Fragile Spectral and Temporal Auditory Processing in Adolescents with Autism Spectrum Disorder and Early Language Delay

Citation: Boets, Bart et al. "Fragile Spectral and Temporal Auditory Processing in Adolescents with Autism Spectrum Disorder and Early Language Delay." Journal of Autism and Developmental Disorders 45.6 (2015): 1845–1857.

As Published: http://dx.doi.org/10.1007/s10803-014-2341-1

Publisher: Springer US

Persistent URL: http://hdl.handle.net/1721.1/105895

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

J Autism Dev Disord (2015) 45:1845–1857
DOI 10.1007/s10803-014-2341-1

ORIGINAL PAPER

Fragile Spectral and Temporal Auditory Processing in Adolescents with Autism Spectrum Disorder and Early Language Delay

Bart Boets · Judith Verhoeven · Jan Wouters · Jean Steyaert

Published online: 14 December 2014

Abstract We investigated low-level auditory spectral and temporal processing in adolescents with autism spectrum disorder (ASD) and early language delay compared to matched typically developing controls. Auditory measures were designed to target right versus left auditory cortex processing (i.e. frequency discrimination and slow amplitude modulation (AM) detection versus gap-in-noise detection and faster AM detection), and to pinpoint the task and stimulus characteristics underlying putative superior spectral processing in ASD. We observed impaired frequency discrimination in the ASD group and suggestive evidence of poorer temporal resolution as indexed by gap-in-noise detection thresholds. These findings question the evidence of enhanced spectral sensitivity in ASD and do not support the hypothesis of superior right and inferior left hemispheric auditory processing in ASD.

Keywords Autism spectrum disorder · Auditory processing · Hemispheric lateralization · Spectral · Temporal · Pitch

Introduction

Autism spectrum disorder (ASD) refers to a spectrum of early onset neurodevelopmental disorders characterised by poor social reciprocity and communication, combined with repetitive and stereotyped patterns of behaviour, interests and activities (American Psychiatric Association 2000, 2013). Hyper and hyposensitivity to sensory stimulation (e.g., Kern et al. 2006; Khalfa et al. 2004) as well as atypical sensory processing abilities (e.g., Leekam et al. 2007; Simmons et al. 2009; Talay-Ongan and Wood 2000) are often reported and have been included in the new diagnostic criteria of ASD in DSM-5 (American Psychiatric Association 2013). Delayed or deviant speech and language development are also often reported but are no longer incorporated in the diagnostic criteria of the disorder (American Psychiatric Association 2000, 2013).

During the last decade there has been a growing interest in the study of auditory processing and speech perception in ASD, as evidenced by a recent series of review papers (Bomba and Pang 2004; Haesen et al. 2011; Hitoglou et al. 2010; Jeste and Nelson 2009; Kujala et al. 2013; O'Connor 2012; Ouimet et al. 2012; Samson et al. 2006). One of the most prominent observations concerns the evidence for enhanced pitch perception in children on the autistic spectrum and in a subgroup of adolescents and adults with

Electronic supplementary material The online version of this article (doi:10.1007/s10803-014-2341-1) contains supplementary material, which is available to authorized users.

B. Boets (✉) · J. Steyaert
Child and Adolescent Psychiatry, Department of Neurosciences, University of Leuven (KU Leuven), Herestraat 49, Box 7003, 3000 Leuven, Belgium
e-mail: bart.boets@med.kuleuven.be

B. Boets
Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

B. Boets · J. Verhoeven · J. Steyaert
Leuven Autism Research (LAuRes), University of Leuven (KU Leuven), 3000 Leuven, Belgium

J. Verhoeven
Department for Epilepsy, Kempenhaeghe, 5590 AB Heeze, The Netherlands

J. Wouters
ExpORL, Department of Neurosciences, University of Leuven (KU Leuven), 3000 Leuven, Belgium

ASD, especially those with early developmental language delay and language-related difficulties (O'Connor 2012). Superior pitch processing has been established regardless of stimulus complexity (e.g., for pure tones, complex tones, contours, nonwords, words and sentences) using a variety of psychophysical tasks (e.g., identification, discrimination, categorization, memory and labeling) (e.g., Bonnel et al. 2003, 2010; Heaton 2005; Heaton et al. 2008a, b, c; Järvinen-Pasley and Heaton 2007; Jones et al. 2009; O'Riordan and Passetti 2006; Stanutz et al. 2014). The majority of research using event-related potentials (ERP) also revealed enhanced neural detection of frequency changes in ASD at the pre-attentive level (using mismatch negativity or MMN) (e.g., Ferri et al. 2003; Gomot et al. 2002; Kujala et al. 2007; but see Jansson-Verkasalo et al. 2003; see Haesen et al. 2011 for an extensive recent review of the psychophysical and electrophysiological literature on auditory processing in ASD). Relevant is also the increased prevalence of absolute pitch and musical savants in the ASD population (e.g., DePape et al. 2012; Heaton et al. 2008a, b, c; Miller 1989; Mottron et al. 2013) and the increased prevalence of autistic traits among possessors of absolute pitch (e.g., Dohn et al. 2012). The occurrence of this superior pitch processing contrasts with the inferior temporal processing abilities in ASD (such as impaired gap-in-noise detection, duration discrimination, temporal-envelope processing, temporal order judgement; e.g., Alcántara et al. 2012; Bhatara et al. 2013; Kwakye et al. 2011; Lepisto et al. 2005, 2006; Samson et al. 2011; but see Jones et al. 2009; Kasai et al. 2005) and the evidence of speech perception impairments (Alcántara et al. 2004; Bhatara et al. 2013; Groen et al. 2009) and generally delayed speech and language development (e.g., Anderson et al. 2007). Speech perception has been shown to be particularly impaired while presented in noise with temporal dips (Alcántara et al. 2004; Groen et al. 2009) or in a competing talker condition (Alcántara et al. 2004; Bhatara et al. 2013).

It has been suggested that the increased sensitivity to fine-grained spectral changes may impede speech development in ASD by generating overly specific categories of sounds that inhibit learning of higher-level abstract patterns (Crespi 2013; Järvinen-Pasley et al. 2008a, b; Van de Cruys et al. 2014). In typically developing infants there is a natural shift from an initial focus on absolute pitch to the eventual dominance of relative pitch (Saffran and Griepentrog 2001; Stalinski and Schellenberg 2010). Absolute pitch refers to the encoding or identification of a pitch independent of its relation to other sounds, and relative pitch refers to the encoding of changes in pitch between sounds (intervals), which are invariant over transpositions in absolute pitch (e.g., Takeuchi and Hulse 1993). Relative pitch is computationally more complex, but more useful for processing speech and phonetic structure. Learning to ignore absolute pitch in favor of relative distances is necessary in order to generate general and abstract speech sound categories. Relying on absolute pitch information, instead, would result in overly specific categories of sounds with little room for generalization (Crespi 2013; Saffran and Griepentrog 2001). Relevant in this regard is the observation that 7-month-olds can only generalize words across voices when the speakers are of the same sex, but not when speakers differ in sex, presumably due to the different frequency ranges of male and female voices. Ten-month-olds, however, can generalize across speaker sex, suggesting that with development infants can more readily ignore irrelevant absolute pitch cues in speech and consequently build up more abstract higher-order speech representations (Houston et al. 1998). Against this background, it should not be too surprising that a substantial proportion of individuals with ASD shows early developmental language delay as well as broader linguistic impairments later in life, and that these are exactly the individuals who are most prone to present superior acoustic processing of pitch (e.g., Bonnel et al. 2010; Heaton et al. 2008c; Jones et al. 2009).

Conversely, basic impairments in auditory temporal processing may also hamper speech and language development, because speech perception requires an accurate tracking of several temporal cues (e.g., Schwartz and Tallal 1980; Shannon et al. 1995). Extensive research during the last decades suggests that auditory temporal processing deficits may affect the development of well-defined and robust phonological representations, hence producing the language and literacy problems characteristic of specific language impairment and developmental dyslexia (e.g., Boets et al. 2011; Corriveau et al. 2007; Goswami 2011; Hämäläinen et al. 2013; Tallal and Gaab 2006; but see Bishop et al. 1999; Rosen 2003). Likewise, auditory temporal processing problems in ASD may also impact upon early speech perception, thereby contributing to the characteristic autistic deficits in communication and social interaction (Bhatara et al. 2013).

It has been suggested that the enhanced auditory spectral processing abilities on the one hand and the reduced temporal, speech and language processing on the other, may reflect atypical hemispheric specialization in individuals with ASD (Fein et al. 1984; Haesen et al. 2011). In the general population, speech and language processing are largely lateralized to the left hemisphere, a specialization which is already apparent in infancy (e.g., Dehaene-Lambertz et al. 2002). Several studies have linked hemispheric specialization for speech to an asymmetry in cortical auditory tuning and revealed that the auditory cortices are differentially sensitive to particular spectrotemporal features: slow acoustic amplitude modulations (3–7 Hz AM) and spectral aspects, like pitch, are preferentially processed in the right auditory cortex, whereas temporal aspects, like duration, rhythm and faster modulations (12–50 Hz AM), are more left lateralized (e.g., Boemio et al. 2005; Jamison et al. 2006; Poeppel 2003; Rosen et al. 2011; Schönwiesner et al. 2005; Zatorre and Belin 2001; Zatorre and Gandour 2008). Given that speech perception requires an accurate tracking of fast temporal cues, e.g., formant transitions (Schwartz and Tallal 1980), it seems natural that speech perception, and by extension linguistic processing, is lateralized to the left hemisphere (Telkemeyer et al. 2009; but see Abrams et al. 2008).

Against this background, it has been proposed that individuals with ASD may have a brain which somehow promotes right hemispheric functions like spectral processing, at the disadvantage of left hemispheric functions, like temporal, speech and language processing. In this regard, a number of electrophysiological and neuroimaging studies reported right hemisphere dominance of auditory processing and speech perception in individuals with ASD, while controls showed left hemisphere dominance (e.g., Boddaert et al. 2003; Bruneau et al. 1999; Eyler et al. 2012; Flagg et al. 2005; Müller et al. 1998, 1999; Redcay and Courchesne 2008; Roberts et al. 2008; but see Whitehouse and Bishop 2008). Flagg et al. (2005), in particular, observed a reversed maturational pattern of lateralization: Whereas controls matured from bilateral activation to left hemisphere dominance in the processing of speech sounds, children with autism matured towards right hemisphere dominance.

The current psychophysical study aimed at investigating low-level auditory spectral and temporal processing in ASD. In line with previous findings, we generally expected to observe superior pitch processing and inferior temporal processing in ASD. The underlying neurophysiological mechanism behind the putative superior spectral processing was investigated by comparing pitch processing within a high-frequency domain (solely accessible by the tonotopic place mechanism of the basilar membrane) versus pitch processing within a low-frequency domain (accessible for neural phase-locking to the stimulating waveform) (Moore and Peters 1992; Moore 2007). The influence of general task characteristics was investigated by comparing pitch discrimination relative to a fixed reference tone versus pitch discrimination relative to a variable reference tone, hence exploiting the perceptual anchoring phenomenon (Ahissar et al. 2006). This phenomenon shows that listeners are sensitive to the implicit context of stimulus presentations across trials. The use of an identical or fixed reference tone throughout the entire task allows the construction of a 'perceptual anchor', which generally assists and improves pitch discriminability by reducing the involvement of auditory short-term memory. Given that individuals with ASD may be less sensitive to the broader context of the task (cf. reduced global processing; Happé and Frith 2006) or may apply a different processing strategy which relates more closely to absolute pitch processing (e.g., Heaton et al. 2008a, b, c), we expected a reduced contextual modulation by this fixed versus variable reference tone manipulation in ASD. Finally, by administering a series of auditory measures that preferentially target right versus left auditory cortex processing, we aimed at interpreting the pattern of strengths and weaknesses in auditory processing abilities in ASD in terms of superior right versus inferior left hemisphere processing. Along these lines, we hypothesized that individuals with ASD would outperform controls on measures of spectral processing and slow AM processing, while underperforming on measures of gap detection and fast AM processing. Note that performance on the slow AM tracking task is crucial to differentiate between a general auditory temporal processing impairment (comprising the temporal processing of signals with slow and fast modulations) and a left auditory cortex processing impairment (comprising only the processing of fast temporal signals). Given the heterogeneity of ASD and in light of recent accounts emphasizing the relevance of analysing subgroups of ASD, we focused upon a subsample of adolescents with ASD who showed early developmental language delay, because these individuals may be more prone to present superior pitch processing or more likely to present temporal processing impairments.

Methods

Participants

Twenty-one adolescents with ASD (age range 12–19 years; 16 boys, 5 girls) and 21 typically developing adolescents (TD; age range 12–19 years; 16 boys, 5 girls) participated in the study. All participants were right-handed, native Dutch speakers with normal hearing (audiometric pure-tone average of 0.5, 1 and 2 kHz < 25 dB HL). All participants had normal intelligence with a performance or full scale IQ above 80. Participants were excluded if there was an important medical history or an abnormal neurological examination or if ASD was associated with a genetic syndrome. Participants were recruited from the sample of Verhoeven et al. (2012), complemented with additional subjects who fulfilled the same criteria.

Inclusion criteria for the ASD group were (1) a diagnosis of ASD made by a multidisciplinary team in a standardized way according to DSM-IV-TR criteria (American Psychiatric Association 2000); (2) scores equal to or greater than 15 on the Social Communication Questionnaire (SCQ) (Rutter et al. 2003) and/or above 65 on the

Social Responsiveness Scale (SRS T-scores) (Constantino and Gruber 2005; Roeyers et al. 2011); and (3) a significant history of language delay or impairment, defined by the absence of two-word combinations at the age of three, need for intensive speech therapy during pre-school years, or the presence of language problems at the time of diagnostic assessment.

The TD sample comprised healthy volunteers, matched for age, gender and performance IQ. None of them had a history of neurological or psychiatric conditions, nor a current medical, developmental or psychiatric diagnosis. They did not report any language problems. Parents of the control children completed the SCQ and SRS questionnaires to exclude the presence of substantial ASD symptoms.

Descriptive statistics for both groups are displayed in Table 1, showing that they did not differ for gender, age and performance IQ. Evidently, both groups differed highly significantly on verbal IQ, and SRS and SCQ scores.

The study was approved by the local Ethical Board and informed consent was obtained from all parents/guardians according to the Declaration of Helsinki, with additional assent from all participating children.

Materials

IQ Measures

An abbreviated version of the Dutch Wechsler Intelligence Scale for Children, Third Edition (WISC-III-NL) (Wechsler 1992), was administered at the time of study intake. Performance IQ was estimated by the subtests Block Design and Picture Completion, verbal IQ by the subtests Vocabulary and Similarities (Sattler 2001).

Auditory Testing

Overview Auditory processing was assessed by means of an audiometric pure-tone hearing test and seven psychophysical threshold tests. Auditory measures were selected to preferentially target right auditory cortex processing (frequency discrimination, 4 Hz AM) and left auditory cortex processing (gap-in-noise detection, 20 Hz AM). The frequency discrimination tasks were additionally designed to investigate the influence of phase-locking (500 vs. 6,000 Hz frequency domain), context-sensitivity or anchoring (fixed vs. variable reference tone) and dynamic versus steady-state spectral processing [2 Hz frequency modulated (FM) tone vs. steady-state pure tone]. Exemplary stimuli for each of the auditory tests can be found in the Supplementary Material (Online Resource 1).

Stimulus Presentation and Psychophysical Procedure All stimuli were generated in MATLAB 5.1 and saved as 16-bit wav-files (sample frequency 44,100 Hz) on the hard disc of a Dell Latitude C800 portable computer. They were presented using an external RME Hammerfall DSP Multiface II sound card in order to control the level of presentation. Stimuli were presented monaurally (right ear) over a calibrated TDH-39 headphone at 70 dB SPL with an inter stimulus interval (ISI) of 350 ms.

All auditory psychophysical thresholds were estimated using a three-interval forced-choice oddity paradigm, embedded within APEX, a software module developed for psycho-acoustical and psycho-electrical auditory testing (Laneau et al. 2005; Francart et al. 2008). On each trial participants were presented a sequence of three auditory stimuli: one target stimulus and two reference stimuli. Synchronously with the presentation of each stimulus, a corresponding square (numbered from 1 to 3) lighted up on the screen. Participants had to identify the 'odd' stimulus, the one that sounded different from the other two, by pointing with a mouse click on the corresponding square on the screen. Visual feedback was provided after every trial. The difference in frequency, the depth of FM or AM modulation, and the length of the silent gap were adjusted adaptively using a two-down, one-up rule, which targeted the threshold corresponding to 70.7 % correct responses

Table 1 Participant characteristics

	ASD ($n = 21$)		TD ($n = 21$)		p value[a]
	M	*SD*	*M*	*SD*	
Age (years)	15.7	1.7	16.1	1.6	.43
Performal IQ[b]	101	13	104	8.8	.32
Verbal IQ[b]	92	15	115	13	<.0001
Social Responsiveness Scale[c]	90	18	44	8	<.0001
Social Communication Questionnaire	20.0	8.2	2.2	1.9	<.0001

[a] Two-sample t test

[b] Standardized scores with population average $M = 100$ and $SD = 15$

[c] Standardized scores with population average $M = 50$ and $SD = 10$

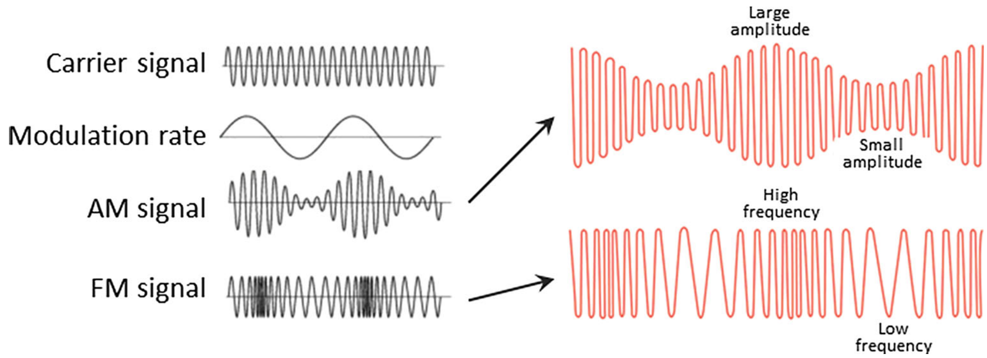

Fig. 1 A schematic visual representation of an AM and FM stimulus. The *x-axis* represents time, the *y-axis* represents amplitude (≈volume), and the cycling rate of the signal represents frequency (≈pitch)

(Levitt 1971). A threshold run was terminated after eight reversals and the threshold of an individual run was calculated by the geometric mean of the values of the last four reversals. After a short period of practice, to familiarize participants with the stimuli and tasks, two thresholds were determined for every measure and for every subject.

Prior to administering any auditory psychophysical test we assessed all children on an audiometric pure-tone detection task to check for any hearing loss within the 250–8,000 Hz domain. All but three children (2 ASD, 1 TD) obtained a pure-tone average (PTA) score below the 25 dB HL criterion for the right ear. For these three children adequate PTA scores were obtained for the left ear, hence for these children all further auditory testing was presented to the left ear.

Frequency Discrimination (FD) Task In the FD-task participants were presented a series of three pure tones and had to detect the one that differed from the other two. Threshold was defined as the minimum frequency difference that could still be detected (i.e. the just noticeable difference, expressed as percentage frequency change relative to the reference stimuli). The target tone differed from the reference tones with a frequency difference varying from 71 to 0.001 % with a decreasing factor of 1.4. The target stimulus was always lower than the reference stimuli. The length of the reference and target stimuli was 1,000 ms including 50 ms cosine-gated onset and offset. Three variants of the task were administered: (1) the *500 Hz fixed reference tone FD task* assessed FD sensitivity relative to fixed reference tones of 500 Hz; (2) the *500 Hz variable reference tone FD task* assessed FD sensitivity relative to variable reference tones within the 500 Hz domain (i.e. 460, 480, 500, 520 and 540 Hz) which were randomly chosen on every trial; (3) the *6,000 Hz variable reference tone FD task* assessed FD sensitivity relative to variable reference tones within the 6,000 Hz domain (i.e. 5,400, 5,700, 6,000, 6,300 and 6,600 Hz) which were randomly chosen on every trial.

Frequency Modulation (FM) Detection A frequency modulated signal consists of a carrier signal (a pure tone in this study), a modulation rate that determines the rate of frequency variation (2 Hz in this study), and a modulation depth that describes the degree of modulation (i.e. the difference between the maximum and minimum frequencies divided by the carrier frequency). In the FM detection test participants had to detect a 2 Hz sinusoidal frequency modulation of a 1,000 Hz carrier tone with varying modulation depth. The reference stimuli were pure tones of 1,000 Hz. Threshold was defined as the minimum depth of frequency deviation required to detect the modulation. Modulation depth started at 100 Hz (i.e. modulating between 900 Hz and 1,100 Hz) and decreased with a factor 1.2 towards 11 Hz, from where a fixed step size of 1 Hz was used. The length of the reference and target stimuli was 1,000 ms including 50 ms cosine-gated onset and offset. Participants were instructed to listen to three consecutive tones and detect the one which had a slight, slowly modulating, wobble. Thus they had to detect the tone with frequency changes from high to low to high to low again. The wobble was well audible at the beginning of the experiment but became more and more flat and undetectable throughout the experiment. A schematic visual representation of an FM stimulus is depicted in Fig. 1.

Amplitude Modulation (AM) Detection An amplitude modulated signal consists of a carrier signal (speech-weighted noise in this case) which varies in amplitude over time, a modulation rate that determines the rate of the amplitude variation (4 and 20 Hz in this study), and a modulation depth that defines the degree of modulation. For an AM stimulus, the modulation depth describes the ratio of the maximum amplitude to the minimum amplitude in the AM signal. Hence, when the modulation is 100 % the amplitude envelope decreases to zero every modulation cycle. In the AM detection task participants had to detect a sinusoidal amplitude modulation of a speech-weighted noise signal with varying modulation depth. The reference stimuli were unmodulated speech-weighted noise signals. Threshold was defined as the minimum depth of amplitude deviation required to detect the modulation. Modulation depth decreased with a factor 1.26 from 100 to 0.1 % modulation depth. The length of the reference and target stimuli was 1,000 ms including 50 ms cosine-gated onset and offset. Two variants of the task were administered: one with a slow 4 Hz AM modulation rate and one with a faster 20 Hz AM modulation rate. Participants were instructed to listen to three consecutive noise signals and detect the one which contained a beat or ruffle, i.e. an amplitude change from large to small to large again (4 times per second for the 4 Hz AM signal, and 20 times per second for the 20 Hz AM signal). The beat was well audible at the beginning of the experiment but became more and more flat and undetectable throughout the experiment. A schematic visual representation of an AM stimulus is depicted in Fig. 1.

Gap-in-Noise Detection In the gap detection test, subjects had to detect a silent interval (gap) in a white noise stimulus. The reference stimuli were uninterrupted white noise signals. Threshold was defined as the minimum gap length required for detecting the silent interval. Stimuli were cosine gated on and off with 50 ms rise and fall times. Gap rise and fall times were 0.5 ms and were not included in the reported gap sizes. Gap length decreased with a factor 1.2 from 100 towards 6.5 ms. From here on gap length decreased with a fixed step size of 0.4 towards 0.1 ms. In order to prevent participants from using overall duration as a cue for detection, the length of the target and reference stimuli varied randomly from presentation to presentation. In the target stimulus, the length of the markers (i.e. the noise components surrounding the gap) varied between 250, 400, 500 and 650 ms including on and off set. The length of the reference stimuli was randomly chosen at 750, 900 or 1,050 ms including on and off set.

Statistical Analysis

Prior to analysis, all psychophysical thresholds were $\log_{10}$-transformed to obtain a normal distribution and outliers were identified (typically, one or two outlier points per task). All analyses were performed with outliers included as well as excluded, but this did not yield any different results. In the present report, analyses including outliers are reported. Generally, a repeated-measures mixed model analysis (MMA) with group (ASD vs. TD) as between-subject variable and measurement (measurement 1 vs. measurement 2) as within-subject variable was carried out on all psychophysical data. Post-hoc analyses were corrected for multiple comparisons using the Tukey procedure ($\alpha = .05$). Group effect sizes were calculated by dividing the estimated group difference (least square means) in the full repeated-measures model by the pooled standard deviation. An effect size ranging from 0.2 to 0.3 is considered small, values around 0.5 are medium and values of 0.8 or above are considered large effects (Cohen 1988). Whole-sample Pearson correlations were calculated to investigate the association between auditory thresholds, verbal and performance IQ and quantitative autism traits.

Table 2 Average psychophysical thresholds (across both runs) and corresponding group effect sizes

	ASD		TD		Effect size
	M	*SD*	*M*	*SD*	
Frequency discrimination					
500 Hz fixed reference (%)	1.5	2.0	1.4	1.1	.15
500 Hz variable reference (%)	3.5	3.2	2.0	1.2	.63*
6,000 Hz variable reference (%)	5.1	4.8	3.5	1.7	.36
2 Hz FM detection (%)	0.57	0.37	0.48	0.41	.36
Temporal measures					
4 Hz AM detection (%)	7.9	4.1	6.9	1.3	.28
20 Hz AM detection (%)	7.8	1.6	7.8	1.1	−.12
Gap-in-noise detection (ms)	2.8	0.8	2.5	0.6	.46

* $p < .05$

Results

Before investigating group differences, we performed a power analysis to calculate the power to detect true differences. While sample sizes were relatively modest, the power of the study was substantially enhanced by using a repeated-measures design with highly reliable measurements (the correlation between two consecutive threshold measurements ranged between $r = .67$ and $r = .75$, all $p < .0001$). A power analysis with *G*Power 3* (Faul et al. 2007) revealed a power of .93 to detect a medium between-factors group difference (effect size = .50), which indicates that the study design yielded adequate power.

Table 2 displays average thresholds and corresponding effect sizes comparing ASD versus TD groups. For each of these psychophysical tests, a lower threshold is indicative of better performance and thus higher sensitivity. Accordingly, a positive effect size is indicative of poorer performance in the ASD group. A repeated-measures MMA on the 500 Hz fixed reference FD task revealed no main effect of group [$F(1, 40) = 0.26$, $p = .61$], no effect of measurement [$F(1, 40) = 0.79$, $p = .38$] and no group × measurement interaction [$F(1, 40) = 2.21$, $p = .15$]. An MMA on the 500 Hz variable reference FD task revealed a significant effect of group [$F(1, 40) = 4.48$, $p = .04$] indicative of reduced sensitivity in the ASD sample, no effect of measurement

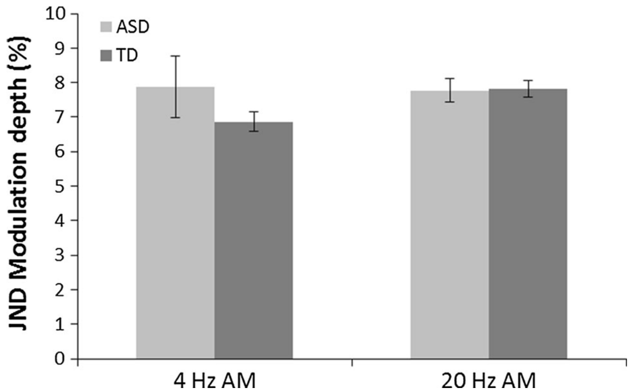

Fig. 2 Right (4 Hz AM) versus left (20 Hz AM) auditory cortex processing in ASD and TD. *Error bars* indicate ±1 standard error

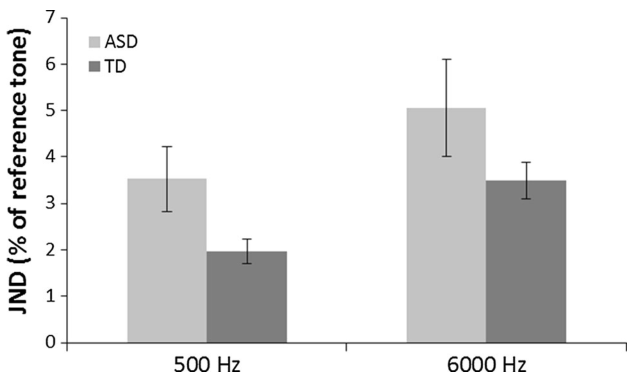

Fig. 3 Frequency discrimination by means of phase-locking (500 Hz) versus tonotopic place mechanism (6,000 Hz) in ASD and TD. *Error bars* indicate ±1 standard error

$[F(1, 40) = 0.77, p = .39]$ and no group × measurement interaction $[F(1, 40) = 0.02, p = .90]$. An MMA on the 6,000 Hz variable reference FD task revealed no effect of group $[F(1, 40) = 1.34, p = .25]$, no effect of measurement $[F(1, 40) = 0.76, p = .39]$ and no group × measurement interaction $[F(1, 40) = 0.14, p = .71]$. An MMA on the 2 Hz FM detection task revealed no effect of group $[F(1, 40) = 1.42, p = .24]$, a main effect of measurement $[F(1, 40) = 6.96, p = .02]$ and no group × measurement interaction $[F(1, 40) = 1.05, p = .31]$. An MMA on the 4 Hz AM detection task revealed no effect of group $[F(1, 40) = 0.8, p = .38]$, no effect of measurement $[F(1, 40) = 0.51, p = .48]$ and no group × measurement interaction $[F(1, 40) = 3.34, p = .08]$. An MMA on the 20 Hz AM detection task revealed no effect of group $[F(1, 40) = 0.15, p = .70]$, no effect of measurement $[F(1, 40) = 1.24, p = .27]$ and no group × measurement interaction $[F(1, 40) = 1.24, p = .27]$. An MMA on the gap-in-noise detection task revealed no effect of group $[F(1, 40) = 2.2, p = .15]$, no effect of measurement $[F(1, 40) = 0.78, p = .38]$ and no group × measurement interaction $[F(1, 40) = 0.31, p = .58]$. Inspection of the group

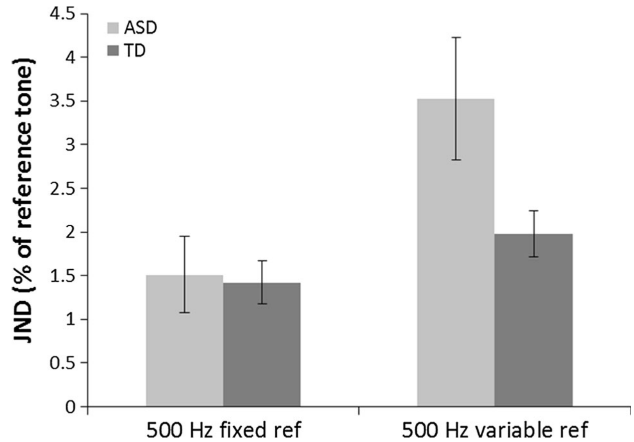

Fig. 4 Perceptual anchoring phenomenon: 500 Hz frequency discrimination by means of fixed versus variable reference tone in ASD and TD. *Error bars* indicate ±1 standard error

averages and effect sizes in Table 2 indicates that adolescents with ASD performed more poorly on most of the auditory tests, and this effect was substantial and significant on the 500 Hz variable reference FD task and moderate but insignificant on the gap-in-noise detection test.

To investigate more directly whether there was evidence of differential performance for AM stimuli which are preferentially processed in right (4 Hz AM) versus left (20 Hz AM) auditory cortex, an MMA was calculated on the average threshold across both runs with group as between-subject variable and with both variants of the AM detection task as within-subject variables (4 vs. 20 Hz AM). This analysis revealed a main effect of AM modulation rate $[F(1, 40) = 5.67, p = .02]$, but no effect of group $[F(1, 40) = 0.21, p = .65]$ nor group × modulation rate interaction $[F(1, 40) = 1.25, p = .27]$ (Fig. 2). To investigate the differential effect of pitch processing with and without the involvement of phase-locking to the stimulating waveform, an MMA was calculated with group as between-subject variable and frequency domain (500 vs. 6,000 Hz) as within-subject variable. This analysis yielded a significant effect of frequency domain $[F(1, 40) = 44.97, p < .0001]$, a trend towards poorer performance in the ASD group $[F(1, 40) = 3.21, p = .08]$ and no group × frequency domain interaction $[F(1, 40) = 1.97, p = .17]$ (Fig. 3). To investigate whether the context of using a fixed versus variable reference tone (i.e. the so-called perceptual anchoring phenomenon) had the same impact on FD sensitivity in ASD versus TD subjects, an MMA was calculated on the average 500 Hz FD thresholds with group as between-subject variable and type of reference stimulus as within-subject variable (Fig. 4). This analysis yielded no main effect of group $[F(1, 40) = 0.64, p = .43]$, a huge main effect of reference type $[F(1, 40) = 54.41, p < .0001]$ and a significant group × reference type interaction $[F(1, 40) = 9.58, p = .004]$. Post-hoc testing revealed that both groups had

Table 3 Whole-sample Pearson correlations between auditory thresholds, verbal and performance IQ and quantitative autism traits

	Verbal IQ	Performance IQ	Social Responsiveness Scale	Social Communication Questionnaire
500 Hz fixed reference FD	.16	−.15	−.04	.08
500 Hz variable reference FD	−.20	−.32*	.35*	.41**
6,000 Hz variable reference FD	−.03	−.29°	.24	.37*
2 Hz FM detection	−.25	−.25	.24	.26°
4 Hz AM detection	−.03	−.21	.05	.06
20 Hz AM detection	.10	−.20	−.03	.00
Gap-in-noise detection	−.23	−.27°	.35*	.35*

° $p < .10$; * $p < .05$; ** $p < .01$

significantly more difficulty with the variable reference paradigm [TD: $t(40) = -3.03$, $p = .02$; ASD: $t(40) = -7.40$, $p < .0001$], but this difficulty was more substantial for the ASD as for the TD group.

Next, we investigated the association between auditory spectral and temporal processing abilities and autistic characteristics in a more continuous manner by calculating whole-sample Pearson correlations between auditory thresholds on the one hand and (log-transformed) ratings on the SRS and SCQ on the other. Correlations between thresholds and autism traits, as well as between thresholds and VIQ and PIQ are displayed in Table 3. None of the auditory measures was significantly related to verbal or performance IQ, except for the 500 Hz FD task where better thresholds were associated with better PIQ. Both the 500 and 6,000 Hz variable reference tone FD thresholds and the gap-in-noise detection thresholds were significantly related to quantitative autism traits as measured by SRS or SCQ. This is in line with the findings for the group comparisons and implies that the presence of more severe autism traits is associated with poorer auditory spectral and temporal resolution. Visual inspection of the scatter plots and reanalysis through non-parametric Spearman's rank correlations, confirmed that these associations were genuine and not merely determined by the group differences or by a few outlying data points. Within-group analyses indicated that the correlations between SRS ratings and thresholds for frequency discrimination and gap detection were mainly driven by the TD group ($r = .37$, $p = .10$ and $r = .46$, $p = .04$, respectively), whereas the correlations between SCQ ratings and thresholds for frequency discrimination and gap detection were mainly determined by the ASD group ($r = .48$, $p = .04$ and $r = .38$, $p = .10$, respectively).

Discussion

The current study investigated low-level auditory spectral and temporal processing in a sample of adolescents with ASD who presented developmental language delay early in life. Findings were compared to thresholds obtained in a sample of TD adolescents, with similar age, gender and PIQ. The aim of the study was twofold. First, we aimed at replicating the classical finding of superior pitch processing in ASD, and corroborating the growing evidence for inferior temporal processing in ASD. In particular, we aimed at pinpointing the specific task and stimulus characteristics that may underlie superior spectral processing. Second, we aimed at investigating whether the pattern of strengths and weaknesses in auditory processing abilities may be indicative of enhanced right versus decreased left hemisphere processing in ASD. Therefore, auditory measures were designed to preferentially target right auditory cortex processing (i.e. pitch processing and slow AM tracking) versus left auditory cortex processing (i.e. temporal processing as investigated by faster AM tracking and gap-in-noise detection). In line with previous findings and the hypothesis of superior right and inferior left hemisphere processing in ASD, we hypothesized that individuals with ASD would outperform controls on measures of spectral processing and slow AM processing, while underperforming on measures of gap detection and fast AM processing.

The auditory psychophysical test battery administered in the current study is among the broadest used in autism research, with paradigms and tests which have proven to be reliable and sensitive to differentiate between clinical samples and controls (e.g., Boets et al. 2007; Laneau et al. 2005; Vandewalle et al. 2012). The clinical sample under study comprised adolescents with ASD and early developmental language delay, i.e. a specific ASD subsample which may be more prone to present superior pitch processing or which may be more vulnerable to present temporal processing impairments. Yet, in spite of the rigorous study design and meticulous participant selection, generally, very few group differences were observed.

As regards pitch processing, we could not provide any evidence of superior performance in ASD (cf. Altgassen et al. 2005; Bhatara et al. 2013). Quite the opposite, group comparisons revealed significantly impaired frequency discrimination sensitivity in ASD, in particular when paradigms with a varying reference stimulus were applied. Also the more continuous correlational approach revealed a significant negative association between individual differences in the quantity of reported autism traits along the ASD and TD population and individual differences in frequency discrimination sensitivity. This pattern was the most pronounced for the lower frequency domain (500 Hz) but also indicative for the 6,000 Hz domain, which suggests that results are robust and independent of any particular underlying neurophysiological mechanism involved in pitch processing.

Generally, spectral resolution of the auditory system is accomplished by two complementary neurophysiological mechanisms: (1) the 'place mechanism' of the tonotopically organized basilar membrane which resonates to corresponding frequency bandwidths of the incoming sound, and (2) the 'temporal phase-locking mechanism' which exploits the temporal alignment of the neural firing pattern to the frequency of the stimulating waveform (Moore 2007). In human listeners, it has been inferred that pitch processing within a low-frequency domain (up till about 4 kHz) is mainly resolved by phase-locking towards the stimulating waveform, whereas pitch processing within a higher frequency domain is dominated by the tonotopic place mechanism (e.g., Moore 2007; Palmer and Russell 1986). While this study aimed at illuminating the particular underlying neurophysiological mechanism behind the putative superior pitch processing in ASD, in light of the present findings we can only conclude that individuals with ASD (or TD individuals with more ASD characteristics) perform slightly inferior on frequency discrimination tasks resolved by either the tonotopic place mechanism or the phase-locking mechanism. Recently, however, Bhatara and colleagues (2013) studied adolescents with ASD and reported a selective and significant deficit in frequency discrimination around 4,000 Hz but not around 500 and 1,000 Hz (although the group difference was substantial and significant without multiple testing correction at 1,000 Hz). In as far as frequency discrimination in the 4,000 Hz domain mainly depends upon the tonotopic place mechanism, these authors related the selective frequency discrimination deficit to wider auditory filters in ASD (cf. Plaisted et al. 2003).

Two slightly different variants of the FD task have been administered in this study: one with a fixed identical reference tone throughout the task, and one with a series of variable reference tones throughout the task. Although both tasks are identical at single-trial level, the first variant with fixed reference tone allows for the gradual emergence of a so-called perceptual anchor, which substantially simplifies the task as it reduces task requirements to the identification of the non-anchor stimulus. The second variant with various reference tones across trials, however, requires that all three auditory stimuli are perceived and simultaneously maintained in auditory memory in order to identify the odd-one-out. Hence, this makes a much stronger appeal on auditory memory (Ahissar et al. 2006). The intact performance on the fixed reference tone FD task indicates that adolescents with ASD are sensitive to the implicit context of the task (i.e. the recurrent occurrence of an identical reference tone) and are able to construct a perceptual anchor. The selectively lower performance on the variable reference variant of the task suggests that this slightly inferior performance in individuals with ASD (characteristics) may perhaps not reflect inferior pitch processing per se but may be due to limitations in auditory working memory (cf. Ahissar et al. 2006; Ahissar 2007). Restrictions in auditory short-term memory and working memory have indeed been demonstrated in individuals with ASD (e.g., Barendse et al. 2013; but see Stanutz et al. 2014 for evidence of enhanced pitch memory in ASD) or in individuals with severe language impairment (e.g., Archibald and Gathercole 2006). Yet, in the study of Bhatara et al. (2013) the significant 4,000 Hz FD deficit in adolescents with ASD was observed in a fixed reference FD task which may have minimized memory involvement by allowing the construction of a perceptual anchor. Therefore, their findings corroborate evidence for an intrinsic pitch processing deficit in ASD.

The observation of equivalent or even impaired pitch processing performance in adolescents with ASD contrasts with the widespread general assumption of enhanced pitch processing sensitivity in ASD (as reviewed by Haesen et al. 2011 and O'Connor 2012). A closer look at the literature, however, reveals that surprisingly few studies actually estimated pitch discrimination thresholds for pure tones in ASD. The majority of studies investigated more advanced pitch processing aspects like categorization, labelling, memory or disembedding, and they often used much more complex auditory stimuli or speech stimuli (e.g., Foxton et al. 2003; Heaton 2003; Heaton et al. 2005, 2008b, c; Järvinen-Pasley and Heaton 2007; Järvinen-Pasley et al. 2008a, b; Mottron et al. 2000). Only three studies used a similar adaptive staircase procedure (as we did) to assess pure tone pitch processing (Bhatara et al. 2013; Bonnel et al. 2010; Jones et al. 2009). The first psychoacoustic evidence for enhanced pitch discrimination of pure tones was provided by Bonnel et al. (2003), who observed superior pitch discrimination in adolescents with autism and in adults meeting full criteria for autism but not in those with Asperger syndrome (Bonnel et al. 2010). Partial support for this finding was provided by Jones et al. (2009), who found no differences in frequency discrimination at the group level, but who identified a subgroup of adolescents with ASD and delayed language onset who showed exceptional frequency categorization. Interestingly, the single study that also applied a three-alternative forced choice adaptive staircase paradigm (as we did), obtained similar evidence for impaired frequency discrimination in a mixed sample of adolescents with autism and Asperger syndrome (Bhatara et al. 2013). Thus, combined with our findings, this set of studies offers a mixed pattern of pure tone frequency discrimination performance in individuals with ASD as compared to TD controls (superior, equivalent and inferior performance), and it certainly questions the evidence for superior pitch processing performance in ASD.

As noted by Jones et al. (2009), when drawing conclusions about the presence of enhanced perceptual ability, it is important to distinguish perceptual sensitivity from overarching processing styles that may facilitate performance, particularly in more complex tasks. Indeed, many of the studies providing evidence for superior pitch processing in ASD on the basis of more complex tasks did not observe superior performance on a simple pitch discrimination task (e.g., Altgassen et al. 2005; Foxton et al. 2003; Järvinen-Pasley and Heaton 2007; Järvinen-Päsley et al. 2008a, b). This suggests that superior pitch processing in ASD was not due to enhanced perceptual ability *per se* but rather to an over-focus of attention towards simple perceptual information and resilience to the distracting effect of melodic or linguistic content. Likewise, DePape et al. (2012) found that group differences in pitch memory disappeared as soon when the few ASD subjects with absolute pitch ($N = 3$) were removed from the sample. In line with Jones et al. (2009), we therefore would assert that the superior sensory processing abilities in ASD may rather be determined by general cognitive factors such as memory and disembedding ability (cf. weak central coherence, Happé and Frith 2006). Further research is warranted to disambiguate the relative contribution of these general cognitive factors versus possibly enhanced bottom-up perceptual sensitivity in ASD.

Concerning temporal processing, our study does not provide convincing evidence of impaired auditory temporal processing in ASD. For AM detection, which indicates how well the envelope of the auditory signal is perceived, no group differences were observed. Likewise, for gap-in-noise detection, the group difference was substantial but not significant. However, the more sensitive correlational approach did reveal that a higher incidence of quantitative autism traits was significantly associated with poorer temporal resolution as measured by gap-in-noise detection thresholds. Thus far, few psychophysical studies investigated auditory temporal resolution in ASD. In a small-scale study comparing six children with ASD versus six controls, Alcántara et al. (2012) measured AM sensitivity across a range of modulation rates (i.e. the temporal modulation transfer function) and observed significantly higher modulation-depth thresholds regardless of the rate of modulation. Findings were interpreted as evidence for intact temporal resolution but impaired temporal processing efficiency in ASD. The authors also suggested that impaired temporal envelope processing may underlie the speech-in-noise impairments observed in ASD (Alcántara et al. 2004, 2012; Groen et al. 2009). In a recent study of Bhatara et al. (2013) increased gap detection thresholds were observed in children with ASD, in particular in tonal stimuli but also in broadband noise. Interestingly, individual differences in temporal resolution were positively related to speech-in-noise perception in the ASD sample, which suggests that impaired temporal perception at the ms scale may impact upon speech and language learning, possibly through less optimal consonant discrimination (Bhatara et al. 2013). This fits with findings of electrophysiological studies showing reduced automatic discrimination of consonants in ASD (e.g., Jansson-Verkasalo et al. 2003; Kuhl et al. 2005; Russo et al. 2009).

Taken together, in spite of the theoretical and empirical evidence corroborating associations between low-level auditory spectral and temporal processing, speech perception and language development in ASD, in the present study we did not observe convincing evidence of superior spectral or inferior temporal auditory processing in adolescents with ASD and early developmental language delay. For spectral processing, an inverse pattern of impaired frequency discrimination was observed, questioning the evidence for enhanced frequency discrimination in ASD. For temporal processing, suggestive evidence of poorer temporal resolution as indexed by gap-in-noise detection thresholds was observed. Accordingly, thus far, these findings do not support the hypothesis of superior right and inferior left auditory cortex processing in ASD. While the interaction between low-level auditory deficits and speech, language and literacy problems has gradually begun to be unraveled in other developmental disorders like dyslexia (e.g., Boets et al. 2011) or specific language impairment (e.g., Corriveau et al. 2007; Fraser et al. 2010; Vandewalle et al. 2012), the current findings highlight the need for a further expansion of our understanding of the relation between auditory processing abilities and receptive-language abilities in ASD.

Acknowledgments Bart Boets is a post-doctoral research fellow of the Research Foundation Flanders and a Fulbright Visiting Scholar. The research was financed by a grant from the Research Council of KU Leuven (IDO/08/013). We thank Heleen Luts, Thea Van Werde and Loes Verber for assistance with testing, and all participating children and their families for their time and effort.

References

Abrams, D. A., Nicol, T., Zecker, S., & Kraus, N. (2008). Right-hemisphere auditory cortex is dominant for coding syllable patterns in speech. *Journal of Neuroscience, 28*, 3958–3965.

Ahissar, M. (2007). Dyslexia and the anchoring-deficit hypothesis. *Trends in Cognitive Sciences, 11*, 458–465.

Ahissar, M., Lubin, Y., Putter-Katz, H., & Banai, K. (2006). Dyslexia and the failure to form a perceptual anchor. *Nature Neuroscience, 9*, 1558–1564.

Alcántara, Journal I., Cope, T. E., Cope, W., & Weisblatt, E. J. (2012). Auditory temporal-envelope processing in high-functioning children with autism spectrum disorder. *Neuropsychologia, 50*, 1235–1251.

Alcántara, J. I., Weisblatt, E. J., Moore, B. C., & Bolton, P. F. (2004). Speech-in-noise perception in high-functioning individuals with autism or Asperger's syndrome. *Journal of Child Psychology and Psychiatry, 45*, 1107–1114.

Altgassen, M., Kliegel, M., & Williams, T. I. (2005). Pitch perception in children with autistic spectrum disorders. *British Journal of Developmental Psychology, 23*, 543–558.

American Psychiatric Association. (2000). Diagnostic and statistical manual of mental disorders (4th ed. Text Revision). Washington DC: American Psychiatric Association.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington DC: American Psychiatric Association.

Anderson, D. K., Lord, C., Risi, S., DiLavore, P. S., Shulman, C., Thurm, A., et al. (2007). Patterns of growth in verbal abilities among children with autism spectrum disorder. *Journal of Consulting and Clinical Psychology, 75*, 594–604.

Archibald, L. M., & Gathercole, S. E. (2006). Short-term and working memory in specific language impairment. *International Journal of Language and Communication Disorders, 41*, 675–693.

Barendse, E. M., Hendriks, M. P., Jansen, J. F., Backes, W. H., Hofman, P. A., Thoonen, G., et al. (2013). Working memory deficits in high-functioning adolescents with autism spectrum disorders: Neuropsychological and neuroimaging correlates. *Journal of Neurodevelopmental Disorders, 5*, 14.

Bhatara, A., Babikian, T., Laugeson, E., Tachdjian, R., & Sininger, Y. S. (2013). Impaired timing and frequency discrimination in high-functioning autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *43*(10), 2312–2328.

Bishop, D. V., Carlyon, R. P., Deeks, J. M., & Bishop, S. J. (1999). Auditory temporal processing impairment: Neither necessary nor sufficient for causing language impairment in children. *Journal of Speech, Language and Hearing Research, 42*, 1295–1310.

Boddaert, N., Belin, P., Chabane, N., Poline, J. B., Barthelemy, C., Mouren-Simeoni, M. C., et al. (2003). Perception of complex sounds: Abnormal pattern of cortical activation in autism. *American Journal of Psychiatry, 160*, 2057–2060.

Boemio, A., Fromm, S., Braun, A., & Poeppel, D. (2005). Hierarchical and asymmetric temporal sensitivity in human auditory cortices. *Nature Neuroscience, 8*, 389–395.

Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquiere, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. *Research in Developmental Disabilities, 32*, 560–570.

Boets, B., Wouters, J., van Wieringen, A., & Ghesquiere, P. (2007). Auditory processing, speech perception and phonological ability in pre-school children at high-risk for dyslexia: A longitudinal study of the auditory temporal processing theory. *Neuropsychologia, 45*, 1608–1620.

Bomba, M. D., & Pang, E. W. (2004). Cortical auditory evoked potentials in autism: A review. *International Journal of Psychophysiology, 53*, 161–169.

Bonnel, A., McAdams, S., Smith, B., Berthiaume, C., Bertone, A., Ciocca, V., et al. (2010). Enhanced pure-tone pitch discrimination among persons with autism but not Asperger syndrome. *Neuropsychologia, 48*, 2465–2475.

Bonnel, A., Mottron, L., Peretz, I., Trudel, M., Gallun, E., & Bonnel, A. M. (2003). Enhanced pitch sensitivity in individuals with autism: A signal detection analysis. *Journal of Cognitive Neuroscience, 15*, 226–235.

Bruneau, N., Roux, S., Adrien, J. L., & Barthelemy, C. (1999). Auditory associative cortex dysfunction in children with autism: Evidence from late auditory evoked potentials (N1 wave-T complex). *Clinical Neurophysiology, 110*, 1927–1934.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.

Constantino, J. N., & Gruber, C. P. (2005). *Social responsiveness scale*. Los Angeles, CA: Western Psychological Services.

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech Language and Hearing Research, 50*, 647–666.

Crespi, B. (2013). Developmental heterochrony and the evolution of autistic perception, cognition and behavior. *Biomed Central Medicine, 11*, 119.

Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science, 298*, 2013–2015.

DePape, A. M., Hall, G. B., Tillmann, B., & Trainor, L. J. (2012). Auditory processing in high-functioning adolescents with Autism Spectrum Disorder. *PLoS ONE, 7*, e44084.

Dohn, A., Garza-Villarreal, E. A., Heaton, P., & Vuust, P. (2012). Do musicians with perfect pitch have more autism traits than musicians without perfect pitch? An empirical study. *PLoS ONE, 7*, e37961.

Eyler, L. T., Pierce, K., & Courchesne, E. (2012). A failure of left temporal cortex to specialize for language is an early emerging and fundamental property of autism. *Brain, 135*, 949–960.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175–191.

Fein, D., Humes, M., Kaplan, E., Lucci, D., & Waterhouse, L. (1984). The question of left hemisphere dysfunction in infantile autism. *Psychological Bulletin, 95*, 258–281.

Ferri, R., Elia, M., Agarwal, N., Lanuzza, B., Musumeci, S. A., & Pennisi, G. (2003). The mismatch negativity and the P3a components of the auditory event-related potentials in autistic low-functioning subjects. *Clinical Neurophysiology, 114*, 1671–1680.

Flagg, E. J., Cardy, J. E., Roberts, W., & Roberts, T. P. (2005). Language lateralization development in children with autism: Insights from the late field magnetoencephalogram. *Neuroscience Letters, 386*, 82–87.

Foxton, J. M., Stewart, M. E., Barnard, L., Rodgers, J., Young, A. H., O'Brien, G., et al. (2003). Absence of auditory 'global interference' in autism. *Brain, 126*, 2703–2709.

Francart, T., van Wieringen, A., & Wouters, J. (2008). APEX 3: A multi-purpose test platform for auditory psychophysical experiments. *Journal of Neuroscience Methods, 172*, 283–293.

Fraser, J., Goswami, U., & Conti-Ramsden, G. (2010). Dyslexia and specific language impairment: The role of phonology and auditory processing. *Scientific Studies of Reading, 14*, 8–29.

Gomot, M., Giard, M. H., Adrien, J. L., Barthelemy, C., & Bruneau, N. (2002). Hypersensitivity to acoustic change in children with autism: Electrophysiological evidence of left frontal cortex dysfunctioning. *Psychophysiology, 39*, 577–584.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Science, 15*, 3–10.

Groen, W. B., van Orsouw, L., Huurne, N., Swinkels, S., van der Gaag, R. J., Buitelaar, J. K., et al. (2009). Intact spectral but

abnormal temporal processing of auditory stimuli in autism. *Journal of Autism and Developmental Disorders, 39*, 742–750.
Haesen, B., Boets, B., & Wagemans, J. (2011). A review of behavioural and electrophysiological studies on auditory processing and speech perception in autism spectrum disorders. *Research in Autism Spectrum Disorders, 5*, 701–714.
Hämäläinen, J. A., Salminen, H. K., & Leppänen, P. H. (2013). Basic auditory processing deficits in dyslexia: Systematic review of the behavioral and event-related potential/field evidence. *Journal of Learning Disabilities, 46*, 413–427.
Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36*, 5–25.
Heaton, P. (2003). Pitch memory, labeling and disembedding in autism. *Journal of Child Psychology and Psychiatry, 44*(4), 543–551.
Heaton, P. (2005). Interval and contour processing in autism. *Journal of Autism and Developmental Disorders, 35*, 787–793.
Heaton, P., Davis, R. E., & Happé, F. G. (2008a). Research note: Exceptional absolute pitch perception for spoken words in an able adult with autism. *Neuropsychologia, 46*, 2095–2098.
Heaton, P., Hudry, K., Ludlow, A., & Hill, E. (2008b). Superior discrimination of speech pitch and its relationship to verbal ability in autism spectrum disorders. *Cognitive Neuropsychology, 25*, 771–782.
Heaton, P., Williams, K., Cummins, O., & Happé, F. (2008c). Autism and pitch processing splinter skills: A group and subgroup analysis. *Autism, 12*, 203–219.
Hitoglou, M., Ververi, A., Antoniadis, A., & Zafeiriou, D. I. (2010). Childhood autism and auditory system abnormalities. *Pediatric Neurology, 42*, 309–314.
Houston, D., Jusczyk, P. W., & Tager, J. (1998). Talker-specificity and the persistence of infants' word representations. In A. Greenhill, M. Hughes, M. Littlefield, & H. Walsh (Eds.), *Proceedings of the 22nd annual boston university conference on language development* (pp. 385–396). Somerville, MA: Cascadilla Press.
Jamison, H. L., Watkins, K. E., Bishop, D. V. M., & Matthews, P. M. (2006). Hemispheric specialization for processing auditory nonspeech stimuli. *Cerebral Cortex, 16*, 1266–1275.
Jansson-Verkasalo, E., Ceponiene, R., Kielinen, M., Suominen, K., Jantti, V., Linna, S. L., et al. (2003). Deficient auditory processing in children with Asperger syndrome, as indexed by event-related potentials. *Neuroscience Letters, 338*, 197–200.
Järvinen-Pasley, A., & Heaton, P. (2007). Evidence for reduced domain-specificity in auditory processing in autism. *Developmental Science, 10*, 786–793.
Järvinen-Pasley, A., Pasley, J., & Heaton, P. (2008a). Is the linguistic content of speech less salient than its perceptual features in autism? *Journal of Autism and Developmental Disorders, 38*, 239–248.
Järvinen-Pasley, A., Wallace, G. L., Ramus, F., Happé, F., & Heaton, P. (2008b). Enhanced perceptual processing of speech in autism. *Developmental Science, 11*, 109–121.
Jeste, S. S., & Nelson, C. A. (2009). Event related potentials in the understanding of autism spectrum disorders: An analytical review. *Journal of Autism and Developmental Disorders, 39*, 495–510.
Jones, C. R., Happé, F., Baird, G., Simonoff, E., Marsden, A. J., Tregay, J., et al. (2009). Auditory discrimination and auditory sensory behaviours in autism spectrum disorders. *Neuropsychologia, 47*, 2850–2858.
Kasai, K., Hashimoto, O., Kawakubo, Y., Yumoto, M., Kamio, S., Itoh, K., et al. (2005). Delayed automatic detection of change in speech sounds in adults with autism: A magnetoencephalographic study. *Clinical Neurophysiology, 116*, 1655–1664.
Kern, J. K., Trivedi, M. H., Garver, C. R., Grannemann, B. D., Andrews, A. A., Savla, J. S., et al. (2006). The pattern of sensory processing abnormalities in autism. *Autism, 10*, 480–494.
Khalfa, S., Bruneau, N., Roge, B., Georgieff, N., Veuillet, E., Adrien, J. L., et al. (2004). Increased perception of loudness in autism. *Hearing Research, 198*, 87–92.
Kuhl, P. K., Coffey-Corina, S., Padden, D., & Dawson, G. (2005). Links between social and linguistic processing of speech in preschool children with autism: Behavioral and electrophysiological measures. *Developmental Science, 8*, F1–F12.
Kujala, T., Aho, E., Lepisto, T., Jansson-Verkasalo, E., Nieminen-von, W. T., von, W. L., et al. (2007). Atypical pattern of discriminating sound features in adults with Asperger syndrome as reflected by the mismatch negativity. *Biological Psychology, 75*, 109–114.
Kujala, T., Lepisto, T., & Naatanen, R. (2013). The neural basis of aberrant speech and audition in autism spectrum disorders. *Neuroscience and Biobehavioural Review, 37*, 697–704.
Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L., & Wallace, M. T. (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders. *Frontiers in Integrative Neuroscience, 4*(129), 1–11.
Laneau, J., Boets, B., Moonen, M., van Wieringen, A., & Wouters, J. (2005). A flexible auditory research platform using acoustic or electric stimuli for adults and young children. *Journal of Neuroscience Methods, 142*, 131–136.
Leekam, S. R., Nieto, C., Libby, S. J., Wing, L., & Gould, J. (2007). Describing the sensory abnormalities of children and adults with autism. *Journal of Autism and Developmental Disorders, 37*, 894–910.
Lepisto, T., Kujala, T., Vanhala, R., Alku, P., Huotilainen, M., & Naatanen, R. (2005). The discrimination of and orienting to speech and non-speech sounds in children with autism. *Brain Research, 1066*, 147–157.
Lepisto, T., Silokallio, S., Nieminen-von, W. T., Alku, P., Naatanen, R., & Kujala, T. (2006). Auditory perception and attention as reflected by the brain event-related potentials in children with Asperger syndrome. *Clinical Neurophysiology, 117*, 2161–2171.
Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467–477.
Miller, L. (1989). *Musical savants: Exceptional skill in the mentally retarded*. New Jersey: Lawrence Erlbaum.
Moore, B. C. J. (2007). *An introduction to the psychology of hearing* (5th ed.). London: Elsevier Academic Press.
Moore, B. C., & Peters, R. W. (1992). Pitch discrimination and phase sensitivity in young and elderly subjects and its relationship to frequency selectivity. *Journal of the Acoustical Society of America, 91*, 2881–2893.
Mottron, L., Bouvet, L., Bonnel, A., Samson, F., Burack, J. A., Dawson, M., et al. (2013). Veridical mapping in the development of exceptional autistic abilities. *Neuroscience and Biobehavioural Review, 37*, 209–228.
Mottron, L., Peretz, I., & Ménard, E. (2000). Local and global processing of music in high-functioning persons with autism: Beyond central coherence? *Journal of Child Psychology and Psychiatry, 41*(8), 1057–1065.
Müller, R. A., Behen, M. E., Rothermel, R. D., Chugani, D. C., Muzik, O., Mangner, T. J., et al. (1999). Brain mapping of language and auditory perception in high-functioning autistic adults: A PET study. *Journal of Autism and Developmental Disorders, 29*, 19–31.
Müller, R. A., Chugani, D. C., Behen, M. E., Rothermel, R. D., Muzik, O., Chakraborty, P. K., et al. (1998). Impairment of dentato-thalamo-cortical pathway in autistic men: Language activation data from positron emission tomography. *Neuroscience Letters, 245*, 1–4.

O'Connor, K. (2012). Auditory processing in autism spectrum disorder: A review. *Neuroscience and Biobehavioural Review, 36*, 836–854.

O'Riordan, M., & Passetti, F. (2006). Discrimination in autism within different sensory modalities. *Journal of Autism and Developmental Disorders, 36*, 665–675.

Ouimet, T., Foster, N. E., Tryfon, A., & Hyde, K. L. (2012). Auditory-musical processing in autism spectrum disorders: A review of behavioral and brain imaging studies. *Annals of the New York Academy of Sciences, 1252*, 325–331.

Palmer, A. R., & Russell, I. J. (1986). Phase-locking in the cochlear nerve of the guinea-pig and its relation to the receptor potential of inner hair-cells. *Hearing Research, 24*, 1–15.

Plaisted, K., Saksida, L., Alcántara, J., & Weisblatt, E. (2003). Towards an understanding of the mechanisms of weak central coherence effects: Experiments in visual configural learning and auditory perception. *Philosical Transactions of the Royal Society of London B: Biological Sciences, 358*, 375–386.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as 'assymetric sampling in time'. *Speech Communication, 41*, 245–255.

Redcay, E., & Courchesne, E. (2008). Deviant functional magnetic resonance imaging patterns of brain activity to speech in 2–3-year-old children with autism spectrum disorder. *Biological Psychiatry, 64*, 589–598.

Roberts, T. P., Schmidt, G. L., Egeth, M., Blaskey, L., Rey, M. M., Edgar, J. C., et al. (2008). Electrophysiological signatures: Magnetoencephalographic studies of the neural correlates of language impairment in autism spectrum disorders. *International Journal of Psychophysiology, 68*, 149–160.

Roeyers, H., Thys, M., Druart, C., De Schryver, M., & Schittekatte, M. (2011). *SRS Screeningslijst voor Autismespectrumstoornissen. Handleiding. Nederlandstalige versie*. Amsterdam: Hogrefe Uitgevers B.V.

Rosen, S. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything? *Journal of Phonetics, 31*, 509–527.

Rosen, S., Wise, R. J., Chadha, S., Conway, E. J., & Scott, S. K. (2011). Hemispheric asymmetries in speech perception: Sense, nonsense and modulations. *PLoS ONE, 6*, e24672.

Russo, N., Zecker, S., Trommer, B., Chen, J., & Kraus, N. (2009). Effects of background noise on cortical encoding of speech in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 39*, 1185–1196.

Rutter, M., Le Couteur, A., & Lord, C. (2003). *Social communication questionnaire*. Los Angeles (CA): Western Psychological Services.

Saffran, J. R., & Griepentrog, G. J. (2001). Absolute pitch in infant auditory learning: Evidence for developmental reorganization. *Developmental Psychology, 37*, 74–85.

Samson, F., Hyde, K. L., Bertone, A., Soulieres, I., Mendrek, A., Ahad, P., et al. (2011). Atypical processing of auditory temporal complexity in autistics. *Neuropsychologia, 49*, 546–555.

Samson, F., Mottron, L., Jemel, B., Belin, P., & Ciocca, V. (2006). Can spectro-temporal complexity explain the autistic pattern of performance on auditory tasks? *Journal of Autism and Developmental Disorders, 36*, 65–76.

Sattler, J. M. (2001). *Assessment of children: Cognitive applications*. San Diego, CA: Jerome M. Sattler.

Schönwiesner, M., Rubsamen, R., & von Cramon, D. Y. (2005). Hemispheric asymmetry for spectral and temporal processing in the human antero-lateral auditory belt cortex. *European Journal of Neuroscience, 22*, 1521–1528.

Schwartz, J., & Tallal, P. (1980). Rate of acoustic change may underlie hemispheric specialization for speech perception. *Science, 207*, 1380–1381.

Shannon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science, 270*, 303–304.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Research, 49*, 2705–2739.

Stalinski, S. M., & Schellenberg, E. G. (2010). Shifting perceptions: Developmental changes in judgments of melodic similarity. *Developmental Psychology, 46*, 1799–1803.

Stanutz, S., Wapnick, J., & Burack, J. A. (2014). Pitch discrimination and melodic memory in children with autism spectrum disorders. *Autism*, *18*(2), 137–147.

Takeuchi, A. H., & Hulse, S. H. (1993). Absolute pitch. *Psychological Bulletin, 113*, 345–361.

Talay-Ongan, A., & Wood, K. (2000). Unusual sensory sensitivities in autism: A possible crossroads. *International Journal of Disability, Development and Education, 47*, 201–212.

Tallal, P., & Gaab, N. (2006). Dynamic auditory processing, musical experience and language development. *Trends in Neuroscience, 29*, 382–390.

Telkemeyer, S., Rossi, S., Koch, S. P., Nierhaus, T., Steinbrink, J., Poeppel, D., et al. (2009). Sensitivity of newborn auditory cortex to the temporal structure of sounds. *Journal of Neuroscience, 29*, 14726–14733.

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L. & Wagemans, J. (2014). Precise minds in uncertain worlds: Predictive coding in autism. *Psychological Review*, *121*(4), 649–675.

Vandewalle, E., Boets, B., Ghesquière, P., & Zink, I. (2012). Auditory processing and speech perception in children with specific language impairment: Relations with oral language and literacy skills. *Research in Developmental Disabilities, 33*, 635–644.

Verhoeven, J. S., Rommel, N., Prodi, E., Leemans, A., Zink, I., Vandewalle, E., et al. (2012). Is there a common neuroanatomical substrate of language deficit between autism spectrum disorder and specific language impairment? *Cerebral Cortex, 22*, 2263–2271.

Wechsler, D. (1992). *Wechsler intelligence scale for children (3rd Edition NL)*. London: The Psychological Corporation.

Whitehouse, A. J., & Bishop, D. V. (2008). Cerebral dominance for language function in adults with specific language impairment or autism. *Brain, 131*, 3193–3200.

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 11*, 946–953.

Zatorre, R. J., & Gandour, J. T. (2008). Neural specializations for speech and pitch: Moving beyond the dichotomies. *Philosical Transactions of the Royal Society of London B: Biological Sciences, 363*, 1087–1104.