-peak participants, and equivalent accuracy when compared with each other.
Figure 13. **BDT-peak data for Experiment 3.** BDT-peak data (black asterisk) from the adjustment task for participants with ASD (A), controls (B) and from both groups (C).

In our search experiment, BDT-peak participants from both the ASD (A) and Control (B) groups demonstrated faster reaction times in the target absent condition, while only the controls demonstrated faster reaction times in the target present condition compared to non-BDT-peak participants. Reaction times in the target absent condition were equivalent between BDT-peak participants from each group.
Figure 14. BDT-peak data for Experiment 4. BDT-peak data (black curves) plotted from our search experiment for BDT-peak participants with ASD (A), BDT-peak controls (B). Reaction times are compared between ASD BDT-peak participants (red curves) and controls with BDT-peak (blue curves) in C.

While we do not have enough participants in the BDT-peak groups to perform statistical analyses, our preliminary analyses hint that BDT-peak participants with ASD demonstrate a trend for superior ability in search, enhanced precision of medium and high SFs, enhanced sensitivity of SFs between 1 and 16 cpd, and equivalent accuracy perception of SF to controls. These abilities are for the most part equivalent to BDT-peak individuals from the control group, which agree with findings from Caron et al. (2006) who concluded that high functioning BDT-
peak participants with ASD perform with consistent superiority to full scale IQ matched controls and equivalently to BDT-peak controls.

4.1 Strengths, limitations and future experiments

The goal of our study was to investigate low-level spatial frequency processing and higher-level performance in search in ASD. Our meticulous methods, and well-characterized ASD cohort allowed us to explore low-level spatial frequency processing successfully. One limitation in our study was that we did not include the “easy” condition of the search task (as defined by tilted target among vertical distractors). Because Hessels et al. (2013) found significant differences between their group with ASD and controls in the “easy”, but not “hard” condition, we could not complete a full comparison to all other studies using the same experimental paradigm. However, we did include a much larger sample of ASD participants (N = 20) than the previous search studies that only used 12, 13 and 6 participants with ASD (Hessels et al., 2013; Kemner et al., 2007; O’Riordan et al., 2001). Another limitation to our study was that our low number of BDT-peak participants did not allow us to make conclusive statements regarding the effect of BDT-peak on visuospatial ability as well as SF processing in ASD. Lastly, the large variability in IQ scores may have influenced or produced more significant correlations in our group with ASD, compared to controls, whose IQ scores had less variance.

Our findings show that adults with ASD do not demonstrate enhanced perceptual functioning with respect to low-level spatial frequency processing, or higher-level ability in visual search. Future research should focus on other aspects of low-level vision such as colour or motion perception as a source for a local processing bias. Future work should aim to replicate previous studies indicating superior visuo-spatial ability in ASD with well-characterized cohorts to ensure that common assumptions fueling theories such as EPF are true. Lastly, more research
should aim to investigate whether the presence of enhanced perceptual functioning is specific to a subgroup of ASD individuals, such as those with a BDT-peak, rather than the entire population of people with ASD of average intelligence.

4.2 Conclusions

The Simmons (2009) review of vision in autism states that replicability and the lack of well-characterized ASD groups are the main issues common in autism research, and calls for collaboration between vision scientists who know how to run rigorous psychophysical experiments and more clinically based researchers who can characterize a clinical population effectively. We have assessed spatial frequency perception in a well-characterized ASD cohort, matched on age, IQ, and gender to neurotypical controls. We utilized three rigorous psychophysical experiments, each designed to test a distinct aspect of perception, with meticulous data inclusion criteria. Our results indicate that spatial frequency processing in ASD is equivalent to controls and is not a source of enhanced perceptual functioning, or a local processing bias. We also tested the replicability of a search experiment that has previously shown superior performance in ASD, and found that search was slower or on par with controls in ASD. These results add to the replicability issues common in ASD research and support conclusions from recent work and meta-analyses that search is unremarkable in ASD (Iarocci & Armstrong, 2014; Muth et al., 2014; Van der Hallen et al., 2015). Correlation analysis and preliminary investigation of participants with BDT-peak indicate that enhanced perceptual functioning may be feature of a subgroup of high functioning individuals with autism rather than a characterization of the ASD population with average intelligence as a whole. It should be noted that due to a small number of BDT-peak participants in our ASD group, these results are not
conclusive. Our research shows that like individuals within the neurotypical population, individuals with ASD have unique and varying strengths and weaknesses. Researchers should ensure that they use well-characterized clinical cohorts, properly matched with neurotypical controls and use caution before making general conclusions about such a heterogenous population.
REFERENCES


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