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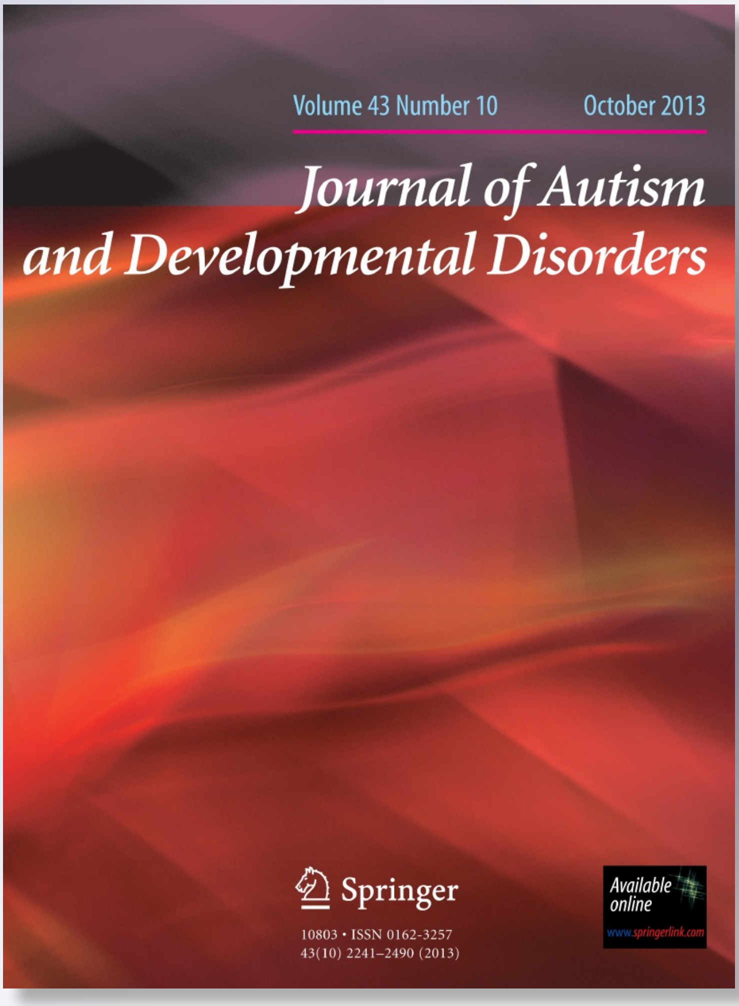

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ORIGINAL PAPER

Impaired Timing and Frequency Discrimination in High-functioning Autism Spectrum Disorders

**Anjali Bhatara · Talin Babikian · Elizabeth Laugeson ·
Raffi Tachdjian · Yvonne S. Sininger**

Abstract Individuals with autism spectrum disorders (ASD) frequently demonstrate preserved or enhanced frequency perception but impaired timing perception. The present study investigated the processing of spectral and temporal information in 12 adolescents with ASD and 15 age-matched controls. Participants completed two psychoacoustic tasks: one determined frequency difference limens, and the other determined gap detection thresholds. Results showed impaired frequency discrimination at the highest standard frequency in the ASD group but no overall difference between groups. However, when groups were defined by auditory hyper-sensitivity, a group difference arose. For the gap detection task, the ASD group demonstrated elevated thresholds. This supports previous research demonstrating a deficit in ASD in temporal perception and suggests a connection between hyper-sensitivity and frequency discrimination abilities.

Keywords Auditory perception · Psychophysics · Hypersensitivity · Asperger syndrome · High-functioning autism

Introduction

Two important aspects of auditory information processed by the human brain are the temporal and spectral qualities of sounds. Temporal cues carry information such as voice onset time in speech, which helps differentiate voiced from voiceless consonants (e.g., the sound of "p" from the sound of "b"). Spectral cues also carry speech information, notably the pitch pattern of speech, which determines a large amount of its prosody. Both of these types of information are important for accurate completion of almost all of our daily auditory tasks, including speech recognition (Shannon et al. 1998), speaker identification (Schvartz and Chatterjee 2012), and sound localization (Musicant and Butler 1984). Therefore, impairment in either type of auditory processing has the potential to cause significant deficits in communication and social interaction, both of which are defining characteristics of autism spectrum disorders (ASD; Diagnostic and Statistical Manual of Mental Disorders, 4th ed., text rev.; American Psychiatric Association 2000). More reason to suspect differences in auditory processing in ASD is given by the growing evidence of enhanced or preserved pitch processing (e.g., Bonnel et al. 2003; Heaton 2003) alongside impaired processing of temporal information (e.g., Alcántara et al. 2012;

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Groen et al. 2009). The present study uses psychophysical methods to investigate both spectral and temporal processing in high-functioning adolescents with ASD, and to our knowledge, it is the first study to measure thresholds of gap detection in ASD.

Many studies have shown evidence of atypical auditory processing in ASD (discussed below), but the specificities of this atypicality as well as the question of where in the auditory system it arises—at the level of the ear, brainstem, or cortex—is as yet unanswered. Below is a brief review of the evidence for abnormalities at each of these levels.

Auditory Function in ASD

Several studies have reported higher-than-normal rates of hearing loss (Klin 1993; Rosenhall et al. 1999; Smith et al. 1985), ear infections (Konstantareas and Homatidis 1987), and abnormal middle ear pressure (Smith et al. 1985) in groups of participants with ASD. A psychophysical study measuring auditory filters in eight adolescent and adult participants with ASD found atypically large auditory filter bandwidths (Plaisted et al. 2003). However, not all studies find abnormalities in ear function; Gravel et al. (2006) reported no differences between groups on any auditory measures, though they excluded participants with hearing loss or middle ear dysfunction to avoid contamination by mild hearing loss.

Klin (1993), in a review of 11 auditory brainstem response studies, concluded that there was no clear evidence for an auditory brainstem dysfunction in autism, but recent investigations suggest otherwise; studies have shown abnormal asymmetry of the medial olivo-cochlear reflex, (Khalfa et al. 2001; see also Collet et al. 1993), abnormal auditory brainstem responses (Rosenhall et al. 1999; Roth et al. 2012) and abnormal brainstem processing of speech sounds (Russo et al. 2008, 2009).

Cortical measures, both ERP and fMRI, show evidence of hyper-reactivity in autism to acoustic change or novel sounds (Ferri et al. 2003; Gomot et al. 2002, 2008, 2011). However, hyper-reactivity may be correlated with level of functioning; Courchesne et al. showed no differences between a group of high-functioning participants and a group of controls in either brainstem or cortical auditory evoked potentials (Courchesne et al. 1985; Grillon et al. 1989).

Spectral Versus Temporal Information

Spectral and temporal information are processed largely on opposite sides of the brain; broadly, spectral information is preferentially processed in the right hemisphere and temporal information is preferentially processed in the left (Hyde et al. 2008; Liégeois-Chauvel et al. 2001; Okamoto et al. 2009; Tervaniemi and Hugdahl 2003; Warrier et al. 2009; Zatorre and Gandour 2008; Zatorre and Belin 2001; Zatorre et al. 2002). Specifically, initial temporal integration of sound at the millisecond level occurs at the brainstem level, before reaching the primary auditory cortex (Griffiths et al. 1998, 2001; Patterson et al. 2002). Though Heschl's gyrus is *bilaterally* activated in both early temporal (Zatorre and Belin 2001) and spectral processing (Patterson et al. 2002), right Heschl's gyrus appears to be necessary for perception of certain complex tones (Zatorre 1988), and stimuli with varying pitch or spectral information result in right-lateralized activation in the auditory belt and parabelt areas, i.e., the superior temporal regions (Patterson et al. 2002; Zatorre and Belin 2001). In contrast, temporally-varying sine waves elicit activation more in the core or primary auditory regions, and this is preferentially weighted toward the left hemisphere (Zatorre and Belin 2001). A later study using more complex stimuli than those of Zatorre and Belin (2001) showed that stimuli with fast temporal modulations were processed in the left superior temporal gyrus, and the strength of the activation covaried with the rate of modulation (Schönwiesner et al. 2005).

Dichotic listening studies and other psychophysical studies have shown left ear advantages for tonal stimuli and/or right ear advantages for speech stimuli, confirming that the contralateral connections between ear and cortex are stronger than ipsilateral connections (Kallman 1977; Kallman and Corballis 1975; Kimura 1961, 1963, 1964, 1967; King and Kimura 1972; Sidtis 1982; Sininger and Bhatara 2012; Sininger and de Bode 2008). In ASD, atypical auditory lateralization has been shown in both a dichotic listening study (Prior and Bradshaw 1979) and neuroimaging studies (Boddaert et al. 2003, 2004; Bruneau et al. 1999). Together, these neuroimaging studies suggest that this atypical lateralization emerges over time as part of an abnormal maturational trajectory (Flagg et al. 2005; Gage et al. 2003a, b) and that, in ASD, the right hemisphere is "taking over" some of the tasks normally allotted to the left hemisphere (Bruneau et al. 2003; Dawson et al. 1986; Gage et al. 2003; Eyler et al. 2012).

Following this, Fein et al. (1984) and later Haesen et al. (2011) propose that a left-hemisphere dysfunction or atypical right-hemisphere dominance underlies many of the impairments in autism. For example, speech perception is often impaired in autism (Rapin and Dunn 2003) and is typically left-lateralized, perhaps because of its high temporal complexity. However, ERP studies have not shown atypical responses specific to speech in ASD; rather, they have shown atypical mismatch negativities to both tone and speech stimuli (Jansson-Verkasalo et al. 2003; Lepistö et al. 2005), atypical automatic orienting to speech sounds (Ceponiene et al. 2003), and, in contrast, *typical* responses to vowel changes (Kemner et al. 1995) or duration changes in speech (Lepistö et al. 2005). These data suggest that it is not specifically a "speech processing" deficit that children with autism have, but instead a deficit in processing of certain types of temporally-complex stimuli.

Along this line, Boucher (2001) and later Allman and Meck (2012) propose that impaired time or duration perception and an anomalous intuitive understanding of time underlie many of the impairments present in autism, ranging from disturbed sleep at the hour to day level to communication problems at the millisecond to second level (the level at which distinctions in speech sounds occur; Mauk and Buonomano 2004). Several studies have shown evidence of impaired timing in the auditory domain in ASD. These studies generally examine timing skills over ranges from hundreds of milliseconds to several seconds. They include reproduction of specific time intervals by synchronization and continuation (Gowen and Miall 2005) or by hitting a "stop" button when the duration of a test tone matches that of a standard (Martin et al. 2010; Szelag et al. 2004); temporal order judgments (Kwakye et al. 2011); same-different judgments of filled (as opposed to silent) durations (Falter et al. 2012); and processing of temporal envelope cues (Alcántara et al. 2012). In addition, an fMRI study showed atypical activation in ASD to temporally complex stimuli but not to spectrally complex stimuli (Samson et al. 2011).

Because the studies described above generally focus on perception of durations of hundreds of milliseconds and higher, the most relevant to the present study (which is focused on timing at the level of single digits to tens of milliseconds) are those by Alcántara et al. (2004) and Groen et al. (2009), which show that individuals with ASD are unable to take advantage of brief temporal dips in noise—thus, they are unable to use brief auditory glimpses to help them hear speech in noise.

Not all studies find impairments in timing, however; Wallace and Happé (2008) tested a group of children and adolescents with ASD on estimation and (re)production tasks and found no impairment. The task used was similar to that from Szelag et al. (2004) and Martin et al. (2010), who found differences between groups, but the task nonetheless differed from these other studies in important ways. First, the judgments were of silent intervals in Wallace and Happé (2008), whereas Szelag et al. (2004) and Martin et al. (2010) used filled intervals. In addition, the durations used in Wallace and Happé (2008) ranged from 2 to 45 s, as opposed to ranges of 1–5.5 s (Szelag et al. 2004) and .5–4.1 s (Martin et al. 2010). It has been suggested that longer duration judgments ($>\sim 1$ s) call upon different brain mechanisms than shorter judgments (Buhusi and Meck 2005; Lewis and Miall 2003), and longer judgments are likely to rely on working memory, whereas shorter judgments are more automatic and more likely to recruit motor circuits (Lewis and Miall 2003). Judgments of longer durations may also allow for counting strategies to be useful (Grondin et al. 1999). In addition, the durations chosen by Szelag et al. (2004) and Martin et al. (2010) may be special because they center around the 2–3 s window of temporal integration, also termed the "psychological present" (see Pöppel 1997, 2004).

Other studies that found no group differences used tasks similar to Falter et al. (2012; standard intervals of 600 and 1,000 ms), asking for duration judgments of silent (Mostofsky et al. 2000; standard interval of 550 ms) or filled intervals (Jones et al. 2009; standard interval of 640 ms) though Jones et al. (2009) reported a subset of individuals in the ASD group who showed exceptionally poor performance in the task. Both of these studies tested adolescents, whereas Falter et al. (2012) tested a much wider age range (14–42 years old), which may have contributed to the discrepancy among the studies.

As individuals with dyslexia or SLI frequently demonstrate temporal impairments (Farmer and Klein 1995; Tallal and Gaab 2006), it is possible that those impairments frequently found in ASD are not associated with the ASD itself but with coexisting language deficits (Oram Cardy et al. 2005). However, temporal impairments are also found in individuals with Asperger syndrome (e.g. Falter et al. 2012) who by definition had normal language development, and Bishop et al. (1999) showed that an auditory processing impairment is not sufficient to cause a language deficit, though it is likely to be a contributing factor.

Because temporal and spectral information are preferentially processed in opposite hemispheres, an impairment in one does not imply an impairment in the other. Indeed, several studies have shown unimpaired or even enhanced pitch processing in individuals with ASD, including pitch discrimination and memory of pure tones, complex tones in a melody, and pitches in speech (Altgassen et al. 2005; Bonnel et al. 2003; DePape et al. 2012; Heaton 2003; Heaton et al. 1998, 2008; Järvinen-Pasley and Heaton 2007; Järvinen-Pasley et al. 2008; O'Riordan and Passetti 2006). Additionally, evidence suggests that absolute pitch may be more common among those on the autism spectrum than in the normal population (DePape et al. 2012) and/or autistic traits may be more common among possessors of absolute pitch (Brown et al. 2003; Dohn et al. 2012). Recently, papers have begun to focus on analyses of subgroups, which may be a wise move given the heterogeneity of ASD: Heaton et al. (2008), though finding no group difference, reported that 3 out of the ASD group but none in the control group scored 4 SD above the group mean in a pitch identification task. Bonnel et al. (2010) showed that enhanced pitch perception was present only in individuals meeting full criteria for autism and not in those with Asperger syndrome. Jones et al. (2009) showed a subgroup of the ASD participants (20 % of the group) that demonstrated "exceptional" frequency discrimination abilities, and 10/16 of these reported delayed language acquisition but normal IQ.

The study by Jones et al. (2009) is notable because it is the only study thus far to compare psychophysical data and reported sensory hypo- or hyper-sensitivity in ASD. The authors found that poor performers on an intensity discrimination task reported more abnormal "auditory sensory behaviors" such as placing their hands over their ears to protect themselves from harmless (soft) sounds, or a preoccupation with particular sounds. Auditory hyper-[1] or hypo-sensitivity are both frequently observed in individuals with ASD (Gomes et al. 2008; Hayes and Gordon 1977; Leekam et al. 2007; Levitin et al. 2004; Rogers et al. 2003; Tomchek and Dunn 2007; Wiggins et al. 2009; Tan 2012). Two studies have shown in-lab "odynacusis" or lowered uncomfortable loudness levels in children with ASD (Khalfa et al. 2004; Rosenhall et al. 1999).

Abnormal sensitivity to sensory stimuli tends to decrease with age in children with ASD (Kern et al. 2006) though Baranek et al. (2006, 2007) found this negative correlation to be with mental age and not chronological age. This implies that maturation affords children with ASD the skills to compensate or at least develop an increased tolerance to sensory stimuli. However, at the same time, this means that young children with autism have the greatest amount of auditory dysfunction, during the time they are acquiring vocabulary and learning to communicate. In addition, though severity and prevalence of sensory abnormalities do not appear to be related to severity of autism symptoms in adolescents and young adults (Kientz and Dunn 1997; Kern et al. 2007), they are related in children aged 3–12, a time of life during which large developmental changes occur (Kern et al. 2007). Thus, sensory sensitivity in early childhood, leading to sound avoidance or lack of exposure, can have a lasting impact on later communicative and perceptual skills.

The present study utilizes two psychophysical tasks and records participants' self-report (and/or their parents' child-report) of sensory sensitivity. The first task is frequency discrimination, to examine spectral/pitch discrimination abilities, which have often been demonstrated to be preserved or enhanced in ASD. In a previous study (Sininger and Bhatara 2012) we found that typical adults demonstrated better frequency discrimination in the left ear, so here we will compare performance in the two ears in typical children and children with ASD. The second task is gap detection, which is detection of a small gap of silence in a sound. It will provide a measure of auditory timing perception at a level (ms to tens-of-ms) that is highly relevant for the study of autism given the communication and language problems often demonstrated in ASD: good temporal resolution at this level is essential for understanding speech. It is at this level that voice onset time and formant transitions, which aid in consonant discrimination, vary (Klatt 1975; Stevens and Klatt 1974). A second reason this was the task chosen is that, though it is a widely-used and reliable measure of temporal resolution in individuals of all ages (Schneider et al. 1994; Shailer and Moore 1983; Trehub et al. 1995) and populations with hearing impairments (Grose et al. 1989) or dyslexia (Schulte-Körne et al. 1998; Van Ingelghem et al. 2001) it has not yet been applied to psychophysical examination of children with ASD. Kujala et al. (2007) performed an ERP study examining mismatch negativities in response to gaps in participants with Asperger syndrome; they found increased amplitude for the Asperger syndrome group relative to the control group and interpreted this as increased sensitivity to gaps, but the gap detection thresholds of the participants were not determined.

Therefore, the present study investigates auditory perception of temporal and spectral information in adolescents with and without ASD who report varying degrees of abnormal auditory sensory behaviors. The aim is to better understand the perceptual functioning of these two groups of adolescents. To this end, participants performed two psychophysical tasks: (1) frequency discrimination and (2) gap detection. We hypothesized that the group with ASD would be impaired in the perception of temporal information, as measured by task 2, but not in the perception of spectral information (as measured by task 1), and a secondary prediction was that they would show atypical laterality of perception, where laterality is measured as differences between ears in discrimination/perception thresholds. Additionally, as recent studies have found that participants with ASD show specific deficits in the use of temporal cues to hear speech in noisy contexts, (Alcántara et al. 2004; Groen et al. 2009) participants also completed a test of speech perception in noise. These data are then examined in the context of participants' reports of auditory sensitivity.

Method

Participants

Sixteen adolescents with high-functioning ASD and 17 chronological age-matched typically developing (TD) participants between the ages of 10 and 14 were recruited for the study. Under the auspices of The Help Group—UCLA

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[1] Auditory hyper-sensitivity is sometimes referred to as hyperacusis, but true hyperacusis refers to lowered hearing thresholds, which are not often demonstrated by children with ASD; thus, here the term "auditory hyper-sensitivity" is used. See Levitin et al. (2005) for a disambiguation of the term "hyperacusis".

Autism Research Alliance, children with ASD were recruited from a specialized non-public school for children with ASD and other social communication difficulties. All participants with ASD had a previous diagnosis confirmed by either a licensed clinical psychologist or psychiatrist using DSM-IV criteria, or through comprehensive assessment by one of California's regional centers and/or the local school district. Additionally, as described below, they all met criteria for ASD on both the Social Responsiveness Scale (SRS; Constantino and Gruber 2005) and Autism Quotient for Adolescents (AQ; Baron-Cohen et al. 2006) or for Children (Auyeung et al. 2008) depending on the participant's age. TD children were recruited from the university and community.

Subjects' handedness was assessed using a modified Edinburgh Laterality Scale (Oldfield 1971) filled out by the participants (with their parents' help if necessary). While the participants completed the testing procedure in the sound attenuating booth, their parents filled out a demographic questionnaire and questionnaires evaluating the participants' ear health history and years of musical experience. Musical experience is important to evaluate because it can have significant effects on auditory perception, even at a basic level (Madsen et al. 1969; Schön et al. 2004; Sininger and Bhatara 2012). During testing, the parents of participants in both groups also completed the two measures of autistic symptoms mentioned above: the SRS and the AQ, as well as the Sensory Profile for children (Dunn 1999). Participants aged 11 and older filled out the Adolescent/Adult Sensory Profile (Brown and Dunn 2002), with their parents' help if needed. Performance IQ (PIQ) and Verbal IQ (VIQ) were measured using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler 1999).

Selection Criteria

Data from two participants in the TD group were excluded from analysis: one participant scored in the ASD range on the SRS and the AQ, and the second participant reported history of a learning disability. In the ASD group, data from four participants were excluded. One participant in the ASD group scored in the TD range on the SRS and AQ, one participant had an IQ below 70, and two participants were unable to complete the psychophysical tasks. Thus, the analyses reported here include 12 adolescents with ASD (1 F, 11 M; 5 with Asperger syndrome and 7 with autistic disorder) and 15 TD (7 F, 8 M).

Ear Health and Function

Otoscopic examination showed that all participants had normally appearing tympanic membranes and un-occluded ear canals. In addition, all participants demonstrated normal middle ear function and hearing threshold levels. Middle ear function was measured with tympanometry, which showed that all participants had normal tympanic membrane compliance and middle ear pressure. Middle ear pressure ranged from −60 to +60 daPa and compliance ranged from .2 to 1.4 ml. Air-conducted hearing thresholds were measured on a standard clinical audiometer (Interacoustics AC-40) at octave frequencies from 500 to 8,000 Hz. The mean average threshold for both ears was 6.29 dB HL with a range of 0–14 dB. No individual threshold was greater than 25 dB at 500 or 8,000 Hz nor greater than 20 dB at all other frequencies. Hearing thresholds are plotted by group on Fig. 1. Visual inspection of the means suggests that the thresholds for the ASD group were higher than those for the TD group; however, *t* tests showed that the groups were not significantly different on any frequency for either ear. In addition, all listeners in the ASD group demonstrated normal cochlear function based on a distortion-product otoacoustic emission test (DPOAE; Biologic Scout; because of equipment malfunction DPOAEs were not obtained from most of the TD group). DPOAEs exceeded noise floor levels by 6 dB or more for 3 of 5 frequencies between 1,500 and 8,000 Hz for each ear of all listeners tested. No participants reported any ear pain or ongoing ear infections. Based on this extensive audiologic test battery, no significant difference was noted in hearing thresholds or ear function between the two groups.

Stimuli

The study comprised two experimental conditions: frequency discrimination and gap detection (detection of a

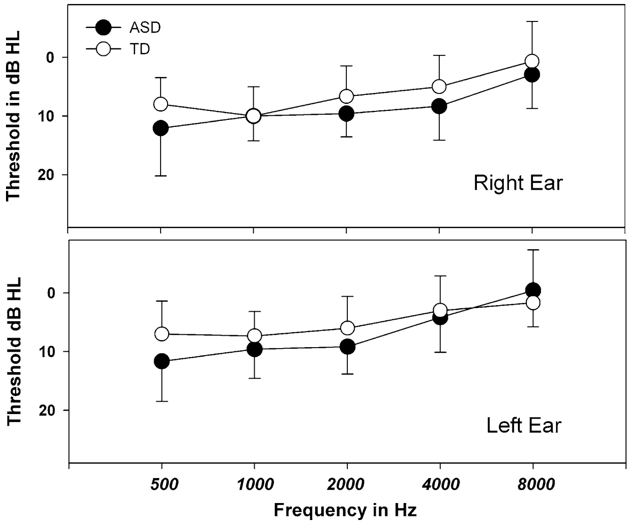

Fig. 1 Mean audiogram data by diagnostic group. *TD* typical development, *ASD* autism spectrum disorders. *Error bars* represent standard deviations

small gap of silence in a stimulus). Both experimental conditions were conducted with tonal stimuli, and the gap detection condition also used broad-band noise stimuli. Generation and presentation of stimuli was accomplished using a TDT System-II and SykofizX software (Tucker-David Technologies, Gainesville, FL). Stimulus levels were calibrated in a 2 cm^3 coupler connected to a Bruel & Kjaer model 2235 unless otherwise stated.

All stimuli were generated by a 16-bit D/A converter with a 44,000 Hz sampling rate and presented to each ear individually via Etymotic ER-3 insert earphones coupled to the ear with foam ear tips. Standard stimuli were broad-band white noise (20–14,000 Hz) and pure tones of 500, 1,000 and 4,000 Hz with random starting phase, all 1,000 ms in duration with a 10 ms cosine taper at onset and offset. All stimuli were presented at 50 dB SPL. In addition, following general calibration, the levels of the right and left earphones were equalized by comparing the digitized outputs on an oscilloscope for amplitude. The output of the left and right earphones thus differed by less than one dB for all stimuli.

The broad-band noise (used only for gap detection) originated from a digital signal of 20–14,000 Hz which produced an acoustic signal through the ER-3 earphones with a flat spectrum from 100 to 4,000 Hz and approximately 6 dB/octave roll off above 4,000 Hz. Short silent gaps were inserted into the center of the marker stimuli for the task. To prevent spectral splatter, the onset and offset of the gaps were linearly-tapered for 5 ms. For tonal stimuli, the phase at the end of the gap preserved the pre-gap phase, as if no gap had occurred.

Procedure

All testing took place in a single walled, sound-attenuating booth. Following consent procedures, listeners were screened for normal ear functions using otoscopy, tympanometry, otoacoustic emissions and standard audiometry (described above). The order of the two experimental conditions (gap and frequency) was counterbalanced, with half of the participants in each group beginning with gap and half beginning with frequency. The task for both was an adaptive three alternative forced choice (3-AFC) paradigm. Three stimuli were presented for each trial with one of the three varying on the experimental parameter (either higher in frequency or containing a gap of silence). Initial difference values for the tasks were 200 Hz for the frequency discrimination task and 50 ms for the gap detection task. These were found to be easily detectable by all participants. Presentation of each stimulus within a trial was accompanied in time by the flashing of one of three lights on a response box. The inter-stimulus intervals were 500 ms. Participants were instructed to listen to all three while watching the indicator lights and then to indicate which of the three stimuli was different from the other two by pressing the corresponding button. They were told that the differences would be easy to detect at first, but eventually would be very difficult so they should guess when unsure. Each participant received training trials on the first task they completed using the 1,000 Hz stimulus until reaching criterion by making six correct responses, at least four of which were consecutive. If a participant did not press the correct button on his or her first two tries, the training was paused and instructions similar to those above were given again, reworded if necessary to ensure that the participant understood. If the training was stopped three times because of incorrect responses, the testing session was discontinued.

Feedback was provided after each trial by flashing of the light on the button box corresponding to the correct choice. The magnitude of the varied parameter was controlled by the system based on the participants' response. After two correct responses, the parameter decreased (became more difficult) and after one incorrect response it increased. This change was by a factor of 1.5 for two reversals followed by a factor of 1.1 for the remainder of the experiment.

The experimental condition was concluded when four (gap detection task) or five (frequency task) reversals occurred on small step sizes. The difference between the two conditions was because pilot tests suggested that it was necessary to shorten the gap detection task to ensure participants' attention. The result was the average of the final eight parameter values. As stated above, initial parameter values were 50 ms for gap duration and +200 Hz for frequency change.

Thus, for each participant there were 3 stimuli × 2 ears = 6 thresholds of detection for the frequency discrimination task, and 4 stimuli × 2 ears = 8 thresholds for the gap detection task. Each task (gap detection or frequency discrimination) lasted approximately 15–20 min.

Between the two tasks, participants were administered the Words-in-Noise test (WIN; Wilson 2003; Wilson and Burks 2005), a short measure of speech-in-noise perception. In this test, participants repeat monaurally-presented monosyllabic words. Over the course of the task, the background noise (multitalker babble) increases in intensity relative to the speech. The total number of correct responses for each participant is used to calculate a speech-to-noise ratio necessary for accurate speech identification. First ear of presentation was counterbalanced across participants.

Following the tasks in the sound booth, participants were led to a table outside the booth, given a short snack break, and their IQs were measured using the WASI.

Results

Background Measures

Results of background measures (Table 1) showed that the two groups did not differ in chronological age (note that all *t* tests reported herein are two-tailed), $t(25) = .26$, $p = .79$, handedness, $t(25) = .66$, $p = .52$, years of musical experience: $t_{years}(25) = -.12$, $p = .91$, number of instruments, $t_{instr}(25) = .79$, $p = .44$, or time spent listening to music (a categorical variable), $\chi^2 = 1.37$, $p = .85$. As reported above, all participants were within normal ranges for tympanometry, audiometry and otoacoustic emissions, and the groups did not differ in the reported number of ear infections, Mann–Whitney $U = 85.5$, $p = .80$. The two groups did not differ in Performance IQ (PIQ), $t(25) = 1.08$, $p = .29$, but the ASD groups' average Verbal IQ (VIQ) was lower than that of the TD group, $t(25) = 3.12$, $p = .005$. Thus, VIQ was included as a covariate in all analyses of the psychophysical task.

Eleven out of the 12 participants in the ASD group reported hypersensitivity to sounds in early childhood on the ear health history questionnaire, whereas none in the TD group reported sensitivity. The average age at which they showed greatest sensitivity to sounds was 2 years, with a range of infancy—4 years. When asked about current sensitivity to sound, only one participant reported current sensitivity that had not changed since early childhood; one reported that the sensitivity was completely gone, and the remaining 9 out of the 11 with sensitivity reported that the sensitivity had decreased with age. Selected subject characteristics are summarized by group in Table 1.

Sensory Profile

The results from the Sensory Profile were analyzed using unequal-variance *t* tests (see Ruxton 2006 for a discussion of this test) to compare the two groups on each of the four categories of the test (Sensory Seeking, Sensory Sensitivity, Low Registration, and Sensation Avoiding) as well as responses on the items that specifically indicate sensitivity to sound. The groups were not different on Sensory Seeking, $t(14) = .23$, $p = .55$, but they did differ on all other measures ([overall] Sensory Sensitivity: $t(19) = 2.91$, $p = .008$; Low Registration, $t(24) = 2.84$, $p = .009$; Sensation Avoiding, $t(11) = 3.41$, $p = .003$; and Sensitivity to Sound, $t(18) = 4.62$, $p < .001$). In all cases, the ASD groups' scores were higher (indicating increased sensitivity, decreased registration/responsiveness, etc. depending on the category; see Fig. 2).

Non-parametric correlations were performed between VIQ/PIQ and the five categories of the Sensory Profile mentioned above. Results showed significant negative correlations between Sensation Avoiding and both IQ measures (VIQ: Kendall's $\text{Tau}_b = -.39$, $p = .03$, PIQ: Kendall's $\text{Tau}_b = .35$, $p = .047$) but no other correlations were significant (correlations between VIQ and PIQ or among the Sensory Profile measures were not investigated). However, when groups were analyzed separately, this correlation remained significantly only for VIQ in the TD group, Kendall's $\text{Tau}_b = -.56$, $p = .03$, and not for

Table 1 Group characteristics of participants with autism spectrum disorders (ASD) and participants with typical development (TD)

	Age in months	Years of musical experience	Handedness (laterality score)	VIQ	PIQ	SRS t-score	Hearing threshold in dB HTL			WIN signal to noise in dB
							500 Hz	1,000 Hz	2,000 Hz	
ASD										
Mean	152	2.5	54	93	99	80	11.9	9.8	9.4	7.3
SD	23	2.7	60	16	16	14	6.9	3.9	4.0	1.7
Range	124–179	0–8	−100–100	71–123	79–136	61–106	0–22.5	2.5–17.5	2.5–15	4.8–10
TD										
Mean	154	3.9	70	111	105	45	7.5	8.7	6.3	5.4
SD	21	2.9	68	13	15	6	4.5	4.1	4.7	1
Range	116–179	.5–9	−100–100	81–126	75–129	38–56	0–15	5–15	0–15	4–7.6
$t(25)^a$	.26	1.26	.68	3.12**	1.08	8.3**	1.98	.72	1.78	5.72*

WIN words-in-noise test

SRS Social responsiveness scale

* $p < .05$; ** $p < .01$

[a] For the WIN data, the results from the univariate ANOVA described in the text are reported here; thus it is an *F* value rather than a *t* value

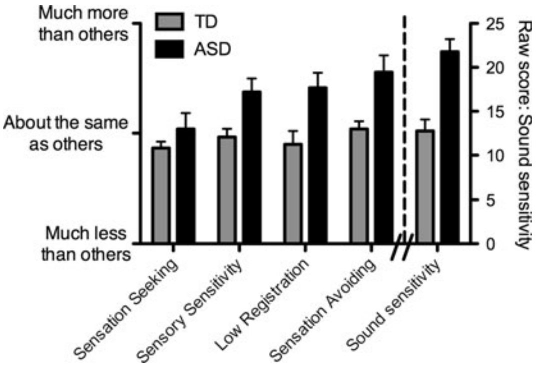

Fig. 2 Mean sensory profile data by diagnostic group. *TD* typical development, *ASD* autism spectrum disorders. *Error bars* represent standard errors

the ASD group, Kendall's Tau$_b$ = .033, p = .91. PIQ was not significantly correlated with any measures for either group.

Speech in Noise Perception

A t test comparing left- and right-ear thresholds from the WIN test showed that there were no differences between participants' left and right ear thresholds, $t(23) = .98$, $p = .34$, (this was also true when groups were analyzed separately, $t_{\text{ASD}}(10) = 1.08$, $p = .31$; $t_{\text{TD}}(13) = .42$, $p = .68$) so they were averaged and compared between groups. For this comparison, a univariate ANOVA was performed with the fixed factor of group and the covariate of VIQ. Results showed that the ASD group required a significantly higher speech-to-noise ratio than the TD group to understand the words, $F(1, 21) = 5.72$, $p = .026$, and VIQ was not a significant covariate, $F(1, 21) = .64$, $p = .43$.

Frequency Discrimination (Difference Limens)

First, the data were examined for outliers. Means were calculated across groups for each frequency, and individual thresholds that were greater than 2 SD above the mean were flagged. The time course of responses for each of these flagged means was then examined for obvious evidence that the participant was not paying attention (large fluctuations in response instead of a smooth trajectory toward the final threshold). These questionable means were excluded, resulting in the exclusion of all data from two participants from the ASD group (1 M, 1 F). Several individual thresholds were excluded from the TD group also, but it did not result in the exclusion of the entirety of any participants' data. Thus, the following analysis includes data from 10 participants in the ASD group and 15 in the TD group.

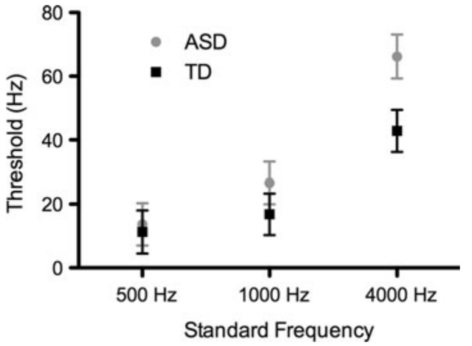

Fig. 3 Frequency difference limens: Thresholds by diagnostic group. *TD* typical development, *ASD* autism spectrum disorders. *Error bars* represent standard errors

A linear mixed-model analysis was run using SPSS with the fixed factors of Ear, Frequency and Group, the random factor of Subject, and covariate of Verbal IQ with threshold of discrimination as the dependent variable. Because frequency difference limens are known to increase as the standard frequency increases, a main effect of Frequency was predicted and found, $F(2, 99) = 60.9$, $p < .001$. In addition to this expected effect, there was also a significant interaction between Group and Frequency, $F(2, 99) = 4.49$, $p = .014$, with the ASD group's thresholds increasing more than those of the TD group as the standard frequency increased (see Fig. 3). Bonferroni-corrected (adjusted alpha = .017) unequal-variance t tests comparing the two groups at each standard frequency level showed that the ASD group's thresholds were significantly higher for 4,000 Hz, $t(48) = 2.72$, $p = .009$, but not for 1,000 Hz, $t(38) = 2.15$, $p = .04$, or 500 Hz, $t(45) = 1.22$, $p = .23$.

A second analysis was run with the factor of Auditory hyper-sensitivity rather than Group. "Auditory hyper-sensitivity" (AudHS) is defined as a binary variable indicating whether participants indicated greater than average responses to the sensitivity and avoidance auditory items on the Sensory Profile (based on normative data for the SP) *and* responded "yes" to the question (on the questionnaire designed for this study) asking if the participant had ever exhibited unusual sensitivity to particular sounds. This "sensitive" group contained 7 participants, all from the ASD group. In this analysis, frequency remained a significant factor, $F(2, 91) = 63.6$, $p < .001$. The main effect of AudHS was also significant, $F(1, 21) = 4.35$, $p = .049$, as was its interaction with Frequency, $F(2, 91) = 4.27$, $p = .017$ as well as its three-way interaction with Ear and Frequency, $F(2, 92) = 3.70$, $p = .029$. The interaction between AudHS and Ear approached significance, $F(1, 89) = 3.62$, $p = .06$. No other main effects or interactions were significant. Thus, when the groups are divided by sensitivity rather than by diagnosis, a significant group difference arises.

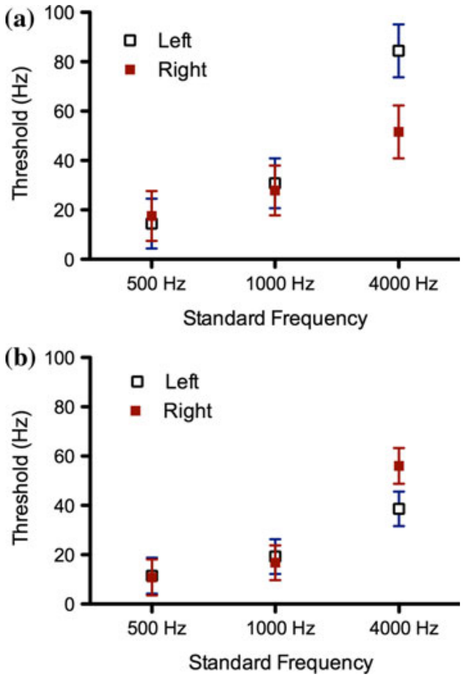

Fig. 4 Frequency difference limens: Thresholds by ear for **a** hyper-sensitive group (7 ASD) and **b** non-sensitive group (3 ASD, 15 TD). *Error bars* represent standard errors

To investigate frequency discrimination interactions among Ear, Frequency and AudHS, the discrimination thresholds were separated by ear, and linear mixed-model analyses were performed with the fixed factors of AudHS and Frequency, and VIQ as a covariate. For the left ear thresholds, AudHS, $F(1, 21) = 9.10$, $p = .007$, and Frequency, $F(2, 34) = 49.5$, $p < .001$ showed significant main effects, with the sensitive group reporting higher thresholds. In addition, the interaction between Auditory hyper-sensitivity and Frequency was significant, $F(2, 34) = 11.09$, $p < .001$. In the analysis of the right ear only, Frequency was significant, $F(2, 32) = 16.99$, $p < .001$, but Auditory hyper-sensitivity, $F(1, 18) = 1.16$, $p = .30$ and the interaction between them, $F(2, 32) = .04$, $p = .96$ were not. The three-way interaction is illustrated in Figs. 4a, b. The two figures are divided by sensitivity group rather than ear to more clearly illustrate the interaction.[2]

Gap Detection Thresholds

Analyses were performed as in the Frequency condition. First, outliers were excluded using the same criteria as above. In this case, however, no subjects were entirely excluded in either group, only individual thresholds. Next, we performed the linear mixed-models analysis with the fixed factors Group, Ear, and Frequency, random factor of Subject, and VIQ as a covariate. Frequency had a significant main effect, $F(3, 146) = 3.62$, $p = .015$. Bonferroni-corrected (adjusted alpha = .008) comparisons showed that the gap detection thresholds for wide band noise (WBN) tended to be lower than those for 500 Hz thresholds, but the difference was not significant, $t(93) = 2.56$ $p = .012$. Group also had significant main effect, $F(1, 27) = 20.5$, $p < .001$; the ASD group had higher average gap detection thresholds ($M = 15$ ms) than the TD group ($M = 5$ ms; see Fig. 5).

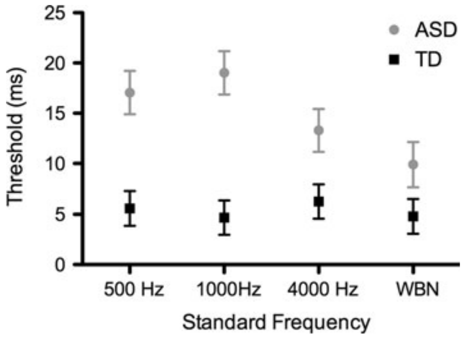

Fig. 5 Gap detection thresholds by diagnostic group and stimulus (*WBN* wide band noise). *Error bars* represent standard errors

The interaction between Group and Frequency was also significant, $F(3, 146) = 4.01$, $p = .009$. To explore this interaction, we performed analyses on each group separately with the factors of Ear and Frequency and the covariate VIQ. For the ASD group, Frequency had a significant main effect, $F(3, 58) = 2.88$, $p = .043$, and no other effects were significant. However, for the TD group, the effect of Frequency was not significant, $F(3, 90) = 1.34$, $p = .27$. Because it appeared from visual inspection of the means that the ASD group was performing differently on the noise condition than the pure tones, we performed a second analysis on each group with the stimulus type factor "Tone/Noise" replacing Frequency; this factor combined the results from the three pure tones and compared these to WBN. Again, for the ASD group stimulus type was a significant factor, $F(3, 63) = 5.17$, $p = .026$, whereas for the TD group it was not $F(3, 94) = .82$, $p = .37$. Thus, stimulus type (noise vs. pure tones) appears to affect gap detection thresholds only for the ASD group, who show lower thresholds (better performance) for the noise stimuli than for the pure tones.

Analyses performed dividing participants by Auditory hyper-sensitivity showed results equivalent to the above analyses using Group; there was a significant group difference for gap detection thresholds, with the sensitive

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[2] Dividing the thresholds by ear and performing this same analysis with Frequency and Group (TD vs ASD) as factors rather than Frequency and AudHS shows similar results, but was not justified because this interaction was not present in the overall mixed-models analysis using the factor Group.

group showing higher thresholds than the non-sensitive group. For brevity, these results will not be discussed in more detail.[3]

Because of previous research finding temporal-processing specific deficits in speech-in-noise perception, we performed a Pearson product-moment correlation between WIN thresholds and gap detection thresholds for each group. A significant positive correlation was found for the ASD group, $r = .38$, $p = .001$, but not for the TD group, $r = -.003$, $p = .98$, demonstrating that better performance on the WIN task was correlated with better performance on the gap detection task only for the ASD group. It is possible that VIQ could be a mediating factor between these two measures; however, this is unlikely to be the case. For both groups, VIQ is also correlated with the results from the WIN task, $r_{ASD} = -.27$, $p = .02$; $r_{\mathrm{TD}} = -.29$, $p = .004$, but it does not correlate with gap detection thresholds, $r_{ASD} = .03$, $p = .81$; $r_{\mathrm{TD}} = .10$, $p = .29$.

Discussion

The aim of this study was to use psychophysical tests of frequency difference limens and gap detection to measure spectral and temporal perception in high-functioning children with ASD. The results of these tests, as well as measures of ear function and reported hyper-sensitivity, were compared with results from a group of age-matched TD participants.

Contrary to previous studies that found higher rates of hearing impairment, ear infections, or physiological abnormalities or in individuals with autism, all participants tested in the present study demonstrated thresholds within the normal range on all measures, and there was no group difference in middle ear function or reported frequency of ear infections. However, as in previous studies of sensory dysfunction in autism (discussed above), there were significant group differences on three of the four quadrants of the Sensory Profile as well as in reported sound sensitivity. The ASD group scored higher on the two quadrants of the Sensory Profile that indicate hyper-sensitivity to stimuli, Sensation Avoiding and Sensory Sensitivity, as well as one indicating hypo-sensitivity, Low Registration.

Our prediction for the psychophysical tests, based on previous studies, was that children with ASD would show a deficit specific to temporal perception alongside typical or enhanced spectral perception. We also predicted that children with ASD would show atypical ear laterality for temporal or spectral perception. In addition, we hoped to use these data to find links between auditory sensitivity and perceptual functioning. The results partially supported these hypotheses and are discussed below, first separated by spectral or temporal perception, and then combined.

Spectral Perception

In the frequency discrimination task, across both groups, we found no main effect of ear and thus no left ear advantage for tonal stimuli, in contrast with previous research with adults (Kallman 1977; Kallman and Corballis 1975; Kimura 1964; Sidtis 1982; Sininger and de Bode 2008; Sininger and Bhatara 2012). In addition, there was no main effect of diagnostic group, indicating no overall impairment (or enhancement) in the ASD group relative to the control group when statistically controlling for VIQ. There were also no interactions between group and ear, indicating that the groups did not differ in their pattern of laterality.

However, there was an interaction between group and frequency. As frequency increased, the ASD group's thresholds increased at a faster rate than those of the TD group. Thus, the ASD group was significantly impaired in frequency discrimination at 4,000 Hz but not at 1,000 or 500 Hz. To our knowledge, this impairment at higher frequencies has not been demonstrated before. It is possible that this impairment existed in other participant groups, but was simply not examined; previous studies have generally tested participants on stimuli with fundamental frequencies below 1,000 Hz (Altgassen et al. 2005; Bonnel et al. 2010; DePape et al. 2012; Heaton et al. 1998, 2008a, b; Heaton 2003, 2005; Järvinen-Pasley and Heaton 2007; Järvinen-Pasley et al. 2008; Jones et al. 2009). Bonnel et al. (2003) and O'Riordan and Passetti (2006) tested higher-frequency stimuli, finding superior pitch discrimination in ASD relative to control groups at a maximum standard frequency of 1,500 and 2,000 Hz, respectively. However, no study has reported data from standard frequencies higher than 2,000 Hz. The results from the present study suggest a specific deficit in discrimination at high frequencies. The deficit could be related to auditory filter bandwidth; Plaisted et al. (2003) showed wider auditory filters in ASD with a center frequency of 2,000 Hz. Studies investigating correlations between frequency resolution (a measure of auditory filters) and frequency discrimination in normal-hearing and hearing-impaired listeners show that they are only weakly related (Moore and Peters 1992; Tyler et al. 1983) unless tested in background noise (Bernstein and Oxenham 2006). Theoretically, it is possible that they will be unrelated at low frequencies because pitch perception at these frequencies relies on phase-locking of the auditory nerve to the stimulus rather than on the sharpness of the

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[3] Because of our a priori hypotheses that there would be either right- or left-ear advantages for the two tasks, we directly compared the data from the left and right ears within each group for each task. However, no significant results were found for either the Gap or Frequency tasks.

auditory filters (e.g., Moore and Peters 1992). But there is an upper limit to this phase-locking, which varies by species (e.g., 5,000 Hz in cats) and is unfortunately unknown in humans (de Cheveigné 2010). If the human limit were to be somewhere near that of cats, around 4,000 Hz, it is likely that at this level both frequency discrimination and frequency resolution would depend on the same mechanisms. Thus, wider auditory filters could lead to impairments in frequency discrimination only at higher frequencies.

An impairment in frequency discrimination or in frequency resolution at these high frequencies could have clinical implications for learning of language. In speech, formants of frequencies ranging from 3,000 to 8,000 Hz are important for distinguishing fricative consonants such as /s/ and /f/ (Jongman et al. 2000). Children (as well as adults, though to a lesser extent) have trouble discriminating fricatives when presented with reduced bandwidth information (<5,000 Hz for a male voice, <9,000 Hz for a female voice; Stelmachowicz et al. 2001).Though the ASD group in this study did not have a hearing impairment in this range, it is possible that a discrimination impairment specific to this range could interfere with speech perception.

In a second analysis of the data that separated the participants by auditory sensitivity rather than by diagnosis, a main effect of sensitivity appeared, with the sensitive group showing higher thresholds (indicating more difficulty with discrimination). Sensitivity interacted with frequency in the same way that group had in the earlier analysis; with increasing frequency, the thresholds of the sensitive group increased faster than those of the nonsensitive group. There was also a three-way interaction among sensitivity, ear, and frequency, and closer investigation of this interaction revealed that only in the left ear were the thresholds significantly different between sensitivity groups, and it was only in the left ear that auditory sensitivity and frequency interacted. In the right ear, only the main effect of frequency was significant.

It is as yet unknown if the left ear advantage for pitch processing is present in adolescence. The data from the current study suggests that it is not yet present; however, the interaction among sensitivity, ear and frequency suggests a difference in laterality between the sensitive and non-sensitive groups. One possible explanation of this interaction is that, among the non-sensitive participants, there was the beginning of a left ear advantage for pitch, but this was not the case for the sensitive participants. However, this cannot be shown conclusively because no significant left ear advantage was demonstrated for the non-sensitive group.

One caveat to this analysis of laterality is that the groups were not exclusively right-handed. Though they did not differ on their handedness laterality index, it is possible that this is the reason we did not find a left ear advantage for the tonal stimuli. However, analyses including only those participants who reported a preference for the right hand did not show any differences between the left and right ears (and so were not reported above). This may be due to a lack of power from the small subject groups.

Timing Perception

In the gap detection task, the results were more straightforward than in the frequency task. There was no main effect of ear or interaction between ear and frequency, suggesting that the right ear advantage sometimes demonstrated in adults (Sininger and de Bode 2008; c.f. Grose 2008) is not yet present in adolescents. The main effect of group was significant, with the average thresholds from the ASD group being higher than those from the TD group. This suggests that adolescents with ASD have more difficulty detecting these small gaps of silence, and thus demonstrate impaired temporal perception at the ms scale.

Frequency also had a significant main effect, though it interacted with group, and when the groups were analyzed separately, only the ASD group showed a significant main effect of frequency. When the thresholds for the tonal stimuli were grouped together and compared to those from the wide band noise, this tone/noise distinction was also significant for the ASD group, who showed lower thresholds for the noise than for the tonal stimuli.

This raises the question of why only the ASD group would find the gap detection task easier when the stimuli are broad-band noise rather than tones. This was not found in adults using the same task (Sininger and Bhatara 2012) nor in the TD group in this study. It is possible that the gap is easier to detect when there are waves at multiple frequencies stopping and restarting simultaneously; however, if this is the case, it should also be true for the TD group and adults. Future research should investigate this further.

As with the impairment in high-frequency discrimination, the impairment demonstrated in the gap detection task could have implications for language learning, specifically consonant discrimination. The difference between stop consonants such as /b/ and /p/ appears to be due to an interaction of voice onset time (VOT) with variable duration of formant transitions at the onset of the consonant (Stevens and Klatt 1974). Both of these fall in the range of <50 ms, where the children with ASD were impaired in the present study's gap detection task. Language impaired children show reduced ability to discriminate consonants based on rapid formant transition duration (e.g., Tallal and Stark 1981; Tallal et al. 1985a, b; Reed 1989). Although there are few studies examining consonant discrimination in ASD, electrophysiological evidence shows that, whereas typical children show a mismatch negativity response distinguishing two consonants that differ only in format transition duration (/ba/, 15 ms, and /wa/, 45 ms), young children with ASD do not (Kuhl et al. 2005) showing reduced automatic discrimination of consonants, which would certainly interfere with language learning. This may also be related to the deficit they show in perceiving speech in noise—delays in children's brainstem responses during formant transitions are correlated with reduced speech-in-noise perception abilities (Anderson et al. 2010). Clearly, more studies are needed to explore consonant discrimination in silence and in noise in ASD.

The results from the WIN test may also be relevant to timing perceptual abilities. Previous studies have shown deficits in speech-in-noise perception in high-functioning ASD (Alcántara et al. 2004; Groen et al. 2009), but in all of these studies the deficits were specific to temporal processing. Participants with ASD were unable to make use of temporal cues to hear the speech in the same way that control participants were, but showed no impairment in making use of spectral cues. This along with recent evidence of impaired temporal envelope processing (Alcántara et al. 2012) suggests that the underlying cause for speech-in-noise impairments in ASD is a deficit in temporal processing. In the present study, the groups were not matched on VIQ, and this difference between groups in IQ could contribute to the difference in word recognition. However, when VIQ was entered as a covariate into the analysis, the difference between groups on the WIN task remained significant. In addition, WIN results and gap detection thresholds were correlated with each other for the ASD group. Although the WIN thresholds are significantly correlated with VIQ for both groups, neither the ASD nor the TD group showed a significant correlation between VIQ and gap detection thresholds, so it is unlikely that VIQ is a mediating factor in the relation between the results from the WIN and the gap detection task.

Spectral Versus Timing

Our hypothesis was that we would find a deficit in perception of timing but not in spectral perception/frequency discrimination, and that the ASD group would show differences in laterality. The first hypothesis was partially supported; a clear deficit in timing perception was demonstrated in autism, and it was the first time this has been shown using the gap detection task. However, there was also a deficit in frequency discrimination, though only at the highest standard frequency. In addition, participants with both auditory hyper-sensitivity and ASD demonstrated an overall deficit in frequency discrimination abilities relative to the non-sensitive group, which consisted of individuals from both the TD and ASD groups.

Regarding the hypothesis of laterality differences between groups, we found no easily interpretable evidence of this in either task; there were no ear differences or two-way interactions with ear. In the frequency task there was a three-way interaction with ear, group, and frequency, showing possible differences in laterality between the sensitive and non-sensitive groups and suggesting less of a trend toward left-ear (right hemisphere) lateralization for frequency discrimination in the sensitive group.

It is important to note that because 7 of the 10 children in the ASD group in the frequency task and 8 out of 12 in the gap task (and none in the TD group) reported hyper-sensitivity, the effect of auditory sensitivity cannot be separated from diagnosis. However, it implies that individuals with ASD who have auditory hyper-sensitivity may also exhibit perceptual impairments. This is important to explore further; if it is true that hyper-sensitivity and perceptual impairments are connected, this should be taken into account when designing therapeutic programs. Thus, an important next step would be to examine perception in groups of hyper-sensitive participants both with and without ASD as well as in diagnosis-matched non-sensitive groups.

A possible explanation for these results is that the participants in the ASD group were simply more uncomfortable performing the task, and thus performed it less well. However, none reported any discomfort during the task or after exiting the booth. Even if this is the case, both groups showed the expected psychophysical pattern of increasing thresholds of discrimination with increasing standard frequency so were likely to be performing the task to the best of their ability. A related second possible explanation of these results is that coping mechanisms that the child has developed over time to deal with ASD or auditory sensitivity have affected his/her perception. A third possibility is that the underlying cause of their auditory hyper-sensitivity or ASD also affects their frequency discrimination (and possibly timing perception) abilities. There is also the remaining question of whether or not feedback was equally helpful to both groups, or whether the TD group was better able to use the feedback provided during the psychophysical tasks, thus performing better. Evidence on the efficacy of feedback in ASD is mixed; there is evidence that individuals with ASD show reduced top-down influence on low-level perceptual tasks (Soulières et al. 2007). However, Martin et al. (2010) in their duration judgment task found no group difference in the effect of feedback between the ASD and control groups. Neurofeedback has sometimes been shown to be effective in participants with ASD; that is, some participants can use top-down processing to regulate their EEG activity in response to feedback (note, however, that there is no control group; Kouijzer et al. 2012), though it is not an effective treatment for symptoms of ASD (Holtmann et al. 2011). Additional psychophysical studies with and without feedback will be needed to clarify the role of feedback in ASD.

One limitation of this study is its small subject groups. However, significant differences between groups arose even after we controlled for VIQ and carefully screened the results for outliers and the participants for ear function and autistic characteristics. In addition, many psychophysical studies use similar numbers of participants (e.g. Agus et al. 2009; Hasuo et al. 2011). A second limitation is variation in diagnosis within the ASD group, including both autism and Asperger syndrome. Though the distinction between high-functioning autism and Asperger syndrome is controversial, and studies have not been consistent in the criteria they use to define the groups (Howlin 2003), there is some evidence for perceptual differences between the groups (Bonnel et al. 2010; Ozonoff et al. 1993) though these group differences coexist with mixed individual profiles and significant overlap between groups (Ghaziuddin 2008; Ghaziuddin and Mountain-Kimchi 2004). Here, we take the perspective that ASD is a spectrum of disorders, also referred to as "the autisms" (Geschwind and Levitt 2007), and so we strove to create a group as homogenous as possible; all participants in the ASD group were high-functioning and attended the same types of classes at their non-public school.

Conclusions and Future Directions

This study has demonstrated impairments in ASD in gap detection, and unexpectedly, an impairment at the highest frequency in a frequency discrimination task. Overall frequency discrimination differences were found only when groups were divided by auditory sensitivity. The impairment in gap detection is more robust, occurring for the group with ASD whether they had auditory sensitivity or not. Thus, this study demonstrates a deficit in timing perception in ASD, but it also shows an impairment in frequency discrimination at high standard frequencies. This does not support the theory of a deficit specific to timing, but may point to a deficit in more general auditory processing, or in using feedback to improve performance on difficult tasks. Future studies should further explore basic auditory perception at different ages and stages of development. Knowing which aspects of sound are difficult for children with ASD to perceive or process will inform studies on perception of more complex sounds, such as consonants in speech, for which temporal and spectral information are both important. Better characterization of the relation between auditory deficits and daily life impairments, such as in language learning, could allow for improved assessments and possibly earlier diagnosis of language or communication problems. It could also lead to development of interventions like those described by Merzenich et al. (1996) and Tallal et al. (1996) for language-learning impaired children. These interventions train specific low-level perceptual functions in an effort to improve higher-level language skills. In addition, as discussed above, future studies should clarify the relationship between auditory hyper-sensitivity and perceptual impairments. If auditory hyper-sensitivity is shown to be reliably connected with perceptual impairments, then this training can be tailored so it does not use sounds that tend to be unpleasant or painfully loud for hyper-sensitive children. In sum, the results of this study suggest that future studies should investigate perception of high frequencies and rapid sound changes in ASD both independently and in the context of speech.

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