

Enhanced Pitch Sensitivity in Individuals with Autism: A Signal Detection Analysis

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Abstract

■ Past research has shown a superiority of participants with high-functioning autism over comparison groups in memorizing picture–pitch associations and in detecting pitch changes in melodies. A subset of individuals with autism, known as “musical savants,” is also known to possess absolute pitch. This superiority might be due to an abnormally high sensitivity to fine-grained pitch differences in sounds. To test this hypothesis, psychoacoustic tasks were devised so as to use a signal detection methodology. Participants were all musically untrained and were divided into a group of 12 high-functioning individuals with autism and a group of 12 normally developing individuals. Their task was to judge the pitch of pure tones in a “same–different”

discrimination task and in a “high–low” categorization task. In both tasks, the obtained psychometric functions revealed higher pitch sensitivity for subjects with autism, with a more pronounced advantage over control participants in the categorization task. These findings confirm that pitch processing is enhanced in “high-functioning” autism. Superior performance in pitch discrimination and categorization extends previous findings of enhanced visual performance to the auditory domain. Thus, and as predicted by the enhanced perceptual functioning model for peaks of ability in autism (Mottron & Burack, 2001), autistic individuals outperform typically developing population in a variety of low-level perceptual tasks. ■

INTRODUCTION

Autism is a pervasive developmental disorder characterized by both negative and positive symptoms. Negative symptoms, which refer to impairments in specific areas of functioning in comparison to typically developing individuals, occur mainly in the social and communication spheres. Positive symptoms refer to the presence of behaviors that are not evident in typically developing individuals, and include the engagement in repetitive movements and intense interest in the perceptual features of objects.

Although the negative symptoms, which are mandatory for the diagnosis of autism, have until recently been the principal focus of scientific investigation, there is now an increasing interest in the positive aspects of the disorder. Empirical investigation of the cognitive bases for atypical, perceptually based behaviors in autism has led to the establishment of superior performance in several cognitive domains. Specifically, enhanced performance has been shown in low-level, visual perceptual tasks such as visual search (O’Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O’Riordan, & Baron-Cohen, 1998) and discrimination tasks (Plaisted et al., 1998). Also, research using hierarchical stimuli in divided

attention conditions revealed a stronger local advantage (or orientation of attention toward the local aspects of compound visual stimuli) in individuals with autism than in their typically developing counterpart (Plaisted, Swettenham, & Rees, 1999; Mottron & Belleville, 1993; Mottron, Belleville, & Ménéard, 1999).

The abovementioned findings have pointed towards the hypothesis of a superior discriminative capacity in the auditory modality as well. Gaining further insight into auditory processing in autism is important for both clinical and theoretical reasons. At the clinical level, a significant number of individuals with autism are known to manifest atypical behaviors in the auditory modality, including aversive reactions to everyday life sounds (Rosenhall, Nordin, Sandström, Ahlsén, & Gillbert, 1999; Lord, Rutter, & Le Couteur, 1994; Ornitz, 1974). Additionally, research on the “musical savant syndrome,” an extreme case of enhanced performance in autism, has shown that a subgroup of individuals with the disorder, musical savants, exhibit outstanding pitch processing abilities (Miller, 1999). This is the case of QC, a young person with autism and with mental retardation (Mottron, Peretz, Belleville, & Rouleau, 1999). In addition to displaying absolute pitch, chord disentangling abilities, and an exceptional musical memory, QC displays a lower than typical hearing threshold and manifests aversive reactions to everyday life sounds.

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To account for these findings, the enhanced perceptual functioning (EPF) model (Mottron & Burack, 2001) proposes that superior pitch processing in autism is one of the manifestations of the overdevelopment of low-level perceptual operations. This model contends that information processing systems devoted to the detection, discrimination, and categorization of perceptual stimuli are enhanced in autism. This should result in superior performance in the abovementioned series of perceptual tasks. It should also result in an “overextension” of perceptual systems beyond their typical domain of application. An example of this overextension is the use of nonalgorithmic processes by a savant individual with autism in the graphic reproduction of 3-D information, a task that is typically performed by perspective algorithms (Mottron & Belleville, 1995).

Enhancement of low-level perceptual processing, from discrimination to categorization, as predicted by the EPF model, should result in low-level perceptual auditory tasks being performed at a higher level by individuals with autism relative to comparison participants. In a first study of the perception of complex auditory information in nonsavant individuals with high-functioning autism, Mottron, Peretz, and Ménard (2000) assessed differential local and global processing using a same–different judgment task on pairs of melodies. In their experiment, local processing was assessed by modifying target melodies at the pitch level, without contour modification, and global processing by modifying melodies at the contour level and through melodic transposition. Results showed that individuals with high-functioning autism were superior to the comparison group at discriminating between nontransposed, contour-preserved melodies that tap local musical processing, a finding that is consistent with an enhanced perception of local pitches in the auditory modality.

The finding that individuals with high-functioning autism are better than comparison participants at discriminating between pitches presented in the form of compound musical stimuli suggests that they should also excel at discriminating between the frequencies of pure tones presented in isolation. Superior abilities in frequency discrimination might account for both auditory aversive reactions and for exceptional pitch processing abilities in some savant individuals with autism (Anastasi & Levee, 1960). Moreover, in the same way that enhanced processing of low-level aspects of information may contribute to a local bias in the visual domain, enhanced pitch discrimination may contribute to a superior detection of local, pitch modifications in musical material.

The present study assesses pitch “sensitivity” using signal detection theory (SDT; Green & Swets, 1966/1974). SDT methods allow the separation of two aspects of an observer’s response. The first of these, called

“sensitivity,” refers to how well the observer is able to make correct judgments and to avoid incorrect ones. The second of these, called “response bias” (or decision criterion), measures the propensity of an observer to favor one response over another (e.g., in a discrimination experiment, “same” vs. “different” responses). As such, SDT provides a measure of response accuracy that is independent from response bias.

Whereas past research assessed pitch processing in the framework of hierarchical, local–global models of processing in autism, using compound musical material, the present experiment assesses pitch sensitivity in the context of pure tones presented in isolation. To this end, two types of low-level, auditory processing tasks were selected, discrimination and categorization of pure tones varying in frequency and presented at a fixed intensity level. Discrimination and categorization tasks may require the intervention of different memory modes and tap different perceptual processes (Bonnell & Hafter, 1998; Durlach & Braida, 1969). In order to discriminate between two sounds presented in pairs, subjects have to rely on sensory or “trace” memory. This trace lasts only a few seconds and is vulnerable to interference (Cowan, 1984). In the categorization of a single sound as high or low in pitch, subjects have to rely on a “context-coding” mode (Durlach & Braida, 1969). In order to make categorical judgments, subjects need to refer to previous trials (Stewart, Brown, & Chater, 2002). That is, subjects have to assess and update the pitch value of any given tone in the context of the preceding tones. This type of task is more demanding in memory and attention load than the discrimination task (Bonnell & Hafter, 1998). Accordingly, the categorization task is expected to be more difficult and to require reliance on a different memory code than the discrimination task.

RESULTS

Experiment 1: Pitch Discrimination

Correlation Between Confidence Ratings, Response Accuracy, and Response Latency

In order to assess whether or not the participants were able to use confidence ratings coherently, the agreement between confidence levels and response accuracy was examined. The percentage of correct responses obtained by participants in the task (all levels of difficulty combined) closely matches the confidence ratings categories. Pearson correlations were significant for the clinical group, with $r = .66$ ($p = .020$), but nonsignificant for the comparison group, $r = -.16$ ($p = .612$). That is, higher confidence responses are significantly associated with higher rates of correct responses for the clinical group.

Additionally, participants’ response latencies were related to their confidence levels. As expected, the lower

the confidence level, the higher the response latency. Pearson correlation were significant for both groups with $r = -.61$ ($p = .036$) and $r = -.86$ ($p = .000$) for the clinical and comparison group, respectively. Thus, participants' responses seem to faithfully reflect their ability to perform the discrimination task.

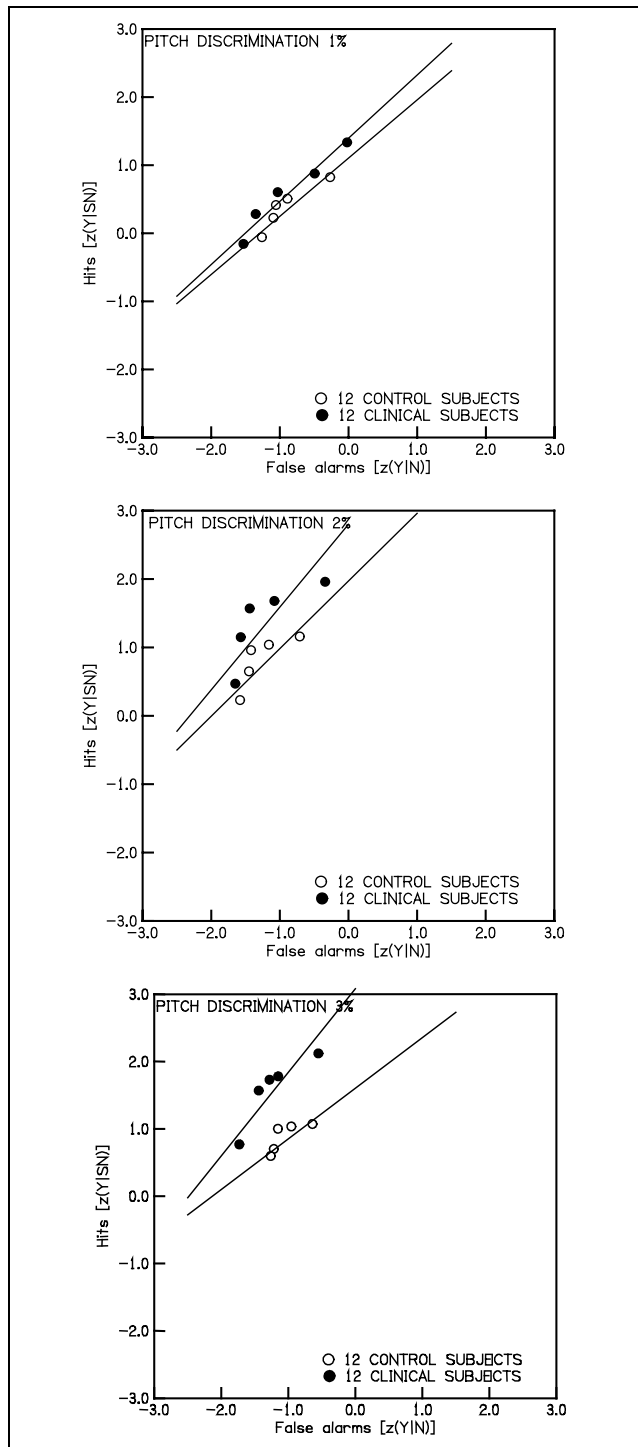


Figure 1. ROC curves observed for each group in the three conditions of the pitch-discrimination task.

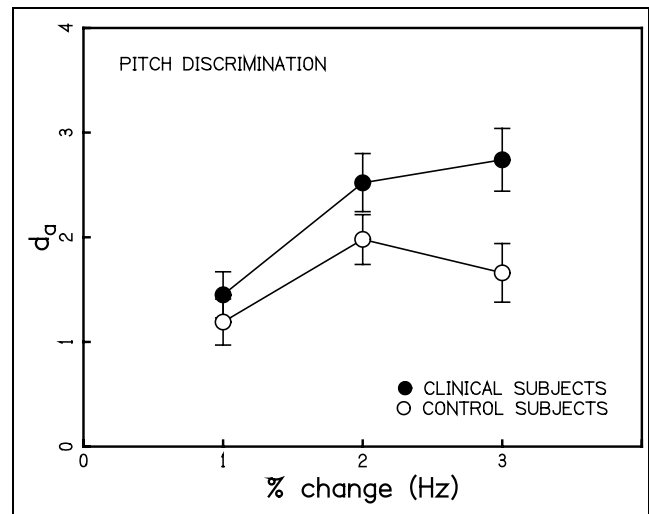


Figure 2. Psychometric functions: sensitivity index observed for each group in the three conditions of the pitch-discrimination task.

Subjects' Use of Confidence Ratings

An independent-samples t test was conducted to ensure that subjects in both groups used each confidence rating category (i.e., high, middle, and low confidence) to a similar extent. This analysis was conducted with the three levels of difficulty combined, as well as separated. In both cases, results revealed no significant differences between the clinical and comparison groups on this variable [e.g., for combined levels of difficulty: $t(22) = .07$, $p = .947$]. These results were also confirmed by Mann-Whitney nonparametric tests. Thus, subjects in both groups made the same use of the confidence ratings.

Receiver Operating Characteristics (ROC) Curves

The ROCs observed for each group in each condition of the discrimination task are presented in Figure 1. As can be seen, the clinical participants exhibit higher ROCs for the two easiest conditions (3% and 2%). However, the most difficult condition (1%) leads to very similar functions for the two groups.

Sensitivity measures. As can be seen in Figure 2, in which participants' performance is expressed in d' sensitivity measures, the superiority of the clinical participants in the discrimination task is significant at $p < .05$ for the conditions 2% and 3% and nonsignificant for the 1% condition. The fact that the 1% condition did not yield significant differences may be explained by a "data limits," or floor effect, due to the insufficient amount of information available to the subject (Norman & Bobrow, 1975).

In addition to the above analysis, for each subject, the rating scale was collapsed in two categories (same/different or low/high) in order to compute a d' index as an estimate of sensitivity [$d' = Z(\text{Hits}) - Z(\text{FA})$]. The

agreement between the d_a (pooled) and d' (average) estimates was quite good.

Experiment 2: Pitch Categorization

As expected, we found in Experiment 1 that high-functioning autistic individuals discriminate frequency

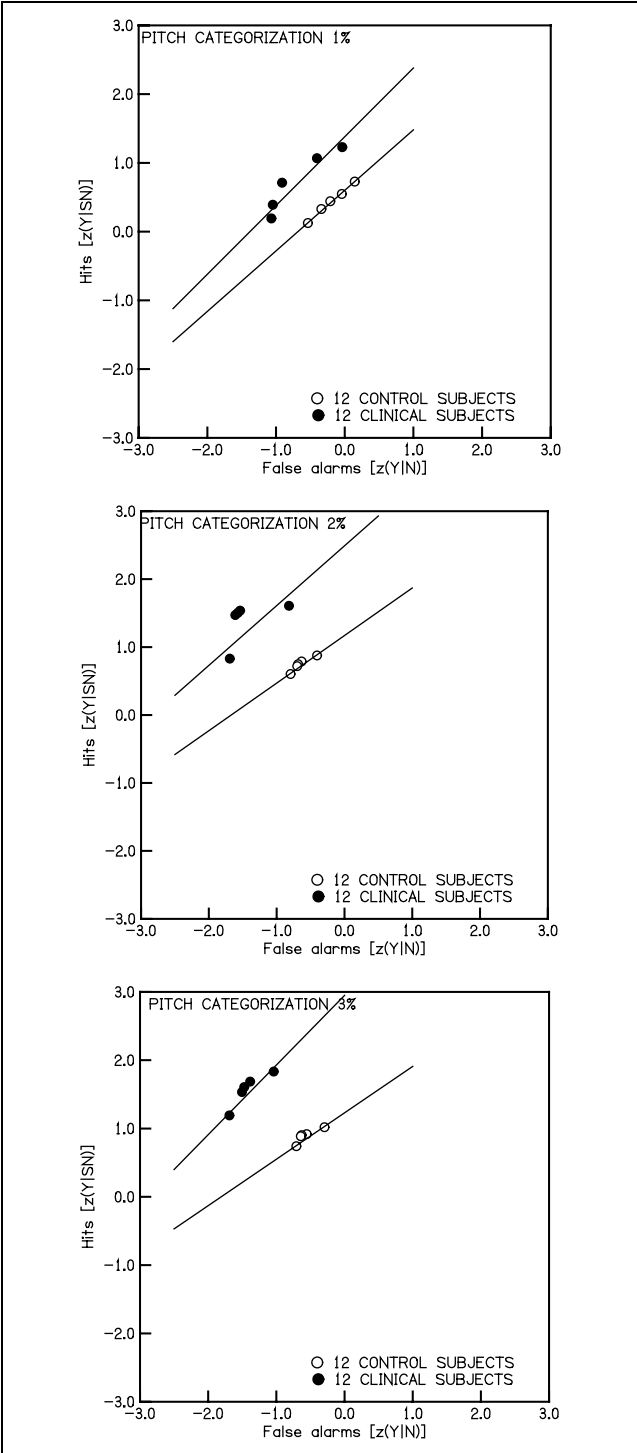


Figure 3. ROC curves observed for each group in the three conditions of the pitch-categorization task.

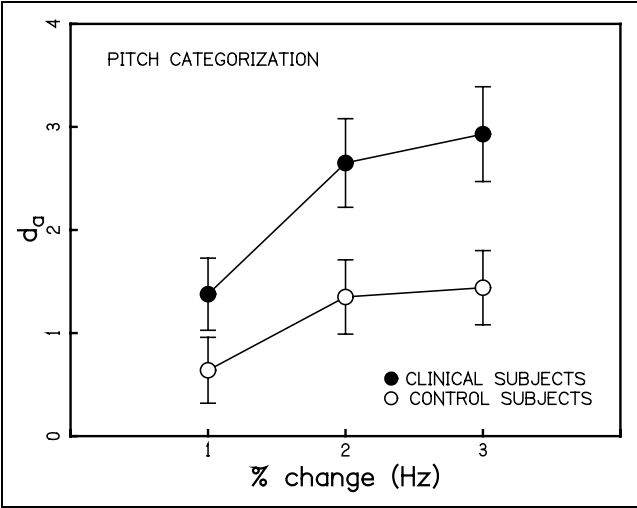


Figure 4. Psychometric functions: sensitivity index observed for each group in the three conditions of the pitch-categorization task.

differences between successive tones better than typically developing individuals. The goal of Experiment 2 was to test whether this heightened sensitivity to pitch found in autistic participants would generalize to the categorization of frequencies as being high or low in pitch in a series of isolated tones.

Correlation Between Confidence Ratings, Response Accuracy, and Response Latency

Preliminary analyses revealed that response accuracy closely follows the confidence ratings. Indeed, higher confidence levels are associated with higher response accuracy. However, Pearson correlations were nonsignificant for both groups, with $r = .33$ ($p = .300$) and $r = -.20$ ($p = .540$) for the clinical and comparison participants, respectively.

As for participants' response latencies, results showed that, as expected, the lower the confidence level, the higher the response latency. Pearson correlations were significant for the comparison group, with $r = -.64$ ($p = .024$), but nonsignificant for the clinical group, $r = -.45$ ($p = .146$).

Subjects' Use of Confidence Ratings

An analyses of participants' use of confidence ratings yielded similar results as in experiment one, demonstrating that both groups used each of the confidence ratings in a similar proportion [e.g., for combined levels of difficulty: $t(22) = .22, p = .827$].

Receiver Operating Characteristics Curves

The ROC curves observed for each group in each condition of the pitch-categorization task are presented in Figure 3. The ROC curves obtained for the clinical

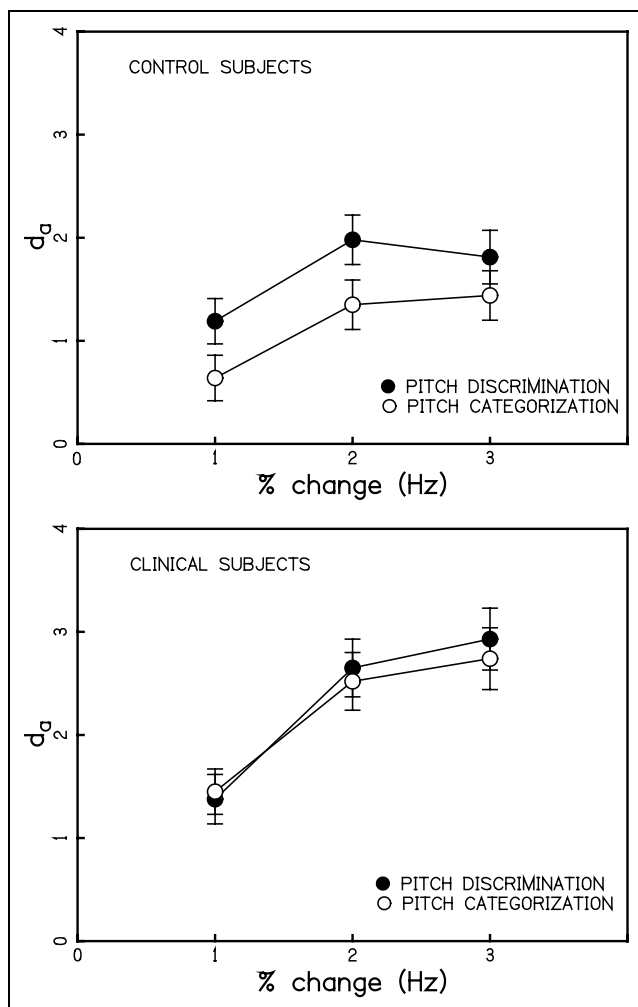


Figure 5. Sensitivity index observed for each group in the two tasks.

group indicate a marked superiority over control participants in each of the three conditions (1%, 2%, and 3%).

Sensitivity measures. This superiority is also apparent when the participants' performance is transformed in d_a sensitivity measures: The clinical participants exhibit higher categorization abilities than normally developing individuals in all three conditions of the categorization task (see Figure 4).

Furthermore, whereas normally developing individuals performed significantly better in the discrimination than in the categorization task ($p < .05$ for each level of difficulty), the clinical participants performed equally well in the two tasks (see Figure 5).

As in Experiment 1, d' indices were computed in order to validate the sensitivity estimation: The agreement between d_a and d' indices was quite good.

GENERAL DISCUSSION

The current study assesses pitch sensitivity of individuals with high-functioning autism in two perceptual tasks involving pure tones: pitch discrimination and pitch

categorization. This study is also the first to apply signal detection methodology to investigate perceptual performance of individuals with autism. Firstly, and as expected in regard to differences in task requirements, the normally developing group performed the categorization task more poorly than the discrimination task. A decrement in performance in the categorization task is consistent with the use of a context-coding mode in this task. By contrast, the clinical group performed these two tasks at the same level. Secondly, individuals with high-functioning autism were superior to normally developing individuals in the discrimination task. Thirdly, the clinical group outperformed the comparison group in the categorization task. In sum, and response bias being removed by the use of the signal detection methodology, these findings demonstrate superior "pitch sensitivity" in high-functioning individuals with autism.

The identical level of performance of the clinical group in the two tasks suggests that individuals with high-functioning autism are less sensitive to differences in task requirements than comparison participants. This may result from the clinical group using a similar, trace-type comparison between the stimulus to be judged and the trace memory of the previous trial in the two tasks. Using this strategy would be possible due to a more accurate, fine-grained representation of pitch, i.e., a trace memory that is more resistant to the various types of noise (temporal decay, pro- and retroactive interference), which affect task performance in the comparison group. A more robust trace memory would explain both superior discrimination abilities as such, and the capacity of the clinical group to keep using the same memory system in the context of more demanding conditions, where comparison participants have to switch to a context-coding type of memory.

This enhanced sensitivity in pitch discrimination and categorization may account for the general observation that autistic individuals excel at music perceptual tasks. There is increasing evidence that fine-grained pitch discrimination is essential for the development of a normal functioning system for music. For example, Peretz et al. (2002) have shown that a degraded pitch perceptual system was associated to a poorly developed musical system in an adult who was otherwise fully functional and, hence, was qualified as congenitally amusic. More generally, musical impairments in perception and memory due to the presence of a brain lesion or of a congenital anomaly are systematically associated with disorders in pitch-related (as opposed to time-related) variations (Peretz, 2003). This recurrent finding led the latter author to propose that, although music processing is implemented in multiple interconnected neural networks, material-specific pitch-related mechanisms are the essential components around which musical competence develops in the normal brain.

In this perspective, enhanced sensitivity to pitch differences would confer a clear advantage in musical

proficiency. This appears to be the case of high-functioning autistic individuals. For example, enhanced pitch sensitivity may contribute to a superior detection of target pitches embedded in a global musical contour. According to this interpretation, the so-called “local bias” evident in high-functioning individuals with autism in the context of auditory hierarchical material (Mottron et al., 2000) would be due to superior pitch perception *per se*. This represents an alternative explanation to the “weak central coherence” (WCC) model for peaks of abilities in autism (Happé, 1999). This model explains superior performance in processing pitch by a locally oriented perception, itself resulting from a deficit in perceiving global aspects of information (Heaton, Hermelin, & Pring, 1998). An alternative explanation following from the current findings would be that, in the same way that superior visual discrimination (Plaisted et al., 1999) suggests that “local” bias in visual hierarchical tasks may be related to a superior processing of the elementary characteristics of visual stimuli involved in low-level visual perception, “local” bias in auditory hierarchical tasks may be based on superior pitch sensitivity.

Finally, these results may be relevant to the interpretation of the higher incidence of “absolute pitch” in musical savants with autism, inasmuch as the ability to memorize a pitch-verbal label association involves fine-grained, long-term representations of differential pitches.

Superior pitch sensitivity in individuals with autism may be related to the uneven patterns of cortical evoked related potentials associated with the detection of pitch modifications in autism. Gomot, Giard, Adrien, Barthélémy, and Bruneau (2002) assessed the brain mechanisms involved in the automatic detection of pitch change in children with autism through the mismatch negativity (MMN). MMN is a cortical temporal potential assumed to be generated by a comparison process between infrequent auditory input and the memory trace of the standard sound. Their task involved passive listening of pure tones differing both in frequency and oddity (standard 1000-Hz sounds vs. deviant 1100-Hz sounds) by individuals with autism and with mental retardation (mean CA: 6 years 10 months, overall MA: 4 years 9 months), and by a CA-matched comparison group. Among differences in the MMN of participants with and without autism, the authors reported a shorter MMN latency and a longer MMN activity in children with autism. They interpreted these findings as resulting from a greater sensitivity to pitch deviancy than in the comparison group, as shorter MMN latencies are recorded for greater frequency deviations. Gomot et al.’s task cannot be assimilated to a pitch-discrimination or identification task, does not control for the attention status of the participants, and compares children of unequal mental age. However, and in addition to the data presented here and with the finding of a normal sensory gating in children with autism (Kemner, Orange, Verbaten, &

Van Engeland, 2002), this finding is consistent with a reorganization of pitch processing at a cortical level in individuals with autism.

Taken together with evidence from past research, the results of the present study are consistent with the enhanced perceptual functioning model of autism. First, the multimodality of perceptual tasks for which a superior performance is found in autism suggests that they result from a similar mechanism. Accordingly, recent findings of superior performance of individuals with high-functioning autism in forming visual categories (Plaisted et al., 1999), of diminished interference in list learning (Mottron, Belleville, Stip, & Morasse, 1998), of more narrow visual perceptual categories (Mottron, Belleville, & Soulières, 2001), and of more accurate item detection in visual search tasks (O’Riordan, 1998; O’Riordan et al., 2001), suggest that superior perceptual traces may be a cross-domain property in autism. In consequence, the explanation of superior performance in the visual modality by a compensation for a deficit occurring within the same modality (Milne et al., 2002) is less plausible. According to these authors, the visual local bias observed in individual with autism results from the compensation of impaired magnocellular pathway by an overfunctioning of the parvocellular pathway. According to our interpretation, this would rather result from a general mechanism involving enhanced processing of psychophysical properties, independently of the modality involved.

Second, the fact that the current study demonstrated superior performance in autistic individuals of normal intelligence (as opposed to those with mental retardation) shows that peaks of abilities in pitch perception in autism are not “relative” to otherwise impaired performance but rather are “absolute” peaks of abilities. Remarkably, this is also the case for most of the visual tasks for which a superior performance has been shown in autism. Finally, the variety of tasks for which superior performance has been found suggests that superior discrimination only (Plaisted, 2001) cannot by itself explain the entire set of performance in which individuals with autism exhibit superior performance.

The EPF model does not provide an explanation for this superiority, but points to two types of possible causal mechanisms: a compensatory overdevelopment of low-level operations, because of a deficit in higher-order operations, as suggested by the paradoxical facilitation model of Kapur (1996), or an intrinsic modification of the learning properties at the cortical tissue level in autism. Recent arguments for the latter proposition arose from the discovery of abnormal spatial organization and density of cortical cells both in the frontal cortex (area 9) and in the temporal cortex (areas 21 and 22) in autism and Asperger syndrome (Casanova, Buxoeveden, Switala, & Roy, 2002a, 2002b).

Finally, an interesting observation that results from the present study is that high-functioning individuals

Table 1. Characteristics of the Clinical and Control Group

Group	Age		Laterality		Global IQ	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Clinical group	17.91	3.76	80.3	18.75	108.08	10.22
Control group	16.58	2.41	35.5	76.62	107.75	9.09

with autism are able to use confidence ratings, therefore allowing the use of signal detection analysis in a variety of perceptual tasks in high-functioning autism.

METHODS

Participants

High-Functioning Autistic Group

Twelve participants with high-functioning autism (11 males, 1 female) were randomly recruited from the database of the Rivière-des-Prairies' specialized clinic for the diagnosis and assessment of pervasive developmental disorders. DSM-IV (American Psychiatric Association [APA], 1994) diagnoses of autism were obtained through the administration of a standardized interview, the Autism Diagnosis Interview—Revised (ADI-R: Lord et al., 1994) and verified through direct standardized assessment (ADOS-G: Lord, Rutter, & DiLavore, 1997). Albeit satisfying ADI-R and ADOS-G criteria for autism, 3 of the 12 participants were also positive for a DSM-IV diagnosis of Asperger syndrome, a subgroup of pervasive developmental disorders characterized by normal (or overdeveloped) language abilities. Recruitment of the clinical group was blind to the ADI items tapping auditory hypersensitivity (Item 78), unusual sensory interests (Item 77), and special abilities in music (Items 106–111), ensuring that the group under study was representative vis-à-vis the general population of individuals with autism. All participants with autism were students or employed in regular jobs, and were living at home or independently at the time of the study.

Normally Developing Group

Twelve normally developing adolescents and young adults (12 males) of normal intelligence (full-scale IQ >85; see Table 1) were randomly recruited from the clinic's database for comparison individuals. To be included in this experiment, and as assessed by a questionnaire, comparison subjects had to be free of any past or present neurological or psychiatric disorders, medication, learning disabilities, and family history of autism or other neurodevelopmental and psychiatric disorders.

Only participants without musical experience, a fortiori without musical "special abilities" were included in this study, as musical expertise may produce a local bias in musical processing (Bever & Chiarello, 1977) or a cortical overrepresentation of pitch (Pantev, Engelen,

Candia, & Elbert, 2001). The two groups were matched at the group level on chronological age, full-scale IQ (Wechsler, 1981; Wechsler, 1974), and laterality (Oldfield, 1971). No statistical differences were found in a *t* test conducted between the two groups on these variables: IQ: $t(22) = .08$; age: $t(19) = 1.01$; laterality: $t(12) = 1.93$.

This study was approved by a local ethical committee. The tasks were explained to subjects and their parents who were asked to sign an informed consent form. Participants were compensated for their participation. Table 1 presents the sociodemographic characteristics of the participants.

Audiometric Hearing Test

All subjects were assessed with a standard audiometric testing procedure. Eighty-five percent of the participants took this audiometric screening test first, as possessing normal hearing was a prerequisite to their inclusion in following experiments. Due to scheduling constraints, the remaining 15% of subjects took the hearing test following Experiments 1 and 2. For these participants, inclusion criteria were thus verified a posteriori.

For each participant, the audiometric test and the two experiments took place on the same day and were separated by a 15-min pause. The audiometric hearing test was conducted by a professional audiologist (M. T.) in a double-walled, double-room, sound-treated, audiometric test chamber whose ambient noise was in accordance with norms (ANSI S3.1-1991). Experiments 1 and 2 were conducted by the same experimenter (A. B.) in a quiet room.

The two experiments—pitch discrimination and categorization—were assigned to the subjects in a counter-balanced order. Because no effect of order was observed, the two tasks will be presented separately.

Participants were first interviewed regarding any history of repeated ear infections, family history of deafness, or auditory trauma. External auditory conducts and the eardrum were then examined in search of objects or cerumen and to verify the absence of ventilation tubes, redness, etc. The audiometric screening procedure consisted of presenting pure tones whose intensity ranged between -10 to 30 dB hearing level (HL). Tone duration varied between 1000 and 2000 msec. Interstimulus intervals (ISI) varied between 2000 and 5000 msec to avoid false alarms because of signal expectation effects. These tones were presented at standard octave frequencies (250 , 500 , 1000 , 2000 , 4000 , and 8000 Hz), and at five additional frequencies (750 , 1062 , 1500 , 3000 , and 6000 Hz). The latter were selected to ensure that the participants had normal hearing in the range of frequencies used in the experimental tasks. The audiometer, a Madsen Electronics* 0B822 equipped with supra-auricular TDH 39 headphones, had been calibrated less than a month before the beginning of the

study. The air conduction calibration was in accordance with the American National Standard Institute norms (ANSI S 3.6-1996).

Participants pressed a button each time they heard a tone. Auditory thresholds were obtained using ASHAS's (1978) ascending–descending procedure. First, the experimenter presented a relatively high intensity tone (30 dB HL). Once the participant had consistently detected this tone, the experimenter lowered its intensity by 10 dB HL each time the participant indicated that a tone was heard, and increased it by 5 dB HL each time no tone was heard. The frequencies were presented in the following order (in Hz): 1000, 1062, 1500, 2000, 3000, 4000, 6000, 8000, 1000, 750, 500, and 250. Auditory thresholds, which were defined as the smallest intensity level at which a subject can detect a tone at least 50% of the time in the ascending mode (ANSI S3. 21-1978), were tested for each frequency and for each ear separately, starting with the right ear. The entire testing lasted between 15 and 20 min. Individual data were then compared to ANSI norms for normal hearing (ANSI S 3.6-1996) in which a cutoff criterion of 15 dB n HL (or normal hearing level) is used to diagnose a hearing impairment. Based on this criterion, all participants had normal hearing levels, with the exception of one subject from the clinical group, who was excluded from further experiments. It should be specified that as a group the participants with autism did not present lower auditory thresholds than typically developing individuals.

Experiment 1: Pitch Discrimination

Stimuli were 100-msec long pure tones presented in pairs. In a pair, the frequency of the first tone took one of the following four values: 500, 750, 1000, and 1500 Hz. The second tone of the pair was either identical to the standard or was higher in frequency. When different, the second tone was 3%, 2%, or 1% higher than the standard tone. For example, for a standard tone of 1000 Hz, the different comparison tone was either 1030, 1020, or 1010 Hz, depending on condition. The tones were generated on a portable Macintosh 5300c/16/750 and presented at 58–60 dB SPL through Koss L TD/60 headphones to the subjects.

The task consisted of a series of same/different judgments on pairs of tones presented successively. The frequency of the first tone in each pair randomly took one of the four possible frequency values in order to ensure that subjects would compare stimuli within each pair, rather than relying on an absolute standard. In half the trials, the two frequencies were identical. In the other half, the comparison tone was higher by one of the abovementioned percentage difference. Each of the three distances was tested in 40 trials, in a fixed order of increasing difficulty. Within each trial, the two tones in the pair were separated by a constant 1-sec silent interval. The intertrial interval was controlled by sub-

jects' response, without upper limit. The following trial appeared 500 msec following subjects' response.

Participants were asked to indicate whether the two consecutive sounds were same or different. They were informed that in half of the trials, the two signals would be identical, and that "same" and "different" trials would be randomly mixed. Participants responded by pressing one of six aligned buttons of a response box. The buttons, set on a white background, were of three different colors. Red buttons (1 and 6) at the two extremes of the box corresponded to high confidence in same/different judgments; orange buttons (2 and 5), to moderate confidence; and yellow, middle buttons (3 and 4), to low levels of confidence.

Practice trials were performed on 4% (easy) and 1% (difficult) conditions. The use of the different response keys was explained based on the difference in judgment certainty between the 4% and 1% conditions. Participants were asked to use as many keys as possible but were told that it was not obligatory to do so. The emphasis was put on response accuracy rather than on the capacity to use all the buttons on the rating scale. During the practice trials, visual feedback on correct responses was provided. Subjects took as many practice trials as needed until reaching an approximately 75% success rate. On average, subjects in both groups received the same number of practice trials. Participants were then assigned to the testing session during which feedback was removed. The entire task lasted about 20 min.

Experiment 2: Pitch Categorization

A 1000-Hz pure tone served as the low reference tone. The high tone was 3%, 2%, or 1% higher in hertz, depending on the condition. For example, in the 3% condition, the 1000-Hz low tone was randomly mixed with 1030-Hz high tones. All tones were 100-msec long and were presented at a constant 58- to 60-dB SPL intensity level. Each condition contained 40 trials. The intertrial silent interval was fixed to 1.5 sec to prevent subjects from using different paces of presentation.

Subjects were tested with the three conditions in an increasing order of difficulty with the same response mode as in Experiment 1. They were requested to categorize each tone as high or low. Participants were informed that on each trial, one high or one low tone would be randomly presented with equal probability.

Practice trials were performed on 4% and 1% difficulty levels. The use of the six different response keys was explained based on the difference in judgment certainty between the 4% and 1% conditions. For instance, because "high" and "low" are relative categories, participants were explained that they would have to guess on the first trial for each of the difficulty levels, and as such, that they should use a lower confidence level response key as their first response. Participants were asked to use as many keys as possible but were told that it was not

obligatory to do so. During the practice trials, visual feedback on correct responses was provided. Subjects took as many practice trials as needed until approximately reaching a 75% success rate. In average, subjects in both groups took about three practice trials. They were then assigned to the testing session during which feedback was removed. The entire task lasted about 20 min.

DATA ANALYSIS

Receiver Operating Characteristics Analysis

For each group of participants, sensitivity was assessed by means of a conventional ROC graph. An ROC curve was computed for each of the three levels of difficulty in the two tasks. The ROC curve relates the proportion of hits (y -axis) to the proportion of false alarms (x -axis) for each confidence rating and represents the variations of response bias for a given degree of sensitivity. Sensitivity is shown by the area under the ROC or by the distance of the ROC from the major diagonal, and a given response criterion is illustrated by a particular point along the ROC. The larger the distance between the ROC and the major diagonal (in the direction of the northwest corner) or the larger the area beneath the ROC, the higher the sensitivity.

In order to plot each ROC, hits and false alarms were obtained as follows: In the discrimination task, a “different” response was defined as a hit when assigned to a pair of different pitches, and was defined as a false alarm when assigned to a pair of identical pitches. Similarly, in the categorization task, a “high” response assigned to the high tone was defined as a hit and as a “false alarm” when assigned to a low pitch.

The ROC curve was constructed as follows. First, “hits,” “false alarms,” and confidence ratings were combined to form six distinct response categories, corresponding to the six decision criteria, from “strict” to “lax.” These categories were ordered from “same pitch, high confidence” (or “low pitch, high confidence” in the categorization task) to “different pitch, high confidence” (or “high pitch, high confidence” in the categorization task) to reflect increasing confidence that there was a difference (or that the high pitch was presented).

The five points on the ROC ($n-1$ criteria) were then transformed into z scores, resulting in a straight line. Estimates of the parameters of each ROC, as well as their variance were then computed using a maximum-likelihood procedure (Dorfman & Alf, 1969). Because the small number of trials per subjects may not allow a stable estimate of ROC data, responses were pooled across subjects before plotting the ROCs.

Sensitivity Measures

In each group and for each of the three ROCs (corresponding to each of the three conditions), sensitivity

was estimated using the index d_a or the perpendicular distance to the linear ROC (which is closely related to the area under the ROC; see Macmillan and Creelman, 1991). The statistical significance of the observed differences in the sensitivity parameter d_a was analyzed using the confidence intervals of d_a yielded by the maximum-likelihood estimation program.

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