Over-Responsiveness and Greater Variability in Roughness Perception in Autism

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Although sensory problems, including tactile hypersensitivity and hyposensitivity (DSM-5) are commonly associated with autism, there is a dearth of systematic and rigorous research in this domain. Here, we report findings from a psychophysical experiment that explored differences in tactile perception between individuals with autism and typically developing control participants, who, using their index finger, rated a series of surfaces on the extent of their roughness. Each surface was rated multiple times and we calculated both the average rating and the variability across trials. Relative to controls, the individuals with autism perceived the surfaces as rougher overall and exhibited greater variability in their ratings across trials. These findings characterize altered tactile perception in autism and suggest that sensory problems in autism may be the product of overly responsive and variable sensory processing. ***Autism Res*** 2014, 00: 000–000. © 2015 International Society for Autism Research, Wiley Periodicals, Inc.

Keywords: autism; tactile; variability; sensory hypersensitivity

Introduction

Atypical sensitivity to touch is commonly reported in individuals with autism, and sensory differences are now considered a part of the autism diagnostic criteria in the DSM-5 (American Psychiatric Association, 2013). Many parental and scientific reports document a wide array of atypical responses to tactile stimulation in individuals with autism, including under- or over-sensitivity to pain, over-sensitivity to light touch, preference for deep pressure, and atypical reaction to social touch. Of individuals with autism, 70.4% report "unusual sensory interests" (e.g., strong/repeated reaction, or seeking sensory sensations), and 66% report having "negative sensory experiences" [Zachor & Ben-Itzchak, 2014]. The adverse reactions elicited by sensory stimuli is well captured in the personal anecdotes of Temple Grandin who, in one example, stated that, "I would stiffen and pull away when people *touched* me, and I was oversensitive to both *touch* and sound," [Grandin, 1989], and it was these very symptoms that motivated her to develop the deep touch pressure device ("squeeze machine") which has subsequently been applied to help calm animals. Despite the abundance of anecdotal evidence and the clearly debilitating effects of these sensory differences (which are also present in vision and audition), there has been rather little systematic investigation of tactile sensitivity in autism.

A handful of investigations have examined tactile responsivity in individuals with autism, but the findings from these studies are rather inconsistent. Conversely, some studies report that individuals with autism exhibit higher sensitivity. Individuals with autism have been reported to have lower pressure pain thresholds than typically developing controls [Fan, Chen, Chen, Decety, & Cheng, 2014], and adults with autism have been reported to show lower tactile detection thresholds (i.e., better performance) for high-frequency vibration compared to controls [Blakemore et al., 2006]. Conversely, other studies report the opposite, that individuals with autism exhibit lower sensitivity. Individuals with autism have been reported to show higher (i.e., worse) temporal-order discrimination thresholds compared to controls, but discriminability was less affected in autistic individuals when vibrotactile stimuli were presented in a synchronized manner to near-adjacent skin sites [Tommerdahl, Tannan, Holden, & Baranek, 2008]. Sensitivity thresholds to thermal stimuli have been reported to be higher, and thermal pain thresholds lower, in individuals with autism

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compared to nonautistic controls [Cascio et al., 2008]. Lastly, children with autism have been reported to have poorer vibration detection and amplitude discrimination thresholds compared to typically developing controls [Puts, Wodka, Tommerdahl, Mostofsky, & Edden, 2014]. In contrast with these positive findings (one way or the other), other studies have reported no group differences for heat detection or ratings of tactile "pleasantness" [Cascio et al., 2008], and no significant difference between autism and control groups in their perception of roughness, despite differences in their perception of auditory tones [O'Riordan & Passetti, 2006]. As evident, much remains to be learned about the psychophysical differences in the sensation of tactile stimuli in autism and the conditions under which altered tactile sensations can be elicited.

We have previously reported atypical fMRI responses to somatosensory stimulation in somatosensory cortex in individuals with autism, but the atypicality was evident as greater variability in the fMRI responses [Dinstein et al., 2012]. BOLD fMRI responses were measured to air puffs delivered to the hand (the somatosensory stimulus) as well as to moving dots (the visual stimulus) and to tones (the auditory stimulus). Although there were no differences in the amplitudes of the fMRI responses between groups in any of the three sensory modalities, the autism group exhibited significantly greater variability (trial-to-trial, within each individual) in the evoked fMRI responses compared with the nonautistic control group. This poor reliability of cortical activity across trials was evident in all three modalities and was weakly correlated with the severity of autism, as measured by the ADOS test. This finding has now been replicated in a subsequent study [Haigh, Heeger, Dinstein, Minshew, & Behrmann, 2015] and an analogous result has also been reported in a visual ERP study where the P1 responses of individuals with autism had greater trial-to-trial variability in amplitude and latency compared to controls during a visual oddball task [Milne, 2011]. These findings suggest that individuals with autism exhibit unreliable cortical responses to sensory stimuli and suggest that abnormally high variability in sensory-evoked cortical activity may account for some of the discrepancies across studies investigating perception in autism.

There is also some evidence of greater trial-to-trial variability in autism in behavioral tasks. Puts et al. [2014] reported elevated tactile thresholds in autism, specifically vibration amplitude and static detection thresholds, but they also reported greater intraindividual variability in responses and reaction times. In addition, Cascio et al. [2012] found greater standard deviation in ratings of pleasant and unpleasantness of textures, despite finding no differences in mean responses between groups.

To characterize tactile perception in individuals with autism, we conducted a psychophysical study of roughness perception. Participants were asked to make roughness ratings for each of a set of plates that differed in surface texture, following a protocol that has been used in previous studies of roughness perception in healthy controls [Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003]. Roughness perception is a subjective sensation and, although it is partly based on the coarseness of each plate's surface texture, the point at which a surface shifts from being very rough to becoming smooth varies between individuals. Our participants repeated multiple trials with each plate, enabling us to measure both the mean roughness rating as well as the variability of ratings across trials for each individual. If there is greater variability in sensory-evoked activity in somatosensory cortex of individuals with autism, we might expect to find greater variability in roughness ratings. If individuals with autism exhibit higher sensitivity to somatosensory stimulation (i.e., lower detection/discrimination thresholds and/or less tolerance), we might expect to find higher mean roughness ratings.

Methods

Participants

Fifteen males and two females (mean age, 25; range, 19–33) diagnosed with autism and no other identifiable etiology such as tuberous sclerosis or fragile-X syndrome consented to participate. Screening tests to determine eligibility of the participants with autism included the Wechsler Adult Intelligence Scale-III [Wechlser, 1997], the Kaufman Test of Educational Achievement (K-TEA) [Kaufman & Kaufman, 1985], the Autism Diagnostic Observation Schedule [Lord et al., 1989], and the Autism Diagnostic Interview (ADI & ADI-Revised) [Le Couteur et al., 1989; Lord, Rutter, & Le Couteur, 1994]. The diagnosis of autism provided by the two structured instruments was confirmed by expert clinical opinion (Dr Minshew). Participants with autism were also required to be in good medical health, free of seizures and have a negative history of traumatic brain injury. The mean full scale IQ score of the autism group was 111.1 (SD 16.7). All participants were cooperative. Demographic characteristics of the participants with autism are provided in Table 1 along with IQ scores.

Fifteen males and two females from Carnegie Mellon University (mean age, 24; range, 18–34) were recruited to serve as age- and gender-matched controls for the perceptual task.

All participants were right-handed and reported no cutaneous or motor impairments. Participants were either paid $20 for their time or were given credit as

Table 1. The ADOS, ADI, and IQ Scores of the Autism Participants

Participant number	ADOS communication	ADOS social	ADOS stereotypical	ADI social	ADI communication	ADI stereotypical	Full IQ
1	5	11	3	20	15	3	107
2	4	5	2	22	15	5	96
3	5	7	3	27	20	6	107
4	4	6	1	21	18	8	123
5	4	10	2	23	18	7	84
6	5	6	6	19	11	4	127
7	6	13	1	23	13	4	88
8	4	8	2	21	17	6	123
9	3	7	1	26	17	3	121
10	3	4	3	11	10	6	129
11	5	12	2	22	20	6	87
12	2	6	3	20	16	7	104
13	3	6	4	20	12	4	95
14	3	5	3	26	18	12	131
15	3	6	1	15	12	2	116
16	2	7	4	10	8	6	123
17	6	10	2	23	17	6	128
Means	3.9	7.6	2.5	20.5	15.1	5.6	111.1

part of their course at Carnegie Mellon University. The Institutional Review Board of Carnegie Mellon and the University of Pittsburgh approved this study, and all participants gave their written consent.

Stimuli

Twelve plates with an interelement spacing varying from 0.625 mm to 3.375 mm in 0.25 mm increments were used in the experiment. The dots were approximately 1 mm in diameter and the spacing of the dots was jittered on the plate. The plates used are described by Klatzky and Lederman [1999] and Klatzky et al. [2003]. The plates were mounted on a stand with a rubber strip and were clipped in place on a tabletop surface to prevent the plate from sliding.

Procedure

We replicated the procedure used in a previous study [Klatzky et al., 2003]. Participants were seated comfortably at a table. During the experimental session, to avoid auditory and visual cues as to how rough the plate was, participants wore headphones playing white noise at a comfortable volume, and an eye mask.

Before the experiment began, participants were told that they would be given a series of plates to rate on how rough they were perceived to be on a Likert Scale from 1 (not rough) to 10 (very rough). No description of "roughness" was provided. They were asked to sweep the surface of the plate lightly using the tip of their index finger on their right hand, and when ready, to rate the plate by stating their Likert value aloud. There were no restrictions as to how many times the participant could feel the plate, but were encouraged to say the first number that came to mind.

Table 2. The Interelement Spacing of the Dots for Each Plate in Order of Presentation

Presentation order	Interelement spacing (mm)	Presentation order	Interelement spacing (mm)
1	1.625	7	0.625
2	3.125	8	1.125
3	2.875	9	2.375
4	1.875	10	2.625
5	0.875	11	3.375
6	1.375	12	2.125

The 12 plates were presented once per block in a random order. There were 14 blocks in total ($n = 168$, each plate repeated 14 times). The order of presentation was the same for all blocks and for all participants, so that each participant had the same experience/context for rating each plate in each block. This ensured that any differences between the groups, and any differences between the blocks were not due to different preceding surfaces that could be affecting the ratings. See Table 2 for presentation order and the interelement spacing for each plate. After every two blocks, participants were given a short break. During one of the breaks, participants were asked to complete the Adult Sensory Profile [Brown & Dunn, 2002].

Results

The mean and standard deviation of roughness ratings were calculated across trials of each plate for each participant. Mixed analyses of variance were used with group as the between-subjects factor, and the

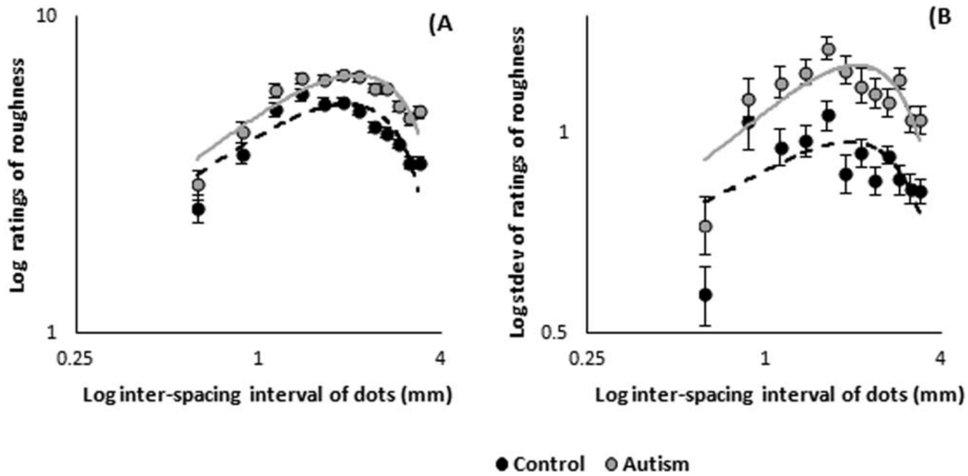

Figure 1. (A) Mean roughness ratings, and (B) standard deviation (across repeated trials) of roughness ratings as a function of the interspacing interval of the dots on the plates, shown separately for the autism group and the control group. Data fitted with a quadratic function. Error bars represent +/- half of the standard error across participants.

interspacing-interval of the plates as the within-subjects factor. Where the assumption of sphericity was violated, Greenhouse–Geisser correction was used to adjust the degrees of freedom.

The autism group rated the plates as feeling rougher than the control group, that is, they gave higher ratings on the Likert scale ($F(1,32) = 5.68$, $P = 0.023$), and there was a significant main effect of the interspacing-interval of the plates ($F(1.8,55.6) = 21.60$, $P < 0.001$; see Fig. 1A). Plates with small and large interspacing-intervals (0.625 mm, 3.125 mm, and 3.375 mm) produced similar roughness ratings, but plates with mid-range interspacing-intervals (0.875 mm, 1.875 mm, and 2.875 mm) produced roughness ratings that were significantly higher ($P < 0.001$, Bonferroni corrected). There was no significant interaction between the groups and the interspacing-interval of the plates ($F(1.8,43.6) = 0.18$, $P = 0.814$). The response function of roughness versus interspacing-intervals was similar to those reported previously for controls [Klatzky & Lederman, 1999; Klatzky et al., 2003]. The response functions were similar in shape for the autism group and the control group (Fig. 1A), suggesting that their fundamental perception of roughness does not obviously differ but that the autism individuals merely perceived the roughness as scaled higher across roughness conditions.

Standard deviation (SD) across trials was significantly larger in the autism group compared to controls ($F(1,32) = 5.71$, $P = 0.023$). There was also a significant main effect of the interspacing-interval of the plates ($F(4.2,113.4) = 4.47$, $P = 0.002$; Fig. 1B): the SDs for the plates with the largest and smallest interspacing-intervals did not significantly differ from each other, but did differ from the mid-range spacing intervals. Specifically, the 1.375 mm plate produced significantly larger SD across trials than the 0.625 mm and the 3.375 mm plates. There was no significant interaction between group and interspacing-interval, indicating that the greater variability in roughness ratings in autism was apparent across all plates ($F(11,352) = 0.39$, $P = 0.962$). There were no significant correlations between the mean and the SD of roughness ratings across *individuals* in either the autism ($r(15) = 0.005$, $P = 0.98$) or the control ($r(15) = 0.32$, $P = 0.21$) groups (Fig. 2A), suggesting that SD did not scale with mean in a consistent manner across participants of either group. In other words, individuals with more variability in their roughness ratings did not necessarily rate the plates as feeling rougher on average. There were, however, significant correlations between the mean and the SD of roughness ratings across *plates* in the autism ($r(10) = 0.866$, $P < 0.001$) and control ($r(10) = 0.700$, $P = 0.011$) groups (Fig. 2B).

A potential confound lies in the order of plate presentation. The rating of plates that were preceded by a relatively rougher plate was compared to the rating of plates that were preceded by a relatively smoother plate. The ratings were ordered in order of presentation, and the average rating of roughness across all participants was calculated. If the average rating of a plate was greater than the average rating of the preceding plate, then the plate was categorized as being preceded by a smoother plate and vice versa. A mixed ANOVA comparing ratings of plates preceded by rougher or smoother plates showed that plates preceded by a rougher plate were rated as feeling less rough, compared to plates that were preceded by a smoother plate ($F(1,32) = 103.44$, $P < 0.001$). However, individuals with autism still exhibited significantly higher ratings than controls ($F(1,32) = 5.68$, $P = 0.023$) and there was no interaction of group and preceding plate roughness ($F(1,32) = 0.22$, $P = 0.646$), suggesting that the group differences were not due to the effects of the preceding

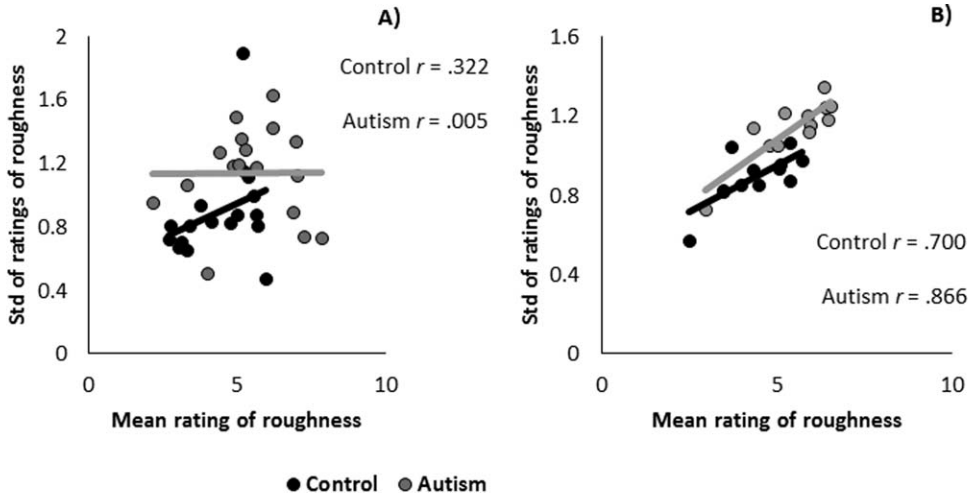

Figure 2. The relationship between the mean roughness ratings and the standard deviation (across repeated trials) of roughness ratings, (A) averaged across all of the plates and shown separately for each individual, and (B) averaged across all individuals in each group and shown separately for each plate. Black circles are controls, and gray circles are individuals with autism.

plate. Another ANOVA showed that variability (SD) of ratings across trials was smaller if the preceding plate was perceived as rougher ($F(1,32) = 13.31$, $P = 0.001$). Yet, here too, the autism group exhibited significantly greater variability in their ratings ($F(1,32) = 5.95$, $P = 0.020$) and there was no interaction of group and preceding plate roughness ($F(1,32) = 1.40$, $P = 0.246$) suggesting that group differences in trial-to-trial variability were not due to the effects of the preceding plate.

Because no roughness referent was introduced in this protocol at the outset, the first presentation of each plate may have been used as a reference for the subsequent ratings of roughness and, thereby affecting the ratings at the beginning of the experiment. The ratings of the first presentation were, therefore, excluded from the analyses and the ANOVAs were recalculated. In this analysis the autism group still rated the plates as feeling rougher ($F(1,32) = 5.71$, $P = 0.023$), and exhibited larger SD in their ratings compared to controls ($F(1,32) = 4.07$, $P = 0.052$). For both measures, there was still a main effect of the plates ($P < 0.001$) and no interaction between the plates and group ($P > 0.05$). This reanalysis confirms that the differences in roughness ratings were still present even after eliminating a potential confound in the initial trials of the experiment.

To assess the relationship between mean and variability of roughness perception, we computed the coefficient of variation (SD divided by mean). A mixed ANOVA showed no significant difference between the groups ($F(1,32) = 0.43$, $P = 0.512$) and no interaction between the groups and the plates ($F(3.8,122.3) = 0.61$, $P = 0.819$) (Fig. 3). This suggests that the larger SD in the autism group was proportional to the larger mean roughness ratings in the autism group, and reflects the significant correlation between mean and SD in rough-

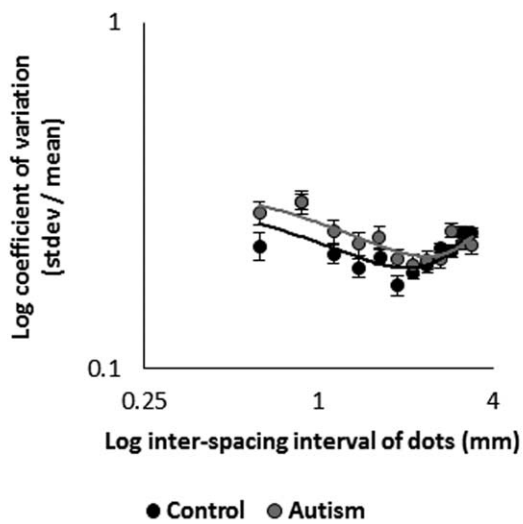

Figure 3. The coefficient of variation as a function of the interspacing-interval of the dots on the plates shown separately for the autism group and the controls. Data fitted with a quadratic function. Error bars represent +/- half of the standard error across participants.

ness ratings across plates (Fig. 2B). However, in an additional analysis, we examined a subset of autism and control participants ($N = 13$) who were matched on their mean rating of roughness (Fig. 4A) and found a significant difference in SD across groups when using a Mann–Whitney test ($P = 0.001$) and an almost significant difference when using an ANOVA ($F(1,24) = 4.13$, $P = 0.053$). There was no significant interaction between group and plate ($F(4.2,101.7) = 1.19$, $P = 0.320$). The analysis of the coefficient of variance showed no significant difference between the groups ($F(1,24) = 2.31$, $P = 0.142$). These results suggest that individuals with autism exhibit greater trial-by-trial SD once groups are

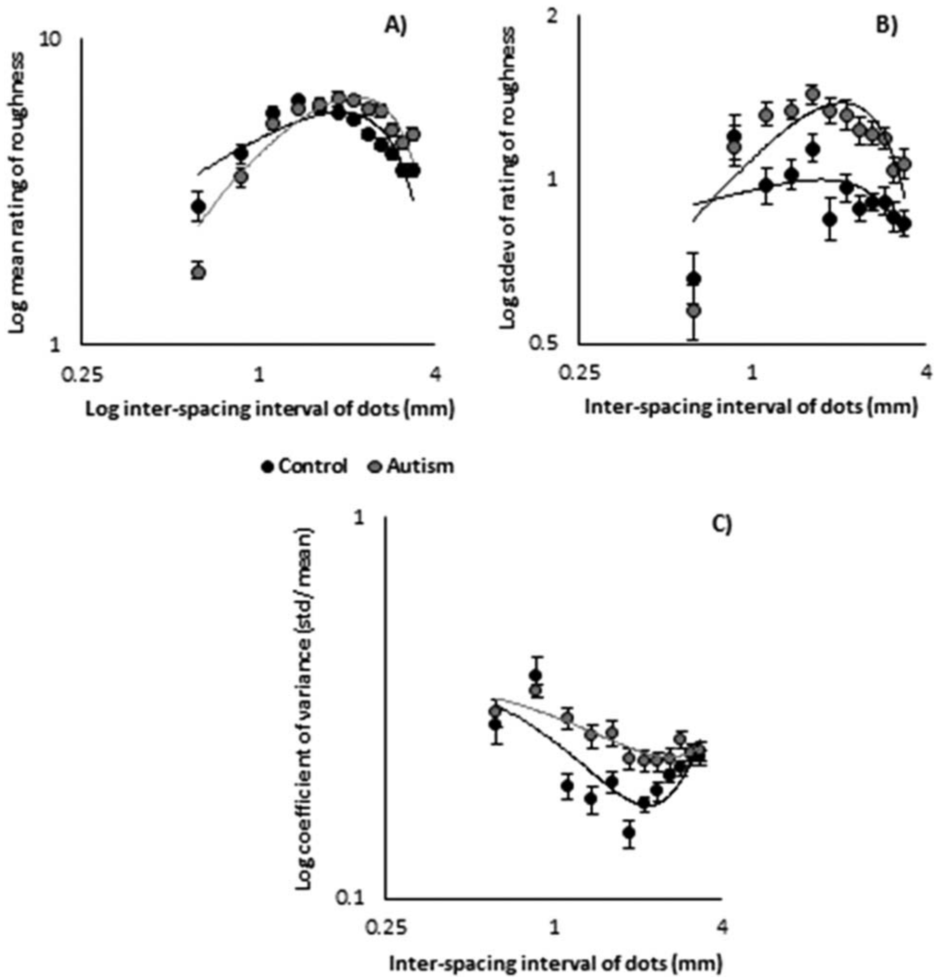

Figure 4. (A) Mean roughness ratings, (B) standard deviation of roughness ratings, and (C) coefficient of variance in ratings for a subset of autism and control participants ($N = 13$) who were matched on their mean rating of roughness. Data fitted with a quadratic function. Error bars represent +/- half of the standard error across participants.

matched on their mean roughness ratings such that SD is not proportional to the mean in the majority of participants (13 out of 17 in each group).

To see if any of the diagnostic measures were related to the measures of ratings of roughness, ADOS and ADI measures for each individual with autism were correlated with their mean and SD of ratings of roughness. There were no significant correlations between ADOS and mean or SD of roughness ratings (correlations with the different ADOS measures ranged between $r = 0.24$ to $r = -0.08$). The correlations with ADI measures and mean or SD of roughness ratings were also not significant (correlations on the different ADI measures ranged between $r = -0.21$ and $r = 0.20$).

Responses from the Adult Sensory Profile [Brown & Dunn, 2002] were analyzed and correlated with the mean and SD in ratings of roughness. Only one of the correlations was significant: controls who, on average, rated the plates as feeling less rough scored high in the "Low Registration" quadrant ($r = -0.70$) but this was not significant in the autism group ($r = -0.33$). No other correlations were significant ($-0.38 > r < 0.40$). Details of the analyses are reported in Supporting Information.

Discussion

Altered sensory responses, either heightened or diminished (and sometimes both even in the same individual), have been included as part of the DSM-5 autism profile and have been described since the very early reports of individuals with autism. Studies using questionnaires to document differences in sensory profile have revealed sensory abnormalities in over 90% of children with autism [Kern et al., 2006; Leekam, Nieto, Libby, Wing, & Gould, 2007; Tomchek & Dunn, 2007], and in adults with autism [Crane, Goddard, & Pring, 2009; Jones et al., 2009; Robertson & Simmons, 2013]. Despite this prevalence, there has been rather little progress in understanding the psychological and neural bases of the alteration in tactile perception in autism. In this study, we adopted a robust psychophysics protocol that allowed us to characterize tactile sensory differences in a group of individuals with autism relative to controls. The goal of this investigation was both to elucidate the tactile differences systematically and to provide a functional metric, which may potentially serve to uncover the corresponding neural correlates in future investigations.

A comparison of the roughness ratings of adults with autism and controls revealed three main findings. First, individuals with autism did not show a qualitatively different roughness profile from that of the controls. Both the autism group and the control group showed the same inverted U-shape function. Second, the mean roughness ratings were higher for individuals with autism relative to the typical controls. This suggests that individuals with autism might be overly responsive to roughness (i.e., with larger responses to the stimuli in one or more class of somatosensory neurons), or alternatively that they exhibit a report bias for higher values. Third, individuals with autism exhibited more variable (less reliable) roughness ratings across trials.

These findings suggest that individuals with autism exhibit over-responsiveness and/or greater variability in roughness perception. When interpreting differences in the mean and the SD of the ratings across groups, it is important to consider the potential relationships across these two measures. If one assumes that the perceptual variability is additive (adds to intrinsic noise), then SD alone would be a good indicator of the perceptual "noise" level of an individual. Because SDs were larger in the autism group, the additive noise model implies greater variability in roughness perception. In support of an additive noise model, there were no significant correlations between mean roughness ratings and SD across individuals in either group (Fig. 2). In addition, when examining subgroups of participants who were equated on mean roughness, there was a significant (or very nearly significant) difference in SD across groups (Mann–Whitney, $P = 0.001$; ANOVA, $P = 0.053$). However, contrary to the additive noise model, there were significant correlations between the means and SDs of roughness ratings, across plates. Thus, alternatively, if one adopts a multiplicative noise model (noise that scales with the strength of the real signal), there are three potential explanations for the current data. The first is that the difference in mean roughness ratings is driven by a report bias in the autism group. On this account, the actual mean percept does not differ across groups (only the report does) and the larger SD in the autism group reflects greater perceptual variability across trials. The second is that individuals with autism truly perceive the stimuli as being rougher (i.e., over-responsiveness) and that SD increases in a proportional manner as a byproduct of the multiplicative noise. The third potential explanation is a combination of the other two, i.e., that autistic individuals exhibit both over-responsiveness and greater variability in roughness perception. In other words, even if we adopt the multiplicative noise model, we can rule out the least interesting possibility that the difference in mean roughness ratings was due to a response bias along with no difference in the variability of the roughness ratings.

O'Riordan and Passetti [2006] reported that individuals with autism were as accurate as healthy controls when distinguishing the roughness of different sandpaper textures, suggesting that high-functioning individuals with autism do not show major deficits in tactile perception. This finding is consistent with our results. The individuals with autism who participated in the current study showed (inverted U-shaped) roughness perception curves that were similar to those of the control group, and the response curves were similar to those reported previously [Klatzky & Lederman, 1999; Klatzky et al., 2003]. Although we found greater variability in roughness ratings for individuals with autism that does not necessarily imply poorer accuracy in distinguishing stimuli with different roughness. The connection between these different measures depends on the spatiotemporal statistics of the noise. Similarly, there could be greater trial-to-trial variability in neural activity [as reported by Dinstein et al., 2012] with no change in thresholds. For example, if noise is highly correlated across a large population of neurons but varies slowly over time (trial to trial), this would explain the greater trial-to-trial variability in fMRI response. This would also predict trial-to-trial variability in ratings if the rating on each trial was proportional to the mean neural activity on that trial. In a 2AFC discrimination task, however, there might be no difference in thresholds, because the noise on each trial could be estimated by averaging across all the neurons in the population.

Cascio et al. [2008] found no difference between autism and control groups in ratings of tactile "pleasantness," in ostensible conflict with our results. It is possible that the small sample sized used by Cascio et al. was not sufficient to detect group differences, or perhaps the demands of the task (rating pleasantness compared to roughness) tap into different perceptual processes.

Consistent with our conclusions, EEG and fMRI studies have reported abnormal somatosensory processing in individuals with autism, suggesting that sensory-evoked responses larger and/or more variable across trials. Miyazaki et al. [2007] reported abnormalities in somatosensory evoked-potentials elicited by nerve stimulation (including larger amplitudes and prolonged peak latencies of the evoked responses), in children with autism with extreme hypersensitivity. Abnormal somatosensory evoked-potentials have also been reported even without obvious behavioral correlates [Hashimoto, Tayama, & Miyao, 1986; Kemner et al., 1994]. These EEG studies did not report variability (across repeated trials) in the evoked responses. As noted in the Introduction, we have previously reported that autistic individuals exhibit greater variability in sensory-evoked fMRI responses (across trials), but with no evidence for a difference in the mean responses amplitudes [Dinstein et al., 2012; Haigh et al., 2015]. We used air puffs for the somatosensory stimuli in those experiments; differences between groups in the mean evoked responses might be evident with other forms of somatosensory stimulation.

Greater trial-to-trial variability produces unreliable (or at least less reliable) sensory-evoked responses, which could be detrimental during development. Human sensory systems learn by detecting statistical regularities in the environment; for example the visual system encodes natural scenes efficiently [Atick, 1992; Attneave, 1954; Barlow, 1961; Field, 1987, 1994; Olshausen & Field, 1996a, 1996b, 1997]. Dan, Atick, and Reid [1996] concluded that the efficiency of neural coding develops through life and is not an intrinsic property of the visual system. We speculate that if individuals with autism do not gain reliable and predictable responses from their sensory environment, this could contribute to the atypical sensory sensitivities and have knock-on effects for more complex sensory processing.

Specifically, having variable neural responses to tactile stimuli might have multiple knock-on effects in which the unreliable responses are propagated to subsequent cortical areas, which encode social touch. For example, Gordon et al. [2013] reported greater BOLD fMRI activation in response to stroking the arm ("social touch") compared to stroking the palm in somatosensory cortex of healthy individuals. Consistent with this, Voos, Pelphrey, and Kaiser [2013] found greater BOLD fMRI activation in somatosensory cortex to the slow (social) touch compared to the baseline (no touch), and no significant difference in fMRI responses to the fast (less social) touch compared to baseline. These authors also reported a negative correlation between participants' Autism-Spectrum Quotient scores (in healthy controls) and the difference in activation between the fast and slow touch conditions in the superior temporal sulcus and the orbitofrontal cortex, indicating that less responsiveness to differentiating between social and nonsocial touch is associated with greater autism traits. Several studies have found evidence of abnormal adaptation in tactile perception individuals with autism – specifically smaller effects of adaptation on vibration and spatial discrimination [Puts et al., 2014; Tannan, Holden, Zhang, Baranek, & Tommerdahl, 2008; Tommerdahl, Tannan, Cascio, Baranek, & Tommerdahl, 2007]. The fluctuating sensory responses and their potential ramification for downstream cortical areas, suggest that the neural variability in somatosensory cortex might have widespread impact across the brain.

Greater responsiveness and variability in tactile perception may be similar to sensory differences in other modalities. For example, superior low-level perceptual processing has been reported in autism [Mottron & Burack, 2001], suggestive of enhanced visual processing due to larger visually evoked responses. Individuals with autism also perceived tones as being louder in volume compared to nonautistic controls, suggesting increased sensory sensitivity [Khalfa et al., 2004]. The neural cause of the visual, auditory and tactile hypersensitivity could result from a processing difference at various levels of sensory processing from differences in the density or sensitivity of sensory receptors to differences in cortical circuits. An abnormality in l*ocal range neural connectivity* in posterior, sensory parts of the cerebral cortex has been suggested to be responsible for the sensory "magnification" in people with autism [Belmonte et al., 2004]. Similar differences in local connectivity in somatosensory cortex may account for the tactile responsiveness, too, with abnormal local connections seen at the synaptic and structural level (for a review, see Belmonte et al., 2004] and at the functional level in EEG recordings [Barttfeld et al., 2011). Of relevance, Coskun, Loveland, Pearson, Papanicolaou, and Sheth [2013] showed evidence for abnormal local connectivity in the somatosensory cortex in individuals with autism, which could contribute to the variability in BOLD fMRI responses to tactile stimuli and the heightened sensory responsiveness observed in autism. Whether the local connections are over- or under-connected is still debated.

Before concluding, we need to raise some cautionary notes. First, the pressure each participant used to feel the surfaces could have differed between groups and this might have affected the roughness ratings differentially. The similar roughness functions for the two groups goes some way to reduce this concern and makes it unlikely that there would be a main effect across groups (across plates) but not an interaction. A second concern is whether the group difference arises from a difference in intellectual function. Although we have IQ scores for the autism group, we did not collect IQ scores for the control participants. The control participants were recruited from in and around the university community (and so presumably had relatively high IQs). If the control group had a significantly higher IQ than the autism group (which may not be the case as the highest IQ in the autism group was 129), then the control participants may have had an advantage in completing this task. The autism group showed a positive (albeit nonsignificant) correlation between mean rating of roughness and full-IQ ($r = 0.21$); the correlation was even weaker with verbal-IQ ($r = 0.15$). By this extension, if higher IQ is associated with higher mean rating of roughness, the control participants (with the potentially higher IQ) should have shown higher mean ratings of roughness compared to the autism group. This is clearly not the case. Moreover, no link has been found between IQ and performance on nonspeeded visual perceptual tasks in either typical [Hammill, 1972; Moore, Hobson, & Anderson, 1995] or autism [Behrmann et al., 2006] groups. Although IQ should be taken into consideration to ensure that there are no group differences in the ability to understand the task, it is highly unlikely that an IQ difference is the critical factor distinguishing the autism and typical group in this study.

Conclusion

Overly responsive and/or unreliable sensory responses may have considerable developmental and behavioral consequences when considering how the brain learns to interact with the environment. Indeed, even basic sensory abnormalities during roughness perception, as reported here, may have direct impact on the development of more complex behaviors, language acquisition, and even social interaction. Much remains to be understood about the sensory atypicalities in autism and their underlying neural causes. We suggest that careful examination of both mean and variance of sensory responses may lead towards a more complete picture.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1. Pearson's correlation coefficients for responses to each of the four quadrants in the Adult Sensory Profile correlated with mean and SD in roughness ratings, shown separately for autism and control groups. Only one correlation was significant ($P < 0.05$) and is highlighted in bold.