The relationship between auditory processing and restricted, repetitive behaviors in adults with autism spectrum disorders

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Abstract

Current views suggest that autism spectrum disorders (ASD) are characterised by enhanced low-level auditory discrimination abilities. Little is known, however, about whether enhanced abilities are universal in ASD and how they relate to symptomatology. We tested auditory discrimination for intensity, frequency and duration in 21 adults with ASD and 21 IQ and age-matched controls. Contrary to predictions, there were significant deficits in ASD on all acoustic parameters. The findings suggest that low-level auditory discrimination ability varies widely within ASD and this variability relates to IQ level, and influences the severity of restricted and repetitive behaviours (RRBs). We suggest that it is essential to further our understanding of the potential contributing role of sensory perception ability on the emergence of RRBs.

Keywords: Autism; auditory processing; restricted, repetitive behaviours; sensory processing

Abbreviations: Autism Spectrum Disorders (ASD), Restricted and repetitive behaviours (RRBs), Stereotyped Behaviours and Restricted Interests (SRBI), Auditory Discrimination Task (ADT), Autism Diagnostic Observation Schedule (ADOS), Verbal Intelligence (VIQ), Performance Intelligence (PIQ), Full Scale Intelligence (FIQ), Two-interval forced-choice (2IFC), Typical group (TYP), Mismatch Negativity (MMN), Magnetic Mismatch Field (MMF)

From the earliest descriptions, unusual sensory experiences have been reported as characterising autism spectrum disorders (ASD) (Asperger, 1944; Kanner, 1943). Sensory symptoms in ASD include atypical sensory sensitivities (i.e., hyper / hypo), which seem to be particularly prevalent in the auditory domain (Dahlgren and Gillberg, 1989; Hermelin and O'Connor, 1970; Ornitz, 1974; Rosenhall, Nordin, Sanstrom, Ahlsen, and Gillberg, 1999). Sensory atypicalities, and in particular anomalous auditory functioning, are beginning to be recognised as a significant contributing factor in ASD (e.g., Jones et al., 2009).

To date, there are mixed findings regarding low-level auditory processing abilities in ASD (for a review see Haesen, Boets and Wagemans, 2011; O'Connor, 2012; Samson, Mottron, Jemel, Belin, and Ciocca, 2006). The contradictory reports may be due to the variability in the populations studied. For example, age and IQ level have been shown to affect frequency discrimination (Heaton, Williams, Cummins and Happé, 2008; Jones et al., 2009) in ASD. Another explanation for the discrepancy in findings may be due to the considerable variation in paradigms used (Marco, Hinkley, Hill and Nagarajan, 2011). Auditory perceptual abilities in ASD may depend on the nature and complexity of the stimulus and the task (Bertone Mottron, Jelenic, and Faubert 2005; Samson et al., 2006; Mongillo et al., 2008). Specifically, Samson et al., (2006) have suggested that auditory tasks comprising simple material (pure tones) and low-level operations (e.g., detection, labelling) that are processed in primary auditory cortical regions are characterised by enhanced performance. In contrast, tasks involving spectro-temporal complex material (e.g., speech) and operations (evaluation, attention) that require higher order auditory processing are characteristically diminished in ASD (Samson et al., 2006; see also Bertone et al., 2005). More importantly, the relationship between auditory processing and autistic symptomatology is far from complete. It has been suggested that future research employing correlational analyses between auditory perceptual abilities and behavioural phenotypes could help to clarify the inconsistencies in the findings (e.g., Marco et al., 2011).

The most consistently investigated auditory parameter has been the perception of frequency. Evidence for enhanced frequency discrimination ability of isolated pure tone stimuli has been found in children with ASD (Bonnel et al., 2003; Heaton, et al., 2008; O'Riordan and Passetti, 2006) and in adults with autism (although not in adults with Asperger's syndrome) in combined four-interval with two-forced choice (2IFC) frequency discrimination tasks (Bonnel et al., 2010). Furthermore, a similar pattern of ability has been observed also at neural levels in electrophysiological studies investigating neural response to changes of frequency in individuals with ASD, at the pre-attentive level (Ferri et al., 2003; Gomot et al., 2011; Gomot, Giard, Adrien, Barthelemy, and Bruneau, 2002; Kujala et al., 2010; Lepistö et al., 2008; 2006; 2005).

Relatively few research studies have investigated intensity and duration discrimination abilities in ASD. Despite the fact that previous research shows that people with ASD have increased sensitivity (Frith and Baron-Cohen, 1987) and reduced tolerance (*hyperacusis*) (Khalfa et al., 2004; Rosenhall et al., 1999) to loudness, intensity discrimination ability appears to be intact in adults and adolescents with ASD (Bonnel et al., 2010; Jones et al., 2009). Of note, one study used pure tones of varying intensities (the 'oddball' paradigm) to investigate auditory stream segregation (mismatch negativity (MMN) responses) in children with ASD (Lepistö et al., 2009). Intensity discrimination was intact in ASD when stream segregation (to separate sounds that come from different sources) was not required. Interestingly, both previous studies exploring intensity discrimination ability in ASD (Bonnel et al., 2010; Jones et al., 2009) utilized paradigms where stream segregation was not needed. Studies on duration discrimination are scarce. It appears that duration discrimination ability is intact in adolescents (Jones et al., 2009) and adults with ASD (Kasai et al., 2005).

To our knowledge only one study has thus far gone beyond single indicators to investigate perceptual discrimination in ASD across a range of primary auditory parameters. Jones and colleagues (2009) explored low-level auditory discrimination ability of intensity, frequency and duration using a 2IFC procedure in a large sample of adolescents with ASD and representing a wide range of IQs and ASD diagnoses. They found that, at the group level, auditory discrimination abilities were not different between individuals with and without ASD and between types of diagnosis (autism vs. other ASD). However, enhanced frequency discrimination was found in a subgroup (20%) of adolescents with ASD that shared particular characteristics (higher IQs and delayed onset of first words). Moreover, enhanced pure tone pitch discrimination has been suggested to represent a cognitive correlate of speech delay in individuals with ASD (Bonnel et al., 2010). Interestingly, Heaton and colleagues (2008) using a pure tone pitch identification task also found exceptional frequency discrimination skills in a subgroup (9%) of high functioning adolescents with ASD, who exhibit more language related impairments compared to other participants with ASD. It appears, therefore, that although atypical auditory discrimination ability is not a characteristic of most people with ASD, enhanced frequency discrimination might be suggestive of a specific phenotype in ASD. The aforementioned findings have led to the broad conclusion that enhanced frequency perception may be related to language ability in ASD.

In sum, research on auditory discrimination abilities in ASD presents a confusing picture. On the one hand some studies report enhanced abilities and support the most prominent view of ASD, the Enhanced Perceptual Functioning (EPF) theory (Mottron, Dawson, Soulières, Hubert, and Burack, 2006), which suggests that low-level perceptual processing is enhanced in ASD. On the other hand, several studies fail to find enhanced performance and instead report either intact abilities on specific parameters or intact abilities in adults but not in children with high-functioning ASD. In general, we know very little about the links between different parameters of auditory discrimination in ASD, and even less about the relation between these parameters and intelligence or key symptomatology such as restricted and repetitive patterns of behaviour, interests or activities (RRB's).

RRBs are part of the core criteria for ASD and represent a heterogeneous class of behaviours. These include atypical sensory behaviours such as hyper/hypo-reactivity to sensory input or unusual interests in sensory aspects of the environment, and an insistence on sameness in the environment (APA, 2013). RRBs vary in their severity and occurrence among people with ASD (e.g., Bodfish, Symons, Parker, and Lewis, 2000). Distinctive subclasses of RRBs have been identified in ASD (Leekam, Prior and Uljarevic, 2011) and are suggested to represent different neural pathways (Langen, Durston, Kas, Van Engeland and Staal, 2011). RRBs are thought to interfere with social adaptation (e.g., Loftin, Odon and Lantz, 2008) as well as the acquisition of skills (e.g., Dunlap, Dyer and Koegel, 1983) and are also associated with anxiety in people with ASD (e.g., Lidstone et al., 2014; Rodgers, Clod, Connolly and McConachie, 2012).

Previous reports indicate that RRBs are linked to sensory features in ASD (e.g., Boyd, McBee, Holtzclaw, Baranek and Bodfish, 2009; Chen, Rodgers and

McConachie, 2009), even after partialling out IQ and age (Boyd et al., 2010; Gabriels et al., 2008). For example, atypical sensory responses to environmental stimulation are highly related with the occurrence and expression of RRBs in ASD (e.g., Baranek, Foster, and Berkson, 1997; Gal, Dyck, and Passmore, 2002; Willemsen-Swinkels, Buitelaar, Dekker, and van Engeland, 1998), and in turn, auditory discrimination ability is found to correlate with auditory sensory behaviours (Jones et al., 2009). Furthermore, it has been proposed that different subclasses of RRBs are associated with different types of sensory features, helping to either increase or reduce sensory stimulation (Leekam et al., 2011). For example, individuals with ASD and hypo-sensitive hearing might actively seek out stimulation by tapping things or making vocalizations and noises such as humming (e.g., Bogdashina, 2003). On the other hand, people with hyper-sensitive hearing often cover their ears to block out loud sounds because they are painful for them (e.g., Williams, 1998). The paucity of information on the association between distinctive auditory perceptual features and RRBs is surprising given their elements could potentially help us to discern the aetiology or function for some types of RRBs. To our knowledge the association between auditory discrimination sensitivity and RRBs remains unexplored. Identifying which, if any, auditory parameters relate to RRBs in ASD would enhance our understanding of how auditory perceptual factors may contribute to the onset and maintenance of RRBs (see also Leekam et al., 2011). This specialised knowledge could facilitate the development of new effective interventions and diagnostic tools.

In the present study we investigated auditory discrimination sensitivity in pairs of pure tones across three auditory parameters (intensity, frequency, duration) in an adult sample with high-functioning ASD. To allow direct comparisons to previous studies that also compared performance across different parameters (Bonnel et al., 2010; Jones et al., 2009), we employed auditory tasks that were similar in terms of the nature of the stimuli, type of discrimination and support (e.g., stepwise procedure, feedback). We also investigated how performance on the three auditory discrimination tasks (ADTs) related to the commonly reported ASD symptomatology of RRBs and to IQ. Based on the only two previous studies that investigated auditory discrimination ability across a range of parameters (Bonnel et al., 2010; Jones et al., 2009), we predicted that intensity and duration discrimination skills would be intact in high-functioning adults with ASD whereas frequency discrimination skills would be enhanced. Also we predicted that enhanced performance on the auditory tasks, that is, lower thresholds, would be related to higher IQ (Heaton et al., 2008; Jones et al., 2009) and increased RRBs in ASD.

Method

Participants

In total 42 native English adult speakers participated in this study. The participants included 21 people with ASD (*M* = 30 years 4 months, SD = 10.4 months, 3 females in each group) and 21 people without ASD (*M* = 29 years 4 months, SD = 11.4 months). Participants with ASD were selected from the database of the Autism Research Network (ARN, Portsmouth) and through a local adult support group for people with ASD. All participants in the ASD group had a formal diagnosis of high-functioning ASD according to standard clinical criteria (APA, 1994). To support their diagnoses, the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000) was administered. The comparison group was recruited through the University of Portsmouth participant pool and local social groups. The exclusion criteria included psychiatric or developmental diagnoses and pharmacological treatments. Ethical approval was obtained from the University of Portsmouth, Psychology Department Ethics Committee. All participants were administered the Wechsler Adult Intelligence Scale-Third Edition (WASI; Wechsler, 1999). Verbal IQ (VIQ), performance IQ (PIQ), full-scale IQ (FIQ) and chronological age characteristics of the participants in the ASD and TYP group did not differ significantly (*t*-test, all $p > .1$). See Table 1 for participant characteristics. Participants received a short hearing test for the standard range of frequencies (250-8000 Hz) using an audiometer. All participants had hearing thresholds equal or better than 25 dB HL range (normal auditory acuity) and no formal musical training, which was a condition of being included in the study.

TABLE 1 ABOUT HERE

Design and general procedure

Auditory Discrimination Tasks

The psychoacoustic stimuli were presented binaurally through headphones at a hearing level comfortable for the participants (74 dB). All participants completed three ADTs: *intensity* (loudness), *frequency* (pitch) and *duration* (temporal processing) over one session. The order of the presentation of the discrimination tasks was counterbalanced across participants. The ADTs were presented using HD-3030 headphones on a sound-calibrated laptop. All three tasks followed the same format, a 2IFC, to evaluate differential discrimination threshold for static pure tones with 500 ms inter-stimulus interval between tones and 2000 ms inter-trial interval. In each pair of tones, the participants were presented with one standard tone and a probe tone that varied according to an adaptive procedure. The thresholds were measured using a combined 2-up 1-down and 3-up 1-down adaptive staircase procedure to alter the gap separating two sounds, targeting the 79.4% level on psychometric function (Levitt, 1971). Specifically, following 2 reversals, the 2-up 1-down staircase procedure shifts into a 3-up 1-down. Finally, the step size halves after the 4th and 6th reversal. Initially, the participants have to make very easy discriminations and larger step sizes were used to increase the level of difficulty. The discrimination becomes easier when an error is made. The task is terminated after 8 response reversals have occurred or alternatively a maximum of 40 trials has been completed. The threshold score was calculated using the mean of the last four reversals in the task (Leong, Hämäläinen, Soltész, and Goswami, 2011). The standard tone was randomized across positions (first/second tone). Participants were requested to be as accurate and fast as possible, at the end of the second tone, by pressing the appropriate one of two buttons in a standard keyboard with their preferred hand. Five practice trials with feedback (verbal and text on the computer screen) including a range of difficulty levels were given prior to each testing to ensure familiarity. All participants understood the procedure at the end of practice. Note that a low threshold (score is close to 0) is indicative of optimal performance.

General stimulus characteristics

The standard stimulus in all three tasks was a pure tone with a frequency of 500 Hz presented at 74 dB. In the intensity discrimination and the frequency discrimination task the duration of the standard tone was 200 ms. In the intensity discrimination task, the intensity of the second tone ranged from 55 to 73.5 dB. The participants were asked to discriminate pairs of tones varying in loudness. Their task was to decide which tone was louder. In the frequency discrimination task the comparison tone ranged from 560 Hz to 500.8 Hz. The participants were asked to discriminate pairs of tones varying in pitch. Their task was to decide which tone sound was ‘higher’. In the duration discrimination task the standard stimulus had 400 ms duration. The duration of the other tones ranged from 410 ms to 600 ms. Participants' task was to decide which tone sound was longer. Full description of the stimuli parameters of the three auditory tasks can be found in Leong and colleagues (2011). The parameters of the three auditory tasks are presented in Table 2.

TABLE 2 ABOUT HERE

Repetitive and Restricted Behaviours

The ADOS (Lord et al., 2000) Module 4 provides accurate assessment and diagnosis of autism for verbally fluent adolescents and adults suspected of having ASD and is commonly used by clinicians and in research. An ADOS assessment takes approximately 40 minutes to complete. The ADOS consists of semi-structured situations and standardized activities, which allow the examiner to observe behaviours important to the diagnosis of ASD such as communication, social interaction, RRBs and play or imaginative use of materials. Stereotyped behaviours and restricted interests (SBRIs) is one of the four ADOS components (i.e. Communication, Reciprocal social interaction, Imagination/Creativity, SBRIs) used for an ASD diagnosis. The SBRI component consists of the following items, unusual sensory interest in play material/person (e.g., preoccupations with parts of objects), stereotyped and restricted patterns of sensory interests (e.g., excessive interest in unusual or highly specific topics or objects), inflexible adherence to routines (e.g., compulsions or rituals) and stereotyped – repetitive motor mannerisms (e.g., hand and finger and/or other complex mannerisms). Thus, we used the ADOS SBRI total scores in order to investigate the relationship between auditory perceptual ability and RRBs in the ASD group.

Results

Low-level auditory discrimination performance

On all three ADTs the ASD group performed significantly worse than the TYP group (using independent samples *t*-tests with Bonferroni correction applied). The *Cohen's d* values reported in Table 3 show that in all three measures these group differences are substantial. There was, however, unequal variance in performance between the two groups on two of the measures. Levene's test for equality of variance revealed greater variability in the ASD group for intensity discrimination ($F = 7.26$, $p = .010$) and for frequency discrimination ($F = 13.1$, $p = .001$), but not for duration discrimination (see Table 3 for *SD*s). Because of the unequal variances we conducted Mann-Whitney tests to check for group differences. These analyses also revealed significant diminished performance in the ASD group across the three tasks (all $p < .05$).

Based on previous reports indicating that enhanced frequency discrimination may be a characteristic of a small subgroup with ASD (Heaton et al., 2008; Jones et al., 2009), we further explored the participants' discrimination scores in each auditory task in order to determine whether we had a subgroup of exceptionally good discrimination skills in ASD. Exceptional discrimination performance in each auditory task was defined by 100% accuracy. As in Heaton et al. (2008), around 9% (9.05%) of the people within the ASD group ($n = 2$) demonstrated exceptional frequency discrimination performance. Also, exceptional intensity discrimination was found in one individual with ASD. However, the number of performers in the TYP group with exceptional discrimination ability in frequency ($n = 3$) and intensity ($n = 2$) tasks were similar to the group with ASD. Thus, the difference in distribution for both enhanced frequency discrimination (X^2 (df = 1) = 0.22, $p = .634$) and enhanced intensity discrimination (X^2 (df = 1) = 0.35, *p* = .549) was not significant. Also, consistent with Jones et al.'s (2009) findings, none of the participants in the ASD group and the comparison group demonstrated exceptional duration discrimination.

We also investigated whether we had a subgroup of exceptionally poor discrimination skills in ASD. In our study, exceptionally poor performance was defined as a threshold score above 3*SDs* from the control mean. In the intensity and frequency discrimination tasks we found five participants with ASD (23.8%) in each task that had thresholds 3*SDs* above the TYP group mean (intensity: *M* = 1.8, *SD* = 0.84; frequency: *M* = 7.10, *SD* = 6.60). In contrast, the TYP group did not include any participants scoring over the 3*SDs* threshold. The difference in distribution for both exceptionally poor intensity discrimination performance (X^2 (df = 1) = 5.67, *p* = .017) and exceptionally poor frequency discrimination performance (X^2 (df = 1) = 5.67, *p* = .017) was significant. Also, none of the participants in the two groups showed exceptionally poor duration discrimination skills. Finally, it is worth pointing out that as in Jones et al., (2009) the participants in the subgroups were distinct, or in other words that good or poor performers were not the same participants across the tasks.

TABLE 3 ABOUT HERE

Correlations between SBRI and low-level ADT performance in ASD

Using Spearman's *rho*, the SBRI scores were significantly negatively correlated with intensity discrimination (*r* = -.730, *p* < .05) and frequency discrimination (*r* = -.653, *p* < .05), but not with duration discrimination (see Table 4). Specifically, participants with enhanced auditory discrimination had higher SBRI scores. These relationships remained the same when VIQ, PIQ and FIQ were partialled out.

TABLE 4 ABOUT HERE

IQ and low-level ADT performance in ASD

In the ASD group VIQ was significantly negatively correlated with intensity discrimination (r = -.461, $p < .05$) and frequency discrimination (r = -.490, $p < .05$) (using Pearson's correlations see Table 5). Higher levels of VIQ related to lower intensity and frequency thresholds. In the TYP group, on the other hand, there were no significant correlations between VIQ and any ADT performance. Both PIQ and FIQ were also significantly negatively correlated with frequency discrimination in the ASD group (r = -.535, $p < .05$; r = -.547, $p < .05$, respectively). In contrast, in the TYP group, the only auditory task to correlate with any IQ measure was duration, which correlated with both PIQ (r = -.439, $p < .05$) and FIQ (r = -.444, $p < .05$).

TABLE 5 ABOUT HERE

Discussion

Four key findings emerged from this study. First, we found diminished performance across all three low-level ADTs in the ASD group relative to the typical group. Second, auditory discrimination ability was characterized by high variability in ASD. Third, the pattern of correlation between IQ and performance on ADTs in the two groups indicates a dissociation between duration discrimination and the other two ADTs (i.e. intensity and frequency). Fourth, there were significant correlations between two of the ADTs (intensity and frequency discrimination) and RRBs in the ASD group.

These findings combine to suggest that low-level auditory discrimination shows a complex picture in ASD. To date the literature on low-level perceptual processing in ASD has been sparse and often contradictory. The current suggestion that low-level auditory discrimination performance is enhanced in ASD (Bertone et al., 2005; Mottron, et al., 2006) is thus challenged by the only two studies to test this so far across a range of auditory parameters, to the extent that it only appears to be true for a subgroup of persons with ASD (see also Jones et al., 2009).

There are several reasons for being cautious about claiming either enhanced or impaired low-level ADT performance in ASD. First, the greater variability found in the ASD sample is typical of findings reported in several domains (Valla and Belmonte, 2013). Conceiving of ASD as a homogenous group on any performance indicator thus seems unwarranted, and sampling variability may explain some of the apparent contradictions between the findings of different studies in this domain. Hence, conceiving performance in terms of deficits or assets at the group level may itself be inappropriate. Second, the current findings support the notion of the presence of a meaningful sub-group of ASD with enhanced frequency discrimination (Heaton et al., 2008; Jones et al., 2009) despite the fact that, in contrast to previous studies, performance at the group level was diminished. Our findings show that individual differences in frequency discrimination ability significantly correlate to levels of IQ. Also, enhanced intensity discrimination was found in one participant with ASD, indicating that enhanced auditory perceptual processing may not be exclusively within the frequency domain in a subgroup with ASD (Jones et al., 2009). Furthermore, two meaningful subgroups (24% each) of exceptionally poor intensity or frequency discrimination were found in the group with ASD, but not in the comparison group. Finally, duration discrimination did not include any participants with either enhanced or reduced performance in both groups. The aforementioned findings taken together suggest that first, auditory perceptual processing in ASD is characterized by high variability and second, that enhanced or reduced auditory discrimination abilities are present only within the intensity and frequency domains.

Conceptualising auditory discrimination ability in autism, which is, after all, a developmental condition, as stable over time may also lead to contradictory findings. Karmiloff-Smith (2009) powerfully shows that understanding the developmental trajectories in any specific domain is crucial for understanding the nature of these impairments; interpretations of specific deficits change when developmental changes are considered (see also López, 2013; Valla and Belmonte, 2013). Visual reception, for instance, develops differently in toddlers with ASD than in neuro-typical toddlers (Landa and Garrett-Mayer, 2006) whereas neurophysiological evidence on the perception of language suggest that the representation of, and attention to, language has an atypical developmental path in ASD (Kujala, Lepisto, and Näätänen, 2013). It is important therefore to further understand the developmental role of auditory sensitivities in the progression of the autistic symptomatology.

In recent years the literature has begun to investigate RRBs as both causal of secondary impairments in ASD and possibly as consequence of other underlying problems (see Leekam et al., 2011 for a review). The linking of RRBs and other low-level perceptual abilities and their developmental interplay may be crucial in understanding the bases of ASD. The large correlation between the ADOS SBRI total scores and intensity and frequency discrimination, suggest that idiosyncratic perceptual characteristics (such as enhanced auditory discrimination) may have an important influence on the presence of greater repetitive, restricted behaviours and interests. For example, it is possible that RRBs represent compensatory behaviours for dealing with sensory hyper/hypo sensitivities that develop over time. We considered Jones et al.'s (2009) findings on the associations between performance on similar auditory tasks and a self-report measure of sensory behaviours as supportive evidence for the aforementioned suggestion.

It has been speculated that RRBs may stem from atypicalities in the detection of novel or salient stimuli (Jeste and Nelson, 2008). Under this view, the preference for insistence to sameness and the repetitive behaviours people with ASD display are thought to relate to their hyper/hypo sensitivities to detect change. Studies in pre-attentional auditory novelty detection and pre-attentive neural responses (e.g., MMN) in children with ASD have provided evidence of enhanced (Ferri et al., 2003), intact (Ceponiene et al., 2003; Kamner, Verbaten, Cuperus, Camfferman, and van Engeland, 1995) and reduced (Gomot et al., 2006; Seri, Cerquiglini, Pisani, and Curatolo, 1999) frequency detection. A similar pattern of results is also evident in the findings across the studies on low-level discrimination ability in ASD. Therefore, it is possible that pre-attentional auditory novelty detection might be related to the auditory discrimination abilities in ASD and in turn to the degree of RRBs. To truly answer this question, one would have to investigate MMN in pre-identified subgroups with specific auditory perception abilities (enhanced, intact, diminished). To our knowledge, this hypothesis has not been explored. The suggestion that initial abilities influence exploratory behaviour, which develops over time into fixed neural and behavioural patterns (see also Valla and Belmonte, 2013), could be meaningfully used to posit perceptual discrimination abilities as the base from which specific subclasses of RRBs develop (see also Leekam et al., 2011).

This study had a few limitations for assessing RRBs that must be mentioned. The ADOS is not the best measure of RRBs as it depends on what the individual spontaneously does in an approximately 40 minute assessment and may not represent the true extent of RRBs in the individuals assessed. Therefore, we suggest that future studies should employ additional clinical tools to assess RRBs. Despite this, the high correlations between auditory perceptual ability and ADOS SBRIs indicate that this relationship is of a great significance. Also, we used the SBRIs total scores as a measure for RRBs. Distinctive subclasses of RRBs have been identified in previous research (for review see Leekam et al., 2001). However, the ADOS SBRIs total score is a composite of different types of behaviours and does not distinguish between subclasses of RRBs. Thus, although our main aim was to identify whether there were any auditory parameters that might be particularly important contributing factors for RRBs (intensity, frequency), we could not show which specific subclasses of RRBs were associated with different auditory parameters. Future research is needed to clarify the latter associations.

Overall, across all these findings, a pattern emerges of the closer integration of two of the ADTs (intensity and frequency discrimination) to the exclusion of the third (duration discrimination). These two abilities correlate with IQ and RRBs in the ASD group. Further, in the TYP group, it was duration discrimination rather than intensity and frequency discrimination that correlated with IQ. Also, the presence of subgroups with ASD with enhanced or reduced discrimination abilities were present only within the intensity and frequency domain. Thus, duration discrimination appears to be a different ability to the other two. This difference between the three low-level ADTs may be due to the way in which different aspects of auditory information are differently processed at the neurological level: the intensity and frequency of auditory input are both represented in the auditory cortex, albeit in a different manner (Lockwood et al., 1999), while duration is processed outside the auditory cortex, in the basal ganglia (e.g., Coull, Nazarian, and Vidal, 2008; Jones and Jahanshahi, 2014) and they play a crucial role for both perceptual and motor timing (for reviews see Coull, Cheng and Meck 2011; Jones and Jahanshahi, 2009; Meck, Penney and Pouthas, 2008; Nayate, Bradshaw and Rinehart, 2005).

Previous studies on time perception in ASD using a variety of auditory paradigms such as duration discrimination of complex tones (e.g., Lepistö et al., 2006), temporal processing of complex low-level auditory information (Alcántara, Weisblatt, Moore and Bolton, 2004; Alcántara, Cope, Cope and Weisblatt, 2012; Groen et al., 2009) and temporal order judgment tasks (Kwakye, Foss-Feig, Cascio, Stone and Wallace, 2011) have provided evidence for diminished abilities in auditory temporal processing. It is also found that children with ASD have difficulties reproducing the lengths of auditory stimuli of standardized durations (Szelag, Kowalska, Galkowski and Pöppel, 2004). Our results on duration discrimination extend these findings by showing that temporal aspects of simple low-level auditory information processing may be impacted in ASD. We considered our results as suggestive evidence that diminished abilities of time perceptual information may also reflect deficits in the basic encoding of auditory stimuli.

It is worth mentioning that our unexpected findings of diminished low-level auditory perceptual processing in ASD at the group level and the presence of meaningful subgroups with ASD (see also Heaton et al., 2008; Jones et al., 2009) may be due to the complexity of the ADTs (Samson et al., 2006). The current study employed three discrimination tasks to assess auditory discrimination ability. However, identification and discrimination tasks may require the intervention of different memory modes and tap different perceptual processes (e.g., Bonnel and Hafter, 1998). For example, identification (e.g., same/different) relies on simpler neural activation than discrimination (e.g., higher, longer). In fact, it is proposed that an identification task would be relatively easier compared to a discrimination task to individuals with enhanced perception such as persons with ASD (Samson et al., 2006). Further research is needed to clarify whether the presence of subgroups with specific discrimination abilities in ASD results from the complexity of the tasks or they reflect the characteristics of the groups tested. However, the fact that we used the same auditory discrimination paradigm as in Jones et al., (2009) suggests that this argument cannot fully account as an explanation for the varying results of previous research.

Another possible explanation for the inconsistencies in the findings of auditory perceptual processing in ASD may relate to the adaptive methodologies of ADTs employed across the studies. For instance, experimental variables that could influence the results include the initial starting value of the stimulus, the step size and the tracking algorithm (Leek, 2001). These variables have not been consistent in the studies exploring auditory perceptual processing in ASD. For example, although we used the same auditory discrimination paradigm as in Jones et al. (2009) there were differences in the adaptive procedures, which may account, to some extent, for the inconsistencies in the results.

Conclusion

This is the first study to report evidence for diminished low-level auditory discrimination abilities across a range of auditory parameters in ASD. However, this unexpected finding may relate to high variability of low-level auditory processing abilities in ASD. We suggest that future studies in ASD should give further consideration on 1) the characteristics of the ASD samples - especially in terms of IQ and age, 2) the nature of the auditory stimuli and complexity of the tasks and 3) the investigation of homogeneous subgroups rather than a heterogeneous broader ASD group might be more helpful to identify the multifarious factors that contribute to RRBs (see also Abrahams and Geschwind, 2008).

To our knowledge, the current study provides the first empirical evidence showing a relationship between low-level auditory processing and RRBs as measured with ADOS SBRIs. Specifically, intensity and frequency discrimination ability correlate with the degree of RRBs, indicating that the expression of these behaviours may be influenced by the degree to which sounds are detected or missed in the environment. We suggest that these findings may be indicative of a specific phenotype in ASD and that further research on the developmental relationship between individual differences in low-level auditory perception and different subclasses of RRBs is essential to enhance our understanding of how RRBs initially emerge (e.g., coping with loudness) and change over time in ASD. Understanding the role of auditory perception in ASD could contribute to identifying behaviours that may have a negative functional impact, and consequently facilitate the development of the autistic behaviours.

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Table 1. Participants' mean scores and standard deviations (SD) for chronological age and IQ scores across groups.

Group		Chronological age	Verbal IQ	Performance IQ	Full IQ
ASD	Mean	30.3	109.8	107.2	109.5
	SD	(10.4)	(18.2)	(15.7)	(18.3)
TYP	Mean	29.5	113.9	114.2	115.9
	SD	(11.4)	(9.2)	(10.7)	(10.6)

Table 2. Parameters of the three auditory discriminations tasks (ADTs).

	Intensity	Frequency	Duration
Standard stimuli	74 dB	500 Hz	400 ms
Starting probe	55 dB	560 Hz	600 ms
Lowest difference between probes	.5dB	.8Hz	5ms
Intensity	Variable	74 dB	74 dB
Frequency	500 Hz	Variable	500 Hz
Duration	200 ms	200 ms	Variable
ISI	500 ms	500 ms	500 ms

Table 3. Mean threshold values (and standard deviations) for the intensity, frequency and duration tasks in the two groups. A low score is indicative for optimal performance.

		ASD	TYP	*t*(df)	*p*	*Cohen's d*
Intensity (dB)	Mean	3.32	1.76	*t* (24) = 2.6	.013	.70
	SD	(3.0)	(.90)			
Frequency (Hz)	Mean	17.90	7.10	*t* (32) = 3.8	.001	1.18
	SD	(11.10)	(6.60)			
Duration (ms)	Mean	79.40	55	*t* (40) = 3.1	.004	.95
	SD	(24.0)	(27)			

Note: Previous studies have excluded outliers. In order to understand the effects of outliers we conducted non-parametric analyses, which demonstrated same effects as parametric, (Intensity, $p = .009$; Frequency, $p = .002$; Duration, $p = .005$).

Table 4. Spearman's *Rho* correlations between auditory discrimination tasks and ADOS scores for ASD participants only.

	Intensity	Frequency	Duration
SBRI	-.730*	-.653*	-.299

* Correlation is significant at .001

Table 5. Pearson correlations between auditory discrimination tasks and three measures of IQ across groups.

		ASD	TYP
VIQ			
	Intensity	-.416*	-.184
	Frequency	-.490*	.018
	Duration	-.244	-.323
PIQ			
	Intensity	-.296	-.261
	Frequency	-.535*	-.300
	Duration	-.306	-.439*
FIQ			
	Intensity	-.415	-.252
	Frequency	-.547*	-.167
	Duration	-.306	-.444*

* Correlation significant at $p < .05$