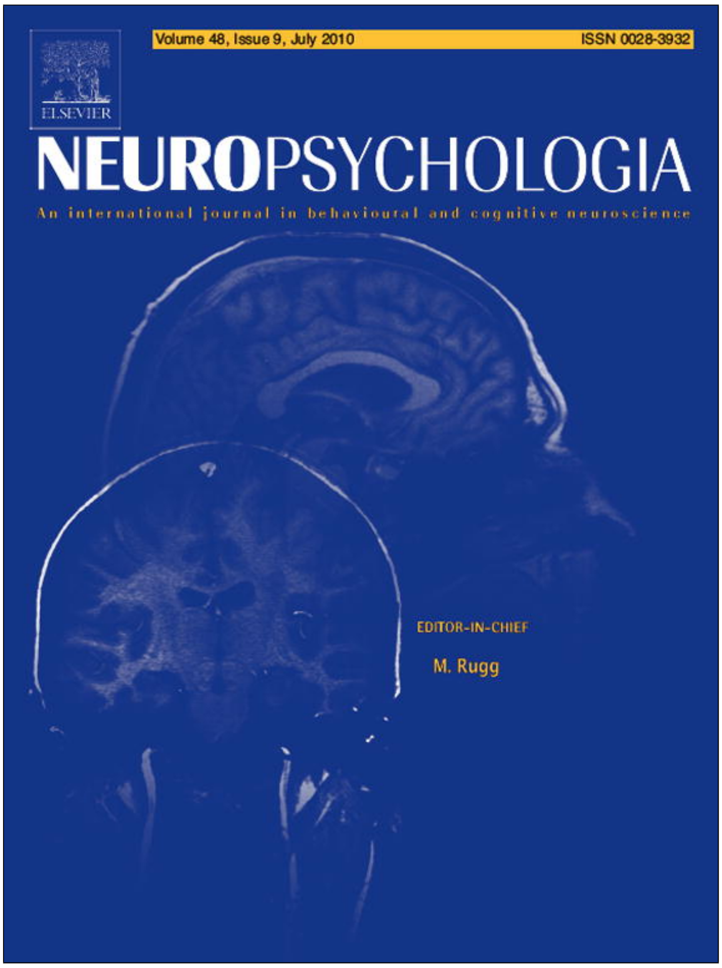
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Enhanced pure-tone pitch discrimination among persons with autism but not Asperger syndrome

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ABSTRACT

Persons with Autism spectrum disorders (ASD) display atypical perceptual processing in visual and auditory tasks. In vision, Bertone, Mottron, Jelenic, and Faubert (2005) found that enhanced and diminished visual processing is linked to the level of neural complexity required to process stimuli, as proposed in the neural complexity hypothesis. Based on these findings, Samson, Mottron, Jemel, Belin, and Ciocca (2006) proposed to extend the neural complexity hypothesis to the auditory modality. They hypothesized that persons with ASD should display enhanced performance for simple tones that are processed in primary auditory cortical regions, but diminished performance for complex tones that require additional processing in associative auditory regions, in comparison to typically developing individuals. To assess this hypothesis, we designed four auditory discrimination experiments targeting pitch, non-vocal and vocal timbre, and loudness. Stimuli consisted of spectro-temporally simple and complex tones. The participants were adolescents and young adults with autism, Asperger syndrome, and typical developmental histories, all with IQs in the normal range. Consistent with the neural complexity hypothesis and enhanced perceptual functioning model of ASD (Mottron, Dawson, Soulières, Hubert, & Burack, 2006), the participants with autism, but not with Asperger syndrome, displayed enhanced pitch discrimination for simple tones. However, no discrimination-thresholds differences were found between the participants with ASD and the typically developing persons across spectrally and temporally complex conditions. These findings indicate that enhanced pure-tone pitch discrimination may be a cognitive correlate of speech-delay among persons with ASD. However, auditory discrimination among this group does not appear to be directly contingent on the spectro-temporal complexity of the stimuli.

Autism spectrum disorders (ASD) include a range of neurodevelopmental variants, including autism and Asperger syndrome, that are characterized by mild to severe atypicalities in communication and social interactions, as well as by restricted behaviors and interests (DSM-IV, American Psychiatric Association, 1994). In addition, idiosyncratic reactions to the auditory environment are often noted with examples of both auditory hypersensitivity and hyposensitivity. The former is evidenced in cases where persons with ASD cover their ears in response to certain sounds that do not bother most others, and the latter in the lack of spontaneous orientation to one's own mother's voice (Grandin, 1997; Leekam, Nieto, Libby, Wing & Gould, 2007). Consistent with these anecdotal observations, persons with ASD display enhanced and diminished patterns of perceptual processing across a variety of auditory tasks (for a review, see Kellerman, Fan, & Gorman, 2005; Nieto Del Rincòn, 2008; Samson, Mottron, Jemel, Belin, & Ciocca, 2006).

The various examples of enhanced auditory processing among persons with ASD include the ability to discriminate between and categorize pure tones on the basis of their pitch or height value (Bonnel et al., 2003; Heaton, Hermelin, & Pring, 1998; O'Riordan & Passetti, 2006), and an increased prevalence of absolute pitch, the rare ability to identify or produce the pitch of a tone without reference to an external standard. Whereas five out of 100 individuals with ASD display absolute pitch (Miller, 1999; Rimland & Fein, 1988), this skill is found in only 1/10,000 individuals in the general population (Takeuchi & Hulse, 1993). In contrast, persons with ASD appear to display a relative difficulty in more complex auditory verbal tasks involving figure/ground discrimination (Alcantara, Weisblatt, Moore, & Bolton, 2004; Groen et al., 2008).

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Together with specific peaks in visuo-spatial and other perceptually related aspects of cognitive and behavioral functioning, these auditory strengths are the hallmarks of the Enhanced Perceptual Functioning Model (EPF: Mottron & Burack, 2001; Mottron, Dawson, Soulières, Hubert, & Burack, 2006). This model identifies a short list of "principles" characterizing autistic perception, its overall enhanced performance, and its enhanced role in typically non-perceptual cognitive operations as well as in guiding behaviors in natural settings. As these auditory strengths and difficulties among persons with ASD are identified within the descriptive EPF framework, the next step is to highlight the relevant psychophysical variables and neural mechanisms that are associated with them.

1. Perceptual complexity in autism: from vision to audition

Conceptualizations of atypical visual processing among persons with ASD (for reviews, see Behrmann, Thomas, & Humphreys, 2006; Dakin & Frith, 2005) may provide frameworks for the more nascent work on auditory processing in this population. The study of the neural basis for atypical visual processing among persons with ASD suggests that patterns of enhanced and diminished visual processing may be contingent upon the neural complexity, or extensiveness of the neural network, that is required to process stimuli. For example, Bertone et al. (2005) found that participants with autism outperformed an age and IQ matched group of typically developing persons in discriminating between simple, luminance-defined visual gratings that are processed primarily at the level of *primary* cortical visual area V1, but displayed a diminished ability to discriminate between complex, texture-defined visual gratings that require additional processing in *associative* cortical areas V2 and V3. Accordingly, Bertone et al. suggested a neural complexity hypothesis in which the atypical visual processing among persons with autism might be contingent upon the *simple* versus *complex* physical attributes of the perceptual stimuli that are processed.

Although there is no direct mapping from vision to audition, the neural complexity hypothesis based on visual processing might be considered to be generalizable to audition on the basis of the following parallels between the two modalities. One, simple and complex perceptual stimuli are processed in a posterior–anterior hierarchical fashion in both the visual (e.g., Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983) and auditory (Hall et al., 2002; Griffiths, 2003; Wessinger et al., 2001) cortices. More specifically, in the auditory modality, stimuli that are spectrally and temporally simple, such as static pure tones, which do not vary in time and consist of a single frequency component, are processed primarily at the level of the primary or "core" auditory cortical area A1 (e.g., Wessinger et al., 2001). In contrast, spectro-temporally complex stimuli, such as band-passed noise bursts (e.g., Wessinger et al., 2001) and speech sounds (Scott & Johnsrude, 2003), require more extensive neuro-integrative processing in primary and associative auditory cortical areas (i.e., belt and lateral parabelt regions). Two, both visual (e.g., Campbell & Robson, 1968; Graham, 1989) and auditory (e.g., Linden & Schreiner, 2003) information are processed according to frequency selective mechanisms in primary perceptual cortices. In vision, neurons that respond preferentially to certain spatial frequencies are grouped together in a columnar fashion (Hubel & Wiesel, 1968; Maffei, 1978). Likewise, in audition, neurons are grouped closely together as a function of their characteristic frequency (i.e., the frequency to which they respond the best) both at the level of the auditory nerve and in the auditory cortex (Moore, 2004).

Drawing from the above structural similarities and from a comprehensive review of the literature on atypical auditory processing among persons with ASD, Samson et al. (2006) proposed that enhanced and diminished patterns of auditory processing among persons with ASD may be linked to the neural complexity required to process acoustic stimuli. They suggested an inverse relationship between gradients of stimulus complexity and patterns of performance on auditory tasks. Accordingly, they predicted that individuals with ASD should display an enhanced ability to discriminate between pure tones in comparison to typically developing persons, because pure tones require minimal neuro-integrative processing at the level of primary area A1. Conversely, they hypothesized that persons with ASD should display diminished auditory discrimination abilities for spectrally or temporally complex tones that require more extensive neural circuitry (i.e., primary and associative auditory cortices). The focus of the present study is to assess this hypothesis at the psychophysical level, to determine if the relevant variables dissociating auditory assets and deficits in autism are related to psychophysical complexity and associated amount of neuro-integrative processing.

2. Preliminary evidence for the neural complexity hypothesis in audition

Samson et al.'s (2006) adaptation of the neural complexity hypothesis is based on consistent evidence that persons with ASD generally outperform age-matched, typically developing participants on auditory tasks that involve pure tones. For example, enhanced processing of simple auditory material is seen in the heightened abilities to: discriminate between and categorize simples tones on the basis of their pitch (Bonnel et al., 2003; Heaton et al., 1998; O'Riordan & Passetti, 2006); identify the individual pitches that make up a chord (Heaton, 2003; Miller, 1989); identify local pitch changes within melodies (Foxton et al., 2003; Heaton et al., 1998; Mottron, Peretz, & Ménard, 2000); label pitch information via absolute pitch (Miller, 1989; Mottron, Peretz, Belleville, & Rouleau, 1999); and memorize pitch information (Heaton et al., 1998; Heaton, 2003). The behavioral findings for enhanced processing of simple auditory material are supported by electrophysiological, auditory event-related potential (ERP) evidence of enlarged Mismatch Negativity (i.e., MNN index of preconscious change detection) responses to pitch changes for simple auditory material among children and adolescents with ASD (e.g., Bruneau & Gomot, 2005; Ferri, Agarwal, Lanuzza, Musumeci, & Pennisi, 2003; Gomot, Giard, Adrien, Barthelemy & Bruneau, 2002; Lepistö et al., 2005).

In contrast to evidence of heightened performance with pure tones, converging behavioral, auditory ERP and brain imaging lines of evidence suggest that persons with ASD generally display diminished auditory processing in tasks involving spectrally or temporally complex stimuli. For instance, a diminished ability to identify speech stimuli presented in noisy backgrounds containing temporal dips (i.e., an intermittent as opposed to constant type of noise) was found among groups of adolescents with autism and Asperger syndrome (Alcantara et al., 2004; Groen et al., 2008). Diminished patterns of auditory processing were also reported in several ERP and brain imaging studies of auditory processing involving spectro-temporally complex speech stimuli. These findings include (1) a diminished ability to discriminate between the prosody of sequences of utterances, as reflected in diminished MMN amplitudes and prolonged latencies for this group (Kujala, Lepistö, Nieminen-von Wendt, Näätänan, & Näätänan, 2005); (2) a lack of orienting response to vowels among children with autism, as suggested by diminished response amplitudes at the level of the P3a index of involuntary attention (Ceponiene et al., 2003); (3) preliminary reports of a failure in a subgroup of adults with autism to activate brain regions that are typically activated in response to vocal stimuli among typically developing individuals (Gervais et al., 2004); and (4) atypical right as opposed to left patterns of cortical activations in the processing of the *temporal* aspects of spectro-temporally complex speech-like stimuli in groups of children and adults with autism (Boddaert et al., 2003, 2004). These lines of evidence provide preliminary support for Samson et al.'s (2006) adaptation of the neural complexity hypothesis that performance on auditory, as on visual, tasks among persons with autism is inversely related to stimulus complexity.

3. Differences in auditory performance between autism and Asperger syndrome

The primacy of the differences in language development between autism and Asperger syndrome, with delayed onset of first words and phrases characteristic of autism and typical developmental milestones of speech characteristic of Asperger syndrome (DSM-IV, APA, 1994), suggests that the efficiency of auditory processing may vary across the subgroups of ASD. This is exemplified in the observation of enhanced pitch discrimination among persons with autism who have a history of delayed speech onset (i.e., Heaton, Davis, & Happé, 2008; Jones et al., 2009) but not among those without such a history. In order to further examine whether the differences would be further manifested among persons with autism and those with Asperger syndrome on tasks of auditory discrimination, groups of persons with each of the diagnoses were tested and analyzed separately in this study.

4. Rationale, objectives and hypotheses

The assessment of the neural complexity hypothesis of ASD in the auditory domain requires the identification of relevant psychoacoustic dimensions and stimuli that may target different levels of neuro-integrative processing. The two studies of most relevance to the neural complexity hypothesis (Alcantara et al., 2004; Groen et al., 2008) involved *auditory disembedding paradigms* that required the detection of words (Groen et al., 2008) or sentences (Alcantara et al., 2004) embedded in various types of background noise (e.g. noise with and without amplitude modulations; noise with and without temporal dips). This is a complex auditory verbal task that requires spectral and temporal integration in both the primary and associative auditory cortical areas (i.e., A1 and A2). However, as these tasks involve high-levels of cognitive load (i.e., attention) and speech-related stimuli exclusively, diminished performance may be associated with factors other than impairments in the extensiveness of the cortical network needed to process spectro-temporally complex stimuli. For example, they might be a function of the linguistic nature of the stimuli or of the attentional component of the task.

In this study, we extended this area of research with the use of elementary auditory discrimination tasks that require minimal cognitive load. A range of spectro-temporally simple and complex speech and non-speech stimuli varying along multiple psychoacoustic dimensions were used to elicit different levels of neuro-integrative processing. The most basic stimuli were spectrally simple pure tones that are comprised of a single, sinusoidal frequency component and are processed in the cortical area A1. The spectrally complex tones were harmonic tones that are comprised of multiple frequency components. These sounds require more extensive neuro-integrative processing as they are processed both in primary cortical area A1 and in associative auditory cortical region A2 (Hall et al., 2002; Griffiths, 2003; Wessinger et al., 2001). The temporally simple stimuli were static (i.e., steady-state) pure tones, which are processed at the level of A1 (e.g., Griffiths, 2003; Wessinger et al., 2001), whereas the temporally complex stimuli were frequency- and amplitude-modulated complex tones that are processed at the levels of A1 and A2 (Hall et al., 2002; Hart, Palmer, & Hall, 2003; Thivard, Belin, Zilbovicius, Poline, & Samson, 2000; Zatorre & Belin, 2001). Spectro-temporally complex, steady-state and modulated vowel-like tones presented in silence and embedded in noise were also included. Because these vowel-like stimuli involve co-varying sources of spectral and temporal complexity (i.e., formants, overtones, etc.), they require more neuro-integrative processing than tones that are spectrally or temporally simple (Scott & Johnsrude, 2003).

The study included four discrimination experiments that required the participants to discriminate between pairs of tones varying in pitch (Experiment 1: height value), timbre or tone quality (Experiments 2 and 3: vocal and non-vocal timbre), and loudness (Experiment 4: intensity). An adaptive staircase procedure was used to assess the auditory discrimination thresholds of groups of adolescents and adults with autism, Asperger syndrome, and typical developmental histories. On the basis of the neural complexity hypothesis, we predicted that the participants with ASD (i.e., autism and Asperger syndrome groups) would display higher auditory discrimination thresholds (i.e., poorer performance) than their TD counterparts for spectrally and temporally complex tones. Conversely, the participants with ASD were expected to display lower pitch discrimination thresholds (i.e., better performance) for the pure-tone condition in Experiment 1. Consistent with evidence that meaningful differences in auditory performance are among those persons with ASD with language delay, both enhanced and diminished performances on auditory tasks were expected to be greater among persons with autism than those with Asperger syndrome.

5. General method

5.1. Participants

The participants included 15 individuals with autism (AUT), 14 persons with Asperger syndrome (AS), and 15 typically developing (TD) individuals with full-scale IQs in the normal range (see Table 1). All the participants were selected from the database of the Rivière-des-Prairies Hospital's (Montréal, Canada) ASD clinic. Exclusion criteria for the ASD groups included a co-morbid DSM-IV axis 1 disorder (except for hyperactivity and language disorders) or relevant axis 3 diagnoses, and pharmacological treatment. For the participants in the TD group, the exclusion criteria included a personal or family history of neurological or psychiatric disorders and pharmacological treatment. The chronological ages ranged from 14 to 36 years for the participants with autism, from 15 to 31 years for those with Asperger syndrome, and from 15 to 32 years for the typically developing participants. These age ranges were selected on the basis of the consideration that auditory systems and structures are fully developed by age 12 (Moore, 2002; Moore & Linthicum, 2007). The average full-scale IQ and age characteristics of the participants in the different groups (see Table 1) did not differ significantly, as indicated by non-parametric Kruskal–Wallis tests [IQ: $\chi^2(2) = 1.296$, $p = .523$; age: $\chi^2(2) = .860$, $p = .650$].

All of the participants had normal auditory acuity (hearing thresholds equal or inferior to 25 dB HL, or hearing level) as assessed in an audiometric testing chamber for the standard range of frequencies (250–8000 Hz). Further, care was taken to ensure that none of the participants had five or more years of formal musical training as musical training is associated with enhanced pitch

Table 1
Participants' characteristics.

Group	Age		Global IQ		Sex ratio
	M	SD	M	SD	Male/female
AUT ($n = 15$)	24.16	7.01	103.87	14.48	13/2
AS ($n = 14$)	22.71	5.85	105.92	16.31	12/2
TD ($n = 15$)	21.40	3.98	108.40	13.10	14/1

Table 2a
Experimental design table: static-sound conditions.

Experiment	I. Pitch		II. Vocal timbre		III. Non-vocal timbre	IV. Loudness
Stimulus	Pure tone	Complex tone	Vocal tone	Vocal tone in noise	Complex tone	Complex tone
Task . . . 4I-2AFC: ‘Which pair contains the different sounds?’						

discrimination (Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Micheyl, Delhommeau, Perrot, & Oxenham, 2006). This study was approved by the boards of ethics of McGill University and Rivière-des-Prairies Hospital, and written informed consent was accordingly obtained for all of the participants, who received financial compensation for their participation in the study.

5.1.1. *Operationalization of ASD diagnoses*

Fourteen of the 15 participants in the autism group and 12 of the 14 individuals in the AS group were diagnosed prior to testing based on the Autism Diagnosis Interview-revised (ADI-R: Lord, Rutter, & Le Couteur, 1994) and/or Autism Diagnostic Observation Schedule (ADOS-G: Lord, Rutter, DiLavore, & Risi, 1999). The remaining three participants were diagnosed based on DSM-IV (APA, 1994) criteria for autism spectrum disorders. Asperger syndrome diagnoses were operationalized on the basis of the ADI-R criteria of *first single words before 24 months* and *first two-word phrases before 33 months*. Three participants in the autism group did not display a delayed speech onset in infancy, however, their atypical language development (i.e., echolalia, stereotyped phrases, etc.) were deemed to justify an autism rather than AS diagnosis. Similarly, two participants in the Asperger group did not clearly fit the above two ADI-R criteria; however, their particular linguistic profile and associated clinical histories were deemed to warrant an Asperger diagnosis. All diagnostic assessments were conducted by a multidisciplinary team of expert clinicians. Among the participants who were diagnosed with the ADI-R, seven individuals with Asperger syndrome and six with autism had a childhood history of auditory hypersensitivity.

5.2. *Apparatus*

The stimuli were created on a Macintosh laptop computer using the Max/MSP program from Cycling ‘74 (Zicarelli, 1998) controlled by the PsiExp environment (Smith, 1995). The acoustic stimuli were converted with an M-Audio Firewire Solo audio interface and delivered over Sennheiser HD280 headphones. All the testing took place in a sound-attenuated chamber at the Rivière-des-Prairies hospital.

5.3. *Tasks and general procedures*

Computer-based, forced-choice tasks were designed to evaluate differential discrimination thresholds for acoustic stimuli varying in levels of spectral and/or temporal complexity. The thresholds were measured using a 3-down/1-up adaptive staircase procedure targeting the 79.4% level on the psychometric function (Levitt, 1971). In each condition, the participants completed five to eight experimental blocks on the basis of their threshold performance. Each experimental block corresponded to a range of 20–40 trials. For each experimental block, the staircase ended after six reversals (i.e., changes of direction or level of difficulty within the staircase procedure), and the final threshold estimate was taken as the average of the last four out of six reversals. Thus, five to eight threshold measurements were taken for each participant in each condition. The median of these threshold measurements, which was deemed to be a more robust estimate than the mean given the small number of estimates taken, was then recorded and used for statistical analyses.

In all four experiments, the participants were asked to discriminate between pairs of tones varying in *pitch* (Experiment I), *vocal timbre* (Experiment II), *non-vocal timbre* (Experiment III), or *loudness* (Experiment IV). A total of 11 conditions were selected on the basis of data from pilot studies. The tones were presented either in their static form, in which case the participants were asked to determine which pair of sounds (the first or the second) contained the different sounds (i.e., A–A – A–B: a four-interval, two-alternative forced-choice task) (see Table 2a), or in their modulated form, in which case the participants were asked to determine which of two sequentially presented sounds was modulated (i.e., A–B: a two-interval, two-alternative forced-choice paradigm) (see Table 2b).

The participants responded by pressing one of two buttons of a simple response box. The order of the static and modulated conditions was counterbalanced across participants in order to minimize practice effects. The participants were presented with a practice block before each condition. Verbal feedback (i.e., a recorded message providing “yes”, “no” feedback following correct and incorrect responses, respectively) was provided both during practice trials and throughout the testing sessions. In order to document possible auditory hypersensitivity reactions to the acoustic stimuli by the participants in the autism and Asperger syndrome groups, the participants were also asked to rate the pleasantness of short sequences of tones taken from the different conditions on a scale from 1 (very pleasant) to 5 (very unpleasant). Overall, the participants in the different groups rated the different signals as generally “pleasant”. Because none of the participants in the ASD subgroups displayed aversive reactions or reported to be bothered by any of the stimuli, this qualitative data was dismissed from further analyses.

5.4. *General stimulus characteristics*

The stimuli had a duration of 190 ms, which included 10-ms linear onset and offset ramps and were presented dichotically at approximately 65 dB SPL (Sound Pressure Level). For the static conditions, two pairs of stimuli were presented. The stimuli in each pair were separated by 210-ms of silence, and the stimulus pairs were separated by 710 ms of silence. The pairs had four equally probable orderings: [A–A – B–A]; [A–A – A–B]; [A–B – A–A] or [B–A – A–A], where A was the standard stimulus, and B the comparison tone. For modulated conditions, a single pair of stimuli separated by a 210 ms silent interval was presented. The two equally probable orderings were [A–B] and [B–A]. Successive experimental

Table 2b
Experimental design table: modulated-sound conditions.

Experiment	I. Pitch		II. Vocal timbre	III. Non-vocal timbre	IV. Loudness
Stimulus	FM pure tone	FM complex tone	Modulated-parameter vocal tone	Modulated-parameter complex tone	AM complex tone
Task . . . 2I-2AFC: ‘Which sound is modulated?’					

trials were initiated automatically 1000 ms after the participant's response.

5.5. General analyses

In each experiment, the data were analyzed using repeated measures ANOVAs. Because our hypothesis was that the participants in the ASD groups would display higher auditory discrimination thresholds than their TD counterparts for spectrally and temporally complex tones, we limited the statistical analyses to tests of "between-group" hypotheses. A restricted number of t-tests was also conducted to assess a-priori, unidirectional hypotheses targeting specific experimental conditions and pairs of groups. Finally, in each experiment, secondary analyses targeting the impact of "order of task presentation" (i.e., order 1: static-modulated, versus order 2: modulated-static) on participants' level of performance were conducted and found to be non-significant.

Before proceeding to the data analyses, we first identified potential outliers by a visual examination of the threshold data pertaining to each participant. Experimental session-notes were then verified to validate the exclusion of a particular participant as an "outlier". Using this procedure, we identified two participants in Experiment 1 that displayed particularly high thresholds, one from the autism group, and the other from the Asperger syndrome group. Because these participants had disclosed that they had difficulty concentrating during the experiment, their data were removed from the final analyses. The participant from the Asperger syndrome group was also identified as an outlier in the other three experiments, and his threshold data were accordingly removed. All results are based on a significance level of $p < 0.05$, and error bars are presented within graphs.

6. Experiment 1: pitch discrimination

6.1. Method

6.1.1. Stimuli

This experiment involved the four conditions of *static pure tone*, *static complex-tone*, *frequency-modulated* (*FM*) *pure tone* and *frequency-modulated* (*FM*) *complex tone*. In the adaptive procedure, the frequency (for pure tones), or the fundamental frequency (F0) for complex tones, was varied as a function of parameter *P*, the deviation in semitones from the F0 of the standard stimulus (500 Hz). For static tones, the adaptive parameter *P* was varied in steps of 0.024 semitones, and the F0 of the comparison stimulus was:

$$\mathrm{F0} = 500 \times 2^{\frac{P}{12}}\ \mathrm{Hz} \tag{1}$$

For frequency-modulated tones (modulation frequency, $f_\mathrm{m} = 10$ Hz), the step size was 0.018 semitones, and the fundamental was:

$$\mathrm{F0} = 500 \times 2^{\frac{P}{12} \times \frac{\sin(2\pi f_\mathrm{m} t)}{2}}\ \mathrm{Hz.} \tag{2}$$

The complex tones were the sum of the first 30 harmonics of the fundamental frequency. The relative amplitudes of the partials were determined by the relative amplitude a_1 of the first harmonic, and by the parameter *S*, the *spectral slope* (held constant at −12 dB/octave).

$$a_n = a_1 \times 10^{S\log_2(n)/20}(\text{relative amplitude}) \tag{3}$$

where

$$S = \frac{20\log_{10}(a_n) - 20\log_{10}(a_1)}{\log_2(n)}\ \text{dB/octave for all } n > 1. \tag{4}$$

Finally, the relative amplitudes a_n were adjusted, in conformance with the above constraints, so that the signal had constant energy:

$$\sum_{k=1}^{30} a_k^2 = \text{constant (total energy, in arbitrary units)} \tag{5}$$

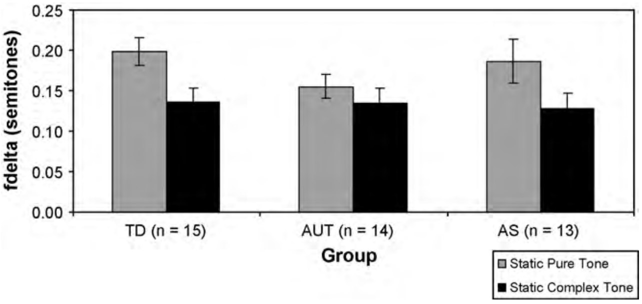

Fig. 1. fdelta average pitch discrimination thresholds (static pure-tone and static complex-tone conditions) for the participants in the three groups.

6.1.2. Hypotheses

On the basis of the neural complexity hypothesis, the participants in the ASD groups were expected to display lower thresholds for the static pure-tone condition in Experiment 1 than those in the TD group and higher pitch discrimination thresholds for the conditions involving complex tones. Moreover, based on previous empirical evidence (i.e., Bonnel et al., 2003), the participants with autism were expected to display lower pitch discrimination thresholds than those in the AS- and TD groups for the static pure-tone condition specifically.

6.2. Results

For the *static pure-tone* and *static complex-tone* conditions, the pitch discrimination thresholds were defined as the smallest detectable change in frequency (i.e., fdelta), measured in semitones. For the *frequency-modulated pure-tone* and *frequency-modulated complex-tone* conditions, the thresholds corresponded to the smallest detectable change in modulation depth (i.e., fdepth), measured in semitones as well. The threshold data were analyzed using a mixed-model ANOVA looking at the effects of *spectral complexity* (pure, complex), *temporal complexity* (static, modulated) and *group* (autism, AS, TD) on pitch discrimination thresholds. In addition, two secondary t-test analyses were conducted targeting our a-priori hypothesis that the participants with autism would outperform the AS and TD participants in the static pure-tone condition. The data are presented in Figs. 1 and 2.

Neither the three-way-[*spectral* × *temporal* × *group*: $F(2, 39) = 0.120$; $p = 0.888$] nor the two-way interactions were significant [*temporal complexity* × *group*: $F(2, 39) = 0.158$; $p = 0.854$; *spectral complexity* × *group*: $F(2, 39) = 0.419$; $p = 0.661$]. The main effect of *group* was non-significant as well [$F(2, 39) = 0.431$;

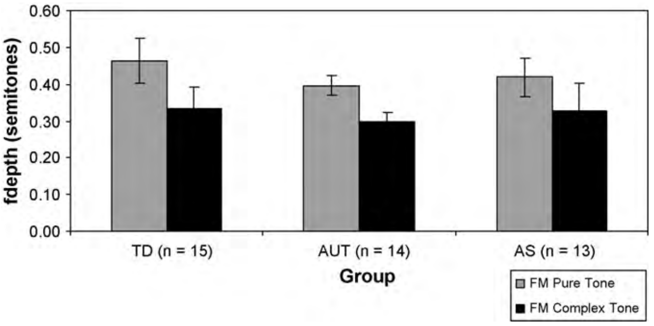

Fig. 2. fdepth average pitch discrimination thresholds (FM pure-tone and FM complex-tone conditions) for the participants in the three groups.

$p = 0.653$]. However, secondary, a-priori t-test analyses targeting the performance of the autism and TD participants in the static pure-tone condition specifically revealed that the participants with autism displayed significantly lower average pitch discrimination thresholds than those in the TD group [$t_{1-\text{tailed}}\,(27) = 1.856$; $p = 0.037$)]. By contrast, the analyses failed to reveal significant differences in the average pitch discrimination thresholds of the participants with AS compared to those in the TD group [$t_{1-\text{tailed}}$ (26) = 0.367; $p = 0.358$].

Thus, the participants with autism displayed enhanced pitch discrimination abilities in the *static pure-tone condition* specifically. However, contrary to our predictions, no significant differences in average pitch discrimination thresholds were found across the static- and frequency-modulated complex-tone conditions for the participants in the different groups.

7. Experiment 2: vocal-timbre discrimination

7.1. Method

7.1.1. Stimuli

This experiment included the conditions of static vocal tone, static vocal tone in noise, and modulated-parameter vocal tone. The stimuli were formant-based synthetic vowel sounds generated with the Max/MSP FOF externals from IRCAM (Clarke & Rodet, 2003). The vowels had three formants, F1, F2 and F3, each characterized by its center frequency, amplitude, and bandwidth. We refer to the three formants grouped together as F_n, with $n = 1$, 2 or 3.

The stimuli's formants were based on two vowels: VI, with formants F_{In}, approximating the vowel [i], and VA, with formants F_{An}, approximating the vowel [a]. Ircam's FOF externals allowed us to vary the formant parameters in real time. They were interpolated between those of F_{In} and F_{An} as a function of V: when $V = -.5$, the formant parameters were those of F_{In}, resulting in the vowel [i]. When $V = .5$, they were those of F_{An}, producing the vowel [a]. For values of n between −.5 and .5, the parameters were interpolated between those of F_{In} and F_{An}, yielding an intermediate vowel between [i] and [a]. For example, the three formants' center frequencies fn were:

$$F_n(V) = (.5 - V)\,F_{\boldsymbol{I}n} + (.5 + V)F_{\boldsymbol{A}n}$$

where V is a dimensionless value between −.5 and .5,

$$F_{\boldsymbol{I}1} = 277\,\text{Hz},\quad F_{\boldsymbol{I}2} = 2131\,\text{Hz},\quad F_{\boldsymbol{I}3} = 2731\,\text{Hz}$$

and

$$F_{\boldsymbol{A}1} = 660\,\text{Hz},\quad F_{\boldsymbol{A}2} = 1200\,\text{Hz},\quad F_{\boldsymbol{A}3} = 2500\,\text{Hz}.$$

The formant frequencies of the standard stimulus, $\mathbf{F}_{\mathbf{standard}\,n}$, corresponding to $V = 0$, produced a vowel sound halfway between $\boldsymbol{V}_\text{I}$ and $\boldsymbol{V}_\text{A}$, roughly equivalent to the vowel [e]. Continuing the example, the center frequencies of the standard frequencies $F_{\text{standard}\,n}$ were:

$$F_{\boldsymbol{standard}\,n} = (F_{\boldsymbol{I}n} + F_{\boldsymbol{A}n})/2.$$

The adaptive parameter P represented deviation from the standard stimulus. For the static vocal tone condition, $V = P$, and the step size of P was 0.015. For the modulated condition, $V = P\sin(2\pi f_\text{m} t)/2$ [$f_\text{m} = 10\,\text{Hz}$], and the step size was 0.03. For the static vocal tone in noise condition, pink noise approximately 40 dB below the level of the stimulus was added.

7.1.2. Hypotheses

Based on the neural complexity hypothesis, we predicted that the participants with ASD would display higher vocal-timbre discrimination thresholds than their typically developing counterparts in all three conditions, because of the spectro-temporally complex, speech-like character of the stimuli.

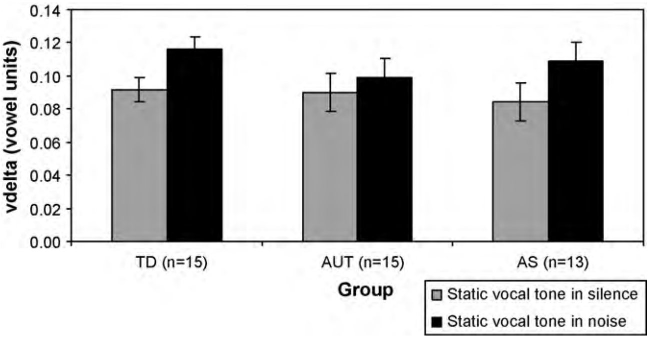

Fig. 3. vdelta average vocal-timbre discrimination thresholds (vocal tone in silence vs. in noise conditions) for the participants in the three groups.

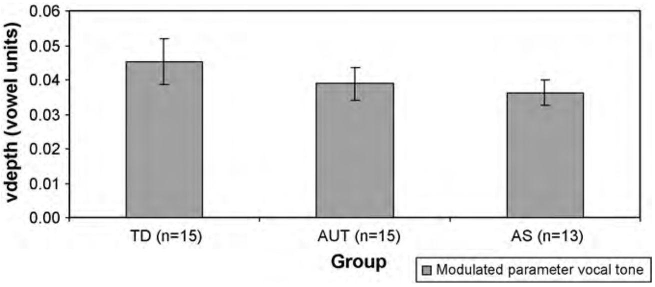

Fig. 4. vdepth average vocal-timbre discrimination thresholds (modulated-parameter vocal tone condition) for the participants in the three groups.

7.2. Results

The vocal-timbre discrimination thresholds of the *static vocal tone* and *static vocal tone in noise* conditions were defined as the smallest detectable change in formant value (i.e., *vdelta*), as measured in vowel-units. The vocal-timbre discrimination thresholds of the *modulated vocal-tone* condition were defined as the smallest detectable change in modulation depth (i.e., *vdepth*), also measured in vowel-units. A two-way mixed-model ANOVA was conducted to assess the effects of *the factors noise, vowel modulation and group* on vocal-timbre discrimination thresholds.

The data from this experiment are presented in Figs. 3 and 4. There was no main effect of *group* [$F(2, 40) = .545$; $p = .584$]. The *noise* × *vowel modulation* × *group* interaction [$F(4, 80) = .729$; $p = .575$] was non-significant as well. Thus, the average vocal-timbre discrimination thresholds of the various groups did not differ across the vocal-tone-in-silence, vocal-tone-in-noise, and modulated-parameter vocal-tone conditions.

8. Experiment 3: non-vocal-timbre discrimination

8.1. Method

8.1.1. Stimuli

The two conditions of this experiment were the *static spectral slope* and *modulated spectral slope*. The stimuli consisted of complex tones with fundamental frequency F0 = 500 Hz. The adaptive parameter P determined the deviation in dB/octave of the comparison tone's spectral slope S from the standard tone's value of $S = -12$ dB/octave. In the static case, $S = P - 12$ and the step size for P was 0.2 dB/octave. For the modulated case, the step size was 0.4 dB/octave and $S = P\sin(2\pi f_\text{m} t)/2 -$

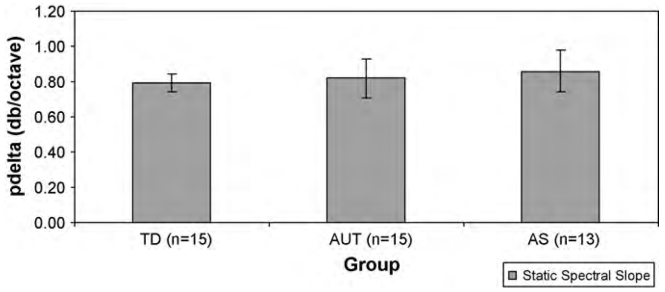

Fig. 5. pdelta average non-vocal-timbre discrimination thresholds (static spectral slope condition) for the participants in the three groups.

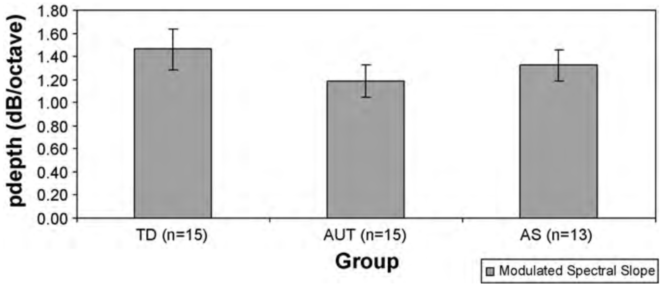

Fig. 6. pdepth average non-vocal-timbre discrimination thresholds (modulated spectral slope condition) for the participants in the three groups.

$12 \quad (f_\mathrm{m} = 10\,\mathrm{Hz})$ dB/octave, with the amplitudes a_n being continually adjusted to satisfy equations (4) and (5) (see Experiment 1 stimuli section).

8.1.2. Hypotheses

The participants in the ASD groups were expected to display higher non-vocal-timbre (i.e., spectral slope) discrimination thresholds than those in the TD group in both conditions because of the spectro-temporally complex character of the stimuli.

8.2. Results

The non-vocal-timbre discrimination thresholds for the *static spectral-slope* condition were defined as the smallest detectable change in spectral slope (i.e., *pdelta*), expressed in dB/octave. The discrimination thresholds for the *modulated-parameter spectral-slope* condition corresponded to the smallest detectable change in modulation depth (i.e., pdepth), expressed in dB/octave as well. The results are presented in Figs. 5 and 6. A two-by-three repeated-measures ANOVA used to assess the effect of *temporal complexity* × *group* on non-vocal-timbre discrimination thresholds revealed neither a main effect of *group* [$F(2, 40) = 0.405$, $p = 0.670$] nor a *temporal complexity* × *group* interaction [$F(2, 40) = 1.094$, $p = 0.345$]. Thus, the non-vocal-timbre discrimination thresholds of the participants in the various groups did not differ across the temporally simple (i.e., static) or complex (i.e., modulated) conditions.

9. Experiment 4: loudness discrimination

9.1. Method

9.1.1. Stimuli

The two conditions of this experiment are *static-level complex tone* and *amplitude-modulated (AM) complex tone*. The stimuli were complex tones with constant fundamental frequency F0 = 500 Hz and spectral slope $S = -12$ dB/octave. In the *static-level complex tone* condition, the adaptive parameter *P* was simply the increase in level of the comparison tone in dB; the step size was 0.5 dB. In the *AM complex tone* condition, the level of the comparison tone relative to the reference tone was $P\sin(2\pi f_\mathrm{m} t)/2\,\mathrm{dB} \quad (f_\mathrm{m} = 10\,\mathrm{Hz})$ total energy, in arbitrary units, and the step size was 0.5 dB.

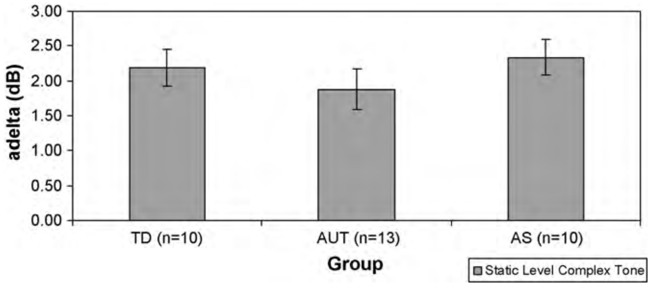

Fig. 7. adelta average loudness discrimination thresholds (static-level complex-tone condition) for the participants in the three groups.

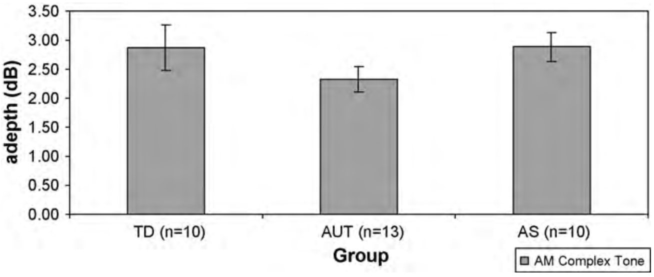

Fig. 8. adepth average loudness discrimination thresholds (AM complex-tone condition) for the participants in the three groups.

9.1.2. Hypotheses

The participants in the ASD groups were expected to display higher loudness-discrimination thresholds than those in the TD group in both conditions of this experiment, because of the spectro-temporally complex character of the stimuli.

9.2. Results

The loudness discrimination thresholds for the *static-level complex-tone* condition were defined as the smallest detectable change in amplitude (i.e., *adelta*), expressed in dB. The loudness discrimination thresholds fon the *amplitude-modulated complex-tone* condition were defined as the smallest detectable change in modulation depth (i.e., *adepth*), expressed in dB. The threshold data were analyzed using mixed model ANOVAs to assess the effect of *temporal complexity* × *group* on *loudness discrimination* thresholds. Only 12 participants with AS and 10 of the TD participants were available to complete this experiment. Among the participants, one person with autism and two with AS were identified as outliers. Therefore, the analyses were based on the data of 13 participants with autism, 10 participants with AS, and 10 TD participants.

The data from this experiment are presented in Figs. 7 and 8. Neither the two-way interaction [*temporal complexity* × *group*: $F(2, 30) = 0.154$; $p = 0.858$] nor the main effect of *group* [$F(2, 30) = 1.365$; $p = 0.271$] were significant. Thus, the current analyses failed to reveal significant differences in the average loudness discrimination thresholds of the participants with ASD and the TD persons across the static-level- and AM complex-tone conditions.

10. General discussion

This study was an initial assessment of auditory discrimination in persons with ASD. A range of spectro-temporally simple and complex tones that varied in pitch, vocal and non-vocal timbre, and loudness were administered to CA-matched groups of musically naïve adolescents and young adults with autism, Asperger syndrome, and typical development with full-scale IQs in the normal range. The primary finding was that the participants with autism, but not those in the other groups, displayed an enhanced ability to discriminate between pure tones on the basis of their pitch. Contrary to our predictions, the participants with ASD did not display diminished abilities to discriminate between complex tones that varied in pitch, timbre, or loudness.

10.1. Implications of the current findings for the neural complexity hypothesis

According to the neural complexity hypothesis (Samson et al., 2006), auditory discrimination abilities should be enhanced with simple tones but diminished with complex tones among persons with ASD in comparison to typically developing individuals. The finding that the participants with autism displayed enhanced pitch discrimination for the simple, pure-tone stimuli is consistent with this hypothesis, but their apparently intact abilities to discriminate between complex tones on the basis of their pitch, timbre, and loudness is not. This pattern of findings may be interpreted in several ways. One possible interpretation is that the acoustic stimuli used in the current study may not have been sufficiently complex to uncover the type of dissociation that was reported in the visual modality. Although the spectro-temporally complex tones used in the current study required different levels of neural integration across primary and associative auditory cortical regions, they might have been too elementary to involve the extensive neuro-integrative mechanisms that might be involved in diminished auditory processing among persons with ASD. Rather, higher-level, *auditory disembedding*-type paradigms that involve amplitude-modulated types of noise, require high-levels of temporal integration and are therefore more similar to language at this level, may be more sensitive to auditory processing difficulties.

A second possible explanation for the finding of intact abilities to discriminate between complex tones is that the origin of the reported deficit in the processing of complex auditory information does not have a *perceptual* origin. Rather, the diminished processing of speech-related stimuli embedded in various types of background noise (i.e., Alcantara et al., 2004; Groen et al., 2008) may be related to the linguistic nature of the material involved, or to the level of attention required to separate figure from ground in auditory disembedding paradigms. This is consistent with the behavioral (Alcantara et al., 2004; Groen et al., 2008) and electrophysiological (Kemner, Verbaten, Cuperus, Camfferman, & Van Engeland, 1995) evidence that vocal-timbre processing does not constitute a particular area of difficulty for persons with ASD when the stimuli consist of vowels presented in continuous, non-modulated noise or of vowels presented in silence. This possibility is also consistent with the electrophysiological evidence that the difficulties that persons with ASD experience in processing complex auditory information may occur at an attentional, rather than a sensory, level of processing. For example, Ceponiene et al. (2003) found that participants with autism displayed a diminished ability to spontaneously orientate to vowel stimuli, as indexed by the P3a component of automatic orientation of attention, whereas the sensory, pre-attentive level of vowel processing was unaffected.

A third, related possibility is that the enhanced auditory discrimination among persons with autism may not only apply to pure tones but also to complex tones, although it may be more marked for pure tones. In the current study, the participants with autism, as compared to the TD participants tended to display lower auditory discrimination thresholds (i.e. superior performance) on 10 of the 11 conditions, and the participants in the AS group outperformed the TD participants on 8 of those conditions. This raises the question of whether additional between-group differences might have emerged with greater sample sizes. A power analysis indicated that the current samples had adequate statistical power (80%) to detect an effect size equivalent to 20% of the total variance, which, according to Cohen (1988), corresponds to a large effect. This suggests that the small sample sizes could have limited the statistical power for detecting medium and small differences across the three target populations. In terms of mechanism, the discrimination tasks in the auditory modality may be successfully achieved by persons with autism through a series of multiple “local” pitch discriminations. According to this hypothesis, complex sounds would be discriminated through “simple” neural networks, rendering them easier to discriminate as more information is available to perform the discrimination task. This is consistent with preliminary findings from a companion paper (Samson et al., submitted) in which increased levels of spectral and temporal complexity were associated with greater activity in primary auditory cortex among persons with autism than among those with Asperger syndrome or among typically developing persons.

The findings presented here indicate that, at a behavioral level, the abilities of persons with ASD to discriminate between elementary tones varying in pitch, timbre and loudness is not directly contingent upon the extensiveness of the neural network required to process the stimuli. Further investigations of the neural complexity hypothesis in the auditory modality should involve experimental paradigms with greater attentional demands, such as tasks of auditory disembedding and others that entail processing in a complex auditory network.

10.2. Are pure tones a special case in autism?

Enhanced frequency discrimination is the most replicated and robust finding associated with atypical auditory processing among autistic persons, as pitch discrimination is enhanced among autistic persons for *pure tones* (Bonnel et al., 2003; Heaton et al., 1998; O'Riordan & Passetti, 2006), *complex non-musical tones* (Heaton et al., 2008; Heaton, Williams, Cummins, & Happé, 2008) and *musical material* (Heaton, 2003, 2005; Heaton et al., 1998; Heaton, Pring, & Hermelin, 2001; Jarvinen-Pasley, Wallace, Ramus, Happé, & Heaton, 2008; Mottron et al., 2000, 1999; Pring, Woolf, & Tadic, 2008). These findings suggest that the ability to discriminate between *pure tones* on the basis of their *pitch* stands out as a “special case” among autistic persons. However, the unexpected trend for the participants with autism to display enhanced auditory discrimination abilities across all four experiments in comparison to the TD participants suggests that, with increased statistical power, enhanced abilities to discriminate between complex tones may also have been observed among this group.

The current findings are consistent with the premise of the EPF model that persons with ASD display enhanced low-level auditory processing abilities (Mottron et al., 2006). This model is based on the notion that the cognitive performance of persons with ASD is more perceptually and locally driven than that of typically developing persons, resulting in enhanced processing of the elementary features of compound perceptual stimuli (e.g., orientation in visual gratings; pitch in acoustic stimuli). However, these findings challenge the notion from the Weak Central Coherence theory (WCC: Happé & Frith, 2006) and the neural complexity hypothesis (Bertone et al., 2005) that enhanced processing of the low-level characteristics of perceptual stimuli, such as pitch in musical materials, either results from or is associated with a deficit at the level of complex information processing. In contrast to this intuitively appealing "inverse hypothesis', Plaisted-Grant and Davis (2009) note that enhanced performance in ASD is not necessarily associated with a related deficit.

Insights into the neural basis of enhanced processing of the pitch of simple, pure-tone stimuli may be gained from neural conceptualizations of enhanced processing of the low-level characteristics of simple visual stimuli. Excessive lateral inhibition at the level of primary visual cortical areas may account for both enhanced and diminished visual processing among persons with ASD (Gustafsson, 1997a,b). Lateral inhibition mechanisms are a fundamental property of the neural response to incoming visual (Gustafsson, 1997a,b) and auditory perceptual input (Oswald, Schiff, & Reyes, 2006). In the primary auditory cortex, neurons that respond best to certain frequencies are grouped closely together in hypercolumns (Abeles & Goldstein, 1970; Linden & Schreiner, 2003). By augmenting the perception of contrast, highly specialized inhibitory and excitatory neural response patterns facilitate stimulus detection and discrimination. Excessive lateral inhibition would result in enhanced orientation-selective mechanisms within the primary visual cortex (see Bertone et al., 2005 for a complete discussion). Applied to the auditory modality, this hypothesis may account for enhanced pitch discrimination for pure tones among persons with ASD.

10.3. *Enhanced pitch discrimination as a correlate of delayed speech onset*

The finding of enhanced pure-tone pitch-discrimination abilities among the participants with autism, but not those with Asperger syndrome, is consistent with evidence of remarkable pitch discrimination abilities in a subgroup of children with autism, the majority of whom had a history of delayed speech onset (Heaton et al., 2008b). The combination of a diminished interest for social/linguistic stimuli and attentional bias toward non-speech sounds may result in an over-specialization of pitch-processing mechanisms for its non-linguistic aspect, such as of musical and non-musical tones (Heaton et al., 2003; Heaton et al., 2008a,b). If this hypothesis is confirmed, it would account both for the evidence of enhanced processing of non-speech sounds, as in pure-tone frequency discrimination, and for evidence of diminished processing of speech material. Research on the processing of speech versus non-speech sounds in young children with ASD suggests that preferential attention to non-speech sounds among persons with autism may limit the development of specialized speech processing mechanisms in this group (Kuhl, Coffey-Corina, Padden, & Dawson, 2005). For example, using behavioral and electrophysiological methods, Kuhl et al. found that pre-school children with autism differed from chronological and mental age-matched typically developing peers in the failure to show the expected MMN neural response to changes in vowel stimuli and in their preferential attention to non-speech analogs of child directed speech-sounds.

The hypothesis of an association between enhanced perceptual abilities and delayed speech onset among persons with autism is further supported by Mottron, Soulieres, Meilleur, and Dawson (2008), who highlighted a strong association between visuo-motor peaks of abilities, as evident in enhanced performance in the block design subtest of the Wechsler Intelligence Scales (Wechsler, 1981), and a history of delayed onset of first words and sentences among persons with autism. These patterns of findings suggest that visual and auditory perceptual peaks of ability may constitute *cognitive correlates* of delayed speech onset among autistics as well as a phenotypic marker of the distinction between autism and Asperger syndrome.

11. Conclusions

Consistent with the extension of the neural complexity hypothesis to the auditory modality, the current findings indicate that persons with autism display a particular strength in discriminating between pure tones that differ in pitch. Together with the evidence of superior processing of visual information in primary visual cortex, the findings indicate that functions served by primary perceptual areas are enhanced in autism. However, contrary to the extension of the neural complexity hypothesis, the abilities of the participants with ASD to discriminate between elementary tones that vary in pitch, timbre, and loudness were not directly contingent on the spectral and temporal complexity of the processed stimuli. Yet, as the discrimination tasks may be successfully performed by persons with autism through the combination of simple mechanisms, they may not be optimal for assessing the extension of the complexity hypothesis to the auditory modality.

The finding that only persons with autism, and not those with Asperger syndrome, displayed enhanced pure-tone pitch discrimination indicates that perceptual peaks of ability may be a sub-typing tool for ASD. More generally, the current set of findings is additional evidence for the premise of the EPF model that strengths outnumber deficits in perceptual processing among persons with autism. These superior performances and the role of perception may be essential to both sub-typing and explaining the cognitive and behavioural phenotypes of autism.

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