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No Difference in Cross-Modal Attention or Sensory Discrimination Thresholds in Autism and Matched Controls

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Abstract

Autism has been associated with abnormalities in sensory and attentional processing. Here, we assessed these processes independently in the visual and auditory domains using a visual contrast-discrimination task and an auditory modulation-depth discrimination task. To evaluate changes in sensory function by attention, we measured behavioral performance (discrimination accuracy) when subjects were cued to attend and respond to the same stimulus (frequent valid cue) or cued to attend to one stimulus and respond to the non-cued stimulus (infrequent invalid cue). The stimuli were presented at threshold to ensure equal difficulty across participants and groups. Results from fifteen high-functioning adult individuals with autism and fifteen matched controls revealed no significant differences in visual or auditory discrimination thresholds across groups. Furthermore, attention robustly modulated performance accuracy (performance was better for valid than invalid cues) in both sensory modalities and to an equivalent extent in both groups. In conclusion, when using this well-controlled method, we found no evidence of atypical sensory function or atypical attentional modulation in a group of high functioning individuals with clear autism symptomatology.

Keywords

autism; vision; audition; attention

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1.0 Introduction

Autism is characterized by a range of atypical behaviors including sensory hypo- and/or hyper-sensitivities (Diagnostic and Statistical Manual 5th edition, DSM-5). One possible explanation is that alterations in sensory sensitivities may be due to abnormal attentional processes, which may cause individuals with autism to become overly fixated on a stimulus (Baron-Cohen et al., 2009; Liss et al., 2006) or easily distracted by other stimuli (Murphy et al., 2014; Burack, 1994). Alternatively, altered sensory sensitivities may be the product of intrinsic differences in the function of the sensory systems themselves (Meilleur et al., 2014), for example, altered signal-to-noise ratios in sensory signals (Rubenstein & Merzenich, 2003; Milne, 2011; Dinstein et al., 2012; Haigh et al., 2015), and may be independent of attention. Whilst sensory and attentional processing are closely related, equating individual differences in one domain may illuminate deficits related to the other.

While some studies have reported that individuals with autism exhibit higher sensory thresholds than controls in discrimination of visual (Milne et al., 2002), auditory (Erviti et al., 2015) and somatosensory (Puts et al., 2014) stimuli, others have reported no significant differences across groups (Cascio et al., 2008; O'Riordan & Passetti, 2006), or even lower (i.e. better) sensory thresholds than controls (Fan et al., 2013; Blakemore et al., 2006). This apparent discrepancy emphasizes the need to control for any individual differences in sensory thresholds when measuring attention to sensory stimuli. For example, individuals with migraine generally show impaired performance on motion detection tasks (McKendrick et al., 2001; 2004; Antal et al., 2005; Ditchfield et al., 2006; Shepherd et al., 2006). However, contrast sensitivity was also found to be abnormal in migraine, and mediated performance on motion tasks (Shepherd et al., 2012), highlighting the effect of early sensory processing on more complex sensory tasks.

Attributing atypical sensory sensitivities to differences in attention in autism may constitute an appealing account. However, the evidence for deficits in attention in autism is mixed, partly confounded by the variability across studies in the attentional processes tested. Several studies, mostly conducted with children with autism, have observed impairments in dividing attention between stimuli (Belmonte et al., 2010), and sustaining attention (Schatz et al., 2002), similar to that seen in individuals with Attention Deficit Hyperactivity Disorder (ADHD) (Corbett & Constantine, 2006). Additionally, deficits in shifting attention have been documented in autism (Williams et al., 2013; Wainwright & Bryson, 1996; Wainwright-Sharp & Bryson, 1993), and the difficulty in switching was exaggerated when participants were required to switch between stimuli from different sensory modalities compared to a single modality (Reed & McCarthy, 2012).

In contrast to the evidence described above, other studies have reported no differences in attentional processing between adults with autism and controls. The majority of these studies used highly controlled psychophysical methods to isolate attention, and found that exogenous and endogenous attention cues robustly modulated visual discriminability to the same extent in both autism and control groups across several different tasks (Grubb et al., 2013a; 2013b). Renner et al. (2006) also found no significant difference in endogenous attention, but found impaired exogenous attention in children with autism. No significant reductions in accuracy or reaction time measures to a selective attention task were also reported in adults with autism regardless of the number of distractors (Remington et al., 2009). Ciesielski et al. (1995) also found no evidence for behavioral differences in focused auditory and visual tasks, or in divided auditory and visual tasks, but did note that attentional modulation of event-related potentials (ERPs) was significantly weaker in individuals with autism. Furthermore, several studies have even reported stronger attentional modulation in autism than controls (Oades et al., 1988), leading to superiority in visual search, which is less affected by the presence of distractors (O'Riordan et al., 2001; Kaldy et al., 2013, Ohta et al., 2012; but see Grubb et al., 2013ba; 2013b). Some have attributed the superior visual search capabilities in autism to attentional, rather than sensory, processes (Happé & Frith, 2006; Kaldy et al., 2013), because visual search performance did not reliably correlate with enhanced perceptual discrimination (Brock et al., 2011). Others have argued that altered sensitivity to sensory stimuli can lead to increased attention to detail (Robertson et al., 2014; 2013a; 2013b; Baron-Cohen et al. 2009; Joseph et al., 2009; Mottron et al., 2009).

A possible source of the discrepancy in the literature is the multitude of methodologies used to measure perception and attention, some being better at controlling for possible confounding variables than others (Ames & Fletcher-Watson, 2010). Tasks that only measure reaction times and not accuracy (Williams et al., 2012; Wainwright & Bryson, 1996; Wainwright–Sharp & Byson, 1993) can lead to ambiguous results: differences in reaction time could reflect differences in either speed of processing, discriminability, or selection criteria. In addition, they could reflect speed-accuracy trade-offs (see, for example, Carrasco & McElree, 2001). In the current study, we adjusted the task to compensate for individual differences in sensory processing, and measured both accuracy and reaction time.

In addition, a key challenge in determining whether the atypicalities in autism derive from differences in sensory or attentional processing results from the fact that investigating sensory processing often involves a task in which attention is directed (i) towards a stimulus to measure the effects of actively processing sensory stimuli, or (ii) away from the stimulus to ensure that sensory stimuli are perceived passively by engaging participants in a separate task. In either case, an attentional manipulation is involved when evaluating sensory processing.

We adopted an approach to evaluate both sensory processing and its modulation by attention in an attempt to parse the effects of sensory processing on attention modulation in autism and controls. We initially examined sensory processing to ascertain differences in visual and auditory thresholds between the two groups. We then probed sensory processing with and without engaging additional attentional demands. The attention task required switching attention between sensory modalities to keep the two channels of sensory information as separate as possible. Attending to one sensory modality or the other ensured that the stimuli were exactly the same across valid and invalid trials, and that only the cue changed. In addition, a measure of sensory sensitivity was collected using the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013). Responses on the questionnaire were compared with discrimination thresholds to assess whether greater self-reported sensitivity were correlated with improved discrimination thresholds. Clinical measures (for example, the ADOS scores for the individuals with autism) were also compared with attention measures and discrimination thresholds to test whether individuals with higher symptomatology also performed more poorly on the attention task and/or on discrimination performance.

In the first sensory experiment, we measured visual contrast-discrimination thresholds to sinusoidal gratings while, in the second, we measured auditory modulation-depth discrimination thresholds. If autism is associated with poor sensory processing, one would expect thresholds to be higher in the autism group. In the attention experiment, we measured discrimination performance while the same visual and auditory stimuli were presented concurrently at the participant's previously determined threshold level. In 75% of the trials, participants were cued to attend and respond to the same stimulus (valid cue), and, in the remaining trials, participants were cued to attend to one stimulus but respond to the non-cued stimulus (invalid cue). This made it advantageous for participants to pay attention to the cues and enabled us to compare the effects of attention on discrimination accuracy (Carrasco, 2011). If autism is associated with abnormal attentional processing, then attentional modulation of discrimination accuracy in valid versus invalid cued trials would be weaker in individuals with autism compared to controls.

2.0 Materials and Methods

2.1 Participants

Thirteen males and two females (mean age 27 years; range 21-42) diagnosed with autism and no other identifiable etiology, including ADHD, consented to participate. Screening tests to determine eligibility of the participants with autism included the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), the Kaufman Test of Educational Achievement (K-TEA) (Kaufman & Kaufman, 1985), the Autism Diagnostic Observation Schedule General (ADOS-G; Lord et al., 2000), and the Autism Diagnostic Interview Revised (ADI-R; Le Couteur et al., 1989; Lord et al., 1994). The diagnosis of autism, provided by the two structured instruments, was confirmed by expert clinical opinion (Dr. Nancy Minshew). Participants with autism were also required to be in good medical health, free of seizures and have no history of traumatic brain injury. The mean full scale IQ score of the autism group was 114.8 (SD 13.4). Demographic characteristics of the participants with autism are provided in Table 1 along with IQ scores.

Thirteen males and two females (mean age 27.4; range 20-43) from Carnegie Mellon University or the surrounding area participated as age- and gender-matched controls.

All participants had normal or corrected to normal vision and none of the participants required hearing aids. Participants were either paid $30 for their time or were given credit as part of their course requirements at Carnegie Mellon University. The Institutional Review Board of Carnegie Mellon and the University of Pittsburgh approved this study, and all participants provided written consent. This study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2 Stimuli

Stimuli were created and presented in MATLAB® using the PsychToolbox extension (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007), on a Dell Latitude E6430 laptop and participants responded using the keyboard. Auditory tones were played on over-the ear JVC headphones.

Visual stimuli were grating patches (sinusoidal modulation of image intensity multiplied by a Gaussian aperture, i.e., Gabor stimuli), presented in the center of a grey screen. The stripes of the gratings were vertical in their orientation, had a spatial frequency of 1.14 cpd, a temporal frequency of 4Hz and subtended 2.8 degrees of visual angle. The mean luminance of the grating patches was equal to that of the grey background. Cross-hairs were presented in the center of the screen and were superimposed on the gratings. The contrast of the gratings was adjusted by multiplying the contrast by a percentage. The contrasts used were equidistant on a log 10 scale.

Auditory stimuli were sinusoidally amplitude modulated tones (1000 Hz) multiplied by a 10 Hz modulator. The stimuli were sampled 44100 Hz with 16-bit resolution. The modulation depth of the modulator frequency was adjusted by multiplying the modulating frequency by a percentage (Bacon et al., 1995). The modulation depths used were equidistant on a dB (i.e., log 10) scale.

2.3.1 Behavioral Procedure—Prior to the attention experiment, contrast discrimination thresholds and auditory modulation-depth discrimination thresholds were obtained. The stimuli used to obtain discrimination thresholds were the same as those presented in the attention experiment. Discrimination thresholds were obtained first to ensure that the attention experiment was equally demanding for all participants and would make attending to both visual and auditory stimuli difficult. The discrimination threshold experiments and the attention experiment all followed the same stimulus presentation protocol. Participants were shown one stimulus, followed by another, and were asked to decide which grating looked “brighter” (had a higher contrast) or which tone sounded “rougher” (which tone had greater modulation-depth). In the attention experiment, gratings and tones were presented simultaneously, but participants were cued to attend to the visual or auditory modality (Figure 1).

2.3.2 Visual contrast discrimination threshold—Participants performed a 2IFC task to indicate which of two gratings had higher contrast. One of the gratings was always presented at 50% contrast and the other grating had a higher contrast. Crosshairs on a grey screen were presented at the beginning of every trial for 500 ms and was followed by the first grating, which was presented for 500 ms. A grey screen was then presented for 500 ms, followed by the second grating for 500 ms. Throughout each trial, participants were instructed to fixate on crosshairs at the center of the screen. Participants were cued to respond when an image of the sun appeared. Participants then indicated whether the first or the second grating was higher contrast. The difference in contrasts varied according to a 3-down, 1-up staircase: if the participant was correct for three consecutive trials at a particular contrast, the difference in contrast decreased; if the participant made an incorrect response, the difference in contrast increased. There were two interleaved staircases that continued throughout the two blocks of trials (staircases did not restart in the second block): one started with a large contrast difference (20% contrast), and the other started with a low contrast difference (0.3% contrast). Four blocks of 50 trials were presented with breaks in between. The last three contrasts displayed from each of the two staircases were averaged to calculate the contrast discrimination threshold.

2.3.3 Auditory modulation depth discrimination threshold—The procedure for measuring modulation-depth (roughness) discrimination was similar to that for measuring contrast discrimination. A pair of tones was presented sequentially during each trial with the same timing as for the visual contrast discrimination task. The modulator tone was presented at -3.01 dB modulation depth, and the other tone had a greater modulation depth. Throughout each trial, a grey screen was presented with cross-hairs in the center of the screen. Participants were cued to respond when an image of a musical note appeared. Participants then indicated which tone sounded "rougher" (i.e., which had greater modulation). Similar to the contrast discrimination protocol, two 3-down, 1-up staircases were used, one which started with a large modulation depth difference (-3 dB), and another which started at low modulation depth difference (-0.4 dB). Modulation depth changed in increments of 0.2 dB. Four blocks of 50 trials were presented with breaks in between. The last three modulation-depths presented from each of the two staircases were averaged to calculate the modulation-depth discrimination threshold.

We measured modulation-depth discrimination thresholds as they were analogous to visual contrast discrimination thresholds: the fluctuations in loudness (due to the modulating tone) are the auditory equivalent of fluctuations in contrast.

2.3.4 Attention experiment—Participants were cued to attend to either the visual grating or to the auditory tone before every trial (50 trials per auditory/visual block). On each trial, a grating and a tone were presented simultaneously for 500 ms, followed by a grey screen for 500 ms, and then immediately followed by another grating and a tone for 500 ms. Participants were instructed to fixate on the cross-hairs that were presented in the center of the screen throughout the trial. One of the tones was presented at -3.01 dB, and one of the gratings was presented at 50% contrast; the other grating was presented at 50% contrast plus the participant's contrast discrimination threshold and the other tone was presented at -3.01 dB plus the participant's modulation-depth discrimination threshold. Following stimulus presentation, the participant was cued to respond to one of the two stimuli. On 75% of the trials, the response cue matched the attention cue (valid-cue trials), and on 25% of the trials it did not (invalid-cue trials). An example trial is shown in Figure 1. Two sessions, each consisting of four blocks containing 50 trials (for a total of 400 trials), were presented with the option for breaks. To act as a break between the two sessions, participants were asked to complete the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013). This was done to prevent participants from becoming overly fatigued with the task. Participants completed 30 trials of the task as practice before starting the experiment (15 trials attending to the visual stimulus and 15 trials attending to the auditory stimulus). Participants were given feedback at the end of every practice trial to help them comprehend and acclimate to the task. These data were not included in the analysis.

2.4 Data Analysis

Contrast-discrimination thresholds were calculated by averaging together the mean of the last three contrast changes from each staircase, producing 80% discrimination accuracy; the same procedure was used to measure modulation-depth discrimination thresholds. These discrimination thresholds were used in the attention experiment to equate task difficulty across participants. Differences in the discrimination thresholds between autism and controls groups were assessed using independent-samples t-tests.

For the attention experiment, the responses to the gratings and the tones were separated into valid-cue trials and invalid-cue trials. For example, we compared performance on those trials during which the participant was cued to attend to the gratings and was asked to respond to the gratings (valid-cue trials) and those trials where the participant was cued to attend to the tones, but was asked to respond to the gratings (invalid-cue trials). Mean accuracy and reaction times were analyzed separately to measure the effect of attention, and to assess any differences in individuals with autism compared to age- and gender-matched control participants. Differences between groups and sensory modalities were assessed using mixed-measures analyses of variance, with group (autism and controls) as the between-subject variable, and sensory modality (visual and auditory) and cue (valid and invalid) as within-subject variables. To ensure that all responses were above chance in the attention experiment, one-sample t-tests were conducted separately for autism and control groups with the test value set at 50%.

Effect sizes were calculated for group differences in responses to the valid and invalid cues for the visual and auditory tasks, using the following formulae:

$$d=\left(\frac{\text{Mean}_C-\text{Mean}_A}{\text{SD}_{\text{pooled}}}\right)$$

$$\text{SD}_{\text{pooled}}=\sqrt{\frac{(N_C-1)\text{SD}_C^2+(N_A-1)\text{SD}_A^2}{N_C+N_A}}$$

Formula 1. Calculations for effect size for each group comparison. N=number of observations; SD=standard deviation; C=controls, A=autism.

Finally, we performed complementary randomization tests to assess the statistical significance of differences across groups. The participants' data were randomly shuffled between the autism group and the control group (i.e., labels permuted) and differences in percent response accuracy and reaction time were computed for the randomly assigned groups. This was repeated 10,000 times, re-randomizing the labels each time, to provide null distributions of the differences across groups, according to the null hypothesis that there was no difference between groups. To be deemed statistically significant, the actual difference between the correctly assigned groups had to exceed the 95th percentile of the null distribution (equivalent to a one tailed t-test, but without assuming that variables are normally distributed).

Responses to the Glasgow Sensory Profile questionnaire were scored 1 (‘Never’) to 5 (‘Always’) and the mean response to the auditory, gustatory, olfactory, proprioception, tactile, vestibular and visual questions were recorded and categorized as hyper- or hypo-sensitive. Responses to the questionnaire were correlated with discrimination thresholds and with performance in the attention experiment. Finally, to test whether IQ was related to sensory or attentional performance, percent accuracy and reaction times were correlated with IQ for the autism group (IQ was not measured for the controls).

3.0 Results

Individuals with autism and controls were statistically indistinguishable on their visual contrast ($t(28)=0.12, p=.903$) and auditory modulation-depth ($t(27)=0.83, p=.417$) discrimination thresholds (Figure 2A). However, the individuals with autism showed a significant correlation between their contrast discrimination thresholds and their modulation-depth discrimination thresholds ($r(13)=.52, p=.046$), whereas the controls did not ($r(12)=.08, p=.784$) (Figure 2B). This may (at least in part) be due to the somewhat wider range of discrimination thresholds in the autism group (range of visual discrimination thresholds: -0.52 to -1.18 dB; auditory discrimination thresholds: -0.47 to -2.34 dB) compared to the controls (range of visual discrimination thresholds: -0.63 to -1.09 dB; auditory discrimination thresholds: -0.66 to -2.43 dB), although Spearman's correlations (nonparametric) produced the same results. There were no significant correlations between visual and auditory discrimination thresholds and ADI ($-.04<r>.28$) or ADOS ($-.33<r>.16$) scores (from Social, Communication and Stereotypical Behavior scales) in the autism group.

In the attention experiment, identical stimuli were presented at each subject's threshold level, thereby ensuring that baseline performance was equated for all participants. Discrimination performance was better than chance for both groups in both visual and auditory trials (all comparisons $p<.001$), and there was no significant difference between groups in discrimination accuracy ($F(1,27)=0.40, p=.535$). Discrimination accuracy was higher in both groups on trials with a valid cue compared to trials with an invalid cue ($F(1,28)=36.71, p<.001$), and performance to valid and invalid cues was indistinguishable across groups ($F(1,28)=0.05, p=.818$). There was no significant difference between visual and auditory modalities in discrimination accuracy ($F(1,28)=0.14, p=.709$), and both groups performed equally well regardless of sensory modality (no significant group × modality interaction, $F(1,28)=1.81, p=.189$). There was no interaction between sensory modality and cue ($F(1,28)=0.94, p=.341$), and no significant three-way interaction with group (sensory modality × cue × group: $F(1,28)=.04, p=.836$) (Figure 3). Effect sizes for group comparisons for each condition showed that there was a small to medium effect size for controls being more accurate than individuals with autism in the valid cue conditions (visual: $d=0.05$; auditory: $d=0.37$), but there was also a small to medium effect size for controls being less accurate than the individuals with autism in the invalid cue conditions (visual: $d=-0.28$;

auditory: $d=-0.01$). There was, however, a large effect size for the effect of valid versus invalid cues in both autism ($d=1.68$) and control groups ($d=1.15$).

Randomization tests showed no significant difference between autism and control groups in percent accuracy in the valid cue conditions (visual: $p=.442$; auditory: $p=.159$), or in the invalid cue conditions (visual: $p=.228$; auditory: $p=.159$).

There were no significant correlations between ADOS (social, communication or stereotypical behavior) measures and percentage accuracy in the attention task to either the valid cue (visual: $-.16<r>.17$; auditory: $-.07<r>.40$) or invalid cue (visual: $-.44<r>-.01$; auditory: $-.47<r>.28$) or with ADI (social, communication or stereotypical behavior) measures (valid visual: $-.13<r>.26$; valid auditory: $-.06<r>.23$; invalid visual: $-.14<r>.11$; invalid auditory: $-.03<r>.20$).

Reaction times were statistically indistinguishable across individuals with autism and controls ($F(1,28)=0.52, p=.475$). Participants were faster at responding in the visual task (regardless of the attention cue) than the auditory task ($F(1,28)=5.64, p=.025$), but this was the case for both the autism and control groups to an equal extent (sensory modality × group: $F(1,28)=0.16, p=.689$). The difference in reaction times between the valid and invalid cues were larger in the visual task compared to the auditory task ($F(1,28)=77.38, p<.001$), but again this was the case for both groups (cue × group: $F(1,28)=1.38, p=.250$) (Figure 4). Effect sizes for group comparisons for each condition showed that there was no difference in response accuracy between controls and individuals with autism for the visual valid cue conditions ($d<0.01$), but a small effect size for individuals with autism being faster to respond than controls ($d=-0.25$). Individuals with autism also responded faster than the controls in the invalid cue conditions (visual: $d=-0.38$; auditory: $d=-0.20$). Again, there was a large effect size for the effect of valid versus invalid cue in both autism ($d=1.05$) and control groups ($d=0.81$).

Randomization tests showed no significant difference between autism and control groups in response accuracy in the valid cue conditions (visual: $p=.503$; auditory: $p=.256$), or in the invalid cue conditions (visual: $p=.151$; auditory: $p=.288$).

There were no significant correlations between ADOS measures and reaction times to either the valid cue (visual: $-.33<r>-.06$; auditory: $-.31<r>-.25$) or invalid cue (visual: $-.31<r>-.13$; auditory: $-.43<r>-.09$) or with ADI measures (valid visual: $-.29<r>.08$; valid auditory: $-.38<r>.17$; invalid visual: $-.20<r>.20$; invalid auditory: $-.31<r>-.05$).

To measure the potential trade-off between invalid and valid cues, we computed the difference between the performance accuracy for valid-cue trials minus invalid-cue trials. The same was done for reaction times. There was no significant difference in trade-off accuracy between autism and control groups ($F(1,28)=1.31, p=.262$), or between visual and auditory stimuli ($F(1,28)=0.14, p=.709$) and no significant interaction ($F(1,28)=1.81, p=.189$). Effect sizes for group comparisons for each condition showed that there was a small effect size for controls showing a greater trade-off than individuals with autism for the visual stimulus (d=0.03), but there was a medium effect size for the auditory stimulus (d=0.57).

There was also no group difference in reaction time trade-off ($F(1,28)=1.38, p=.250$), or a significant interaction with stimulus type ($F(1,28)=0.16, p=.689$), but there was a significant main effect of stimulus type ($F(1,28)=5.64, p=.025$), with the trade-off being greater for the auditory stimulus compared to the auditory stimulus. Effect sizes for group comparisons for each condition showed that there was a small to medium effect size for controls showing a greater trade-off in reaction times than individuals with autism (visual: d=0.29; auditory: d=0.44).

The data were reanalyzed to ensure that trials with exceptionally long reaction times (suggesting lapses), or trials with exceptionally short reaction times (suggesting accidental button-press) were not affecting results. Specifically, we excluded trials in which the reaction time was greater than 3 SD above the mean of the individual's reaction time, or trials in which the reaction time was faster than 150 ms. An average of 3% of trials were excluded for these reasons (max 9%; min 0.75%). Excluding these trials made no statistical difference to the results.

Previous studies have reported that individuals with autism exhibit larger trial-to-trial reaction time variability than controls (Karalunas et. al. 2014), which may be related to larger trial-by-trial variability in sensory evoked fMRI responses (Dinstein et al., 2012; Haigh et al., 2014) in autism. The RT standard deviation across trials, however, was statistically indistinguishable across individuals with autism and controls ($F(1,28)=1.51, p=.229$) in the current study. Note that the lack of difference across groups may be due to the delayed-response nature of the task (participants had to respond after the second cue). Additional analyses showed that RT variability across trials was statistically indistinguishable across responses in the visual (regardless of the attention cue) and auditory domains ($F(1,28)=0.03, p=.861$) to a similar extent in both the autism and control groups (sensory modality × group: $F(1,28)=2.03, p=.166$). The difference in reaction times between the valid and invalid cues were larger in the visual task compared to the auditory task ($F(1,28)=17.22, p<.001$), but again this was the case for both groups (cue × group: $F(1,28)=0.31, p=.581$) (Figure 5).

Randomization tests showed no significant difference in variability in reaction times between autism and control groups in the visual valid cue condition ($p=.435$), but the autism group produced significantly greater variability in the auditory valid cue condition ($p=.048$). There were no significant differences between groups in the invalid cue conditions (visual: $p=.151$; auditory: $p=.288$).

There were no significant correlations between ADOS measures and variability in reaction times in the attention task to either the valid cue (visual: $-.25<r>-.20$; auditory: $-.40<r>-.13$) or invalid cue (visual: $-.33<r>-.19$; auditory: $-.39<r>-.20$) or with ADI measures, except for a significant negative correlation with valid visual cues and social measures ($r(13)=-.55, p=.034$) (valid visual: $-.37<r>-.11$; valid auditory: $-.50<r>-.15$; invalid visual: $-.37<r>.08$; invalid auditory: $-.43<r>.09$).

There were no significant differences between groups across the four blocks of the attention task in percent accuracy (group × block: $F(3,84)=0.71, p=.549$), but controls did produce slower reaction times to the first block compared to the other blocks (group × block: $F(3,84)=3.48, p=.019$).

There were no significant correlations between responses to the auditory questions on the Glasgow Sensory Profile questionnaire and modulation-depth discrimination thresholds, nor between visual responses on the Glasgow Sensory Profile questionnaire and the contrast-discrimination thresholds ($-.5>r<.5$). Average Glasgow Sensory Profile scores were below average for both groups on hyper-sensitivity measures (controls mean=2, SD=0.4; autism mean=2.1, SD=0.6) and hypo-sensitivity measures (control mean=2.1, SD=0.4; autism mean=2.2, SD=0.5), and did not differ significantly between groups (hyper: $t(29)=0.53, p=.598$; hypo: $t(29)=0.55, p=.589$).

IQ did not correlate with attentional performance ($-.1>r<.3$), nor with modulation-depth discrimination thresholds ($r(13)=-.09, p=.775$), but there was a significant correlation with contrast-discrimination thresholds ($r(13)=-.56, p=.048$).

4.0 Discussion

We used robust psychophysical methods to test for perceptual and/or attentional abnormalities in autism compared to a group of healthy control participants. There were several benefits to using this particular empirical protocol. First, we compared the effect of valid and invalid cues with the same stimuli on every trial to isolate the effect of attention (as recommended by Carrasco, 2011). Second, task difficulty was controlled by presenting the stimuli at the participant's individual thresholds. This avoided any effects of attention from being confounded by task difficulty (as highlighted by Shepherd et al., 2012). Third, we measured both accuracy and reaction time to avoid a speed-accuracy tradeoff confound, and to distinguish a change in performance from response bias. These features of the experimental design are both necessary and sufficient to establish unambiguous effects of attention, and consequently these features are also necessary to establishing unambiguous differences in attention between groups.

We found robust attentional effects (valid cue visual, invalid cue visual, valid auditory cue, and invalid auditory cue all significantly different from chance, $p<.001$) in both groups (autism and control) that were indistinguishable between groups. There was also no significant difference in the trade-off between valid and invalid cues between groups. There were several individuals with autism in this study with clear autism diagnoses who do not exhibit attention deficits (see Table 1), and there were no significant correlations with any of the attention measures and ADOS and ADI scores. The effect sizes for group differences in attention were small to medium (Cohen, 1988), suggesting that any deficit/improvement in cross-modal attention in autism is not reliable and does not offer any diagnostic value.

Nor did we find evidence for differences in sensory processing. There were no significant differences in auditory or visual discrimination thresholds between autism and control groups. The autism group did produce a significant correlation between visual and auditory discrimination thresholds, but discrimination thresholds did not correlate with ADOS or ADI scores, and so are not obviously associated with autism severity. There were also no significant correlations with responses on Glasgow Sensory Questionnaire, although the autism group did not report extreme hypo or hyper-sensitivity, which may have limited the correlations. It is therefore possible that individuals with autism who exhibit greater sensory sensitivity may have performed differently in this task. There was a greater range of auditory and visual thresholds in the autism group compared to the controls, suggesting greater heterogeneity in sensory processing abilities across individuals with autism.

One possible cause for the lack of significant difference between groups in attention and sensory measures could be small sample sizes. Psychophysical studies like this are typically based on similar sample sizes. Importantly, it is also not the case that we observed null results across the board; we had sufficient statistical power to find large clear effects of attention in both accuracy and reaction time ($p<.001$), with similar amounts of within group variability (error bars in Figures 3-5) in both the control and autism groups. A power analysis of the largest group effect size that was not significant (visual invalid cue condition; $d=0.38$) would require at least 70 participants per group to have 90% power in the results (Faul et al., 2007; 2009). Participants also completed a large number of trials – 200 trials for each of the discrimination threshold tasks, and 400 trials for the attention task and so we almost certainly have sufficient statistical power to observe possible differences between groups. Last, the effect sizes of group differences for each cue condition in auditory and visual tasks were not consistent in terms of which group was faster to respond or were more accurate, and so any (non-significant) group differences in attention were not consistent across conditions, again showing that it is unlikely that sample size is the cause for the absence of significant group differences.

The individuals with autism who participated in this study had a high average IQ (114.8) and it is possible that higher IQ is associated with better sensory processing (lower discrimination thresholds). Better contrast-discrimination thresholds were associated with higher IQs in the autism group, but this was not the case for the modulation-depth discrimination thresholds. IQ was not measured for control participants, but they are likely to have high IQs given that they were mostly students from Carnegie Mellon University. We cannot ascertain whether there were any correlations between discrimination thresholds and IQ in the control group. Nor can we determine if there were any differences in IQ between the autism and control groups, or if IQ accounted for any variance in the results between the autism and control groups. However, others have reported no significant correlation between IQ and sensory processing in either typical (Hammill, 1972; Moore et al., 1995) or autism (Behrmann et al., 2006) groups. It is our opinion, therefore, that our findings, along with the mixed findings apparent in the literature, suggest that there is a large heterogeneity in sensory processing capabilities across different individuals with autism. Note that the range of sensory discriminations thresholds was larger in the autism group as compared with the control group: several individuals with autism even had better discrimination thresholds than controls (see Figure 2).

Just as there is inconsistency and controversy in the literature regarding the sensory atypicalities in autism, so too is there an ongoing debate in the literature regarding attention deficits in autism. Many previous studies have reported that individuals with autism exhibit attentional deficits, in dividing, sustaining, and shifting attention between stimuli, but the majority of these studies involve children with autism (Williams et al., 2013; Belmonte et al., 2010; Schatz et al., 2002; Corbett & Constantine, 2006; Reed & McCarthy, 2012; Christakou et al., 2013; Di Martino et al., 2013; Funabiki et al., 2012; Fitzgerald et al., 2014), with a couple of studies reporting differential effects of attention on processing sensory stimuli in adults with autism (Robertson et al., 2013b; Koolen et al., 2012). However, there are several studies that corroborate our findings in adults with autism (Grubb et al., 2013a; 2013b; Ciesielski et al., 1995) suggesting that adults with autism do not exhibit deficits in attending to one of two sensory channels compared to healthy controls. One possible explanation for the discrepancy in the literature could be that individuals with autism only show deficits in certain types of attention. Here, we found no significant differences in the tasks we conducted, engaging attention-switching within and across modalities, in adults with autism compared to controls. Other studies have also found no significant difference between autism and controls in spatial attention tasks either (Grubb et al., 2013a; 2013b). It could be that these attentional abilities are intact in individuals with autism, but that other attention tasks, like dividing or sustaining attention, are abnormal. However, our results are in direct contrast with Reed & McCarthy's (2012) study which found that deficits (in children with autism) were more pronounced when switching between sensory modalities. A second explanation could be that individuals with autism perform well at tasks where all the stimuli presented are relevant to the task. For instance, in this task participants were asked to respond to either visual or auditory stimuli, and so the expectations of the task were clear. Deficits in individuals with autism may only become manifest when it is unclear what information is relevant (White, Burgess & Hill, 2009; Van de Cruys et al., 2014), as these latter cases increase the load on autonomous selection (Gottlieb, 2012). This might explain why deficits in attention in autism do not always appear under strict lab conditions, but might appear under more naturalistic settings. A third possible explanation for the ostensible discrepancy in the literature is that attentional abnormalities are prevalent in children with autism, but not in adults with autism. If so, then this would point to a developmental delay in attention, as opposed to a sustained deficit (Williams et al., 2013). Before jumping to this conclusion, however, it would be critical to run an experimental protocol similar to that used for the current study, but with children.

Yet another possibility is that the stimuli differed across experiments. Reed and McCarthy (2012) investigated attention-modulating abilities in autism and found small deficits in modulating attention within the same modality, but found that the deficits were exaggerated when switching between visual and auditory tasks. The main difference between the current task and Reed and McCarthy's task is that they used words and pictures of objects as their stimuli, whereas the stimuli presented in the current study (as well as Grubb et al., 2013a; 2013b and Ciesielki et al., 1995) are much more basic and do not have semantic/linguistic content. It is possible that stimulus complexity emphasizes any deficits in attention: that is, deficits in attention to low-level stimuli are very small and subtle, but complex stimuli involving processing from multiple areas of the brain (in Reed and McCarthy's task, vision, audition and language areas) multiply any small deficits in sensory attention in autism contributing the measurable deficits. In essence, deficits could be occurring further down the processing stream (Robertson et al., 2013a; 2013b; Goldstein et al., 2001).

Stimulus complexity can also potentially explain some of the mixed findings regarding differences in sensory perception between autism and controls. For example, Stevenson et al. (2014) found an extended temporal binding window for simple auditory-visual synchrony judgements – when a flash of light and an auditory beep are presented simultaneously, it creates the illusion that there were two flashes shown. They found an even larger effect when creating the McGurk effect – when a phoneme conflicts with the visual display of a face saying another phoneme creating the illusion of hearing another phoneme; for example, when the phoneme 'ba' is presented with a face mouthing the phoneme 'ga' and the resulting phoneme is perceived as 'da'. The added linguistic component in the McGurk effect appears to magnify the temporal window in autism compared to controls. Therefore, differences in sensory attention in autism may only appear with complex stimuli.

5.0 Conclusion

In conclusion, using rigorous psychophysical methods, we isolated and characterized sensory and attentional processing, in a group of adult individuals with autism. We found robust differences in performance for different attention cues (valid versus invalid) that were indistinguishable between autism and control groups, similar to Grubb et al. (2013a; 2013b). This suggests that high functioning individuals with clear symptoms of autism (total ADOS scores of 7-19) do not necessarily exhibit attentional impairments.

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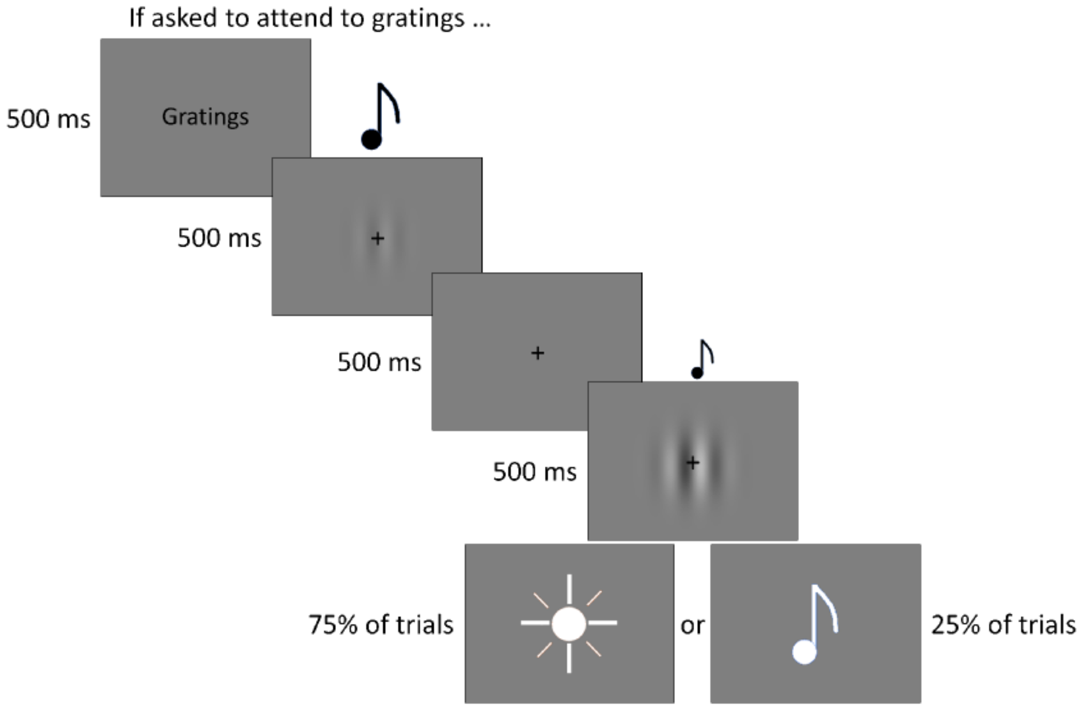

Figure 1.
An example trial where the participant was instructed to attend to the gratings. At the end of the trial, an image of the sun indicated that the participant had to complete the visual contrast discrimination task while an image of the musical note indicated that the participant had to complete the auditory modulation-depth (roughness) discrimination task.

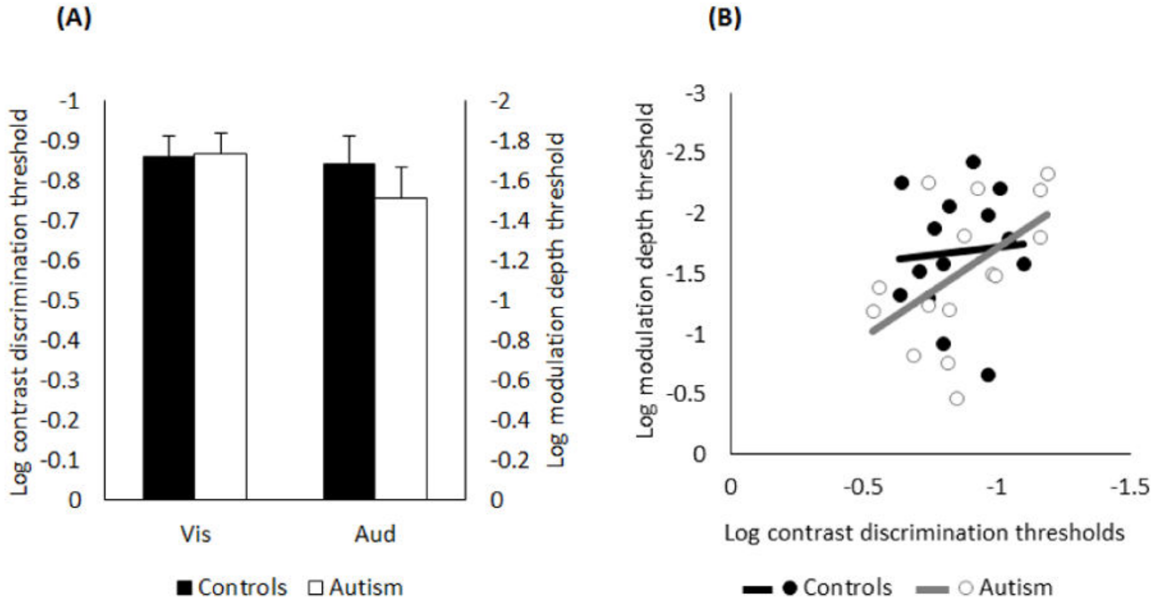

Figure 2.
(A) Visual contrast detection thresholds and auditory modulation-depth detection thresholds in the autism (white) and control groups (black). Error bars show one standard error. (B) Scatter plot of contrast discrimination and modulation-depth discrimination thresholds for the autism and control groups and regression lines.

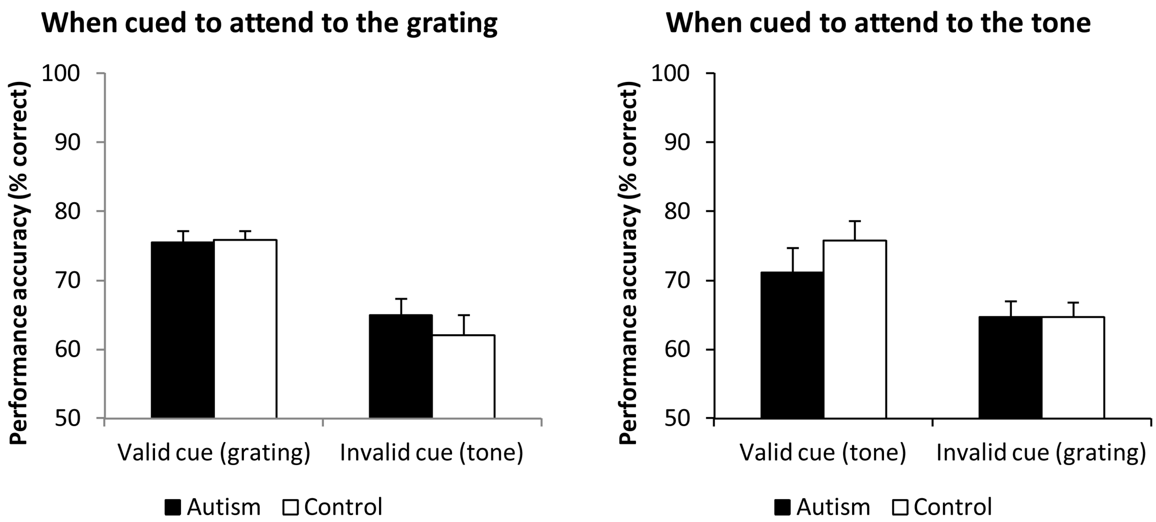

Figure 3.

Performance accuracy (% correct) in the visual (left panel) and auditory (right panel) discrimination tasks for valid and invalid cues in the autism group and the control group. Error bars show one standard error. 50% correct is chance performance.

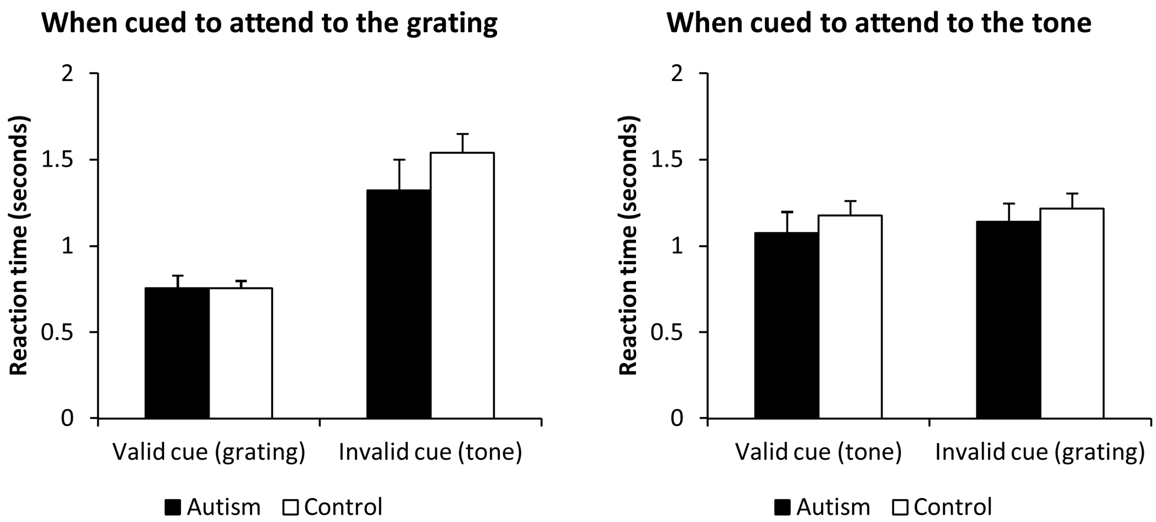

Figure 4.

Reaction times (sec), shown separately for visual (left panel) and auditory (right panel) discrimination tasks and for valid and invalid cues, for the autism group and the control group. Error bars show one standard error.

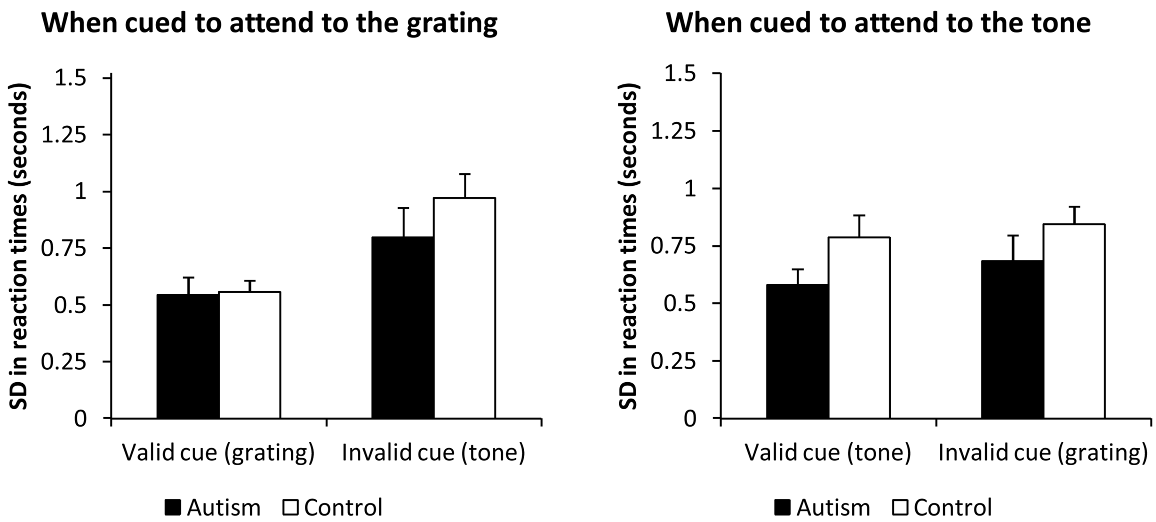

Figure 5.
Standard deviation (SD) in reaction times (sec), shown separately for visual (left panel) and auditory (right panel) discrimination tasks and for valid and invalid cues, for the autism group and the control group. Error bars show one standard error.

Table 1

ADOS, ADI and IQ scores for the individuals with autism

Age (years)	Gender	ADOS Communication	ADOS Social	ADOS Stereotypical	ADI Social	ADI Communication	ADI Stereotypical	Full Scale IQ
19	F	5	7	3	27	20	6	107
22	M	5	6	6	19	11	4	127
33	M	3	5	3	26	18	12	131
31	F	2	7	4	10	8	6	123
27	M	2	6	3	20	16	7	104
23	M	4	6	1	21	18	8	123
22	M	6	13	1	23	13	4	88
36	M	2	8	1	20	11	3	125
19	M	3	7	3	22	15	5	96
22	M	5	11	3	20	15	3	107
20	M	3	4	3	11	10	6	129
39	M	4	7	1	21	16	8	116
29	M	3	6	1	15	12	2	116
20	M	5	9	0	22	17	8	99
21	M	3	5	5	18	15	7	126