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The Role of Attention in Somatosensory Processing: A Multi-trait, Multi-method Analysis

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Abstract

Sensory processing abnormalities in autism have largely been described by parent report. This study used a multi-method (parent-report and measurement), multi-trait (tactile sensitivity and

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Author Contributions ELW conceived of the study, participated in its design and coordination and drafted the manuscript; NAJP participated in the design, interpretation of the data, and revision of the manuscript; EMM participated in the design of the study and revision of the manuscript; RAEE participated in the design of the study and revision of the manuscript; MT participated in the design of the study and revision of the manuscript; SHM participated in the design of the study and revision of the manuscript, and provided participants through his ongoing studies. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest Mark Tommerdahl is co-inventor of the tactile stimulator used in the study and is co-founder of Cortical Metrics, which has a license from the University of North Carolina to distribute the device.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

attention) design to evaluate somatosensory processing in ASD. Results showed multiple significant within-method (e.g., parent report of different traits)/cross-trait (e.g., attention and tactile sensitivity) correlations, suggesting that parent-reported tactile sensory dysfunction and performance-based tactile sensitivity describe different behavioral phenomena. Additionally, both parent-reported tactile functioning and performance-based tactile sensitivity measures were significantly associated with measures of attention. Findings suggest that sensory (tactile) processing abnormalities in ASD are multifaceted, and may partially reflect a more global deficit in behavioral regulation (including attention). Challenges of relying solely on parent-report to describe sensory difficulties faced by children/families with ASD are also highlighted.

Keywords

Autism; Sensory processing; Attention; Vibrotactile; Somatosensory

Introduction

Abnormalities in sensory processing cause substantial functional impairment for children with autism and their families, and are a common symptom of the disorder, with up to 88 % of parents endorsing some alterations in sensory processing for their child with autism spectrum disorder (ASD: Tomchek and Dunn 2007; Hilton et al. 2001; Rogers and Ozonoff 2005). These sensory abnormalities are so prevalent that “hypo- or hyper-reactivity to sensory input” was added to the diagnostic criteria of ASD in DSM-5 (American Psychiatric Association 2013). Such abnormalities include both hyper-responsivity to sounds (e.g., fire alarms), textures (e.g., food selectivity), and sights (e.g., sunlight), as well as hypo-responsivity to the same stimuli and other sensations (e.g., pain). While *hypo*-responsive reactions are concerning to parents, *hyper*-responsivity often generates greater distress, as tantrums, self-injury, and participation-limiting behavioral avoidance are often triggered by, and attributed to, hyper-responsive abnormalities in sensory processing.

Given the impact of abnormal sensory processing in ASD, there is a growing body of research examining its neurobehavioral basis. That said, there are two considerable challenges and limitations to the majority of research published to date in this area. First, although it is known that the behavioral response to sensory stimuli in ASD is altered, it has been challenging to define the mechanism by which this alteration in sensory-driven behavior occurs, and the general assumption is that the deficit leading to the abnormal sensory functioning lies in the sensory system. Deficits in other systems, however, including cognitive systems (e.g., attention), warrant further exploration, as it is likely that multiple related processes lead to the clinical symptom of abnormal sensory processing reported in ASD. For example, consider the child with ASD who cannot ignore a shirt tag. It may be that for this child, the primary sensory representation to a tag is atypical, making the tag *feel* scratchier, or it may be that the child *feels* the tag typically, but processes it (or attends to it) differently. Alternatively, the child may *feel* and process the tag typically, but react differently (behaviorally). Most likely, there is some overlap among these processes that has yet to be delineated.

A second, and equally concerning, limiting factor in the present understanding of abnormal sensory processing in ASD is that until recently (Holden et al. 2012; Puts et al. 2014), reports of sensory processing in ASD have largely been solely reliant on parent report. Although it may be difficult for children with ASD to describe their sensory experience, objective methods other than parent-report should be considered (as parent-report can only describe the behavioral manifestation assumed to be related to the sensory experience).

Performance-Based Measurement of Sensory Processing in ASD

Given this gap in the literature, objective methodologies (i.e., the measurement of tactile thresholds after controlled trial-based tactile stimulation) have been developed to attempt to better quantify sensory processing abnormalities in children with ASD (Holden et al. 2012). Using these techniques, consistent abnormalities in basic tactile detection and thresholds, and difficulties with tactile adaptation (i.e., the ability to adjust one's sense based upon prior sensory experiences) have been identified for individuals with ASD (Puts et al. 2014). While for typically developing (TD) individuals the presence of an adapting stimulus is thought to reduce the perceived intensity of subsequent stimuli through alterations in neuronal firing (Simons et al. 2005); this effect is not consistently observed in individuals with ASD. Specifically, amplitude discrimination (i.e., the ability to identify which stimulus is stronger) and detection threshold (i.e., the minimum stimulus that can be perceived) in TD adults and children worsens with presentation of an adapting stimulus; this effect is not observed in adults and children with ASD (Tommerdahl et al. 2007; Puts et al. 2014). As there are close links between these tasks and cortical mechanisms (Tommerdahl et al. 2010), this initial work has begun to allow associations between altered tactile performance in children with ASD and the mechanisms (related to the inhibitory neurotransmitter GABA) that underlie it. Specifically, abnormal tactile sensation has been shown in children with ASD (Puts et al. 2014) in tasks that have been closely linked to inhibitory function (Tannan et al. 2007; Tommerdahl et al. 2010), suggesting that altered GABAergic inhibition could underlie altered tactile sensation. Puts et al. 2011 shows an association between brain GABA levels and tactile discrimination, with participants with higher GABA showing better performance. In autism, several studies (Gaetz et al. 2014, Rojas et al. 2014) show reduced GABA levels in sensory regions in children with ASD. While the relationship between GABA and tactile sensitivity needs further exploration, given the strong link between GABA and tactile sensation, it is likely that alterations in the GABAergic system at least partially contribute to altered tactile sensation in ASD.

In addition, investigation of the somatosensory (not parent-observed) response/tactile sensitivity could partially explain functional differences in behavior (i.e., while most children habituate to tags in their shirts, children with ASD may not be able). While previous work suggests that tactile abnormalities associate with local somatosensory differences in neuronal function, it would be oversimplified to assume that the measurement of tactile thresholds does not depend on other overlapping or moderating processes, such as attention.

Attention in ASD

Disordered attention has been well researched and is consistently described as a prominent aspect of the ASD phenotype (Ames and Fletcher-Watson 2010; Allen and Courchesne 2001; Casey et al. 1993). In their review of attention in ASD, Ames and Fletcher-Watson (2010) highlight hyper-arousal as most problematic in ASD with an accompanying impairment of selective, goal-oriented attention. Casey and colleagues (1993) suggested that children with ASD are unable to effectively disengage their attention; as such, task-irrelevant stimuli that *should* be ignored consume limited processing resources and detract from efficient processing of task-relevant stimuli. Notably, this description appears to mirror abnormalities in sensory adaptation and habituation, where children with ASD demonstrate atypical somatosensory response when presented with tasks including adaptation stimuli. That said, there has been surprisingly little examination of the association between attention and abnormal sensory processing (tactile or otherwise) in ASD. Given the well-established importance of attention in regulating typical sensory processing (Domínguez-Borràs and Vuilleumier 2013), it is imperative that this potential explanation for the behavior is pursued. Thus, an important next step is to attempt to better understand the relationship between abnormal tactile adaptation and other potentially overlapping or moderating processes.

Purpose

The overall purpose of the present study is to examine the relationship between attention and abnormal somatosensory processing in children with ASD. Previous research has established differences in parent-reported and performance-based tactile sensitivity, as well as parent-reported and performance-based attention in ASD as compared to typically developing peers (Puts et al. 2014; Wodka et al. 2014). As such, the aim of this study is to clarify the underlying process that drives these *functional* differences in ASD by comparing relationships between attention and tactile sensitivity using a multi-trait, multi-method design. This methodology allows for an examination of the construct validity of parent-reported somatosensory processing measures. We hypothesize that the strongest associations will be found within method/between trait (e.g., parent-reported somatosensory processing will correlate with parent-reported attention; performance on measures of attention will correlate with performance on measures of tactile sensitivity). Weaker associations are expected within trait/between method (e.g., parent-reported somatosensory processing and performance on measures of tactile sensitivity).

Methods

Recruitment and Participants

The present study reports on the evaluation of 57 children with ASD, ages 7–14 years (M_{age} = 10.6 years, *SD* = 1.6; 85 % male). Further description of the sample can be found in Table 1. Children were recruited from a larger, on-going study examining motor and sensory processing in children with high-functioning autism; participants were either called back (within 2 years of completing the ongoing study) to complete the sensory measures included in the present study or the tasks were added to the protocol for children recruited and evaluated in the on-going study after the approval of the sensory portion of the aims. While all children in this sample received tactile sensitivity testing and parent-report measures, only a subset of these 57 children (n = 21) received performance-based asssessment of attention. There were no significant differences between those children who did and did not have assessment of attention in outcome variables (i.e., performance-based tactile sensitivity, parent-reported attention funcitoning, parent-reported sensory processing), intelligence, or sex distribution; however, children who had assesment of attention were older ($M_{age} = 11.5$, $SD = 1.4$) than those who did not ($M_{age} = 10.1$, $SD = 1.5$; $t_{(1,56)} = -3.34$, $p = 0.002$).

Children were eligible to participate in the present study if they met the following criteria: a) between age 8 years, 0 months and 14 years, 11 months, 30 days; and b) a Wechsler Intelligence Scale for Children-IV (WISC-IV; Wechsler 2003) Verbal Comprehension Index or Perceptual Reasoning Index ≥80 (with the lower of the two ≥65). A potential participant was excluded from the ongoing study if there was: (a) presence or history of a definitive neurologic disorder; (b) presence of a severe chronic medical disorder; or (c) presence of a major visual or hearing impairment.

ASD Characterization—Diagnosis of autism was made using the Autism Diagnostic Interview-Revised (ADI-R; Lord et al. 1994), and the Autism Diagnostic Observation Schedule (ADOS-G; Lord et al. 2000), with additional history positive for development of spontaneous speech after 36 months of age or some evidence of deviant language development such as delayed echolalia, pronoun reversal, or neologisms; all children were also evaluated by a pediatric neurologist who confirmed the diagnosis. In addition, children must not have had a history of known etiology for autism (e.g., fragile X syndrome) or history of documented prenatal/ perinatal insult, nor met criteria for additional psychiatric diagnoses of conduct disorder, depression, or psychotic disorders based on maternal and child responses from the Diagnostic Interview for Children and Adolescents-IV (DICA-IV; Reich et al. 1997). Children with comorbid anxiety, attention deficit/hyperactivity disorder (ADHD), tic disorders, and learning disabilities were included. Parents were also asked whether their child displays abnormalities in tactile sensory processing (i.e., "is your child over- (or under-) sensitive to textures or touch?"). Only those whose parents answered "yes" were included.

Procedures

The Johns Hopkins University School of Medicine Institutional Review Board approved this study. Written consent was obtained from a parent or legal guardian and assent was obtained from every child. Parents completed telephone interviews regarding their child's behavior, developmental, and medical history prior to their research appointment. Children completed diagnostic measures as well as study measures outlined below over 2–3 days of evaluation; parents completed behavioral measures during their child's appointment. Some measures included in the present study were administered as part of larger, ongoing projects examining sensory and motor development in children with ASD. A summary of measures is provided in Table 2.

Performance-Based Measures

Tactile Sensitivity Measurement—Tactile (Holden et al. 2012). A CM4 four-digit tactile stimulator (Cortical Metrics) was used for stimulation. All stimuli were delivered to the glabrous skin of the left hand on digit 2 (LD2) and digit 3 (LD3) using a cylindrical probe (5 mm in diameter), and presented within the flutter range (25–50 Hz). Visual feedback, task responses, and data collection were performed on an Acer Onebook Netbook. The tactile battery consisted of the following tasks: Reaction Time (Simple and Choice), Detection Threshold (Static and Dynamic), Amplitude Discrimination Threshold (No-Adaptation and Single-site Adaptation), Frequency Discrimination Threshold (Sequential and Simultaneous), and Temporal Order of Judgment (With and Without Carrier Stimulus). See Puts et al. (2013, 2014) for full description of these tasks. Age was significantly correlated with performance on two of these variables—Choice Mean Reaction Time ($r_{55} = -0.41$, $p < 0.01$) and Temporal Order of Judgment without Carrier Stimulus ($r_{48} = -0.39$, $p < 0.01$)—such that older children outperformed younger children.

Test of Everyday Attention for Children (TEA-Ch)—Attention (Manly et al. 1999). The TEA-Ch is a well-normed measure assessing multiple aspects of attention in children ages 6–16 years of age. The Score DT subscale was used to assess performance-based divided auditory attention, which is supported in the literature (Manly et al. 2001). On this measure, children are required to attend to two different auditory streams over 10 trials. After each trial, the child is asked to provide specific information about the presented auditory information. Age-corrected scaled scores were used in analyses.

Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV)—Attention (Wechsler 2003). While the Verbal Comprehension and Perceptual Reasoning Indexes of WISC-IV were administered for study eligibility purposes (as discussed above), the Working Memory Index Standard Score was used as an outcome measure of attention. This index is comprised of the Digit Span subtest (where children repeat presented strings of digits of increasing length either forwards or backwards) and Letter-Number Sequencing sub-test (where the child is expected to repeat numbers/letters in numerical and alphabetical order that are presented jumbled). Age-corrected standard scores were used in analyses.

Attention Network Test—Attention (Fan et al. 2002). The ANT is a measure of visual attention, assessing multiple aspects of attention, including alerting, orienting, and executive functioning. The task lasts approximately 30 min. The ANT requires participants to determine whether a central arrow points left or right. The arrow appears above or below fixation and may or may not be accompanied by flankers. Reaction times and accuracy are measured dependent on task condition (with or without cue and/or flanker) as raw scores; age was not significantly correlated with these variables.

Parent-Report Measures

Sensory Processing Measure-Home Form—Tactile (Parham and Ecker 2007). The SPM is a 75-item, norm-referenced parent report questionnaire of sensory processing in children ages 5–12 years. The standard score for each subscale enables classification of the child's functioning into one of three interpretive ranges: *Typical* ($T_{score} \geq 60$), *Some Problems* ($T_{score} = 60–69$), *or Definite Dysfunction* ($T_{score} \geq 70$). The Total Sensory Symptoms and Touch Sensory subscales were used as dependent variables. Though some of our sample was out of the age range for this measure, the normative data are not stratified by age group, and age was not significantly correlated with raw score in our sample, which was used in analyses.

Conners' Parent Rating Scales—Attention.

The Conners' Parent Rating Scales-Revised (Conners 1997) and the Conners'-3 (Conners 2008) were used in the present study. These measures include 80 items, and are norm-referenced parent report questionnaires of behaviors reflective of inattention and hyperactivity in children age 3–17 years. The (cognitive problems)/inattention subscales from each version of the Conners' scales were combined into a single dependent variable. In the normative sample, there was a strong reported correlation between the Conners'-R and the Conners'-3 Cognitive Problems/ Inattention and Inattention scales, respectively ($r = 0.74$, $p < 0.01$) (Conners 2008).

Statistical Approach

Pearson correlations were completed within method/cross trait (i.e., parent-reported attention with parent-reported somatosensory processing; performance-based attention and tactile sensitivity), within trait/cross method (i.e., parent-reported attention with performance-based attention and parent-reported somatosensory processing with performance-based tactile sensitivity), and between trait and method (i.e., parent-reported attention with performance-based tactile sensitivity; parent-reported somatosensory processing with performance-based attention). Given multiple correlations, statistical significance was considered by a p value of <0.01 or an r value of >0.50 and a p value of <0.05.

Results

Based on published normative information, parents of children in our sample rated their child's inattentive (Conners') and sensory symptoms (SPM) in the clinically significant range (i.e., more than 1 SD above the respective tests' published mean). Additionally, performance on the TEA-Ch auditory divided attention task showed that children in this sample performed in the low end of the average range on the measure (2/3 of a SD below the test's published mean); however, performance was in the average range on a measure of working memory/attention (WISC-IV WMI). See Table 1. On tactile sensitivity measures, we have previously reported differences from typically developing children in a sample overlapping the present cohort in static detection threshold, with an absent effect of a dynamically increasing subthreshold stimulus, as well as in amplitude discrimination and adaptation (Puts et al. 2014).

Within-Trait, Cross-Method Analyses

Pearson correlations were used to examine the relationships between parent-reported and performance-based measures of attention (Table 3) and parent-reported somatosensory processing and performance-based tactile sensitivity (Table 4); no significant associations were found.

Within-Method, Cross-Trait Analyses

Pearson correlations were used to examine the relationships between attention and somatosensory processing as rated by parents, and between attention and tactile sensitivity as measured on performance-based assessment (Table 5). For performance-based tasks, multiple cross-trait correlations were significant, indicating that parent-reported symptoms of inattention and tactile dysfunction increased together and performance on measures of attention and tactile sensitivity decreased together. Specifically, auditory working memory was associated with basic tactile detection threshold ($r = -0.42$, $p < 0.01$; $n = 46$) and simultaneous frequency discrimination ($r = -0.37$, $p = 0.01$; $n = 45$). Additionally, auditory divided attention was associated with sequential frequency discrimination ($r = -0.62$, $p < 0.01$; $n = 19$). Reaction time on a visual attention task was also correlated with both reaction time on a tactile threshold detection task ($r = 0.51$, $p = 0.03$; $n = 19$) and detection threshold without an adapting stimulus ($r = 0.53$, $p = 0.02$; $n = 18$). Lastly, accuracy on the visual attention measure was correlated with basic tactile detection threshold ($r = -0.54$, $p = 0.02$; $n = 18$).

To reduce the overall number of correlations, only one correlational analysis was completed for parent-reported measures targeting inattention and somatosensory processing scales, which showed a significant correlation between parent-reported attention and somatosensory processing ($r = 0.39$, $p < 0.01$; $n = 54$).

Cross Method, Cross Trait Analyses

No significant associations were found between parent-reported somatosensory processing and performance-based attention, or parent-reported attention and performance-based tactile sensitivity.

Discussion

The overall purpose of the present study was to examine the relationship between attention and abnormal somatosensory processing in children with ASD. While frequently described (and now a defining feature of ASD), abnormal sensory processing in ASD is not well understood and difficult to quantify and measure. At present, parent report has been the primary method to characterize these sensory concerns in ASD; however, it is unclear what is actually driving the manifestation of these reported *sensory processing abnormalities*. In this study we aimed to examine the relationship between attention and somatosensory processing, to better inform and understand the clinical presentation of abnormal sensory behavior in children with ASD. To meet this aim, we employed a multi trait, multi method approach, including parent-reported and performance-based measures of attention and somatosensory functioning.

Findings from the present study begin to document an overlapping contribution of abnormal attention and tactile sensitivity in the manifestation of somatosensory processing abnormalities in children with autism, with primarily cross trait, within method associations identified (i.e., significant correlations identified between performance-based measures of tactile sensitivity and attention and parent-reported measures of somatosensory processing and attention). The observed pattern of associations, where within trait, cross method correlations were not significant (parent-reported measures of somatosensory processing and performance-based measures of tactile sensitivity; parent-reported measures of attention and performance-based measures of attention) suggests that parent-reported somatosensory processing and performance-based measures of tactile sensitivity are not measuring the same phenomena. Instead, stronger correlations between parent-reported attention and somatosensory processing and performance-based attention and tactile sensitivity were identified. In other words, parent report of somatosensory processing appears to share greater variance with parent-reported attentional processing (than performance-based tactile sensitivity), and may reflect more global concerns for behavioral regulation in ASD than specific concerns for sensory processing.

In a similar manner, multiple significant associations were identified between measures of performance-based attention and performance on measures of tactile sensitivity. These findings were particularly compelling, as correlations were observed between attention and tactile sensitivity measures that have been previously described as abnormal in children with ASD (primarily detection threshold with and without an adapting stimulus). Therefore, there appears to be some association between attention and the impairments demonstrated in performance-based measures of tactile detection threshold (i.e., the minimum amplitude to which a child responds/detects), which has previously been shown to be significantly higher than in typically developing children (Puts et al. 2014). Additionally, though not previously shown to be abnormal in ASD, highly attentionally demanding measures of tactile sensitivity also correlated with performance-based measures of attention. Thus, correlations are seen between performance-based measures of attention and tactile sensitivity that are, and are not, different between children with ASD and TDC, suggesting that the role of attention in somatosensory processing in ASD is part of a multifaceted system.

These findings also support a more global overlap between attention and somatosensory processing in ASD. More specifically, disordered attention is widely described in ASD (Ames and Fletcher-Watson 2010; Allen and Courchesne 2001; Casey et al. 1993), and contributes to challenges in learning, socialization, and independent functioning. While our group has provided evidence for deficits in lower-level sensory processing (e.g., detection threshold), it appears that execution of these lower level processes are at least partially related to attentional modulation. Therefore, a simple “hypersensitivity” model does not fully explain the functional impairments in somatosensory processing experienced by individuals with ASD, and the role of attention in this model warrants further investigation.

These findings have important implications for treatment delivery. The coordinated development of multiple neurological systems is likely involved in the development of appropriate sensory behavior and the identified overlap between attention and somatosensory processing (both as reported by parents and as demonstrated on performance-based measures) suggests that both sensory and behavioral/ attentional targets be considered in therapies to address abnormal sensory processing in ASD. That said, further work is needed to clarify relationships between neurocognitive functions and low level sensory processing and their role in sensory functioning deficits in ASD before considerable changes can be supported in treatment delivery models. Specifically, while there is an overlap between attention and somatosensory processing, it is not clear on what level this relationship manifests. For instance, it is possible that children with ASD are more inattentive, causing them to have different performance and response to adaptation on measures of tactile sensitivity than typically developing peers. Similarly, it is possible that differences in sensory processing reported by parents of children with ASD reflect broader attention and behavioral dysregulation, described in multiple settings and situations (including in response to sensory information).

Additionally, recent behavioral work (Puts et al. 2013) has shown abnormalities in tasks linked to GABAergic mechanisms (Blankenburg et al. 2003; Favorov and Kursun 2011; Zhang et al. 2011). For instance, GABAergic lateral inhibition plays an important role in separating neuronal signals and application of a GABAergic antagonist removes this separation of signals (Whitsel et al. 2003). Behaviorally, this can be tested using measures of tactile sensitivity (i.e., amplitude discrimination task); children with ASD show worse amplitude discrimination, consistent with poorer lateral inhibitory function. While further work is needed to link these metrics to in vivo GABA levels, other studies (Gaetz et al. 2014; Rojas et al. 2014) have shown reduced sensory and motor GABA levels in children with ASD. In addition, sensorimotor GABA levels predict frequency discrimination performance in both healthy adults (Puts et al. 2011) and healthy children (Puts et al. 2015) showing a link between tactile performance and in vivo GABA.

To further test these hypotheses, future research should include use of neuroimaging and/or electrophysiological techniques to examine early markers of attention, possibly clarifying the role of attention in abnormal sensory processing in ASD. Similarly, treatment studies where children are randomly assigned to treatment protocols with and without consideration of attention in the planning of treatment goals could also clarify whether appreciating the role of attention in the sensory experience promotes better functioning and outcomes for children with ASD and their families. Further, treatment studies targeting the GABA system to evaluate the impact of altered GABA on somatosensory processing in ASD should be considered.

This study has several notable strengths, including careful sample characterization of children with ASD and atypical somatosensory processing, as well as the inclusion of both performance-based and parent-reported measures of sensory and attentional functioning. Nevertheless, there are several limitations. First, our sample size, particularly for performance-based measures of attention, was small and may have limited the power to detect significant associations. An additional weakness is the reliance on solely correlational analyses. This is the first study to include both performance-based measures of tactile sensitivity and parent-reported somatosensory processing, and we apply a straightforward correlational analysis with relatively soft corrections for multiple comparisons, appropriate for exploratory analyses. Similarly, given the exploratory nature of this study, we were not able to employ additional measures of autonomic levels to control for differences in baseline arousal levels or related experiences that could contribute to performance. Further exploration of these relationships through alternative measures and analyses, including autonomic control measures (e.g., cortical levels, pupil status), is warranted. Additionally, our results are limited by probe-related variance (i.e., parents who report negatively on one aspect of behavior may be more likely to report negatively on another, and children who perform poorly in one domain may be more likely to perform poorly in other domains). That said, our multi-method analyses (i.e., examining relationships between parent-report and child performance) would not be impacted by this effect, and reflect a strength in our approach. Lastly, our sample, including school-age, high-functioning children with ASD, limits the generalizability of findings to the diverse population of ASD as a whole; however, the study also serves as an important first step in understanding the ability of children with ASD to participate in structured assessment of tactile sensitivity, supporting future research in using similar (and perhaps modified tasks) with younger and lower-functioning children with ASD.

In conclusion, this is the first study to our knowledge to simultaneously examine performance-based and parent-reported measures of somatosensory functioning and attention in a sample of children with ASD. Through this examination, we documented overlap between attention and somatosensory functioning, particularly for within method correlations (i.e., parent-report correlating with parent-report and performance-based measures correlating with performance-based measures). This suggests that performance-based measures of attention and tactile sensitivity and parent-reported measures of attention and somatosensory processing are more related than within trait, cross method associations (parent-reported and performance-based measures of sensory functioning or attention). As such, it appears that parent-reported somatosensory processing describes behavior that is somewhat different from the difficulties demonstrated by children with ASD on measures of tactile sensitivity detection, and instead, parents may be identifying concern for more global behavioral dysregulation (inattention) than sensory processing, specifically.

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References

Allen G, Courchesne E. The problem with using eye-gaze to infer desire: A deficit of cue inference in children with autism spectrum disorder? Journal of Autism and Developmental Disorders. 2001; 37:1761–1775.

American Psychiatric Association. Diagnostic and statistical manual of mental disorders. 5th. Washington, DC: American Psychiatric Publications; 2013.

Ames C, Fletcher-Watson S. A review of methods in the study of attention in autism. Developmental Review. 2010; 30(10):52–73.

Blankenburg F, Taskin B, Ruben J, Moosmann M, Ritter P, Curio G, et al. Imperceptible stimuli and sensory processing impediment. Science. 2003; 299:1864. [PubMed: 12649475]

Casey BJ, Gordon CT, Mannheim GB, Rumsey JM. Dysfunctional attention in autistic savants. Journal of Clinical and Experimental Neuropsychology. 1993; 15:933–946. [PubMed: 8120129]

Conners, CK. Conners' Parent Rating Scale-Revised (L). Tonawanda, NY: Multi-Health Systems; 1997.

Conners, CK. Conners' Parent Rating Scale-Third Edition. Tonawanda, NY: Multi-Health Systems; 2008.

Domínguez-Borraàs, J.; Vuilleumier, P. Affective biases in attention and perception. In: Armony, J.; Vuilleumier, P., editors. The Cambridge handbook of human affective neuroscience. New York, NY: Cambridge University Press; 2013.

Fan J, McCandliss BD, Sommer T, Raz M, Posner MI. Testing the efficiency and independence of attentional networks. Journal of Cognitive Neuroscience. 2002; 14:340–347. [PubMed: 11970796]

Favorov OV, Kursun O. Neocortical layer 4 as a pluripotent function linearizer. Journal of Neurophysiology. 2011; 105:1342–1360. [PubMed: 21248059]

Gaetz W, Bloy L, Wang DJ, Port RG, Blaskey L, Levy SE, et al. GABA estimation in the brains of children on the autism spectrum: Measurement precision and regional cortical variation. Neuroimage. 2014; 86:1–9. [PubMed: 23707581]

Hilton CL, Harper JD, Kueker RH, Lang AR, Abbacchi AM, Todorov A, et al. Sensory responsiveness as a predictor of social severity in children with high functioning autism spectrum disorders. Journal of Autism and Developmental Disorders. 2001

Holden JK, Nguyen RH, Francisco EM, Zhang Z, Dennis RG, Tommerdahl M. A novel device for the study of somatosensory information processing. Journal of Neuroscience Methods. 2012; 204:215–220. [PubMed: 22155443]

Lord C, Rutter M, Le Couteur A. Autism Diagnostic Interview-Revised: A revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. Journal of Autism and Developmental Disorders. 1994; 24:659–685. [PubMed: 7814313]

Lord C, Risi S, Lambrecht L, Cook EHJ, Leventhal BL, CiLavore PC, et al. The autism diagnostic observation schedule-generic: A standard measure of social and communication deficits associated with the spectrum of autism. Journal of Autism and Developmental Disorders. 2000; 30:205–223. http://www.ncbi.nlm.nih.gov/pubmed/11055457. [PubMed: 11055457]

Manly T, Anderson V, Nimmo-Smith I, Turner A, Watson P, et al. The differential assessment of children's attention: The Test of Everyday Attention for Children (TEA-Ch), normative sample and ADHD performance. Journal of Child Psychology and Psychiatry. 2001; 42:1065–1081. http://www.ncbi.nlm.nih.gov/pubmed/11806689. [PubMed: 11806689]

Manly, T.; Robertson, IH.; Anderson, V.; Nimmo-Smith, I. The Test of Everyday Attention for Children. Bury St. Edmunds: Thames Valley Test Company Limited; 1999.

Parham, LD.; Ecker, C. Sensory processing measure-home form. Los Angeles, CA: Western Psychological Services; 2007.

Puts NA, Edden RA, Evans CJ, McGlone F, McGonigle DJ. Regionally specific human GABA concentration correlates with tactile discrimination thresholds. Journal of Neuroscience. 2011; 31:16556–16560. [PubMed: 22090482]

Puts NAJ, Edden RAE, Wodka EL, Mostofsky SH, Tommerdahl M. A vibrotactile behavioral battery for investigating somatosensory processing in children and adults. Journal of Neuroscience Methods. 2013; 218:39–47. [PubMed: 23660524]

Puts NAJ, Harris AD, Crocetti D, Nettles C, Singer H, Tommerdahl M, et al. Reduced GABAergic inhibition and abnormal sensory symptoms in children with Tourette syndrome. Journal of Neurophysiology. 2015; 114:808–817. [PubMed: 26041822]

Puts NAJ, Wodka EL, Tommerdahl M, Mostofsky SH, Edden RAE. Impaired tactile processing in children with autism spectrum disorder. Journal of Neurophysiology. 2014

Reich, W.; Welner, Z.; Herjanic, B. The Diagnostic Interview for Children and Adolescents-IV. North Tonawanda: Multi-Health Systems; 1997.

Rogers SJ, Ozonoff S. Annotation: What do we know about sensory dysfunction in autism? A critical review of the empirical evidence. Journal of Child Psychology and Psychiatry. 2005; 26:1255–1268. http://www.ncbi.nlm.nih.gov/pubmed/16313426. [PubMed: 16313426]

Rojas DC, Singel D, Steinmetz S, Hepburn S, Brown MS. Decreased left perisylvian GABA concentration in children with autism and unaffected siblings. Neuroimage. 2014; 86:28–34. [PubMed: 23370056]

Simons SB, Tannan V, Chiu J, Favorov OV, Whitsel BL, et al. Amplitude-dependency of response of SI cortex to flutter stimulation. BMC Neuroscience. 2005; 21:43–57. http://www.ncbi.nlm.nih.gov/pubmed/15969752. [PubMed: 15969752]

Tannan V, Simons S, Dennis RG, Tommerdahl M. Effects of adaptation on the capacity to differentiate simultaneously delivered dual-site vibrotactile stimuli. Brain Research. 2007; 1186:164–170. [PubMed: 18005946]

Tomchek SD, Dunn W. Sensory processing in children with and without autism: A comparative study using the short sensory profile. American Journal of Occupational Therapy. 2007; 61:190–200. http://www.ncbi.nlm.nih.gov/pubmed/17436841. [PubMed: 17436841]

Tommerdahl M, Tannan V, Cascio CJ, Baranek GT, Whitsel BL. Vibrotactile adaptation fails to enhance spatial localization in adults with autism. Brain Research. 2007; 11:116–123. http://www.ncbi.nlm.nih.gov/pubmed/17498672. [PubMed: 17498672]

Tommerdahl M, Favorov OV, Whitsel BL. Dynamic representations of the somatosensory cortex. Neuroscience and Biobehavioral Reviews. 2010; 34:160–170. http://www.ncbi.nlm.nih.gov/pubmed/15969752. [PubMed: 19732790]

Wechsler, DL. Wechsler Intelligence Scale for Children. 4th. San Antonio, TX: The Psychological Corporation; 2003.

Whitsel BL, Kelly EF, Quibrera M, Tommerdahl M, Li Y, Favorov OV, et al. Time-dependence of SI RA neuron response to cutaneous flutter stimulation. Somatosensory Motor Research. 2003; 20:45–69. [PubMed: 12745444]

Wodka EL, Koriakin T, Puts NAJ, Mahone EM, Edden RAE, et al. Relationship between attention, hyperactivity/impulsivity, and sensory behavior in autism. Journal of the International Neuropsychological Society. 2014; S1(20):203.

Zhang Z, Francisco EM, Holden JK, Dennis RG, Tommerdahl M. Somatosensory information processing in the aging population. Frontiers of Aging Neuroscience. 2011; 3:18.

Table 1

Demographic information: total sample

	N	Mean	SD
Age (years)	56	10.6	1.6
TEA-Ch Score DT (scaled score)	21	8.1	3.3
Conners inattention (T-score)	54	68.2	12.3
SPM Touch Subscale (raw score)	53	19.4	6.3
SPM Touch Subscale (T-score)	53	61.7	9.2
WISC-IV VCI (standard score)	50	109.6	17.2
WISC-IV PRI (standard score)	51	107.3	12.3
WISC-IV WMI (standard score)	50	99.7	16.3

TEA-Ch Test of Everyday Attention for Children, *SPM* sensory processing measure, *WISC-IV* Wechsler Intelligence Scale for Children-Fourth Edition, *VCI* Verbal Comprehension Index, *PRI* Perceptual Reasoning Index, *WMI* Working Memory Index

Table 2

Measures

Measure	**Method**	**Trait**
Tactile threshold detection	Performance	Sensory
TEA-Ch Score DT	Performance	Attention
WISC-IV Working Memory Index	Performance	Attention
Attention Network Test	Performance	Attention
Sensory processing measure	Parent-report	Sensory
Conners	Parent-report	Attention

Table 3

Within trait (attention)/cross method (performance and parent-reported) correlations

Measures	*1	*2	*3	*4	*5	*6	*7	+8
*1. ANT alerting (performance)	–	–	–	–	–	–	–	–
*2. ANT orienting (performance)	.04	–	–	–	–	–	–	–
*3. ANT conflicting (performance)	−.05	−.29	–	–	–	–	–	–
*4. ANT reaction time (performance)	−.02	−.08	.20	–	–	–	–	–
*5. ANT accuracy (performance)	.04	−.52	−.12	−.54	–	–	–	–
*6. TEA-Ch Score! (performance)	−.29	−.34	.29	.00	.21	–	–	–
*7. WISC-IV WMI (performance)	−.07	−.36	−.03	−.161	.36	.43	–	–
+8. Conners' inattention (parent-reported)	*.23*	*.10*	*.10*	*.10*	*−.30*	*.10*	*−.35*	–

(n = 18 except for WISC-IV WMI where n = 48)

ANT Attention Network Test, *TEA-Ch* Test of Everyday Attention for Children, ScS Scaled Score, *WISC-IV* Wechsler Intelligence Scale for Children-Fourth Edition, *WMI* Working Memory Index

Measures * 1–7 are performance-based; +measure 8 is parent-reported. Values in italic reflect cross method analyses. All correlations $p > 0.01$

Table 4

Within trait (sensory)/cross method (performance and parent-reported) correlations

Measures	*1	*2	*3	*4	*5	*6	*7	*8	*9	*10	+11
*1. Simple RT (performance)	–	–	–	–	–	–	–	–	–	–	–
*2. Choice RT (performance)	**.57****	–	–	–	–	–	–	–	–	–	–
*3. Static Det Thres (performance)	**.30***	**.33***	–	–	–	–	–	–	–	–	–
*4. Dyn Det Thres (performance)	.25	−.09	**.40****	–	–	–	–	–	–	–	–
*5. Amp Discr (performance)	.23	**.30***	**.50****	**.35***	–	–	–	–	–	–	–
*6. Amp Discr Adap (performance)	−.04	.08	**.29***	.04	.25	–	–	–	–	–	–
*7. Freq Discr Seq (performance)	.03	.26	**.37****	.27	**.34***	.08	–	–	–	–	–
*8. Freq Discr Sim (performance)	.10	.04	−.06	.02	.16	.02	**.32***	–	–	–	–
*9. TOJ Sim (performance)	.15	.24	.27	.16	**.33***	.20	.04	.14	–	–	–
*10. TOJ Car (performance)	−.13	.25	.19	.17	**.35***	−.08	.22	−.03	**.48****	–	–
+11. SPM Touch (parent-reported)	*−.01*	*−.15*	*.13*	*.03*	*−.08*	*−.07*	*.09*	*.06*	*−.18*	*.11*	–

(n = 46–56)

RT reaction time, *Det Thres* detection threshold, *Amp Discr* amplitude discrimination, *Amp Discr Adap* amplitude discrimination with single site adaptation, *Freq Discr Seq* frequency discrimination sequential, *Freq Discr Sim* frequency discrimination simultaneous, *TOJ Sim* temporal order of judgment simultaneous, *TOJ Car* temporal order of judgment with carrier, *SPM Touch* sensory processing measure, Touch Subscale Raw Score

Coefficients printed in bold are significant (* $p < 0.05$, ** $p < 0.01$).

* Measures 1–10 are performance-based, +measure 11 is parent-reported. Values in italic reflect cross method analyses

Table 5

Within method (performance)/cross trait (sensory and attention) correlations

Measures	*1	*2	*3	*4	*5	*6	*7	*8	*9	*10	*11	*12	+13	+14
*1. Simple RT (tactile)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
*2. Choice RT (tactile)	**.57****	–	–	–	–	–	–	–	–	–	–	–	–	–
*3. Static Det Thres (tactile)	.30	.33	–	–	–	–	–	–	–	–	–	–	–	–
*4. Dyn Det Thres (tactile)	.25	−.09	**.40****	–	–	–	–	–	–	–	–	–	–	–
*5. Amp Discr (tactile)	.23	.30	**.50****	.35	–	–	–	–	–	–	–	–	–	–
*6. Amp Discr Adap (tactile)	−.04	.08	.29	.04	.25	–	–	–	–	–	–	–	–	–
*7. Freq Discr Seq (tactile)	.03	.26	**.37****	.27	.34	.08	–	–	–	–	–	–	–	–
*8. Freq Discr Sim (tactile)	.10	.04	−.06	.02	.16	.02	.32	–	–	–	–	–	–	–
*9. TOJ Sim (tactile)	.15	.24	.27	.16	.33	.20	.04	.14	–	–	–	–	–	–
*10. TOJ Car (tactile)	−.13	.25	.19	.17	.35	−.08	.22	−.03	**.48****	–	–	–	–	–
*11. ANT RT (tactile)	.51	**.52***	.49	**.53***	.34	.15	−.13	.21	.43	.17	–	–	–	–
*12. ANT Accuracy (tactile)	−.32	−.45	**−.54***	−.27	−.12	−.32	−.05	−.29	−.30	.02	.54	–	–	–
+13. TEA-Ch Score! (attention)	*−.42*	*−.32*	*−.37*	*−.44*	*−.39*	*.03*	*−.47*	**−.62****	*−.12*	*−.04*	*−.01*	*.23*	–	–
+14. WISC-IV WMI (attention)	*−.17*	*−.06*	**−.42****	*−.14*	*−.31*	*−.09*	*−.14*	*−.37*	*.07*	*.03*	*−.16*	*−.36*	*.46*	–

(n = 18–56)

RT reaction time, *Det Thres* detection threshold, *Amp Discr* amplitude discrimination, *Amp Discr Adap* amplitude discrimination with single site adaptation, *Freq Discr Seq* frequency discrimination sequential, *Freq Discr Sim* frequency discrimination simultaneous, *TOJ Sim* temporal order of judgment simultaneous, *TOJ Car* temporal order of judgment with carrier, *ANT* Attention Network Test, *TEA-Ch* Test of Everyday Attention for Children, *WISC-IV* Wechsler Intelligence Scale for Children-Fourth Edition, *WMI* Working Memory Index

Coefficients printed in bold are significant (* $p < 0.05$, ** $p < 0.01$).

* Performance-based measures of tactile threshold detection. +Performance-based measures of attention. Values in italic reflect cross trait analysis