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PERCEPTION IN AUTISM

Sensory Symptoms and Processing of Nonverbal Auditory and Visual Stimuli in Children with Autism Spectrum Disorder

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Abstract Atypical sensory responses are common in autism spectrum disorder (ASD). While evidence suggests impaired auditory–visual integration for verbal information, findings for nonverbal stimuli are inconsistent. We tested for sensory symptoms in children with ASD (using the Adolescent/Adult Sensory Profile) and examined unisensory and bisensory processing with a nonverbal auditory–visual paradigm, for which neurotypical adults show bisensory facilitation. ASD participants reported more atypical sensory symptoms overall, most prominently in the auditory modality. On the experimental task, reduced response times for bisensory compared to unisensory trials were seen in both ASD and control groups, but neither group showed significant race model violation (evidence of intermodal integration). Findings do not support impaired bisensory processing for simple nonverbal stimuli in high-functioning children with ASD.

Keywords Autism · Visual · Auditory · Sensory integration · Bisensory facilitation · Sensory profile

Introduction

Sensory abnormalities are among the most common clinical features observed in autism spectrum disorder (ASD), affecting all sensory modalities (auditory, visual, tactile and taste/smell) (Kern et al. 2006, 2007; Marco et al. 2011). Clinical observations suggest a 30–100 % prevalence of sensory symptoms in people with ASD (Dawson and Watling 2000). As suggested in a review by Iarocci and McDonald (2006), behavioral and physiological responses to visual and auditory stimuli in children with ASD frequently differ from those seen in typically developing (TD) children. Indeed, atypical responses to sensory stimuli may differentiate ASD from other developmental disorders (Gillberg and Coleman 2000; Dunn et al. 2002; Coleman and Gillberg 2012).

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Auditory difficulties in individuals with ASD can include lack of response to one's name, distress over sound, or distractibility by background noise (Dunn 1999). A review by O'Connor (2012) indicates that auditory impairments in ASD apply selectively to complex stimuli, whereas processing of simple auditory stimuli may actually be superior in comparison with TD controls. Visual difficulties include both hyper- and hypo-responsiveness, which can range from severe dislike of bright light or rapidly moving stimuli, to staring intently at objects or people, and fascination with brightly colored objects (Dunn 1999; Brown and Dunn 2002). Reviews by Dakin and Frith (2005) and Simmons et al. (2009) suggest that vision in ASD is characterized by an uneven profile, with islands of superior processing of fine details (as in visual search), but potential impairment at the global level, as well as with respect to visual attention, biological motion, and color vision.

Sensory symptoms in ASD have been examined using the Sensory Profile (Dunn 1999). Kern et al. (2006, 2007) found abnormal sensory processing in all modalities in children and adults with ASD. In each sensory modality, children with ASD may either show little or no response to sensory cues (high threshold) or, conversely, may be overwhelmed by stimuli (low threshold). While the Sensory Profile was designed for ages 3–10 years, an adaptation for older participants, the Adolescent/Adult Sensory Profile (AASP), is also available (Brown and Dunn 2002). The AASP classifies sensory behaviors according to four quadrants: low registration (high threshold, passive response pattern), sensation seeking (high threshold, active response pattern), sensory sensitivity (low threshold, passive response pattern), and sensation avoiding (low threshold, active response pattern). Results from the few studies that have implemented this measure indicate that sensory abnormalities persist in adolescents with ASD (Jones et al. 2009; Crane et al. 2009).

In natural environments, sensory perception is typically multimodal, with concurrent stimulation in several sensory modalities. Stein and Meredith (1993) found that multisensory cells in the midbrain (superior colliculus) showed more intense activation for congruent bisensory stimuli than the summed activation for the corresponding two unisensory stimuli. Miller (1991) demonstrated that bisensory detection involves the interaction of congruent targets rather than separate activation of each unisensory target. Specifically, facilitation through interactive audiovisual processing can be tested when response times (RT) violate the 'race model', i.e., when bisensory RT is faster than expected from independent unisensory stimulus processing that competes for response initiation (Molholm et al. 2004). Reduced RT for congruent bisensory stimuli has been termed bisensory facilitation (Miller 1991).

It has been suggested that ASD may be associated with impaired integration of audiovisual information (Iarocci and McDonald 2006). For example, two recent studies suggested that the temporal window during which auditory and visual information is integrated is atypically prolonged in children with ASD (Foss-Feig et al. 2012; Miller 1982). Studies of audiovisual integration in speech have produced mixed results. Mongillo et al. (2008) found that children with ASD performed significantly worse on a vowel match/mismatch task and exhibited a significantly weaker McGurk effect compared to TD children. These results were attributed to reduced processing of visual cues (lip-reading) in children with ASD. Smith and Bennetto (2007) used full-length sentences to study unisensory processing and audiovisual integration. Although no differences for auditory ability were found, children with ASD had more difficulty than TD children on lip-reading (visual-only) and audiovisual integration tasks. Conversely, Williams et al. (2004) reported poorer accuracy during unisensory auditory and visual trials for children with ASD, compared to TD children. Significant group differences for audiovisual integration in a speech paradigm were attributed to impaired unisensory performance in ASD. More recently, Foxe et al. (2015) found that word recognition gain for multisensory (audiovisual) compared to unisensory stimuli was severely reduced under environmental noise conditions in 7–12 year old high-functioning children with ASD, whereas it approached normal levels in 13–15 year-olds.

A study including both verbal and non-verbal stimuli suggested that a bisensory integration deficit in ASD might be specifically verbal. Bebko et al. (2006) studied audiovisual integration in a preferential looking paradigm, using synchronous and asynchronous nonverbal (video of 'Mousetrap'), simple verbal, and complex verbal stimuli. Results indicated that children with ASD differed from TD children and children with other developmental disorders only on the complex linguistic condition, in which they did not show preference to synchronous versus asynchronous stimuli. Conversely, Brandwein et al. (2013) failed to detect bisensory facilitation for simple auditory and visual stimuli in 7–16 year old children with ASD.

While studies using language stimuli directly tap into communicative deficits in ASD, the question thus remains whether basic abnormalities of sensory processing and integration may contribute to higher-level cognitive and sociocommunicative impairments. Therefore non-social and non-verbal paradigms are needed to examine basic mechanisms of sensory integration. The current study used a simple non-verbal auditory–visual paradigm, for which bisensory facilitation effects (reduced response times for congruent bimodal stimuli) have been reported in typically developing adults (Miller 1991). The Adolescent/Adult Sensory Profile (Brown and Dunn 2002) was additionally administered to examine sensory symptoms in ASD and to explore potential links between sensory symptoms and bisensory facilitation. We hypothesized that children with ASD would show atypical sensory profiles and reduced bisensory facilitation. Additionally, based on the results of previous studies using the AASP (Crane et al. 2009; Jones et al. 2009), it was hypothesized that—in comparison to the TD group—ASD participants would show more sensory behaviors in the low registration, sensory sensitivity, and sensation avoiding quadrants, but reduced behaviors in the sensation seeking quadrant. Furthermore, we predicted that atypical sensory responses and reduced bisensory facilitation would be associated with higher diagnostic scores and reduced functional level (VIQ, NVIQ).

Methods

Thirty-three children with ASD aged 8–18 years participated (Table 1). Diagnosis of Autism, Asperger syndrome or PDD-NOS was confirmed by co-author AJL, based on DSM-IV criteria (American Psychiatric Association 2000) and using the Autism Diagnostic Interview Revised (ADI-R; Lord et al. 1994) and the Autism Diagnostic Observation Schedule (ADOS; Lord et al. 1989). The TD control group included 37 participants without history of neurological, psychiatric, or developmental disorders. IQ was assessed using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler 2000). The study was approved by the San Diego State University and University of California, San Diego Institutional Review Boards. Written informed consent and assents were acquired from participants and caregivers.

Sensory Profile

Thirty-three TD participants and twenty-five participants with ASD completed the full AASP during their visit. Note that this subsample included six TD and eleven ASD participants aged 8–10 years, i.e., slightly below the prescribed age range for the AASP. Independent sample *t*-tests confirmed that these ASD (n = 25) and TD subsamples (n = 33) were matched for age, $t(56) = .661$, $p = .64$, nonverbal IQ, $t(54) = .358$, $p = .70$, and verbal IQ $t(54) = -.095$, $p = .305$.

The Adolescent/Adult Sensory Profile (Brown and Dunn 2002) was administered to assess sensory symptoms. The measure was explained and then either self-administered or read aloud and marked, if help with comprehension was needed. The AASP includes 60 items scored in four quadrants; low registration, sensation seeking, sensory sensitivity, and sensation avoiding. Responses range from almost never (1) to almost always (5), with higher scores reflecting more sensory behaviors within a given quadrant. AASP data were analyzed using full-scale quadrant raw scores (all

Table 1 Participant characteristics by group and analysis

	ASD[a] (n = 25)		TD (n = 33)	
Sample for AASP data	Mean	SD	Mean	SD
Age (years)	13.1	2.8	13.6	2.7
WASI				
Verbal IQ	108.1	16.2	107.8	12.7
Nonverbal IQ	110.5	14.9	110.9	11.8
Full Scale IQ	110.6	15.5	110.8	12.9
ADOS				
Social interaction	8.5	2.0	N/A	N/A
Communication	3.4	1.9	N/A	N/A
Combined	11.9	3.3	N/A	N/A
Repetitive/restricted	2.2	1.7	N/A	N/A
Sample for experimental task	ASD[b] (n = 24)		TD (n = 29)	
	Mean	SD	Mean	SD
Age (years)	12.8	2.9	12.9	3.0
WASI				
Verbal IQ	106.6	15.6	109.3	12.6
Nonverbal IQ	110	13.7	111.4	12.3
Full Scale IQ	109.4	15.3	111.9	13.5
ADOS				
Social interaction	8.0	2.3	N/A	N/A
Communication	3.6	2.4	N/A	N/A
Combined	11.6	3.6	N/A	N/A
Repetitive/restricted	2.4	1.6	N/A	N/A
Subsample for experimental task with AASP data	ASD[c] (n = 18)		TD (n = 25)	
	Mean	SD	Mean	SD
Age (years)	12.9	2.8	13.3	3.0
WASI				
Verbal IQ	108.7	17.6	109.5	13.2
Nonverbal IQ	110.4	14.5	112.1	12.8
Full Scale IQ	110.9	15.8	112.5	14.2
ADOS				
Social interaction	8.2	2.0	N/A	N/A
Communication	3.4	1.9	N/A	N/A
Combined	11.6	3.3	N/A	N/A
Repetitive/restricted	2.5	1.7	N/A	N/A

[a] Autistic disorder n = 10; Asperger's disorder n = 15
[b] Autistic disorder n = 10; Asperger's disorder n = 14
[c] Autistic disorder n = 6; Asperger's disorder n = 12

modalities). Scores for each quadrant can range from 15 to 75 with higher scores indicating a higher incidence of sensory symptoms. Since our experimental paradigm employed auditory and visual stimuli we further examined quadrant scores specifically for auditory and visual modalities.

Experimental Task

Twenty-six children with ASD and thirty-one TD children participated in a session that included the behavioral paradigm and intelligence testing. One TD participant was excluded for low performance (<70 % accuracy) and three participants (2 ASD, 1 TD) were excluded due to computer malfunction. Independent sample *t* tests confirmed that the final ASD (n = 24) and TD groups (n = 29) remained matched for age, $t(51) = .16$, $p = .87$, nonverbal IQ, $t(50) = .387$, $p = .70$, and verbal IQ $t(50) = .658$, $p = .51$.

The experimental task consisted of three stimulus types: unisensory auditory, unisensory visual, and bisensory (congruent auditory and visual stimuli). Each task block lasted 2 min and 28 s, including 36 stimulus trials and 38 jittered null trials (pseudo-randomly inserted using AFNI's [afni.nimh.nih.gov] RSFgen), with a 2,000 ms duration for each trial. Stimuli were presented using PsyScope X (http://psy.ck.sissa.it/). In the visual condition (V), a dot appeared in either the top or bottom box of a vertical rectangle (Fig. 1). The auditory condition (A) consisted of a high tone (4,000 Hz) and a low tone (1,600 Hz). The bisensory condition (B) included congruent visual and auditory stimuli (top-box/high tone and bottom-box/low tone). Participants were instructed to "respond as quickly and as correctly as possible." They were shown how to respond using the laptop and were provided with practice trials. Participants indicated their responses with right index and middle fingers as either 'high' or 'low', using two keys with corresponding location (up, down) on the laptop keyboard. Block orders (AVB, VAB, BVA) were pseudorandomly counterbalanced within each group.

Results

Sensory Profile

Independent samples *t* tests were conducted to test for differences between the ASD and TD groups for the four quadrants of the AASP. The ASD group reported significantly fewer sensory behaviors than the TD group for the sensation seeking quadrant, $t(56) = 2.95$, $p = .005$, $r = .37$ The ASD group trended towards more sensory behaviors than the TD group for the low-registration quadrant, $t(56) = -1.516$, $p = .135$, $r = .20$ (See Fig. 2a). In a secondary analysis, excluding participants below the

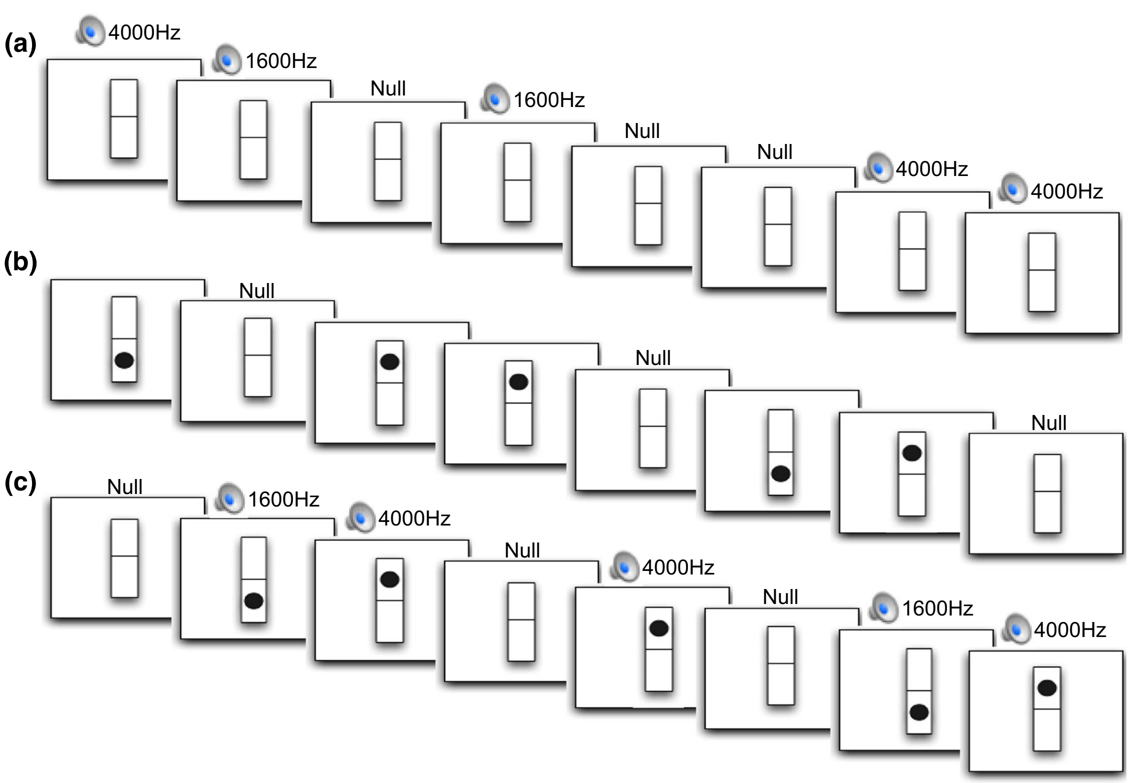

Fig. 1 Bisensory task paradigm including (**a**) auditory, (**b**) visual, and (**c**) bisensory conditions (blocks). Each task block lasted 2 min and 28 s, with each individual trial lasting 2 s

recommended age range for the AASP (i.e., all 8–10 year olds), ASD participants reported significantly fewer sensory behaviors than the TD group for the sensation seeking quadrant, $t(49) = 3.059$, $p = .004$, $r = .40$ and significantly more sensory behaviors than the TD group for the low-registration quadrant, $t(49) = -2.106$, $p = .040$, $r = .29$.

We also tested for group differences in the four quadrants separately for auditory and visual processing domains. The ASD group reported significantly more auditory behaviors than the TD group for the low-registration quadrant, $t(56) = -2.795$, $p = .007$, $r = .35$ as well as significantly more sensory behaviors for the sensory sensitivity quadrant, $t(56) = -2.63$, $p = .011$, $r = .33$. The TD group reported significantly more auditory sensory behaviors than the ASD group for the sensation seeking quadrant, $t(56) = 3.17$, $p = .002$, $r = .39$. There were no significant differences for any of the quadrants in the visual modality (see Fig. 2b). A secondary analysis (including only 11–18 year olds) showed significantly more auditory behaviors in the ASD than in the TD group for the low-registration quadrant, $t(49) = -3.083$, $p = .003$, $r = .40$ as well as a trend toward more sensory behaviors for the sensory sensitivity quadrant, $t(49) = -1.863$, $p = .068$, $r = .26$. TD participants reported significantly more auditory sensory behaviors than ASD participants for the sensation seeking quadrant, $t(49) = 3.435$, $p = .001$, $r = .44$. No significant differences between diagnostic subgroups (autistic vs. Asperger's disorder) were detected for AASP data.

Experimental Task

Group means for behavioral performance are shown in Table 2. All response times (RTs in ms) were transformed using a natural log due to a skewed distribution. Only responses with RTs between 250 ms and 2 s were included as valid responses. A mixed-design repeated measures ANOVA was used to investigate the differences in RT for all correct trials and accuracy for the three conditions (auditory, visual, and bisensory) across the two groups.

For RT, a main effect of trial type was detected, $F(2,51) = 40.43$, $p < .001$, $\eta_p^2 = .442$. No main effect of group was found ($p > .5$), indicating TD and ASD adolescents had similar response times. Follow-up tests were conducted protecting the alpha level at .05 using the Scheffé critical value of 6.37. Response times were significantly shorter in both groups for bisensory compared to averaged auditory and visual trials, $F(1,51) = 86.87$, $p < .05$, $\eta_p^2 = .630$, as well as for auditory trials, $F(1,51) = 84.95$, $p < .05$, $\eta_p^2 = .625$, and for visual trials, $F(1,51) = 28.1$, $p < .05$, $\eta_p^2 = .355$. RT was also significantly faster for visual than for auditory trials, $F(1,51) = 14.83$, $p < .05$, $\eta_p^2 = .225$ (Fig. 3a). While not part of our planned analyses, we noted a significant RT difference for auditory trials between the diagnostic subgroups within the ASD group, with longer RTs in participants with autistic disorder compared to those with Asperger's disorder, $F(1,22) = 5.18$, $p = .033$, $\eta_p^2 = .191$.

For accuracy (percent correct), a main effect of trial type was found, $F(2,51) = 8.02$, $p < .01$, $\eta_p^2 = .243$ indicating that the type of sensory information presented had an effect on accuracy. For group, the main effect was only marginally significant, $F(1,51) = 3.96$, $p = .052$, $\eta_p^2 = .072$, reflecting overall slightly reduced accuracy in the ASD group. Follow-up tests were conducted protecting the alpha level at .05 using the Multivariate Scheffé critical value of 6.51. Both groups were significantly more accurate for bisensory than for auditory trials, $F(1,51) = 15.09$, $p < .05$, $\eta_p^2 = .228$, and for visual compared to auditory trials, $F(1,51) = 16.3$, $p < .05$, $\eta_p^2 = .242$. There was no significant difference between accuracy for bisensory versus visual trials in either group (Fig. 3b).

We also performed identical analyses excluding 6 ASD and 8 TD participants who were <11 years old (i.e., below the age range for the AASP). For RT, a main effect of trial type was found, $F(2, 36) = 38.921$, $p < .001$, $\eta_p^2 = .684$. The main effect of group was not significant ($p > .5$). In follow-up tests, response times were significantly shorter in both groups for bisensory trials than for averaged auditory and visual trials, $F(1,37) = 72.124$, $p < .05$, $\eta_p^2 = .661$, as well as for auditory trials, $F(1,37) = 71.691$, $p < .05$, $\eta_p^2 = .660$, and for visual trials, $F(1,37) = 19.810$, $p < .05$, $\eta_p^2 = .349$. RT was also significantly faster in both groups for visual than for auditory trials, $F(1,37) = 13.431$, $p < .05$, $\eta_p^2 = .266$. For accuracy, we found a main effect of trial type, $F(2, 36) = 7.802$, $p = .002$, $\eta_p^2 = .302$, but not of group, $F(1,36) = 1.422$, $p = .241$. Follow-up tests showed that both groups were significantly more accurate for bisensory than for auditory trials, $F(1,37) = 12.713$, $p < .05$, $\eta_p^2 = .256$, and for visual compared to auditory trials, $F(1,37) = 15.750$, $p < .05$, $\eta_p^2 = .299$. There was no significant difference between accuracy for bisensory versus visual trials in either group.

We further tested whether shorter RTs for bisensory (compared to unisensory) trials reflected separate activation (independently for each stimulus modality) versus coactivation (of processes in each modality) (Molholm et al. 2002). Following procedures previously applied by Molholm et al. (2002), we examined the cumulative probability (CP) of RT at each latency *(t)* and determined whether the CP of observed latencies for bisensory trials was below or equal to the summed CPs for unisensory trials, after subtraction of the joint CP of unisensory trials: $CP_{(t)bisensory} \leq (CP_{(t)visual} + CP_{(t)auditory}) - (CP_{(t)visual} \times$

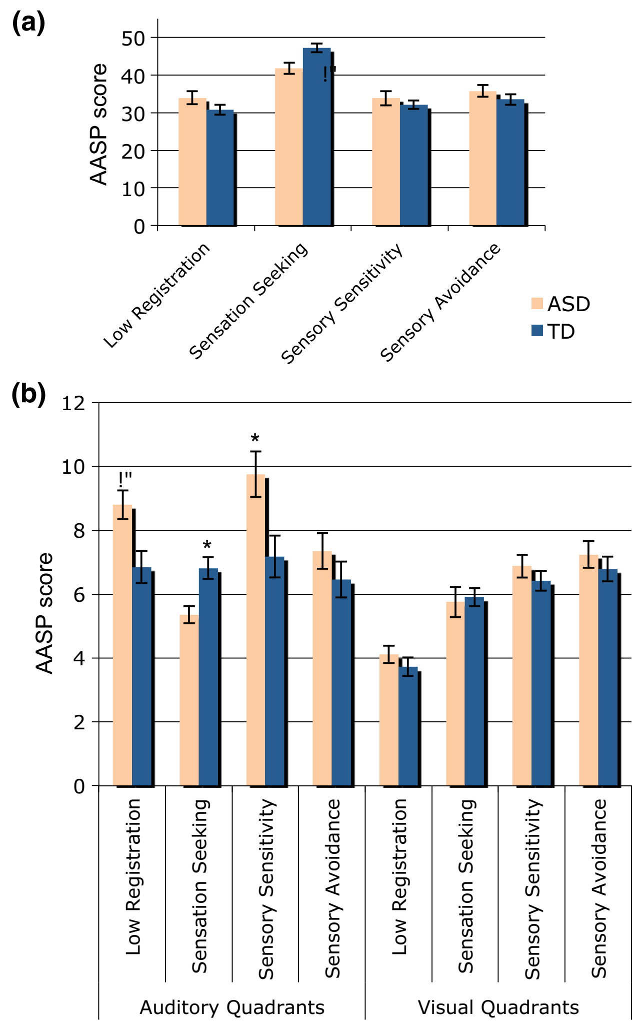

Fig. 2 Mean AASP quadrant scores by group with standard error. (**a**) AASP full-scale quadrant scores. (**b**) Auditory and visual quadrant scores

Table 2 Behavioral performance on experimental task by group

	ASD (n = 24)		TD (n = 29)	
	Mean	SE	Mean	SE
Reaction time (log_e)				
Auditory task	6.387	.046	6.454	.036
Visual task	6.325	.042	6.325	.041
Bisensory task	6.208	.040	6.239	.041
Accuracy				
Auditory task	.84	.037	.92	.014
Visual task	.95	.015	.97	.005
Bisensory task	.95	.012	.96	.010

$CP_{(t)auditory}$) (Fig. 3c). For each participant the range of RTs from correct trials was converted into quantiles in 5 % increments. Actual CPs for bisensory trials were compared to predicted CPs [($CP_{(t)visual} + CP_{(t)auditory}$) − ($CP_{(t)visual} \times CP_{(t)auditory}$)], using paired *t* tests to test for violations of the race model. No significant violation of the race model was detected in either group, despite overall reduced RTs for bisensory compared to unisensory trials (Fig. 3).

Pearson's correlations were calculated using task performance and AASP scores with the critical *p* value of .01. After controlling for age and IQ (i.e., partialling out these variables, which were significantly correlated with performance), significant negative correlations were found for the ASD group between visual accuracy and the sensation seeking full-scale quadrant, $r(13) = -.646$, $p < .01$ as well as the auditory only sensation-seeking quadrant, $r(13) = -.734$, $p < .01$, indicating that children with ASD that scored low on sensation seeking behaviors were more accurate on the visual task. No correlations reached significance between the auditory quadrant scores and RT or accuracy for the auditory condition. When excluding 5 ASD and 4 TD participants <11 years of age (those outside the age range for the AASP), significant positive correlations in the ASD group were found between auditory RT and the sensation avoiding full-scale quadrant, $r(8) = -.943$ $p < .001$ as well as the auditory only sensation-sensitivity quadrant, $r(8) = .814$, $p = .004$. Note, however, that sample size for this particular analysis was low in the ASD group (n = 13). No correlations reached significance in the TD group.

Age was also not correlated with accuracy in either group. In order to further explore what factors were involved in accuracy for the auditory condition, Pearson's *r* partial correlations were also calculated to assess the relationship between the performance on the auditory condition and IQ while controlling for age. For both groups, IQ was significantly correlated with accuracy on the auditory task. In the TD group, auditory accuracy was significantly correlated with non-verbal IQ, $r(25) = .497$, $p = .008$ and marginally with verbal IQ, $r(25) = .437$, $p = .023$; whereas in the ASD group, auditory accuracy was significantly correlated with both verbal IQ, $r(21) = .603$, $p = .002$, and non-verbal IQ, $r(21) = .671$, $p < .001$ (Fig. 4a, b).

Neither verbal nor nonverbal IQ was correlated with RT for any of the three tasks. The relationship between age and RT was therefore explored using partial correlations while controlling for verbal and nonverbal IQ scores. The TD group showed a significant negative correlation between age and visual RT $r(24) = -.575$, $p = .002$ and bisensory RT, $r(22) = -.518$, $p = .007$. The ASD showed similar significant negative correlations between age and auditory RT, $r(20) = -.592$, $p = .004$, visual RT, $r(20) = -.754$, $p < .001$, and bisensory RT, $r(20) = -.772$, $p < .001$ (Fig. 4c–e). For the ASD group further partial correlations

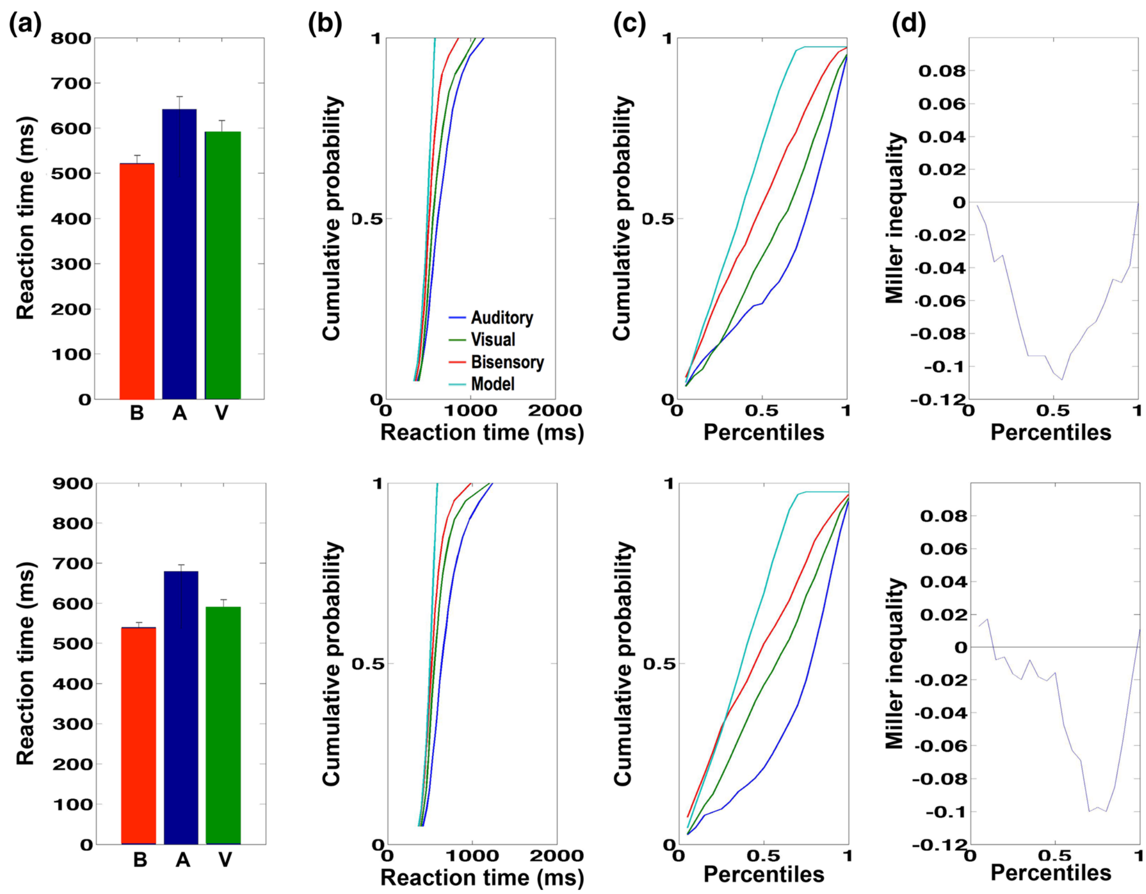

Fig. 3 (**a**) Response time for bisensory (B), auditory (A), and visual (V) trials in TD group (*top row*) and ASD group (*bottom row*) with standard error; cumulative probabilities (CPs) for each condition and group, as well as predicted CP from race model, by (**b**) reaction time and (**c**) percentile; (**d**) Miller Inequality. A significant violation of the race model was not detected in either group

were calculated to assess the relation between RTs and diagnostic scores as measured by the ADOS. The repetitive/restrictive ADOS score was significantly negatively correlated with visual task accuracy after controlling for age, $r(22) = -.617$ $p = .001$. After controlling for IQ, the reaction times for the auditory task were positively correlated with scores on the social and social communication scales and reaction times for the bisensory task were positively correlated with scores on the social and restricted, repetitive scales (Table 3).

Discussion

We used the Adolescent/Adult Sensory Profile (AASP; Brown and Dunn 2002) and an experimental test of bisensory facilitation to test for sensory abnormalities and links with sensory integration in children and adolescents with ASD. As expected, ASD participants reported more atypical sensory behaviors on the AASP, although our findings were overall less robust than those from other studies (Kientz and Dunn 1997; Tomchek and Dunn 2007) and were specific to the auditory modality. Results from the experimental task further showed reduced RTs for bisensory compared to unisensory trials in both groups. However, a significant violation of the race model was not detected in either group.

Correlation analyses revealed no links between sensory symptoms and bisensory facilitation. Instead, IQ and age were found to be associated with task performance.

On the AASP, sensory symptoms trended toward greater prevalence in the ASD group compared to the TD group for one out of the four sensory quadrants, the low registration quadrant, meaning that children with ASD more frequently reported behaviors such as missing cues in the environment and difficulty following rapid or unfamiliar conversations. The TD group displayed significantly more behaviors on the sensation-seeking quadrant than the ASD group, consistent with a study by Crane et al. (2009) in adults with ASD.

In view of the nature of the experimental task, quadrant scores were also calculated specifically for auditory and visual modalities. For the auditory modality, the ASD group had significantly more sensory behaviors in the low

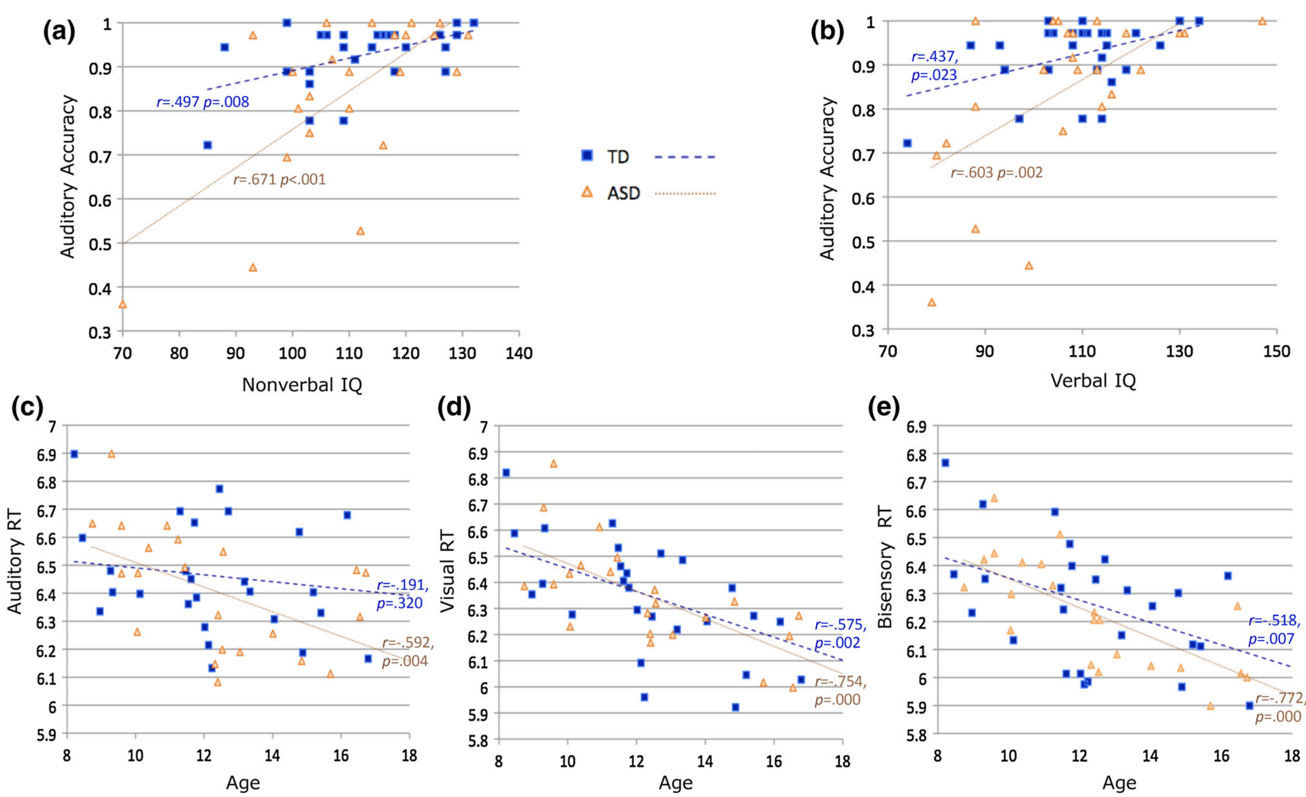

Fig. 4 Partial correlations between auditory accuracy and (**a**) nonverbal and (**b**) verbal IQ by group. Correlations between age and RT for (**c**) auditory, (**d**) visual, and (**e**) bisensory condition per group

Table 3 Correlations between task performance and ADOS scores in the ASD group (n = 24), controlling for IQ

	Social	Communication	Social communication	Restricted, repetitive
Reaction time				
Auditory task	.573*	.191	.509*	.213
Visual task	.408	.225	.416	.156
Bisensory task	.472*	.158	.419	.430*
Accuracy				
Auditory task	.130	−.023	.075	.138
Visual task	.033	−.412	−.228	−.702**
Bisensory task	.240	−.402	−.081	−.581*

* $p < .05$; ** $p < .001$

registration and the sensory sensitivity quadrants, but fewer in the sensation-seeking quadrant, as compared to the TD group. These results are consistent with previous studies that have shown seemingly paradoxical responses to auditory stimuli including both hypo- and hyper-sensitivity to auditory stimuli (Baranek 1999; Dahlgren and Gillberg 1989; Tomchek and Dunn 2007; Kern et al. 2007). Jones et al. (2009) found a similar pattern, using questions from the AASP that pertained to the auditory modality. Their ASD group showed significantly more behaviors than their TD group for the low registration, sensation sensitivity, and sensation avoiding quadrants, but the opposite trend for the sensation-seeking quadrant.

The results from Crane et al. (2009) as well as Jones et al. (2009) indicate that high frequency of sensory behaviors in the sensation-seeking quadrant is a characteristic of neurotypical development, in comparison with ASD, probably related to social factors. This quadrant includes items such as “I find activities to perform in front of others (for example, music, sports, acting, public speaking, and answering questions in class)”, “I choose to engage in physical activities”, and “I like to attend events with lots of music”, which may apply more often to TD adolescents than to those with ASD because they include social components rather than solely reflecting basic sensory processing (Jones et al. 2009).

For the visual modality, no differences were found in any of the four quadrants. To our knowledge, no previous study has examined this specific aspect using the AASP. It is possible that visual items on the AASP may not specifically tap into visual abnormalities in ASD. However, a recent meta-analysis of functional neuroimaging evidence has been interpreted as indicating potential sparing of the visual domain in ASD (Samson et al. 2012; see also reviews by Milne et al. 2009, and Simmons et al. 2009). In addition, neuroanatomical studies suggest that visual regions in the occipital lobe may be spared with respect to early brain overgrowth and cytoachitectonic abnormalities observed in other forebrain lobes (Carper and Courchesne 2005; Palmen et al. 2004).

Although expected atypical sensory behaviors were detected in the ASD group, our findings of sensory symptoms from the AASP were not as robust as reported in previous studies including younger children (Kientz and Dunn 1997; Tomchek and Dunn 2007). Relatively subtle group differences might thus reflect improvement with age in ASD (Kern et al. 2007). Although no significant correlations between AASP scores and age were detected in our cohort, the data for the sensory sensitivity quadrant showed a trend of diminished symptoms with age. Samples from the cited two studies by Dunn and colleagues also differed from ours because ASD and TD groups were not IQ matched, whereas ASD participants in the current study were high functioning and IQ matched.

Our experimental paradigm was based on a study by Miller (1991) that showed significantly faster reaction times for congruent bisensory stimuli compared to unisensory cues in TD adults. Our second hypothesis, which predicted reduced bisensory facilitation in the ASD group, was not confirmed. Reduced RTs for bisensory compared to unisensory trials were found for both groups. In addition, there were no group differences in accuracy for any of the three conditions. This absence of group differences in RT and accuracy may support previous studies that have found intact low-level audio-visual integration in children and adults with ASD (van der Smagt et al. 2007; Mongillo et al. 2008). However, note that a bisensory facilitation effect reflecting crossmodal integration could not be demonstrated, as no significant violation of Miller's race model (Miller 1982) was detected in either group.

Our findings stand in contrast to two recent studies. Collignon et al. (2013) found that adolescents and adults with ASD performed better than matched TD participants on a visual search task involving line orientation and color changes. However, an added auditory alert improved performance solely in the TD group, suggesting a lack of bisensory facilitation in the ASD group. The complexity of the visual task (with error rates up to 20 % and RTs up to 8.5 s in the TD group) makes findings from this paradigm hard to compare with ours, given the extreme simplicity of our visual task. Note that ASD and TD participants actually performed at similar levels in the bisensory condition in this study. Brandwein et al. (2013) found bisensory facilitation and violation of the race model for very simple auditory and visual stimuli in only a minority of 7–10 year-old children with ASD. A potentially crucial difference in task paradigms was that our study required participants to make a discriminatory decision (stimulus 'high' or 'low'), whereas in the study by Brandwein et al. (2013), participant response only indicated the detection of a stimulus. Attentional abnormalities have been documented in a large ASD literature (Keehn et al. 2013), and these may affect performance less when a task design forces participants to attend to stimuli, as in our study. Aside from attentional implications, our null finding for race model violations in the TD group is consistent with observations by Barutchu et al. (2009) who found that multisensory (audiovisual) coactivation does not fully mature in TD children until after age 11 years. Furthermore, the pattern of results from our study and the literature is in line with a dichotomy between low-level sensory integration, which may be mostly intact in ASD, and audio-visual integration for verbal stimuli, which has been reported to be disrupted (Samson et al. 2006; Bebko et al. 2006).

Whereas AASP scores were not correlated with bisensory facilitation, age and IQ were found to be associated with performance on unisensory as well as bisensory tasks. This pattern of findings may shed light on why our ASD group, which was matched on age and IQ to the TD group, reported more abnormal sensory responses on the AASP, while performing at normal levels on the experimental task. Performance on the experimental sensory task was heavily affected by age and IQ, whereas this was not the case for sensory behaviors on the AASP. Increasing age was associated with faster RTs for two of the tasks in the TD group and all three in the ASD group. The results for the TD group are consistent with findings of age-dependent decreases in RTs for simple tasks in childhood and adolescence (Kail 1991). Our findings further suggest that similar age-dependent changes occur in high-functioning children and adolescents with ASD.

We also found links between IQ and auditory accuracy in both groups. Correlations were robust in the ASD group for both verbal and nonverbal IQ, whereas in the TD group they reached significance only for nonverbal IQ. No developmental causality can be easily attributed to these correlations. The link between auditory accuracy and nonverbal IQ in the TD group appears puzzling, but may indicate general effects of attention on performance in the relatively difficult auditory condition. The relation between auditory accuracy and IQ in the ASD group may reflect similar general effects, but the specific correlation with verbal IQ could also imply some causal role of low-level auditory processing, which has been found impaired in some studies (Gage et al. 2003; Gervais et al. 2004; Rosenhall et al. 1999; Siegal and Blades 2003), in language delay and mildly impaired language outcome.

Such links between subtle auditory impairments and cognitive deficits in ASD, especially for language, have been suggested (Tanguay and Edwards 1982; Siegal and Blades 2003; Hitoglou et al. 2010). There are reports of comorbid hearing loss and deafness in children with autism (Rosenhall et al. 1999) as well as of more subtle impairments, such as difficulty with auditory filtering (Rogers et al. 2003), and hypo-responsiveness and unusual sensitivity to auditory stimuli (Dahlgren and Gillberg 1989). Bomba and Pang (2004) reviewed findings of abnormal event related potentials corresponding to impaired regulation and selective attention to auditory stimuli, reversed hemispheric dominance, and impairments of auditory information encoding in children with ASD. Imaging studies have also found reduced or reversed hemispheric dominance for nonverbal and verbal auditory stimulation (Boddaert et al. 2004; Eyler et al. 2012; Müller et al. 1999). Subtle auditory abnormalities may affect early stages of language acquisition in some children with ASD, possibly through similar mechanisms as in developmental dyslexia (McAnally and Stein 1996; Rapin and Dunn 2003).

Lower scores on the sensation-seeking quadrant were associated with greater accuracy on the visual task. This correlation was specifically detected for auditory items in this quadrant, suggesting that reduced auditory sensation-seeking behaviors in ASD were associated with better low-level visual processing. This effect was exclusively found in the ASD group (in the full sample that included children <11 years of age) and may reflect compensatory links between low-level auditory and visual functions, possibly related to visual sparing or superiority, as discussed above. Since no analogous relationship was seen in the TD group, it is likely that the correlation between auditory sensation-seeking behaviors and visual detection accuracy reflects atypical sensory function in ASD.

We further found a negative correlation between the ADOS diagnostic scores for repetitive/restrictive behaviors and accuracy on the visual task, suggesting that presence of repetitive behaviors may be detrimental to low-level visual processing. Since the visual task was extremely simple, our finding may imply a link between repetitive behaviors and impaired attention in ASD. Our finding may therefore relate to results reported by South et al. (2007) that suggest associations of repetitive behaviors with executive impairment in ASD. ADOS scores for repetitive/restrictive behaviors were also related to increased response times and decreased accuracy in the bisensory task after controlling for IQ. Additionally, increased response times were associated with higher ADOS social and social communications scores, which suggests that some sensory processing difficulties may be related to symptomatology in ASD.

Limitations of the current study concern the inclusion of nine of the participants (4 TD, 5 ASD) slightly below the recommended age range for the AASP, which is designed for ages 11 years and older. In addition, complete matching of stimulus presentation between auditory and visual modalities was hard to achieve and the auditory condition proved to be overall more difficult, presumably since there was no auditory equivalent to the continuous presentation of a box in the visual condition.

Consistent with our first hypothesis and with previous studies (Kern et al. 2006; Tomchek and Dunn 2007), our results indicate that high-functioning children with ASD frequently show atypical sensory behaviors, in particular in the auditory modality. This may relate to auditory sensitivities and difficulty with auditory filtering that have been identified as among the earliest ASD symptoms in retrospective videotape studies (Rogers 2009; Rogers et al. 2003). Our second hypothesis of reduced sensory integration in ASD was not confirmed. Instead, our experimental results suggest that bisensory facilitation of simple nonverbal stimuli may not be impaired in ASD. This was unexpected, given theories of impaired integrative processing in ASD (Brock et al. 2002; Happé and Frith 2006; Iarocci and McDonald 2006; Mottron et al. 2006). However, our results are consistent with some recent studies suggesting potentially intact audiovisual integration for simple, non-social stimuli (Mongillo et al. 2008; Van der Smagt et al. 2007). Alternatively, our null finding may relate to the low ecological validity of the experimental paradigm. As one of the fundamental principles of cognitive psychology, the need for tight experimental control tends to go along with use of stimulus designs that differ vastly from more complex and less controlled real-life experience. We therefore cannot rule out that bisensory facilitation for non-verbal stimuli of greater complexity and ecological validity may be affected in ASD.

Given the null finding for the second hypothesis, it is not surprising that our third hypothesis was not confirmed either. No direct relationship was found between sensory symptoms and performance on the experimental sensory detection task in ASD participants. Abnormalities in sensory behaviors were not found to translate into impaired task performance, presumably due to the absence of competing stimuli in the experimental setting that contrasts with typical everyday environments assessed by the AASP.

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