Visual perceptual load reduces auditory detection in typically developing individuals but not in individuals with Autism Spectrum Disorders

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Abstract

Objective: Previous studies examining selective attention in individuals with autism spectrum disorder (ASD) have yielded conflicting results, some suggesting superior focused attention (e.g. on visual search tasks), others demonstrating greater distractibility. This pattern could be accounted for by the proposal (derived by applying the Load theory of attention, e.g. Lavie, 2005) that ASD is characterized by an increased perceptual capacity (Remington, Swettenham, Campbell, & Coleman, 2009). Recent studies in the visual domain support this proposal. Here we hypothesize that ASD involves an enhanced perceptual capacity that also operates across sensory modalities, and test this prediction, for the first time using a signal detection paradigm. *Method:* 17 neurotypical (NT) and 15 ASD adolescents performed a visual search task under varying levels of visual perceptual load while simultaneously detecting presence/absence of an auditory tone embedded in noise. *Results:* Detection sensitivity (d') for the auditory stimulus was similarly high for both groups in the low visual perceptual load condition (e.g. 2 items: p = .391, d = 0.31, 95% CI [-.39, 1.00]). However, at a higher level of visual load, auditory d' reduced for the NT group but not the ASD group leading to a group difference (p = .002, d = 1.2, 95% CI [.44, 1.96]). As predicted, when visual perceptual load was highest, both groups then showed a similarly low auditory d' (p = .9, d = 0.05, 95% CI [-.65, .74]). *Conclusions:* These findings demonstrate that increased perceptual capacity in ASD operates across modalities.

Keywords: Autism Spectrum Disorders; auditory detection sensitivity; attention; perceptual load

Introduction

Individuals with Autism Spectrum Disorders (ASD) show impairments in social relatedness and reciprocity, as well as restrictive patterns of behaviour, thinking and interests including atypical responses to sensory input (DSM-5, American Psychiatric Association, 2013). Apart from these core diagnostic features, attentional and perceptual atypicalities have also been commonly reported (Ames & Fletcher-Watson, 2010; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006; Sanders, Johnson, Garavan, Gill, & Gallagher, 2008). With the growing recognition that atypical attention may be one of the earliest identifiable features of ASD (Elsabbagh et al., 2009), affecting the development of later cognitive and daily living skills (Grandin, 1997; Johnson & De Haan, 2010), an increasing body of research has focussed on understanding attentional processes in individuals with the condition.

Research examining selective attention in ASD has, however, produced a puzzling range of conflicting results. While a number of studies suggest a deficit in selective attention in ASD as evidenced by higher distractibility to task-irrelevant stimuli (Adams & Jarrold, 2012; Burack, 1994; Christ, Holt, White, & Green, 2007; Christ, Kester, Bodner, & Miles, 2011; Ciesielski, Courchesne, & Elmasian, 1990), others suggest that ASD is characterized by superior selective attention. For example, individuals with ASD have been reported to be faster and more accurate at detecting a target shape embedded within a complex design (e.g. Jolliffe & Baron-Cohen, 1997; Shah & Frith, 1983), identifying local targets within a global figure (Plaisted, Swettenham, & Rees, 1999), and finding a unique target item hidden among multiple non-target items (Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; O'Riordan, 2004; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998). So, while on some tasks individuals with ASD appear to demonstrate superior selective attention, on others they display impaired selective attention as evidenced by increased distractor processing.

A recent proposal has attempted to account for these discrepant findings in terms of an increased perceptual capacity in ASD (Remington et al., 2009; Remington, Swettenham, & Lavie, 2012; Swettenham et al., 2014) by applying Lavie’s Load theory of attention and cognitive control to ASD research (Lavie, 1995). Load theory asserts that the extent to which irrelevant distractors are processed depends on whether the level of perceptual processing (perceptual load) of a task exhausts the perceptual capacity of an individual or whether spare capacity is left over to be automatically allocated to the processing of task-irrelevant stimuli. Thus, a task will only exhaust an individual’s perceptual capacity if it has a high enough perceptual load. Perceptual load can be manipulated by altering the number of task-relevant stimuli in the display (e.g. number of items in a search task), or the perceptual processing requirement of a task (e.g. the subtlety of a line discrimination) (Lavie, 2005). A task with high load is likely to exhaust perceptual capacity so that no additional task-irrelevant stimuli are processed, whereas a task with low load is unlikely to exhaust capacity, resulting in a ‘spill-over’ of attentional resources and the automatic processing of task-irrelevant stimuli until overall capacity is reached.

In light of the previous research suggesting superior performance on visual search tasks, particularly when array sizes are large (e.g. O'Riordan et al., 2001), Remington et al. (2009) hypothesized that ASD could be characterized by an enhanced visual perceptual capacity. This led to a number of predictions regarding the extent to which task-irrelevant stimuli would be processed at different levels of perceptual load by individuals with ASD versus neurotypical (NT) controls on visual selective attention tasks. First, when the visual perceptual load of a task is low there should be no difference between groups in the processing of task-irrelevant stimuli, as both ASD and NT groups would have spare capacity ‘spilling over’ into the processing of task-irrelevant stimuli. Second, a task with a higher level of perceptual load could fill capacity in the NT group but not the ASD group, resulting in the processing of task-irrelevant stimuli in the ASD group but not the NT group. Thirdly, a task could have a level of load so high that it exhausts capacity in both NT *and* ASD participants, resulting in no group differences in task-irrelevant processing. These predictions were verified experimentally in the visual domain with tasks that measured perceptual load effects on visual distractor processing (Remington et al., 2009), visual detection sensitivity (Remington et al., 2012), and the detection of an unexpected task-irrelevant visual stimulus in an inattentional blindness task (Swettenham et al., 2014).

These previous tasks were conducted solely within the visual domain. In this paper we consider whether an enhanced perceptual capacity in ASD operates across sensory modalities. Does increasing the visual perceptual load of a task also differentially affects the processing of task-irrelevant *auditory* stimuli in ASD compared to NT participants? There is some evidence that it does. In contrast to NT subjects who show reduced detection of auditory stimuli at high- relative to low levels of visual perceptual load (i.e. load-induced inattentional deafness; Macdonald & Lavie, 2011; Molloy, Griffiths, Chait, & Lavie, 2015; Raveh & Lavie, 2015), children with ASD have been found to show similar auditory detection across high-and low load conditions of a visual task (Tillmann, Olguin, Tuomainen, & Swettenham, 2015). Tillmann et al. (2015) asked participants to discriminate which arm of a cross was longest (i.e. horizontal or vertical) on seven visually presented trials, performing in either a low load condition (gross line discrimination) or high load condition (more subtle line discrimination). On the seventh trial, an unexpected auditory stimulus was played through headphones at the same time as the visual cross stimulus appeared and participants were subsequently asked whether they had noticed anything else. The results demonstrated that fewer NT children in the high perceptual load group noticed the auditory stimulus compared to NT children in the low perceptual load group – visual perceptual load affected awareness of a task-irrelevant auditory stimulus. By contrast, the proportion of ASD children who reported noticing the auditory stimulus was equally as high in both the high and low load conditions – visual perceptual load had no effect on awareness of the unexpected auditory stimulus in the ASD group (Tillmann et al., 2015).

Although this study provides some support for our hypothesis that the effect of perceptual load on attention in ASD is cross-modal, differences in inattentional deafness rates across load conditions may not necessarily reflect a shift in conscious perception. For example, the retrospective measure of awareness with a delayed surprise question about an unexpected stimulus raises the possibility that the failure to report presence of the auditory stimulus may reflect, in some cases, rapid forgetting (Wolfe, 1999). Another possibility is that the findings reflect a difference between groups in response criterion such that TD individuals may be more reluctant to admit noticing an unexpected stimulus for which there is only a weak memory trace in conditions of high perceptual load. Since the inattentional deafness paradigm only allowed analysis of a single awareness trial, i.e. the unexpected auditory detection stimulus could only be presented once per participant, measures of detection sensitivity and response bias could not be assessed in this study.

In the present study, we therefore set out to measure the effect of visual perceptual load on perceptual detection of an auditory tone using a dual-task paradigm with *multiple* trials, which would allow us to measure detection sensitivity and take response bias into account. On each trial, participants were required to first search for a target letter ‘X’ or ‘N’ in a centrally presented ring of letters, and then to indicate the presence/absence of a critical auditory tone presented simultaneously with the visual stimulus. We manipulated visual perceptual load in the primary task by increasing the visual search set-size (1,2,4 or 6 items). The tone (embedded in noise) in the secondary task was present on 50% of trials. This procedure therefore includes hits and false alarms for multiple auditory detection trials and allows for the measurement detection sensitivity and response bias. This procedure is based on a study by Raveh and Lavie (2015) who recently demonstrated that increasing visual perceptual load reduces auditory detection sensitivity in a neurotypical population. We use it here, for the first time, to test whether individuals with ASD differ with NT participants by showing a different pattern.

We were also careful to take into account any individual differences in auditory sensitivity that could bias the results by adjusting the intensity of the target tone to each participant’s individual threshold. Sensory disturbances, especially in the auditory modality, have sometimes been reported in some individuals with ASD. These can range from reports of completely ignoring sounds (Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998) to oversensitivity to loud noises or particular sounds (Grandin, 1995; Jones et al., 2009; Rosenhall, Nordin, Sandström, Ahlsen, & Gillberg, 1999). By presenting participants with an auditory tone embedded in noise adjusted to their individual threshold, yet keeping the absolute difference between signal (target sound) and noise the same across all participants, the effect of visual perceptual load on auditory detection could be examined without any confounding effects of individual differences in auditory perceptual sensitivity.

It was predicted that at low levels of visual perceptual load there would be no difference between groups in auditory detection sensitivity. At a higher level of perceptual load, auditory detection sensitivity would be reduced in the NT group but not the ASD group, while at the highest level of visual perceptual load auditory detection sensitivity would be equally low for both groups. In addition, we predicted that none of the effects on auditory detection sensitivity could be accounted for by error rate or reaction time on the visual task (which we predicted to be similar for both groups), or by auditory detection thresholds.

Method

Participants

This study included 20 typically developing (TD) adolescents and 18 adolescents with ASD. TD adolescents were recruited from secondary mainstream schools, while adolescents with ASD were recruited from local schools that cater specifically for the educational needs of children and adolescents with ASD. Prior to testing, all participants with ASD had received a clinical diagnosis of ASD from a trained, independent clinician according to the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed., American Psychiatric Association, 1994). In addition, ASD symptomatology was assessed using the lifetime version of the Social Communication Questionnaire (SCQ, Rutter, Bailey, & Lord, 2003). All participants in the ASD group scored above the recommended cut-off score of 15 for suspected ASD.

Participants were excluded if, for any set size manipulation, response accuracy on the letter search task was lower than 50% (i.e. visual task response was below chance level) or detection accuracy of the auditory target stimulus was lower than 30%. The lower cut-off value for detection accuracy was chosen in order to capture more variability in detection performance as a function of perceptual load conditions. On the basis of these exclusion criteria, three participants with ASD and three TD participants were removed prior to the analysis. The remaining 17 TD and 15 participants with ASD were matched for non-verbal ability (using the Raven's Standard Progressive Matrices, Raven, Raven, & Court, 1998) and chronological age (see Table 1 for descriptive statistics). Independent samples t-tests indicated that there were no significant differences between groups on any of these measures (maximum t-value = .519, minimum p-value = .607).

Apparatus and Stimuli

Microsoft Visual Basic (version 6) was used to create computer-based stimuli that were presented on an IBM Lenovo Thinkpad 14.1” personal laptop. Viewing distance was 60cm. The task involved a dual-task paradigm, adopted from Remington et al. (2012), that required participants to identify a visual target letter (‘X’ or ‘N’) presented in the middle of the screen and then indicate the presence or absence of an auditory target sound embedded in noise (critical stimulus: CS).

On each trial, six equally spaced letters were placed around the circumference of a circle, centered at fixation, with a radius of 1.7° visual angles. The background of the display was black (RGB: 0, 0, 0) and the letters were white (RGB: 255, 255, 255). One of the letters presented in the ring was the target letter (a capital letter ‘X’ or ‘N’, equally likely to appear; 0.6° x 0.6° visual angles) that was presented randomly, but with equal probabilities, in one of six possible locations. Depending on the condition, the other ring positions were occupied by perceptually similar non-target letters (H, K, V, Y or Z; 0.6° x 0.6° visual angles) or an easy to distinguish, perceptually non-similar, small letter *O* (0.2° x 0.2° visual angles). The perceptual load of the search task was manipulated by increasing the number of perceptually similar non-target letters to the display to create four different set sizes: one (target letter and five *O*’s), two (target letter, one non-target letter, and four *O*’s), four (target letter, three non-target letter, and two *O*’s), and six (target letter and five non-target letter).

On each trial, participants also had to indicate the presence or absence of an auditory target sound embedded in noise. Starting at the onset of each trial, a speech-shaped noise masker (48db SPL), which is noise with amplitudes at different frequencies to match those of natural speech (Nelson, Jin, Carney, & Nelson, 2003), was played continuously through a pair of Sennheiser HD 25-1-II stereo headphones for 2 seconds (see Figure 1). On half of all trials, simultaneously with the presentation of the letter-search task, an auditory target sound (i.e. beep tone) was played together with the speech-shaped noise. On the other half of the trials, the noise continued to play until completion. The target sound was a saw-tooth wave (frequency range of 85-150Hz) and was matched for duration with the visual presentation time of the central letter search task (i.e. 176ms).

Presentation of (a) the target sound + noise or (b) noise-only stimulus was randomized across trials. All sound files were prepared with Audition and SFSWin and calibrated prior to the experiment by a Bruel & Kjaer 4153 artificial ear together with an Ono Sokki CF-350Z spectrum analyzer. To combine the saw-tooth wave and speech-shaped noise, a total of 25 stimuli were created that ranged in terms of signal-to-noise ratio (SNR) from -2db to -14db in 0.5db steps. More negative SNR values therefore indicate better performance in detecting the target sound in noise. Prior to performing the dual task paradigm, the perceptual threshold for the auditory stimulus in noise was established for each participant using a two alternative forced-choice (2AFC) adaptive threshold procedure. On each trial, participants had to detect the target sound (beep tone + noise) among another noise-only stimulus. Two consecutive correct responses reduced the SNR by -0.5db in the following trial (i.e. made it more difficult to detect the target sound in noise). An incorrect response led to an increase in the SNR by 0.5db (i.e. made it easier to detect the target sound in noise). Individual thresholds were based on an average of five reversals (point at which direction is changed, i.e. either when producing a correct answer followed by an incorrect answer or when producing two correct answers after an incorrect answer). The threshold level for each participant subsequently informed the choice of the SNR mix used in the letter search task. A five unit increase in the SNR (i.e. +2.5db) was added to each participant's threshold level (making it easier to detect the target sound in noise). This guaranteed that the individual SNR mix used in the main experiment was well above each individual's threshold. So for example, someone with a SNR threshold of -9.5db was presented with a SNR mix of -7.0db in the main experiment. Each participant was therefore presented with an auditory tone embedded in noise adjusted to their individual threshold, yet across participants, the absolute difference between signal (target sound) and signal threshold level was always the same. There were no group differences between the ASD and the TD group in SNR thresholds.

Procedure

On each trial, together with a fixation cross that was displayed centrally for 1000ms, the speech-shaped noise started to play (see Figure 1). This was followed by the visual search array for 176ms, which could be accompanied either by the presence or absence of the target sound. A blank screen was then displayed until a response to the visual input was made. Immediately following this response, a white question mark was presented centrally until a response was made regarding the presence or absence of the auditory stimulus. Participants were told that they would see a central ring made up of letters and that one letter would be either an X or an N. They were instructed to indicate as quickly but also as accurately as they can whether an 'X' or an 'N' is present via an appropriate keypress. They were then told that on some of the trials (50%), they would also hear a short beep tone hidden in noise whilst the ring of letters appeared on the screen. Participants were instructed to first make the visual target letter response and then indicate via a separate keypress whether the sound in noise was present or absent. Participants performed a total of 196 trials, administered in four blocks according to each set size (1, 2, 4, and 6). Participants always completed one set size first, before moving on to the next set size. For each set size, a total of 48 trials were presented and presentation of both the visual target letter (‘X’ or ‘N’) and auditory stimulus (auditory tone + noise or noise-only) was randomized (visual and auditory stimuli were equally often presented). Presentation of blocks was randomized and counterbalanced across participants and participants were able to take breaks after each block. Prior to the main experiment, participants completed a set of practice trials. For the letter search task, reaction time (RT) and discrimination accuracy was recorded, whereas for the auditory detection task accuracy was recorded.

Results

Letter search task

Trials with an incorrect target letter response and trials with RTs above 2500ms were discarded prior to analysis. A mixed Analysis of Variance (ANOVA) with group (ASD vs. TD) as a between-subjects factor and set size (one, two, four, and six) as a within-subjects factor on average correct RTs and search error rates revealed that participants across groups were significantly slower to respond to trials with higher set sizes (set size 1: M = 1022, SD = 288; set size 2: M = 1207, SD = 289; set size 4: M = 1370, SD = 301; set size 6: M = 1429, SD = 277), $F(3, 90) = 52.332$, p $< .001$, $\eta_p^2 = .64$, 95% CI [.50, .71])**.** Higher set sizes also resulted in significantly lower accuracy rates (set size 1: M = .943, SD = .090; set size 2: M = .950, SD = .043;

set size 4: *M* = .855, *SD* = .070; set size 6: *M* = .727, *SD* = .091), *F*(2.5, 90) = 66.767, $p < .001$, $\eta_p^2 = .69$, 95% CI [.57, .75]. This suggests that the manipulation of perceptual load was effective, as significantly slower RT scores and higher error rates (index of higher processing demands) were observed as a function of the perceptual load of the task. No significant main effect of group for both RT (*F*(1, 30) = 1.951, p = .173, $\eta_p^2 = .060$, 95% CI [0, .26]) and error rates (*F*(1, 30) = .016, p = .899, $\eta_p^2 = .001$, 95% CI [0, .08]) was found (see Table 2 for a summary of descriptives). The interaction between set size and group was also not significant for RT and error rates (F values < 1). Any differences in detection rates between groups are therefore unlikely to be due to a generalised reduction in processing speed in individuals with ASD.

Detection of the critical auditory stimulus

The percentage detection rate, detection sensitivity (*d'*) of the auditory stimulus and the response bias (c) for each group at each set size was calculated. A repeated measures ANOVA indicated that increasing perceptual load significantly reduced detection rates across participants, *F*(3, 90) = 14.705, $p < .001$, $\eta_p^2 = .33$, 95% CI [.16, .45]. Comparing groups, the ASD group was found to have significantly higher detection rates than the TD group, *F*(1, 30) = 4.906, p = .035, $\eta_p^2 = .141$, 95% CI [0, .36]. The presence of a significant interaction between set size and group (*F*(3, 90) = 2.753, p = .047, $\eta_p^2 = .084$, 95% CI [0, .18]) suggested that this difference in detection rates between the ASD and TD group was dependent on set size (see Figure 2). Post-hoc ANOVA for each set size demonstrated that whilst there were no significant differences between groups in detection rates at set size 1 (ASD = 91.7%, TD = 89.6%; *t*(30) = .967, p = .341, d = 0.35, 95% CI [-.36, 1.04]) and set size 2

(ASD = 87.1%, TD = 86.2%; $t(30) = .254$, $p = .802$, $d = 0.09$, 95% CI [-.61, .78]), the ASD group had significantly higher detection rates than the TD group at set size 4 (ASD = 90.4%, TD = 77.9%; $t(30) = 3.581$, $p = .001$, $d = 0.81$, 95% CI [.49, 2.0]). There was no significant difference in detection rates between groups at set size 6 (ASD = 79.9%, TD = 71.3%; $t(30) = 1.518$, $p = .140$, $d = 0.54$, 95% CI [-.17, 1.24]). The pattern and significance of the results was also observed when controlling for non-verbal ability scores.

The d’ measure, an index of sensitivity or discrimination, was subsequently calculated for each individual at each set size. Measures of detection sensitivity provide a more accurate reflection of task performance by taking into account participant’s detection rate as well as false alarm rate. A repeated measures ANOVA revealed a significant main effect of set size, $F(3, 90) = 17.317$, $p < .001$, $\eta_p^2 = .366$, 95% CI [-.19, .48], with detection sensitivity being lower at higher set sizes. There was no significant effect of group, $F(1, 30) = .950$, $p = .337$, $\eta_p^2 = .03$, 95% CI [0, .28]. The interaction between set size and group approached significance, $F(3, 90) = 2.394$, $p = .074$, $\eta_p^2 = .074$, 95% CI [0, .17], suggesting that the pattern of sensitivity is changing differently for the two groups as the perceptual load increased (see Figure 3). A priori specified t-tests showed that there was a significant difference in sensitivity between the two groups at set size 4 (*d’*; ASD = 2.65, TD = 1.81; $t(30) = 3.411$, $p = .002$, $d = 1.2$, 95% CI [.44, 1.96]) yet this difference disappeared at set size 6 (*d’*; ASD = 1.79, TD = 1.75; $t(30) = .126$, $p = .9$, $d = 0.05$, 95% CI [-.65, .74]). There was also no significant difference between groups at set size 1 (*d’*; ASD = 2.93, TD = 2.75; $t(30) = .621$, $p = .539$, $d = 0.2$, 95% CI [-.48, .91]) and set size 2 (*d’*; ASD = 2.76, TD = 4.88; $t(30) = .871$, $p = .391$, $d = 0.31$, 95% CI [-.39, 1.00]). As for detection rates, controlling for non-verbal ability scores did not change the pattern and significance of the results.

The response bias (i.e. response criterion: c) for each participant at each set size was also calculated, where a response criterion with a value greater than 0 indicates a bias towards the no response, a value of less than 0 indicates a bias towards the yes response and the value of 0 indicates no bias towards a yes or no response. A repeated measures ANOVA revealed that the response criterion did not differ significantly across set sizes (*F*(2.7, 90) = .933, p = .422, η_p^2 = .03, 95% CI [0, .09]) or groups (*F*(1, 30) = 3.048, p = .091, η_p^2 = .092, 95% CI [-.39, 1.00]). The interaction between set size and group approached significance, *F*(2.7, 90) = 2.507, p = .07, η_p^2 = .077, 95% CI [0, .17]. Follow-up contrasts revealed no significant group differences in response bias at set size 4 (c; ASD = -0.13, TD = 0.06; *t*(30) = 1.635, p = .112, d = 0.6, 95% CI [-.05, .41]), suggesting that participants across groups adopted a similar response style. At set size 6 however, a significant group difference was found, (c; ASD = -0.09, TD = 0.25; *t*(30) = 2.616, p = .014, d = 0.92, 95% CI [.08, .61]), with participants in the TD group adopting a more stringent response criterion (i.e. bias towards responding ‘no’) than the ASD group (see Table 2).

An additional analysis was carried out to ascertain whether the finding of higher auditory detection rates and sensitivity in the ASD group was the result of the ASD group prioritizing the auditory detection task over the visual detection task. In other words, the ASD group may have treated the auditory detection task as primary while the TD group (in keeping with task instructions), treated the auditory detection task as secondary. To test for this possibility, reaction times and accuracy rates for each set size were re-calculated depending on whether a trial featured the critical stimulus or not. A difference score was subsequently created for each participant reflecting the extent to which task performance (RT and accuracy rates) was different for CS-present trials compared to CS-absent trials). If the ASD group was indeed prioritizing the auditory detection task over the visual task, they would show higher RTs on CS-present compared to CS-absent trials reflecting a slowing of response times (i.e. a positive RT difference score), as well as higher error rates (i.e. a negative error difference scores) on CS-present compared to CS-absent trials. Inspection of these difference scores across set size and group conditions however revealed that neither group recorded positive RT difference scores (set size 1: TD = -114ms; ASD = -73ms; set size 2: TD = -14ms; ASD = -80ms; set size 4: TD = -30ms; ASD = -23ms; set size 6: TD = -16ms; ASD = -49ms), $F(1, 30) = .471$, $p = .498$, $\eta_p^2 = .015$, 95% CI [0, .18], or increased error rates on CS-present vs. CS-absent trials (set size 1: TD = 1.4%; ASD = 4.5%; set size 2: TD = 1.2%; ASD = 2.2%; set size 4: TD = -3%; ASD = -3.9%; set size 6: TD = -1.0%; ASD = -3.1%), $F(1, 30) = .001$, $p = .977$, $\eta_p^2 = .001$).The interaction between set size and group for both RT and error rates was also not significant (both $F < 1$).

Discussion

The results presented here demonstrate an increased perceptual capacity on a cross-modal auditory detection task in individuals with ASD compared to typically developing individuals matched for chronological age and non-verbal ability scores. When the perceptual load of the visual task was low (one or two items in the central search array), detection rates for a simultaneously presented auditory stimulus did not differ between groups. However, when the perceptual load was higher (four items in the search array) detection rates for the auditory stimulus were significantly reduced in TD individuals compared to individuals with ASD who maintained a high level of detection. At even higher levels of perceptual load (six search array items), there was no difference between groups in detection rates. The fact that auditory detection rates in the ASD group were not affected by the perceptual load of the visual task until there were six items in the search array (compared to four items in the search array for the neurotypical group) confirms our hypothesis of an increased perceptual capacity in ASD.

A number of observations further add to this conclusion. The signal detection analysis established that the observed advantage in auditory detection in individuals with ASD reflects a superior perceptual sensitivity rather than a shift towards a more lenient response criterion. By isolating the effects of perceptual load on detection accuracy from those of response bias, an alternative account of increased detection in the ASD group as a result of a tendency to respond with ‘stimulus present’ can be ruled out. In addition, participants were presented with individually generated signal-to-noise stimuli matched to their perceptual threshold. That is, the intensity of the auditory tone relative to the surrounding noise was adjusted to each participant’s signal-to-noise threshold. While these signal-to-noise stimuli differed between participants, the relative difference in intensity between the target signal used in the experiment and the individual threshold level for the target signal-in-noise was always the same across participants. This allowed us to control for any individual differences in auditory sensitivity that could have influenced detection performance in the main experiment. Given that a detection advantage was observed for the ASD group at higher levels of perceptual load despite controlling for individual characteristics in perceptual sensitivity, we could rule out basic differences in hearing sensitivity as an explanation for group differences. It is also important to point out that central search task performance, as indexed by target letter RTs and search accuracy, was found to be equivalent between groups across set size conditions, suggesting that both groups were performing similarly. A general reduction in processing speed and/or task accuracy is therefore unlikely to account for the group differences in the results reported here.

It is worth considering whether or not undiagnosed symptoms relating to Attention Deficit/Hyperactivity Disorder (ADHD) may have contributed to the present findings. High rates of clinical comorbidity between individuals with ASD and ADHD have been reported (de Bruin, Ferdinand, Meester, de Nijs, & Verheij, 2007; Leyfer et al., 2006; Simonoff et al., 2008), and ADHD-like traits are also commonly found in individuals with ASD (Gadow, DeVincent, & Pomeroy, 2006; Sinzig, Walter, & Doepfner, 2009). In addition, individuals with ADHD often display difficulties in selective attention in daily life such as distractibility to extraneous events. In fact, "being easily distracted by extraneous events" forms part of the diagnostic symptoms of ADHD according to DSM-5 diagnostic criteria (American Psychiatric Association, 2013, p. 59). This may suggest the presence of an attentional phenotype common to both disorders. However, there is no evidence that individuals with ADHD perform any differently to neurotypical individuals in response to increasing perceptual load on selective attention tasks (Chan et al., 2009; Forster, Robertson, Jennings, Asherson, & Lavie, 2014; Huang‐Pollock, Nigg, & Carr, 2005). Across these studies, increasing perceptual load was as effective in reducing distraction for individuals with ADHD as for TD individuals. It is therefore unlikely that ADHD-like traits in individuals with ASD have contributed to the results.

The present findings extend previous behavioural demonstrations of an increased perceptual capacity in ASD. These studies highlighted how selective attention in individuals with ASD is less affected by the perceptual load of a task, leading to enhanced processing of extraneous information relative to neurotypical individuals under high load conditions. In the visual domain, this was shown on tasks that measured perceptual load effects on distractor processing (Remington et al., 2009) detection sensitivity (Remington et al., 2012), and detection of an unexpected task-irrelevant stimulus (Swettenham et al., 2014). Interestingly, an enhanced perceptual capacity also seems to relate to the degree of autistic traits in the typically developing population (Bayliss & Kritikos, 2011). These authors reported that in a large sample of neurotypical individuals, those individuals with higher scores on the Autism-spectrum Quotient (AQ, Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) showed greater interference effects by distractors on a visual search task at high levels of perceptual load. This preliminary evidence suggests that an increased perceptual capacity may be part of the broader autism phenotype.

Although the results of these studies manipulating perceptual load in individuals with ASD suggest that an increased perceptual capacity can be conceived as a perceptual advantage rather than a deficit, being able to process more information can also have adverse effects. According to load theory, while attention is a limited capacity system, all stimuli falling within this limit are processed regardless of whether they are irrelevant and potentially distracting. Interestingly, clinicians and parents often report that individuals with ASD are able to perform in a well-controlled environment, yet experience difficulties if the environment features too many sensory stimuli (Marco, Hinkley, Hill, & Nagarajan, 2011). An interesting case study in this context is Temple Grandin, an author with ASD. She described how minor background noises distracted her: “I still have problems with losing my train of thought when distracting noises occur. If a pager goes off when I am giving a lecture, it fully captures my attention and I completely forget what I was talking about”

(Grandin, 1995, p. 67-68). It is possible then, that this experience might be related to an increased perceptual capacity that operates across sensory modalities.

The increased perceptual capacity account might also be able to provide some insight into why individuals with ASD have been found to demonstrate higher distractibility in auditory-only tasks featuring multiple auditory inputs. Teder-Sälejärvi, Pierce, Courchesne, and Hillyard (2005) for example found that individuals with ASD have more difficulty selectively attending to an auditory target stimulus whilst ignoring distracting noise bursts relative to controls. When presented with eight sound sources and a continuous stream of sounds, individuals with ASD were slower and less accurate at identifying a target signal from a specific spatial location, but performed as accurate as controls on a less demanding task with only three sound sources. ERP results also confirmed this finding, with broader N1 and shallower P3 peaks in the ASD compared to a control group, indicative of a diminished ability to attend to one sound source among many (Teder-Sälejärvi et al., 2005). The finding that individuals with ASD were slower and less accurate than typically developing subjects when presented with eight sound sources indicates that they were processing competing information, despite being told to ignore them. Interestingly, the more demanding condition with eight sound sources could potentially reflect a high perceptual load condition, whereas the less demanding condition with three sound sources might represent a low perceptual load task. The finding of equivalent performance between groups in the less demanding task, yet higher distractibility in individuals with ASD relative to controls on a more demanding task would fit with the increased perceptual capacity account. An increased perceptual capacity in ASD would allow enhanced processing of auditory information even if it interferes with the relevant task. It is however also important to stress that because participants were required to segregate sounds from multiple input streams, an underlying impairment in auditory streaming abilities might have also been responsible for these results. In another study, Hismjatullina (2006) presented a set of experiments that measured selective attention in the auditory modality in children with ASD and various matched control groups. On a dichotic listening task, although differences in reaction times between groups were not observed, the ASD group displayed significantly higher error rates. Although it is not clear from this paper why reaction times remained stable whilst error rates were increased, this pattern of results would in fact be predicted by an increased perceptual capacity account. The observation that reaction times were unaffected (i.e. subjects were still able to attend to the relevant stream), whilst error rates were increased (i.e. reflecting processing of information in the unattended channel), could suggest that individuals with ASD had processing resources left-over to also attend to the unattended stream.

The findings reported in this paper that high visual perceptual load reduced auditory sensitivity across all participants adds to the growing literature on the cross-modal effects of perceptual load on attention and replicates previous findings in typically developing individuals (Macdonald & Lavie, 2011; Molloy et al., 2015; Raveh & Lavie, 2015). Extending previous behavioural findings, Molloy et al. (2015) recently also investigated the neural underpinnings of auditory processing under visual perceptual load. Using magnetoencephalography (MEG), auditory cortical responses were measured to a pure tone that was time-locked with a visual search task at varying levels of perceptual load. They found that high perceptual load reduced auditory evoked responses in early- (reflected by a load-dependent modulation in the aM100 response) and late processing components (reduction in the P3 amplitude) compared to when the search task had a low load on perceptual resources. There is also fairly robust evidence from neuroimaging studies in the visual domain demonstrating perceptual load effects at the neural level. For example, increasing perceptual load has been associated with a reduction in brain activity in the visual cortex (Pinsk, Doniger, & Kastner, 2004; Rees, Frith, & Lavie, 1997; Schwartz et al., 2005; Yi, Woodman, Widders, Marois, & Chun, 2004), and reduced neural activity in the posterior parietal cortex and particularly the inferior parietal sulcus (Goldstone, 1998; Wojciulik & Kanwisher, 1999). Interestingly, Mitchell and Cusack (2008) demonstrated that the inferior parietal sulcus is characterized by a capacity-limited response to perceptual load, such that when the number of tracked items exceeds individual capacity, neural activity in the IPS asymptotes. This suggests that processing of extraneous visual information depends on the allocation of limited-capacity resources that is mediated by modulations in cortical excitability in parietal and visual areas, potentially reflecting a neural marker for perceptual capacity.

Functional magnetic resonance imaging (fMRI) has also been used to investigate perceptual load effects at the neural level in individuals with ASD (Ohta et al., 2012). During performance of a visual search task at different levels of perceptual load, brain responses evoked by irrelevant visual distractors were measured in adults with ASD and a neurotypical comparison group. It was found that increasing perceptual load reduced activation in visual cortices for both groups, yet this reduction in activity at high perceptual load was significantly more pronounced for typically developing adults than for adults with a diagnosis of ASD, suggesting that visual cortex activity in response to task-irrelevant distractors was less affected by the perceptual load of the task in individuals with ASD. These results are in line with the increased perceptual capacity account and prior behavioural findings. Another possible neurophysiological mechanism that could underlie increased perceptual capacity in ASD is larger extrastriate population receptive fields (pRF). Schwarzkopf, Anderson, de Haas, White, and Rees (2014) measured response selectivity of the visual cortex in individuals with and without ASD by fitting a pRF model to fMRI signals in response to flickering bar stimuli traversing the visual field. They found significantly larger extrastriate pRF in adults with ASD compared to TD adults, suggesting that this may reflect hyper-excitability of the visual cortex in ASD.

A number of challenges remain for future work in understanding the extent, causes and consequences of increased perceptual capacity in ASD. For example, it is still unclear whether an increased capacity is specific to ASD and not found in other neurodevelopmental disorders, although there is evidence that at least it is not typical of those with a primary diagnosis of ADHD. Existing studies have also only been carried out with intellectually able individuals, meaning that we do not yet know whether there are differential perceptual load effects for other ASD subgroups. Is an increased perceptual capacity seen across the spectrum of IQ and severity? It will also be important to trace in more detail the developmental trajectory of increased perceptual capacity in ASD; identifying neural correlates as well as devising behavioural tasks appropriate for infants and children. Finally, a future challenge will be to evaluate current educational and working environments in order to limit the disadvantages yet also exploit the advantages of increased perceptual capacity in ASD.

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Table 1 Sample demographics by diagnostic group

Group	**Statistic**	**CA** (years : months)	**Raven's Score**	**SCQ score**
ASD (n= 15)	M	14:8	44.9	26
	SD	1:0	6.2	4.5
	Range	12:5 – 17:5	33 - 56	21 - 35
TD (n= 17)	M	14:5	45.8	
	SD	1:1	4.6	
	Range	11:7 – 15:5	36 - 54	

Note:
CA = Chronological Age
SCQ = Social Communication Questionnaire

Figure 1 Example trial with an auditory tone present in noise at set size four

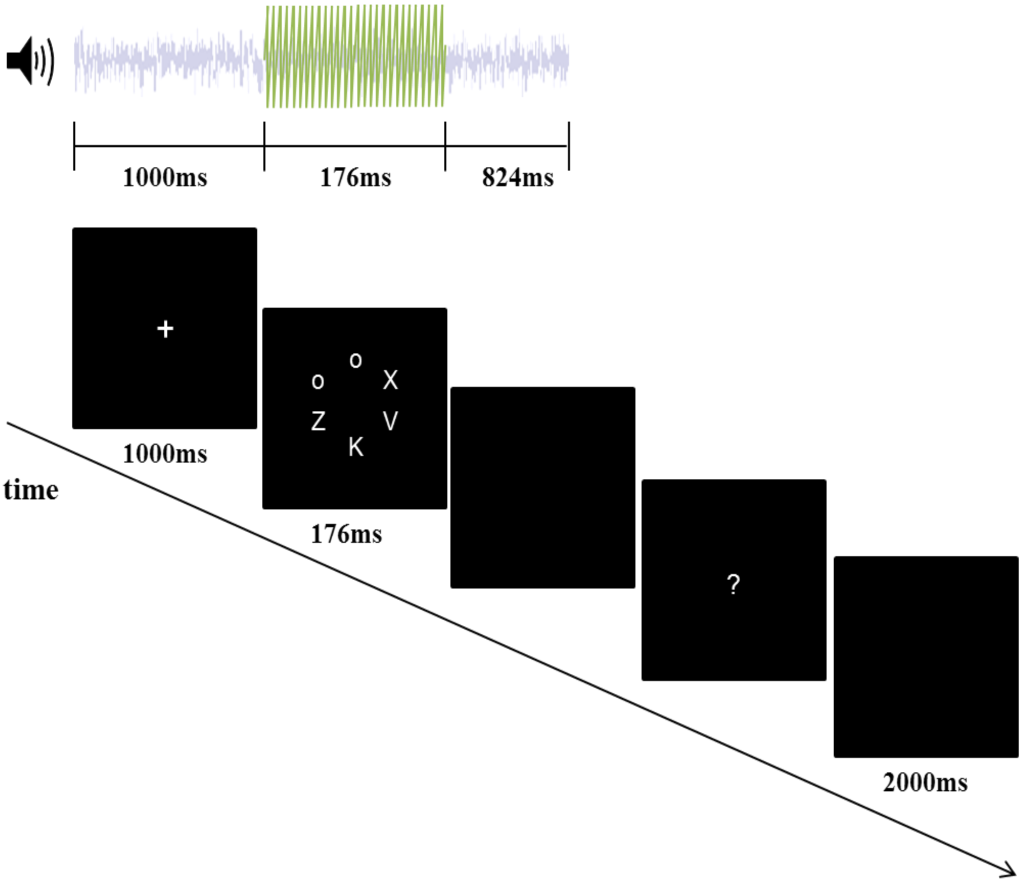

Table 2 Measures of task performance according to diagnostic group and set size

		Reaction time (in ms)		**Error rate** (in %)		**False alarm rate** (in %)		**Response bias** (c)	
Set size	**Statistic**	**ASD**	**TD**	**ASD**	**TD**	**ASD**	**TD**	**ASD**	**TD**
1	M	1075	977	6	6	10.3	12.4	-.03	0.03
	SD	(160)	(366)	(10)	(8)	(11.1)	(14.6)	(.37)	(.29)
2	M	1272	1150	4	6	11.0	12.4	0.07	0.03
	SD	(205)	(344)	(2)	5	(13.5)	(8.9)	(.37)	(.29)
4	M	1432	1316	14	15	14.4	18.7	-0.13	0.06
	SD	(223)	(353)	(6)	(8)	(11.6)	(11.2)	(.34)	(.30)
6	M	1522	1346	29	26	22.7	17.4	-0.09	0.25
	SD	(185)	(322)	(10)	(8)	(12.0)	(14.6)	(.36)	(.38)

Note: M = Mean; SD = Standard Deviation

Figure 2 Auditory detection rate (in %) as a function of set size and group (error bars: 95% CI)

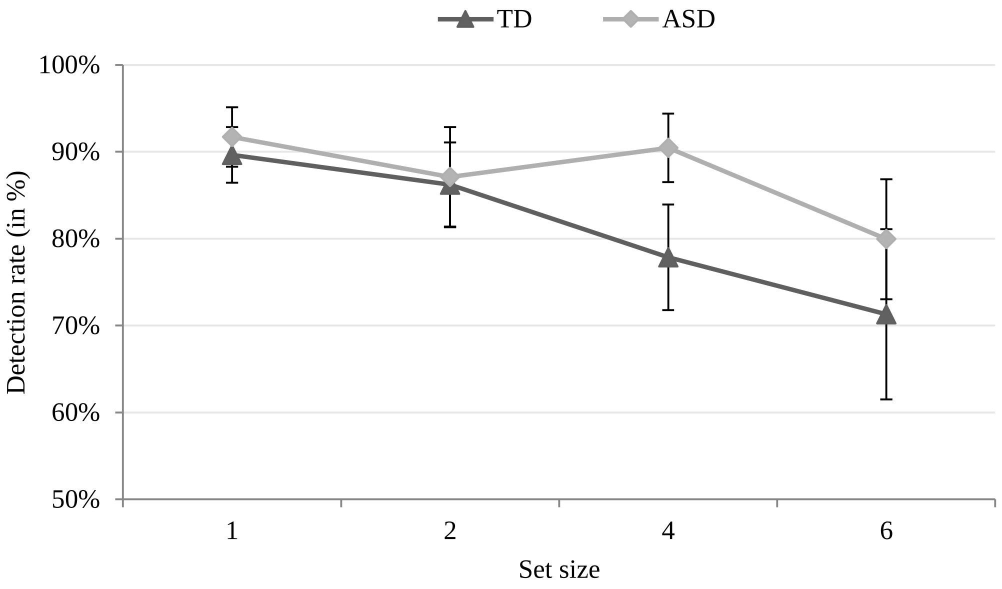

Figure 3 Auditory detection sensitivity (d’) as a function of set size and group (error bars: 95% CI)