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A sound advantage: Increased auditory capacity in autism

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ABSTRACT

Autism Spectrum Disorder (ASD) has an intriguing auditory processing profile. Individuals show enhanced pitch discrimination, yet often find seemingly innocuous sounds distressing. This study used two behavioural experiments to examine whether an increased capacity for processing sounds in ASD could underlie both the difficulties and enhanced abilities found in the auditory domain. Autistic and non-autistic young adults performed a set of auditory detection and identification tasks designed to tax processing capacity and establish the extent of perceptual capacity in each population. Tasks were constructed to highlight both the benefits and disadvantages of increased capacity. Autistic people were better at detecting additional unexpected and expected sounds (increased distraction and superior performance respectively). This suggests that they have increased auditory perceptual capacity relative to non-autistic people. This increased capacity may offer an explanation for the auditory superiorities seen in autism (e.g. heightened pitch detection). Somewhat counter-intuitively, this same 'skill' could result in the sensory overload that is often reported – which subsequently can interfere with social communication. Reframing autistic perceptual processing in terms of increased capacity, rather than a filtering deficit or inability to maintain focus, increases our understanding of this complex condition, and has important practical implications that could be used to develop intervention programs to minimise the distress that is often seen in response to sensory stimuli.

1. Introduction

Autism Spectrum Disorder (ASD) is most often associated with social communication difficulties and the presence of rigid and repetitive behaviors (APA, 2013). Alongside these symptoms, however, are unusual perceptual and attentional processes that are increasingly being considered as central to the condition (Taylor et al., 2013). Indeed, altered sensory processing was included in the most recent set of diagnostic criteria (DSM-5; American Psychiatric Association, 2013), highlighting the timely nature of research in this area. Existing research on attention and perception in autism has revealed an intriguing profile of strengths and difficulties. Autistic individuals show evidence of superior discrimination abilities and yet also cases of increased distractibility (see Ames & Fletcher-Watson, 2010 for a review).

One possible explanation for this diverse set of observations is that autistic individuals have an increased perceptual capacity relative to neurotypical individuals which allows them to process more information at any given time. This hypothesis is based on the Load Theory of Attention and Cognitive Control (Lavie, 2005), which asserts that the extent of distractor processing depends on the level of perceptual load in a given task. When perceptual load is high, such that the task exhausts perceptual capacity, irrelevant distractor processing is eliminated. Conversely, on tasks with low perceptual load, the spare capacity that remains will automatically 'spill over' and result in irrelevant distractor processing. Hence, with respect to autism, an increased capacity could underlie both superiorities and deficits: in some cases the additional capacity would be useful and promote enhanced task performance, and in other cases the same extra capacity would result in task-irrelevant processing, thereby increasing susceptibility to distraction. Our previous work on autistic visual attention has shown evidence for both these hypotheses. First, on selective attention tasks autistic adults and children demonstrated increased processing of irrelevant peripheral information under high levels of perceptual load, compared to neurotypical children and adults, despite having intact performance on the central attention task (Remington, Swettenham, Campbell, & Coleman, 2009; Swettenham et al., 2014). Second, on a dual-task paradigm where participants were asked to perform a central search task and a secondary detection task, autistic adults showed equivalent performance on the central task and superior performance on the detection task,

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particularly under high levels of load (Remington, Swettenham, & Lavie, 2012) Together, these studies suggest that autistic individuals have a greater perceptual capacity – at least in the visual domain.

There are many reasons to believe that the phenomenon should extend to the auditory domain. There is a great deal of evidence suggesting altered auditory processing in autism (see O'Connor, 2012 for review). For example, autistic individuals appear to show superior pitch perception (Bonnel et al., 2003) and better identification of, and memory for, musical notes (Heaton, Hermelin, & Pring, 1998). Akin to the findings in the visual domain, there also seems to be a local-processing bias with auditory stimuli. Bouvet, Simard-Meilleur, Paignon, Mottron, and Donnadieu (2014) used hierarchical stimuli to demonstrate that autistic individuals showed intact global processing, but superior local processing and reduced global interference when compared to neurotypical adults. Indeed the Enhanced Perceptual Functioning model of autism (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006), which consolidated a number of experimental findings to propose an explanation for the observed superior attentional behavior in the condition, highlighted increased levels of processing both visual and auditory stimuli. The importance of this line of auditory research is further emphasized when considering the difficulties that seem to accompany these areas of ability. Autistic individuals often show hypersensitivity to certain sounds, leading to great distress in noisy environments (Gomes, Pedroso, & Wagner, 2008). Clinical observations and testimonies reveal the high levels of anxiety that can surround auditory processing (Grandin, 1995, 1997). This, in turn, leads to a variety of coping behaviors that range from grimacing and ear shielding to screaming (Attwood, 1998).

We suggest that both the strengths and difficulties seen with respect to auditory processing in autism might be subserved by increased perceptual capacity. For example, being able to process more auditory information at any given time could offer an advantage on auditory detection tasks but also lead to an overwhelming level of arousal. Here, we use two different attention paradigms to test auditory capacity in autism. To our knowledge, this is the first time that auditory capacity has been directly assessed in autistic individuals.

2. General methods

2.1. Participants

Twenty autistic adults and 20 neurotypical adults (aged 17–34 years) were recruited through social networking websites and autism support groups around London. Sample size was determined by previous research using similar paradigms (Remington, Campbell, & Swettenham, 2012). Participants in the ASD group had received a clinical diagnosis of autism from a trained, independent clinician who used the criteria listed in the Diagnostic and Statistical Manual of Mental Disorders, Fourth or Fifth Edition (American Psychiatric Association, 1994, 2013) and reached threshold for an ASD on Module 4 of the Autism Diagnostic Observational Schedule (ADOS; Lord, Rutter, DiLavore, & Risi, 2002). Three participants with a clinical diagnosis of ASD did not meet the ADOS criteria and were therefore excluded. The remaining group of autistic participants showed a mean ADOS score of 9.8 (SD = 2.0). None of the participants reported having any other mental or neurological disorder.

In order to improve group matching, one neurotypical individual was excluded due to an extremely high IQ (greater than 2 S.D. above the mean) (see Table 1 for resulting participant groups). The resulting 17 ASD (13 males) and 19 neurotypical adults (11 males) did not differ in IQ, as measured by the Wechsler Abbreviated Scale for Intelligence – Second Edition (Wechsler, 2011) (mean ASD IQ: 110, SD = 13.0; mean neurotypical IQ: 114.5, SD = 10.0; $p = 0.26$). The autism group was significantly older than the neurotypical group (mean ASD group age: 30 years, SD = 3.6; mean neurotypical group age: 23.6 years, SD = 5.0; $p < 0.001$). All participants had their audiometric thresholds measured prior to taking part in the study, following the procedure recommended by the British Society of Audiology (2004). Audiometric air-conduction thresholds were measured for the left and right ears for octave-spaced frequencies from 250 to 8000 Hz using a Kamplex Diagnostic Audiometer AD17 and Telephonics TDH39P headphones. All participants had normal hearing, defined as audiometric thresholds equal to or better than 15 dB HL for all frequencies between 250 and 8000 Hz in both ears. Participants took part in both Experiments in the same testing session, and the task order was counterbalanced.

2.2. Ethics

All procedures were carried out in accordance with the British Psychological Society code of ethics, and were approved by the UCL Institute of Education Ethics Committee. All participants gave written informed consent prior to participation.

2.3. Apparatus

The experiments were presented using OpenSesame (version 2.8.3) experimental software (Mathôt, Schreij, & Theeuwes, 2012) on a Dell Latitude 15 5000 series laptop computer using Audio-Technica ATH-M30X Professional Monitor Headphones.

3. Experiment 1

In Experiment 1, we used an auditory dual-task paradigm previously developed by the authors (Fairnie, Moore, & Remington, 2016). The primary task was an auditory search task, and the secondary task was an auditory detection task. Participants were asked to listen to an array of animal sounds, presented simultaneously, that appeared to emanate from different positions located on an imaginary semi-circle around their head. One sound was the target (a dog bark or a lion roar) and the others were non-target animals (duck, cow, chicken, rooster, crow). The perceptual load of the task was altered by varying the number of non-target sounds in the array to create four set sizes: one (target alone), two (target plus one non-target sound), four (target plus three non-target sounds) and six (target plus five non-target sounds). In addition, a non-animal sound (a car, the critical stimulus, CS) was presented on 50% of trials concurrently with the array of animal sounds. The CS was positioned on an imaginary semi-circle around the listener's head, with greater eccentricity than the animal sounds (see Fig. 1). All sounds had a duration of 100 ms (including a 10 ms fade in and a 10 ms fade out). The position of each sound in space was set by manipulating interaural amplitude and time differences, and overall level differences. Previous research has confirmed that participants do indeed perceive the elements to be spatially distinct (Fairnie et al., 2016). For full temporal and spectral properties of the sounds, see Table S1 in supplementary materials. Participants were told that they would hear a number of animal sounds concurrently, and were asked to indicate with a keypress (as quickly as possible) whether the dog or lion sound was present. They were informed that on some trials there would also be a car sound, and that after responding to the main task (dog/lion) they should indicate whether the car sound was present or absent. Visual prompts on the screen reminded participants when, and how, to respond.

Table 1
Mean RT (ms) and mean percentage error rates on the auditory search task for each group and set size. Standard deviations are presented in parentheses.

	Set Size 1		Set Size 2		Set Size 4		Set Size 6	
	Mean RT	% Errors	Mean RT	% Errors	Mean RT	% Errors	Mean RT	% Errors
Autism group	895 (228)	5 (7)	1028 (233)	9 (9)	1108 (238)	12 (10)	1131 (236)	12 (10)
Typical group	927 (199)	4 (5)	1099 (214)	10 (10)	1093 (219)	16 (11)	1149 (250)	16 (13)

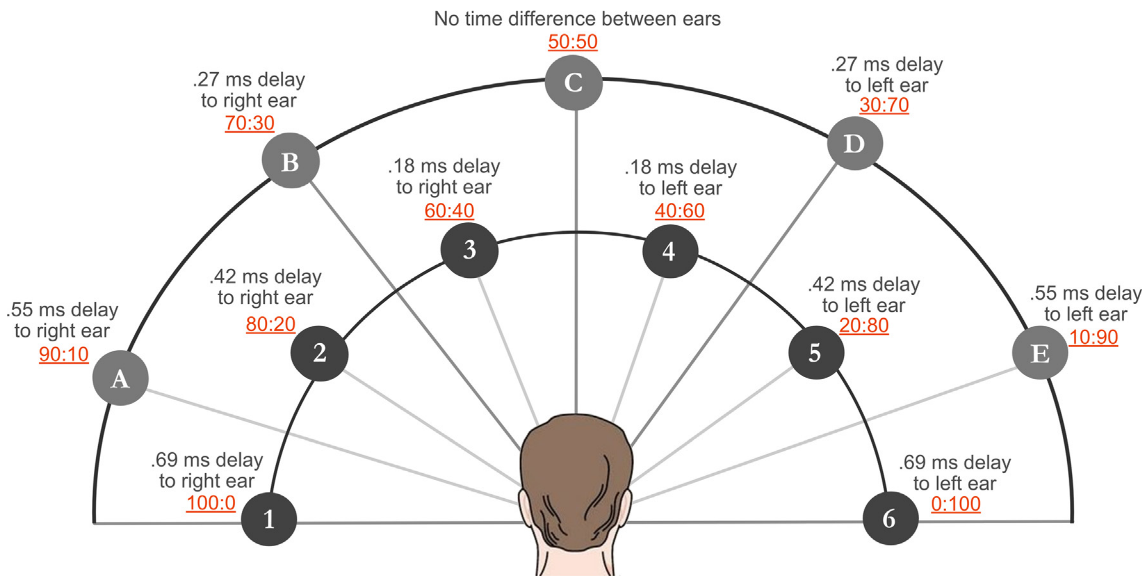

Fig. 1. Interaural time differences (grey text) and interaural amplitude differences (underlined text indicating the relative amplitudes at the left and right ears) for the experimental stimuli in Experiment 1. Numbered circles indicate possible positions for the target and non-target auditory stimuli, while circles with letters indicate possible positions for the CS. Sounds on the outer ring were presented at a level 9 dB lower than those in the inner ring.

Following a practice set of 16 trials, participants completed 288 experimental trials. These were split into two blocks of trials for each set size (eight blocks in total). The blocks were presented in a counterbalanced order (one of each set size, followed by the reverse order; such that a participant who began – for example – with a block of set size two trials would end the experiment with the second block of set size two trials). Participants were able to take breaks between blocks if necessary. The entire task lasted approximately 30 min. Following the experimental blocks, a control block of 64 trials (16 for each set size, 50% with the CS) was presented where participants were asked to perform only the secondary CS detection task (and not the dog/lion search task) in order to ensure that the CS was audible under conditions of full attention. This block was necessary to confirm that any inability to detect the CS in the experimental task was due to auditory load of the primary task and not a general inability to detect the car sound. Accuracy and reaction time (RT) were recorded by the computer program for each trial.

3.1. Results

3.1.1. Primary search task

Percentage error rates were calculated for each group at each level of perceptual load (see Table 1). A repeated-measures analysis of variance (ANOVA), with group and load as factors, indicated that there was a significant main effect of load; error rates increased as set size increased ($F(3,102) = 19.200$, $p < 0.001$, $\eta p^2 = 0.361$). However, accuracy levels remained high with a rate of over 83% for all set sizes. No other main effects or interactions were significant ($p > 0.2$). Mean RT for each group at each set size was calculated for trials on which a correct response was provided on the dog/lion search task and when the RT was less than 1.5 s. A repeated-measures ANOVA revealed a significant main effect of load: RT increased with set size ($F(3,102) = 48.185$, $p < 0.001$, $\eta p^2 = 0.586$). There was no significant main effect of group ($p = 0.715$) or interaction between group and load ($p = 0.228$).

The increase in RTs and error rates with set size suggests that perceptual load was manipulated effectively. Crucially, the lack of significant group effects and interactions indicate that both groups were performing at similar levels on the primary task.

3.1.2. Secondary detection task

Trials were excluded from the detection task analyses if the search response was incorrect. Detection sensitivity for the CS (taking into account hits and false alarms) was calculated for each participant at each set size (see Fig. 2). As the hits and false alarm rates were not normally distributed, A (a corrected version of a' (Zhang & Mueller, 2005) – the non-parametric equivalent of d'- was used. Note that A takes values between zero and one, where 0.5 typically indicates that signal cannot be distinguished from noise and one indicates perfect detection (Stanislaw & Todorov, 1999). A repeated-measures ANOVA indicated a significant main effect of set size ($F(3,102) = 59.644$, $p < 0.01$, $\eta p^2 = 0.637$), corresponding to a reduction in the ability to detect the CS as the load of the primary task increased. There was no overall main effect of group ($p = 0.262$). There was, however, a significant interaction between group and set size ($F(3,102) = 13.703$, $p < 0.001$, $\eta p^2 = 0.287$), suggesting that load had a differing impact on the detection rates of the two groups.

Inspection of Fig. 2 suggests that the significant interaction was driven by the greater drop in A for the neurotypical group. To further investigate the source of this interaction, planned comparisons were carried out between the groups at each set size. Independent *t*-tests confirmed this pattern: groups were equivalent at lower set sizes (all $p > 0.2$) but there was a significant group

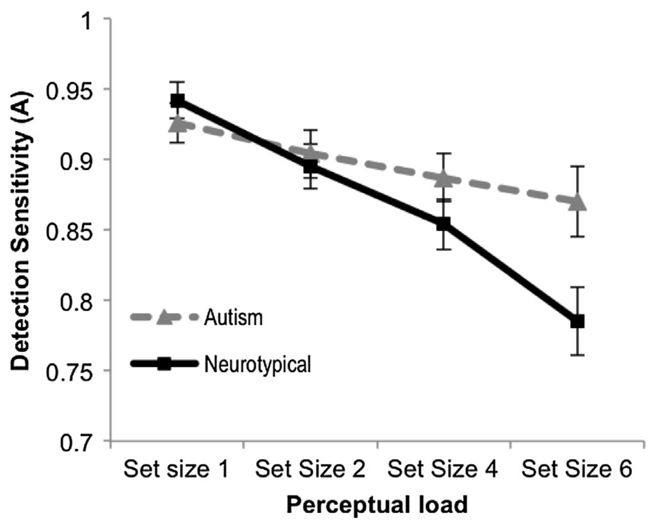

Fig. 2. Detection sensitivity (A) for both groups (autism and neurotypical) at each set size. Error bars represent one standard error of the mean.

difference at set size 6 (ASD group mean A = 0.87, neurotypical group mean A = 0.79, p = 0.02).

Response Bias (β) was also calculated for both groups at each level of load. There was no significant main effect of load (p = 0.065) or group (p = 0.137), and no significant interaction between group and load (all p = 0.531). The tendency to respond 'CS present' did not change under different levels of load, and did not differ between the groups.

3.1.3. Control block

All participants were able to detect the CS to a high degree of accuracy (81% or higher) under each load condition, confirming that failures on the experimental trials were due to the demands of the primary task. There was no main effect of group (p = 0.446) and no interaction between group and load (p = 0.663). Importantly, there was no impact of load on accuracy levels in the control block (p = 0.569). Mean detection rates were 95.4%, 95.9%, 96.4% and 95.3% for set sizes 1, 2, 4 and 6, respectively. This showed that the CS was easily and equally detected in all load conditions when there was no primary task to perform. This was vital to confirm that the car was separable from the animal sounds and not treated as an additional non-target item in the array. In addition, the high level of ability in both groups under conditions of full attention suggest that the differing performance on the experimental blocks is not due to overall group differences in stream segregation ability.

4. Experiment 2

Experiment 2 used a 69 s auditory scene, recorded binaurally by Dalton and Fraenkel (Dalton & Fraenkel, 2012), that conveys a realistic sense of three-dimensional auditory space. In the scene, four characters can be heard moving around the room and preparing for a party (two women wrapping a present and two men preparing food and drink). After 33 s, an additional male character entered from the back of the room and walked through the scene, passing by the left of the head, continually repeating the phrase "I'm a gorilla" for 19 s. This task was chosen to examine whether the additional perceptual capacity demonstrated in Experiment 1 would result in increased processing of task-irrelevant information in conditions of relatively low perceptual load. In this case, we predicted that more autistic participants would notice the auditory gorilla, while still maintaining focus on the central task conversations in order to correctly answer questions about the content of the scene.

4.1. Procedure

Participants worked through the experiment at their own pace by pressing the Spacebar to advance through each stage. Participants were asked to listen carefully to the binaural scene and pay specific attention to the women's conversation in order to answer some questions immediately after the sound clip. At the end of the scene, participants were asked to respond via a keypress to the following questions: (1) Did you hear anything unusual that didn't fit in with the scene? (2) Did you hear anyone other than the four people preparing for the party? Those who answered 'yes' to either question were asked to give the experimenter further details about what they had heard. The experimenter noted down this information and coded whether the participant heard the "I am a gorilla" speech or not. Participants were then asked a question about the content of the scene ("Did the women choose silver or pink wrapping paper?") to ensure that all participants were attending to the central conversation and understood the task demands. Crucially, we also examined whether participants could hear the 'gorilla' under conditions of full attention (to ensure that any failures to notice the 'gorilla' in the experimental trial were due to a lack of attention rather than auditory processing difficulties). Participants were asked to listen to the scene again, but to focus on the men's voices and listen for 'anything unusual'. Following the scene, the same questions were asked and it was noted down whether the participant was now able to detect the 'gorilla'. The experiment took less than ten minutes to complete and participants were fully debriefed at the end of the experiment.

4.2. Results

Two neurotypical adults failed to detect the gorilla stimulus on this trial, and their data were excluded. Note that the fact that only two out of 36 participants failed to notice the gorilla stimulus on the control trial indicates that the stimulus was clearly audible under conditions of full attention. The remaining 17 ASD and 17 neurotypical adults were included in subsequent analyses.

All participants correctly answered the content question, demonstrating that they were all attending to the central conversation in the scene. Table 2 presents the detection rates for the 'gorilla' in each group. In the neurotypical group, only 12% of the participants spontaneously mentioned the 'gorilla' in response to the first question. In contrast, almost half of the participants in the ASD group (47%) noticed the 'gorilla'. This resulted in a significant group difference ($X^2 = 5.1$, df = 1, p = 0.02) on this test of auditory attention.

5. Associations between task-performance on experiments 1 and 2

Our hypothesis asserts that the same increased capacity may underlie superior performance on Experiment 1 and increased awareness of distractors on Experiment 2. To further explore this, a repeated-measures ANOVA was carried out to examine whether performance on the detection task in Experiment 1 differed between those who noticed the 'gorilla' in Experiment 2, and those

Table 2
Detection rates for the unexpected gorilla stimulus in each group.

	Detected 'gorilla' stimulus	Did not detect 'gorilla' stimulus
Autism	8	9
Typical	2	15

who did not, with 'noticed' as a between group factor and 'detection sensitivity' as the within group factor (diagnostic group was collapsed for this analysis). As expected, a significant main effect of set size was seen ($F(3,102) = 30.423$, $p < 0.01$, $\eta p^2 = 0.472$), corresponding to a reduction in the ability to detect the car stimulus as the load of the primary task increased. There was also a significant main effect of group (noticed vs. not noticed) ($F(1,34) = 4.797$ $p = 0.035$, $\eta p^2 = 0.124$), reflecting the fact that those who noticed the 'gorilla' produced higher overall detection rates in Experiment 1. Crucially, there was a significant interaction between group and set size ($F(3,102) = 2.949$, $p = 0.036$, $\eta p^2 = 0.080$), suggesting that load had a reduced impact on the detection rates of those who noticed relative to those who failed to notice the 'gorilla' (see Fig. 3).

To further explore whether a common mechanism was seen for autistic and non-autistic participants, those who did and did not notice the gorilla were also split by diagnostic group (see Fig. 4). Due to the small numbers in each group (e.g. only two in the neurotypical group who noticed the gorilla) no statistical analyses were performed. However, inspection of the data revealed parallel trajectories within each diagnostic group, with those who noticed performing better than those who did not in each case. In addition, both autistic groups (noticed and missed the gorilla) showed a slower decline in detection sensitivity as perceptual load increased compared to the typical groups.

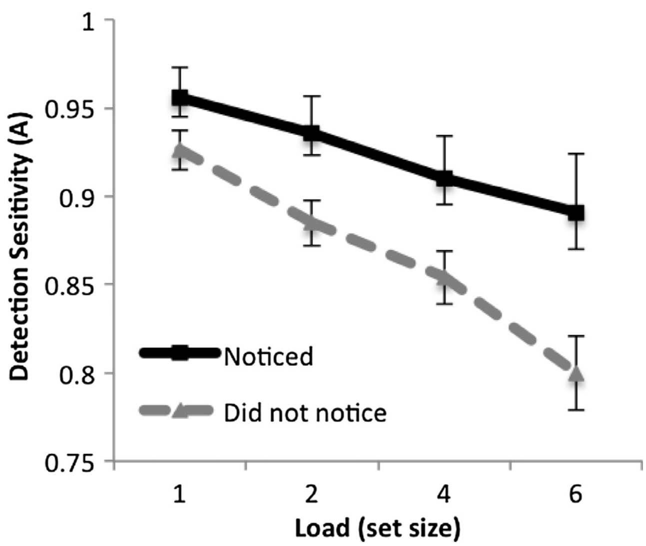

Fig. 3. Detection sensitivity (A) on Experiment 1 for participants who noticed and did not notice the 'gorilla' at each set size (Experiment 2 results). Error bars represent one standard error of the mean.

6. Discussion

The results reported here provide evidence, from two separate attention tasks, that auditory perceptual capacity is increased in autistic adults. In the first, a dual-task paradigm with different levels of perceptual load, participants were asked to identify an auditory target and also perform a secondary auditory detection task. Both the autistic and neurotypical groups performed the primary target identification task to the same level (no significant group differences in RT or error rates). However, whereas neurotypical performance on the detection task dropped as load increased, autistic participants remained able to detect the critical stimulus under high levels of auditory load. This is reflected in significantly better performance by the autistic participants on the secondary task at the highest level of load. As such, these results suggest that the autistic adults have increased auditory capacity that, in this particular case, is an asset: capacity is available to perform both the primary and secondary aspects of the task.

In the second experiment, the same participants' auditory capacity was tested on a more ecologically valid task that involved a binaural recording of an auditory scene. In this selective attention task, participants were asked to pay attention to a conversation between two women and answer a subsequent question about what they had said. In the middle of the scene an unexpected and unusual stimulus was presented: a man walking through the scene repeatedly saying "I'm a gorilla". Immediately after listening to the auditory scene, participants were asked whether they had heard this unusual event. As in Experiment 1, both groups were able to successfully complete the primary task (answering the question

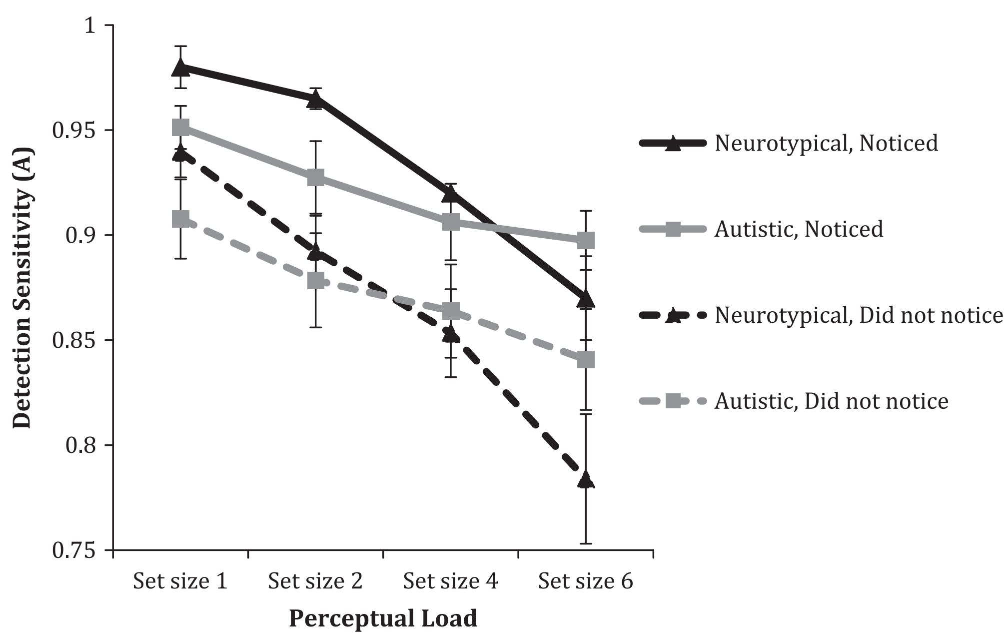

Fig. 4. Detection sensitivity (A) on Experiment 1 for participants who noticed and did not notice the 'gorilla' at each set size (Experiment 2 results) split by diagnostic group. Error bars represent one standard error of the mean.

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correctly about the women's conversation). With respect to the 'gorilla', 88% of neurotypical participants failed to notice the unexpected stimulus (replicating results of inattentional deafness in the mainstream population (Dalton & Fraenkel, 2012). Conversely, 47% of the autistic participants were aware of the 'gorilla', suggesting that they had the capacity to attend to the additional character as well as the central scene conversation. In this case, the increased capacity manifests as increased susceptibility to distraction, though not at the expense of task-performance (the 'gorilla' was task-irrelevant but did not conflict with the target response).

Our demonstration that auditory perceptual capacity appears to be enhanced in autism may allow a reinterpretation of some of the previous literature on auditory processing. Past research has reported a diverse set of atypicalities with respect to autistic audition, assessing aspects that range from basic physical properties (such as pitch) to more complex components (such as prosody) (see 8 for a review). Here, when considering auditory perceptual capacity, it is most relevant to focus on low-level auditory processing. It has been noted that a much higher proportion of autistic individuals show absolute (or 'perfect') pitch (5%, compared to 0.01–0.05% in the general population, (Rimland & Fein, 1988). Similarly, autistic children were more accurate at identifying and remembering musical notes (e.g. Heaton, 2003) and pitch discrimination (e.g. Bonnel et al., 2003; Heaton, 2005; Jarvinen-Pasley, Wallace, Ramus, Happe, & Heaton, 2008; O'Riordan and Passetti, 2006). In adolescents and adults on the autism spectrum, these advantages were primarily noted for those individuals who also displayed language difficulties (Bonnel et al., 2010; Heaton, Williams, Cummins, & Happe, 2008; Jones et al., 2009). In addition,

In many cases, however, this increased ability appears to be accompanied by a feeling of over-arousal (an overwhelming level of sensory input) or hyperacusis (where seemingly innocuous sounds are perceived as distressing) (Gomes et al., 2008). In the few studies examining loudness perception (despite many clinical observations), autistic children showed lower loudness discomfort thresholds (Khalfa et al., 2004) and were more likely to show discomfort to sounds below 80 dB(HL) compared to neurotypical individuals (Rosenhall, Nordin, Sandstrom, Ahlsen, & Gillberg, 1999). However, on tests of volume discrimination, autistic and non-autistic performance was equivalent (Bonnel et al., 2010). Closely related to this work, other research suggests autistic people may be more susceptible to distraction from auditory stimuli (Teder-Salejarvi, Pierce, Courchesne, & Hillyard, 2005) and appear to have a wider auditory filter than non-autistic individuals (Plaisted, Saksida, Alcantara, & Weisblatt, 2003). Consequently, there is mixed evidence regarding the ability of autistic individuals to extract speech from background noise, with some suggesting a reduced ability (Alcantara, Weisblatt, Moore, & Bolton, 2004) based on difficulties with stream segregation (Lepisto et al., 2009), while others highlight increased stream segregation abilities (Lin, Yamada, Komine, Kato, & Kashino, 2015). This issue is of particular interest when considering any links between auditory processing and social abilities.

In light of our current findings, we suggest that increased auditory capacity might, in part, underlie the superior performance observed on tasks of auditory processing. If autistic individuals were able to process more information at any given time, performance would be enhanced on tasks that require participants to memorize and discriminate pitch and melodies. Conversely, this same increase in capacity could be detrimental to task performance in other situations: giving rise to additional auditory processing that results in distractibility, over-arousal and hyperacusis. Indeed, our cross-experiment analyses suggested that, irrespective of diagnosis, performance on the two tasks were related: those who noticed the auditory 'gorilla' also showed greater ability to detect the car stimulus under high levels of load. As such, increased auditory capacity could offer an explanation for the mixed picture of superiorities and difficulties seen with respect to auditory processing in autism.

At this point, it is also important to consider the potential neural mechanisms that may underlie the increased auditory capacity. Electrophysiological studies (using various oddball paradigms) have identified shorter N1 latencies to simple tones (Ferri et al., 2003; Oades, Walker, Geffen, & Stern, 1988), greater mismatch negativities (MMN) to pitch change and shortened MMN latencies to pitch changes (Gomot, Giard, Adrien, Barthelemy, & Bruneau, 2002) in children with autism, suggestive of more efficient early auditory processing components in autism. However, findings in this area have been mixed, with others showing the opposite pattern in response to more complex tones (see Haesen, Boets, & Wagemans, 2011, for discussion). On a neuroanatomical level, it has been shown that grey matter thickness was greater in the Heschl's gyri of autistic individuals (compared to neurotypical controls), a region in the primary auditory cortex which is the first to process incoming auditory stimuli (Hyde, Samson, Evans, & Mottron, 2010). This perhaps reflects an increased availability of low-level auditory processing resources. Interestingly, this increased cortical thickness was also seen in other neural regions, including the visual and parietal cortices. This is therefore in line with our previous research showing increased visual perceptual capacity and superior performance on visual attention tasks in autism (Remington et al., 2012).

The importance of understanding of the mechanisms underlying autistic sensory processing should not be underestimated, given that it often causes a great deal of distress for those with the condition. In addition, difficulties with these basic perceptual processes risk disrupting numerous other areas of functioning as they may also reduce access to learning and employment opportunities.

Interestingly, research that has examined links between auditory discrimination ability and self-report sensory symptoms identified some associations between increased performance on auditory duration discrimination tasks and an increased level of reported sensory symptoms (Jones et al., 2009). However, in the same study intensity discrimination ability seemed to show the opposite relationship: with lower levels of sensory symptoms seen in those who were able to better discriminate between different auditory intensities.

While it is clear that further research is warranted, our findings reframe the altered behaviors in terms of increased capacity, rather than a filtering deficit or inability to maintain focus. This reinterpretation fits well with anecdotal reports from autistic people who describe their ears being "like microphones", picking up all the surrounding sounds indiscriminately (Grandin, 1996). Our results may also offer suggestions to ameliorate auditory difficulties. To reduce the impact of unwanted distraction in autism that results from increased capacity, we need to both reduce background noise but also increase the level of perceptual load in a given task (to exhaust more of the processing capacity with task-relevant information). This somewhat counterintuitive prediction is at odds with the common view that tasks and stimuli should be simplified for autistic children in schools. It is also a prediction that needs to be carefully applied in order to avoid over-arousal. As such, we view the present findings as the starting point for an interesting line of subsequent experimental and applied research.

Author contributions

Both authors developed the study concept, contributed to study design, created the tasks and carried out data collection and analyses. A. Remington drafted the manuscript and J. Fairnie provided critical revisions. Both authors approved the final version of the manuscript for submission.

Author Note

Jake Fairnie is now at UCL Institute of Cognitive Neuroscience.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.04.002.

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