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# The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception

**Carissa J. Cascio**,
Vanderbilt University, USA

**Jennifer H. Foss-Feig**,
Vanderbilt University, USA

**Courtney P. Burnette**,
Center for Development and Disability, University of New Mexico

**Jessica L. Heacock**, and
Vanderbilt University, USA

**Akua A. Cosby**
Vanderbilt University, USA

## Abstract

In the rubber hand illusion, perceived hand ownership can be transferred to a rubber hand after synchronous visual and tactile stimulation. Perceived body ownership and self–other relation are foundational for development of self-awareness, imitation, and empathy, which are all affected in autism spectrum disorders (ASD). We examined the rubber hand illusion in children with and without ASD. Children with ASD were initially less susceptible to the illusion than the comparison group, yet showed the effects of the illusion after 6 minutes. Delayed susceptibility to the illusion may result from atypical multisensory temporal integration and/or an unusually strong reliance on proprioception. Children with ASD who displayed less empathy were significantly less likely to experience the illusion than those with more intact ability to express empathy. A better understanding of body representation in ASD may elucidate neural underpinnings of social deficits, thus informing future intervention approaches.

### Keywords

autism; proprioceptive; visual; tactile; multisensory integration; empathy

## Intxxroduction

The development of a sense of body ownership is crucial not only for motor skills such as navigating one's environment (Piaget, 1952), but also for social and cognitive abilities that necessitate differentiation of self from other (Schütz-Bosbach et al., 2006) and comparisons between self and other (Meltzoff, 2007). This process of identification, differentiation, and comparison between self and other is believed to be an important prerequisite for



**Corresponding author:** Carissa J. Cascio, PhD, Department of Psychiatry, Vanderbilt University, 1601 23rd Ave South Suite 3057, Nashville, TN 37212, USA. carissa.cascio@vanderbilt.edu.

understanding others as intentional agents (Gallese, 2003), and thus for the ability to make inferences about their emotions, thoughts, or inten-tions. These skills are in turn foundational for the development of imitation, empathy, and other social relational behaviors (Gallese et al, 2004; Chaminade et al., 2005).

The hallmark of autism spectrum disorders (ASD) is a global impairment in the development of fundamental social and communication skills, which emerges during the first few years of life (American Psychological Association, 2000). In toddlers with ASD, deficits in spontaneous imitation and imagi-native play are pervasive (Stone et al., 1990; Rutherford et al., 2007) and diagnostically critical (Stone et al., 1994; Charman et al, 1997; Rogers et al., 2003). Although clearest later in childhood and less central to initial diagnosis, a diminished capacity for empathy is also a clinically relevant feature of ASD (Charman et al., 1997) that has been observed in empirical studies (Baron-Cohen and Wheelwright, 2004; Lombardo et al., 2007) and considered a central deficit in ASD by proponents of the theory-of-mind deficit hypothesis of ASD (Baron-Cohen et al., 1985). Williams (2008) has proposed that the deficits in empathy in children with ASD may be related to deficits in spontaneous imitation.

The sense of self versus other depends on converging input from the proprioceptive, somatosensory (Schütz-Bosbach et al., 2009), and visual systems (Maravita et al., 2003; Jeannerod, 2004), and can be disrupted when inputs received by two or more of these systems are in conflict (Aspell et al., 2009). Previous research has altered perception of body ownership by manipulating the usual spatial and temporal correlations among these sources of sensory input using tasks such as the ‘rub-ber hand illusion’ (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005). In the rubber hand illusion, the sense of body ownership is altered by delivering regular brush strokes to the participant’s visually obscured hand while simultaneously administering identical strokes to the same somatic location on a visible rubber hand that the participant is instructed to watch. After a short period of synchronous brushing, participants often report that the visual and tactile inputs seem to arise from a common source, or that it begins to feel as if the rubber hand is the participant’s own hand. These illusory effects are not reported when the tactile (own hand) and visual (rubber hand) brush strokes are delivered asynchronously. In addition to assessing a participant’s subjective experience of the illusion, an objective measure of the effect can also be obtained by asking the participant to localize his or her hidden hand before and after the brushing. After synchronous brushing, the perceived location of the participant’s own hand drifts reliably in the direction of the rubber hand.

The rubber hand illusion arises from multisensory processing in which information streams from vision and touch converge to influence proprioception, and, more broadly, body surface representa-tion (Botvinick, 2004). Studies of motor coordination and adaptation suggest that individuals with ASD depend more heavily on proprioceptive than visual input when the two are incongruent (Masterson and Biederman, 1983; Haswell et al., 2009) and that they may be less likely than those with typical development to integrate proprioceptive information with input from other senses (Minshew et al., 2004; Glazebrook et al., 2009). From these studies in the motor system, we hypoth-esized that children with ASD might also rely more heavily on proprioceptive input and/or show reduced multisensory integration in the context of the rubber hand paradigm. We therefore hypoth-esized that children with ASD would be less likely to experience the rubber hand illusion than a comparison group of typically developing (TD) children. Because of the important role of perceived body ownership in the acquisition of social skills, such as imitation and empathy, we further predicted that susceptibility to the rubber hand illusion would be related to clinical measures of impairment in these skills in the ASD group. Although previous studies have not yet examined the rubber hand illusion in children, we predicted that the TD comparison group would experience the illusion after synchronous brushing as adults do, given that visual and proprioceptive information are integrated to produce flexible, coordinated reaching movements by 7–9 months of age (Morrongiello and Rocca, 1989) and that an explicit sense of the bodily self is present by 2 years of age (Rochat, 2010).

# Methods

## Sample

Twenty-one children with ASD and 28 TD children between the ages of 8 and 17 years were included in the study. Participants in the ASD group were recruited from the university medical center and surrounding community, and diagnosis of ASD (autistic disorder, Asperger's disorder, or pervasive developmental disorder – not otherwise specified) was confirmed with research-reliable administra-tions of the Autism Diagnostic Observation Schedule (ADOS, Lord et al., 1999) and the algorithm items from the Autism Diagnostic Interview-Revised (ADI-R, LeCouteur et al., 2003), as well as the judgment of a licensed clinical psychologist based on DSM-IV criteria (American Psychiatric Association, 2000). Comparison participants were screened for autism symptoms using the Social Communication Questionnaire (SCQ, Rutter et al., 2003); any children in the comparison group meeting the SCQ risk cutoff, having a first degree relative with an autism spectrum disorder, or having any diagnosed psychiatric or learning disorder were excluded. All participants were screened and excluded for reported comorbid genetic or neurological conditions, as well as reported uncor-rected sensory problems that affect visual or tactile perception. In order to ensure comprehension of task instructions, inclusion was limited to participants with full-scale IQ scores above 85, as measured by the Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999) or the Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV, Wechsler, 2003). To prevent skewing of our sample toward individuals with particularly high cognitive functioning, we set an equivalent upper limit for cognitive functioning, such that all included participants had IQ scores within one standard deviation above or below the normative mean (that is, between 85 and 115). Participant characteristics are summarized in Table 1; no significant group differences were found for age ($t(47) = –1.854$, $p = 0.07$) or IQ ($t(47) = –0.594$, $p = 0.56$). The trend for a group difference in age was addressed by using age as a covariate in statistical analyses. Chi-square tests confirmed that there were no significant differences in gender or handedness between the two groups (gender: $\chi^2(1)=2.72$, $p = 0.10$; handedness: $\chi^2(1)=0.567$, $p = 0.45$). All procedures were performed in accord-ance with the ethical standards established in the 1964 Declaration of Helsinki. All parents gave informed consent and children gave informed assent before their participation in the study and children were compensated for their participation.

## Experimental procedure

Following the general methodology of Botvinick and Cohen (1998), each child was seated comfort-ably in front of a table directly across from the experimenter, who was blind to the hypothesis of the study. A two-chambered box with open sides facing both the participant and the experimenter rested on top of the table (Figure 1). The participant placed his/her left hand into the left chamber of the box, which had an opaque black top that prevented visibility of his/her left hand. A drafting ruler was affixed to the top of this chamber along the edge closest to the experimenter. The numbers on the side of the ruler that faced the participant were obscured with opaque tape. In the right chamber was a realistic rubber left hand, matched approximately to the participant's hand for size, which was vis-ible to the participant through the clear top of this chamber. The experimenter verified that the rubber hand was visible to the participant and instructed the child to attend to it visually throughout the experiment. Compliance with these instructions was monitored closely and the experimenter provided verbal prompts if the child did not appear to be visually attending. This compliance criterion resulted in exclusion of four children in the initial ASD group who completed the task but whose data were excluded based on experimenter impression that the child did not show sufficient visual attention to the rubber hand. Among the 21 children with ASD and 28 children with TD included in these analyses, the need for verbal prompts was infrequent, and did not, by the subjective impression of the experimenter, occur more often in one group than the other among included children.

The experimenter began the session by using the drafting ruler to measure the actual position of the participant's left index finger. Subsequently, the participant was asked to make three consecutive proprioceptive judgments about the location of his/her own left index finger, by moving his/her right index finger along the top edge of the drafting ruler until he/she felt it was resting directly above the left index finger in the chamber. During this and all subsequent proprioceptive measure-ments, the participant kept his/her eyes closed. The experimenter recorded the actual position of the finger and all proprioceptive judgments.

Following the initial proprioceptive judgments, the experimenter used a pair of identical soft cos-metic brushes to stroke both the visible rubber hand and the hidden actual hand, in a proximo-distal direction between the second and third knuckles of the index finger (Figure 1a). Strokes were delivered manually by the experimenter at a rate of approximately 0.5–1 Hz, and stroking was administered in two 3-minute blocks. For each participant, this was done under two conditions, the order of which was counterbalanced across participants. In the synchronous condition, the real and rubber hands were stroked simultaneously, whereas in the asynchronous condition, each stroke of the participant's actual hand was offset by approximately 500 ms from the stroke delivered to the rubber hand.

For each condition, after each three-minute block of brushing, the participant was asked to close his/her eyes and repeat the three proprioceptive judgments made before brushing (Figure 1b). Following the proprioceptive judgments at the end of the second 3-minute block for each condition, the participant answered nine questions (Botvinick and Cohen, 1998) about his/her subjective illusory experience (Table 2). Each question was answered on a seven-point scale, with –3 representing strong disagreement with the statement and +3 representing strong agreement. The questionnaire was explained to each child by the experimenter.

## Statistical analysis

Drift in proprioceptive judgment toward the rubber hand was calculated for each block by subtract-ing the mean of the three post-brushing judgments from the mean of the three pre-brushing judg-ments. To determine whether the effect differed between groups or conditions, a repeated-measures ANOVA was performed with drift as the dependent variable, condition and block as within-partic-ipants factors, and group as the between-participants factor. Group differences in response to the questions in Table 2 were tested using a 9 × 2 × 2 (question × condition × group) MANOVA, with age included as a covariate.

Because the rubber hand illusion has not previously been reported in children regardless of developmental status, one-sample t-tests were conducted for drift in the synchronous condition, which produces the illusion in adults, to determine whether the rubber hand illusion occurs in chil-dren, as well as for the asynchronous condition, to confirm the specificity of the illusion. The pres-ence of the illusion was indexed by proprioceptive drift that was significantly different from zero. Given our hypotheses that the illusion would be reduced or absent in ASD, these comparisons were conducted separately by group and by block.

Finally, for children in the ASD group, secondary correlational analyses were performed with drift, answers to the most pertinent questions in Table 2, and relevant items from the ADI-R and ADOS.

## Results

### Proprioceptive drift

The mean proprioceptive drift (in cm) for each group in each condition and block is summarized in Table 3 and Figure 2. To ensure that there were no group differences in localization ability or comprehension of task instructions we assessed the accuracy of pre-brushing finger localization before beginning each block (by subtracting the participant's perceived finger position indexed by his/her mean pre-brushing proprioceptive judgment from the actual position of the index finger measured by the experimenter), and this did not differ between groups ($t(47) = -0.530$, $p = 0.60$).

To directly compare susceptibility to the illusion across groups, conditions, and blocks, a repeated-measures ANOVA was performed using proprioceptive drift in the direction of the rubber hand as the outcome variable, condition and block as within-participants factors, and group as the between-participants factor, with chronological age included as a covariate. No main effects or two-way interactions reached statistical significance, although there was a trend for a significant main effect of condition (condition: $F(1,38) = 2.89$, $p = 0.097$; group: $F(1,38) = 1.96$, $p = 0.17$; block: $F(1,38) = 0.29$, $p = 0.59$; group × condition: ($F(1,38) = 1.17$, $p = 0.29$), block × group ($F(1,38) = 0.019$, $p = 0.89$); condition × block ($F(1,38) = 0.982$, $p = 0.33$). No interactions with age were statistically significant. The only statistically significant result revealed by the repeated-measures ANOVA was a three-way interaction between group, condition, and block (group × condition × block: $F(1,38) = 4.77$ $p = 0.035$). This interaction is depicted in Figure 2 and reflects the fact that, whereas drift was equivalent across blocks within each condition for children with TD, children with ASD showed similar susceptibility to the illusion across conditions following the first brushing block, but displayed a marked increase in drift in the synchronous condition and decrease in drift in the asynchronous condition following the second brushing block.

To confirm these results and further investigate the presence of significant proprioceptive drift in each condition within each group of children, one-sample t-tests were performed for each com-bination of group, condition, and block. In the TD comparison group, proprioceptive drift was significantly different from zero in both blocks of the synchronous condition (block 1: $t(27) = 2.98$, $p = 0.006$; block 2: $t(27) = 2.54$, $p = 0.017$), confirming that the rubber hand illusion extends to TD children. One-sample t-tests for the asynchronous condition in the TD group were non-significant for both blocks (block 1: $t(27) = 1.04$, $p = 0.31$; block 2: $t(27) = 1.47$, $p = 0.15$), indicating that, as in adults, the illusion is specific to synchronous brushing of the real and rubber hands in TD children. For the ASD group, there was no significant proprioceptive drift toward the rubber hand in the first block of the synchronous condition ($t(20) = 1.55$, $p = 0.14$), but a significant effect emerged fol-lowing the second synchronous brushing block ($t(20) = 2.15$, $p = 0.04$). As in the TD group, neither block within the asynchronous condition had mean drift that was significantly different from zero (block 1: $t(20) = 1.39$, $p = 0.18$; block 2: $t(20) = 0.54$, $p = 0.59$). In summary, the rubber hand illusion occurred during synchronous brushing for both children with and without ASD, but was evident after 3 minutes (and maintained at 6 minutes) of synchronous brushing in children with TD, whereas its onset was delayed in children with ASD (absent at 3 minutes, but present after 6 minutes).

### Reported sense of illusion

We performed a MANOVA to determine whether the groups differed in their subjective report of the illusion. Overall, there were statistically significant main effects of both group ($F(9,83) = 3.46$, $p = 0.001$) and condition ($F(9,83) = 2.32$, $p = 0.022$), but the group × condition interaction was not statistically significant. Follow-up between-groups t-tests revealed that the group effect was driven by a significant difference for question 2 ('It seemed as though the touch I felt was caused by the brush touching the rubber hand') in the asynchronous condition ($t(46) = 2.69$, $p = 0.009$). This was the only item among the 18 (nine questions in each of the two conditions, see Table 2) for which there was a statistically significant group difference. The ASD group was less likely to negatively endorse this item in the asynchronous condition than the comparison group (mean score: ASD: –0.03, TD: –1.33; possible range: −3.0 to +3.0), indicating that whereas, on the whole, children in the TD comparison group were likely to disagree with the statement that the touch they felt was caused by the brush touching the rubber hand during asynchronous brushing, children with ASD were split in their agreement with this statement. The significant main effect of condition was further explored with paired t-tests, which revealed statistically significant differences between the asyn-chronous and synchronous condition in the endorsement of questions 1–3 (question 1: $t(47) = –2.85$, $p = 0.006$; question 2: $t(47) = –3.04$, $p = 0.003$; question 3: $t(47) = –5.11$, $p = 0.000$).

### Relations with clinical variables in ASD

For participants with ASD, we looked for correlations between proprioceptive drift and two clinical variables: one item from the ADI-R (parent report of spontaneous imitation of actions between ages 4 and 5 years) and one from the ADOS (empathy scored during direct assessment). These items were chosen because early childhood imitation (Chaminade et al., 2005) and empathy (Thomas et al., 2006; Lawrence et al., 2007) have been shown to depend in part on body representation and the ability to map one's own body schema onto that of another person. Because the distributions of ADOS and ADI-R scores were non-Gaussian, nonparametric correlations (Spearman's $\rho$) were performed. Proprioceptive drift after synchronous brushing, but not asynchronous brushing, was negatively correlated with empathy scores ($\rho(20) = –0.733$, $p = 0.002$) as measured by the ADOS, such that lower levels of drift were associated with more impaired empathy. This relation is depicted in Figure 3. Imitation in the preschool years, as measured by the ADI-R, was not correlated significantly with proprioceptive drift in either condition.

We also performed correlations between these two ADOS and ADI-R items and relevant items from the self-report questionnaire. Specifically, of the nine questionnaire items, we chose two questions (questions 2 and 3) to use in follow-up correlational analyses. Questions 2 ('It seemed as though the touch I felt was caused by the brush touching the rubber hand') and 3 ('I felt as if the rubber hand were my hand') have been highly endorsed in previous studies (Botvinick and Cohen, 1998) and address alterations in the perception of hand ownership as a result of the brushing. Further, our follow-up t-tests indicated that these two questions drove the significant effect of condition in the MANOVA results reported above. As for correlations with proprioceptive drift, nonparametric correlations (Spearman's $\rho$) were performed because the distributions of ADOS, ADI-R, and rubber hand questionnaire variables were non-Gaussian. Neither the ADI-R measure of imitation nor the ADOS measure of empathy was significantly correlated with responses to questions 2 or 3, in either the synchronous or asynchronous conditions.

## Discussion

The current study demonstrates that TD children exhibit proprioceptive drift in the direction of the rubber hand after synchronous, but not asynchronous, brushing of the real and rubber hand, as has been demonstrated in adults using the rubber hand illusion. This occurred after three minutes of brushing, and sustained after 6 minutes of brushing. In contrast, the ASD group did not exhibit significant proprioceptive drift in the direction of the rubber hand in the synchronous brushing condition after 3 minutes, but did after 6 minutes, suggesting that they took longer to experience the rubber hand illusion than did the comparison group. This was supported by the ANOVA results with a significant group × condition × block interaction, and confirmed by the results of the t-tests performed separately for group, block, and condition. In fact, as illustrated in Figure 2A, after the first block, the ASD group had somewhat higher drift in the asynchronous than the synchronous condition, with the drift increasing significantly after the second block for the synchronous condition but decreasing after the second block for the asynchronous condition. This delay in the perception of the illusion suggests that children with ASD have the ability to integrate visual and tactile information to influence proprioception, but the timing and/or efficiency of this integration is reduced in comparison with TD children.

One explanation for this may be that children with ASD did not initially perceive the asynchronous brushing as asynchronous, which is consistent with previous work from our group demonstrating an extended temporal window of audiovisual binding in ASD (Foss-Feig et al., 2010, Kwakye et al., 2011). If the approximately 500 ms offset between visual and tactile stimulation in the asynchronous condition was not large enough to be outside of a similarly extended window for visuotactile integration, asynchronous stimulation may have been perceived similarly to the synchronous brushes. The elevated level of drift in the initial block of the asynchronous condition for the ASD group is consistent with this hypothesis. Further, the significant group difference found in the subjective report of whether the seen touch was perceived as causing the felt touch (question 2) in the asynchronous condition is consistent with the idea that children with ASD did not clearly differentiate their experiences between asynchronous and synchronous brushing conditions. The ASD group, although averaging a response to this question that was near zero ('unsure'), showed a bimodal distribution, with a small subgroup endorsing the question negatively (as the majority of TD children did and as is expected for this question following asynchronous stimulation), whereas a larger subgroup endorsed it affirmatively.

If a wider temporal binding window is the reason for the observed group differences, differential proprioceptive drift between conditions following the second block suggests that, given sufficient time, children with ASD may be able to hone their perception of synchrony, perhaps through a narrowing of the temporal window for multisensory binding. Specifically, as is apparent from the one-sample t-tests, Figure 2, and the group × condition × block interaction in the ANOVA, after an extended period of brushing, children in the ASD group show the predicted condition-specific effect of the illusion, showing a difference between the two conditions similar to that observed in the TD group. If the initial pattern of results after the first block is indeed attributable to differences in temporal aspects of multisensory integration, this suggests that the binding window may be malleable with repeated or prolonged exposure to consistent stimulation. The relevance of the extended multisensory binding window, as well as its potential malleability, for the observed results could be tested in future studies by parametrically varying the amount of asynchrony between brushes and the time it takes for the effects of synchronicity to emerge depending on the offset between visual and tactile stimulation.

As an alternative to the multisensory temporal binding hypothesis, the delayed effect of the rubber hand illusion in children with ASD may reflect a stronger tendency for individuals with ASD to focus preferentially on proprioceptive signals in the presence of competing input from other modalities, rendering the proprioceptive percept less susceptible to bias resulting from discrepant inputs from touch and vision. Such a bias could explain the fact that the relative drift between the two conditions was initially quite similar (after the first brushing blocks), because proprioceptive information does not differ across conditions in the rubber hand illusion. However, our results suggest that with prolonged cross-modal stimulation, the proprioceptive signals were eventually overridden by the visual and tactile input, as was seen from the outset in the comparison group. This explanation is consistent with previous findings in the motor system in ASD (Masterson and Biederman, 1983; Haswell et al., 2009). Future studies could investigate this possibility by systematically varying the brushing period between 3 and 6 minutes.

Evidence suggests that the acquisition of a sense of body ownership and differentiation of self from other are developmental processes involving multimodal integration that are important precursors to more complex social behaviors, such as social referencing, imitation, and empathy (Gallese, 2003; Chaminade et al., 2005). Empathy, defined as the ability to understand the emotions of others, is a complex social process that requires the integration of multiple affective components with different developmental trajectories (Decety, 2010), and the recognition of self–other equivalences in emotion (Meltzoff, 2007). In the current study, we found a significant correlation between empathy impairments, as measured by the ADOS, and degree of proprioceptive drift shown by children with ASD under synchronous brushing conditions. Specifically, children with more impaired empathy were less likely to show proprioceptive drift in the direction of the rubber hand after synchronous brushing. This finding suggests that the ability to allow multimodal sensory input to induce a feeling of body ownership over the external rubber hand is related to the ability to recognize and understand the emotional states of others.

Although it is accepted that early imitation gives rise to self–other distinction and is a precursor to empathy (Meltzoff, 2007), no significant correlations were found between susceptibility to the rubber hand illusion and imitation scores on the ADI-R among children with ASD. It may be that the sensory nature of the rubber hand task is more comparable to recognizing sensory features of emotion in others than it is to engaging motoric processes during imitation. Another possible explanation for a lack of association between imitation and the rubber hand illusion is temporal proximity of imitation skills described to administration of the rubber hand task. The imitation item on the ADI-R measures the developmental history of imitation skills, but not current imitation skills, once children are over the age of ten; because only five children in our ASD sample were younger than ten, our measure was derived from parents' report of imitation skills in earlier childhood. In contrast, our measure of empathy was taken from the ADOS (direct observation) and was therefore contemporaneous with the rubber hand task. It would be interesting to repeat this experiment with a larger sample of children under ten to assess possible relations between imitation and the rubber hand illusion, to directly assess imitation in a similarly aged group of children to those in our sample, and to explore differences between spontaneous and elicited imitation and their relative relations to susceptibility to the rubber hand illusion.

Interestingly, there were no significant correlations between subjective response to questionnaire items that characterize the illusion and either imitation or empathy abilities in children with ASD. The specificity of sensorimotor proprioception's relation to empathy may be related to a distinction between automatic and conscious processes. Specifically, subjective report of one's experience during brushing probably requires more conscious, introspective reflection than do proprioceptive judgments for identifying the perceived location of one's finger. Automatic self–other matching has been demonstrated to be more related to empathy than conscious comparisons between self and other (Williams, 2008), consistent with our finding of significant relations between empathy and proprioceptive drift. In contrast, the conscious process of imitation may engage more similar processes to those tapped by questionnaire items demanding conscious, introspective thought; the lack of such a relationship in our sample may be a result of the unavailability of a current measure of the integrity of imitation skills in most children. This putative dichotomy between the sensorimotor and subjective perceptual aspects of the illusion is consistent with recent evidence suggesting that the proprioceptive drift and subjective report of the rubber hand illusion are not always closely associated and are likely to rely on entirely separate mechanisms of neural integration (Rohde et al., 2011). Future studies identifying differential relations between sensorimotor and subjective aspects of the rubber hand illusion and specific social deficits in ASD would be useful.

The neural basis of the rubber hand illusion has been investigated using functional imaging techniques, and seems to involve a cortical network that includes multisensory regions in the bilateral ventral premotor cortex (Ehrsson et al., 2004; Ehrsson et al., 2005), the intraparietal sulcus (Ehrsson et al., 2005), and the right posterior insula (Tsakiris et al., 2007). The ventral premotor cortex is also part of the putative mirror neuron system (Iacoboni, 2005) that is purported to have a critical role in imitation (Leslie et al., 2004; Molenberghs et al., 2009) and has been demonstrated to respond atypically in ASD (Dapretto et al., 2006; Martineau et al., 2010). There is ample evidence that imitation is related to perspective-taking and empathy (Kaplan and Iacoboni, 2006; Iacoboni and Mazziota, 2007), and neural circuits that underlie empathy may overlap with those for imitation (Shamay-Tsoory et al., 2009). Our results suggest that the malleability of the sense of body ownership is compromised in ASD, which may correspond to an altered cortical representation of the bodily self (Lombardo et al, 2010). This in turn may give rise to diminished capability for perspective-taking and empathy, as is seen in ASD.

Although the social implications for altered multisensory integration affecting self-perception are readily apparent, there is indirect evidence to suggest that impaired perception of body ownership could also influence repetitive behaviors, another diagnostic feature of ASD. Schütz-Bosbach and colleagues (2006) found that during the rubber hand illusion, when self-attribution of the rubber hand occurred in the synchronous condition, watching that hand perform an action produced a prolonged inhibition in primary motor cortex. One interpretation for this result was that it reflected an intrinsic inhibitory mechanism designed to prevent motor perseveration, or 'self-imitation'. It is conceivable that in individuals with ASD, an aberrant sense of self versus other may lead to less imitation of others and more 'self-imitation,' or repetitive behaviors, while also resulting in a diminished capacity for understanding the actions or intentions of others. Future work should explore potential relations between body representation and repetitive behaviors in ASD.

The present study has demonstrated that children with ASD do show the expected conditionspecific proprioceptive drift in the rubber hand illusion, but that they are delayed in doing so relative to TD children. Our results also revealed that the initial lack of susceptibility to the illusion was characterized by abnormally low drift in the experimental condition, but also by abnormally elevated proprioceptive drift in the control condition. The latter finding is supported by the fact that a subgroup of children with ASD was significantly more likely than TD children to subjectively report perceived causality between the visual and tactile inputs in the control condition. These findings are consistent with a malleable, though initially extended temporal window for multisensory binding. They could also be explained by an enhanced influence of proprioception compared with visual and tactile cues.

Future studies will 1) explore the temporal multisensory binding window hypothesis by parametrically modulating asynchrony in the control condition, and 2) use neuroimaging techniques to investigate neural differences in individuals with ASD during the rubber hand illusion. These studies may clarify the potential roles of decreased multisensory integration and enhanced proprioceptive processing in this phenomenon. Finally, we demonstrated that children with ASD who show diminished capacity for understanding others' emotions were less likely to show proprioceptive drift in the synchronous condition than children with better empathy abilities. Future studies will investigate the relation between the rubber hand illusion and concurrent imitation skills to better understand the relations among empathy, imitation, and susceptibility to the rubber hand illusion. A better understanding of the perceptual and neural basis of a potentially altered sense of self versus other will have significant impact on therapeutic approaches that target social behavior, and may also shed light on repetitive behaviors in ASD.

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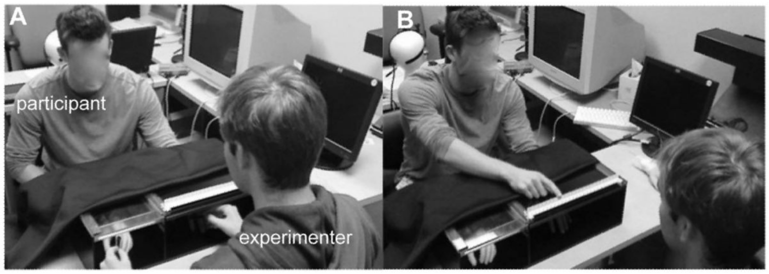


**Figure 1.**
Experimental setup for the rubber hand illusion. (A) The experimenter (right, front) brushes the same somatic location on the participant's real hand and the rubber hand, while the participant attends visually to the rubber hand, and tactually to their own hand, for two blocks of 3 minutes each. (B) Before and after each brushing block, the participant makes three judgments about the location of his obscured hand, using the straight edge, with their eyes closed. The difference between the average pre- and post-brushing judgments is used as the outcome variable: proprioceptive drift in the direction of the rubber hand.

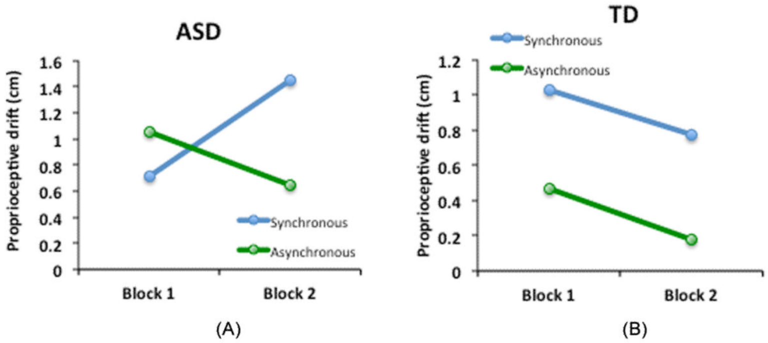


**Figure 2.**
Mean proprioceptive drift in the direction of the rubber hand in the (A) ASD and (B) TD group following each 3-minute block of brushing.

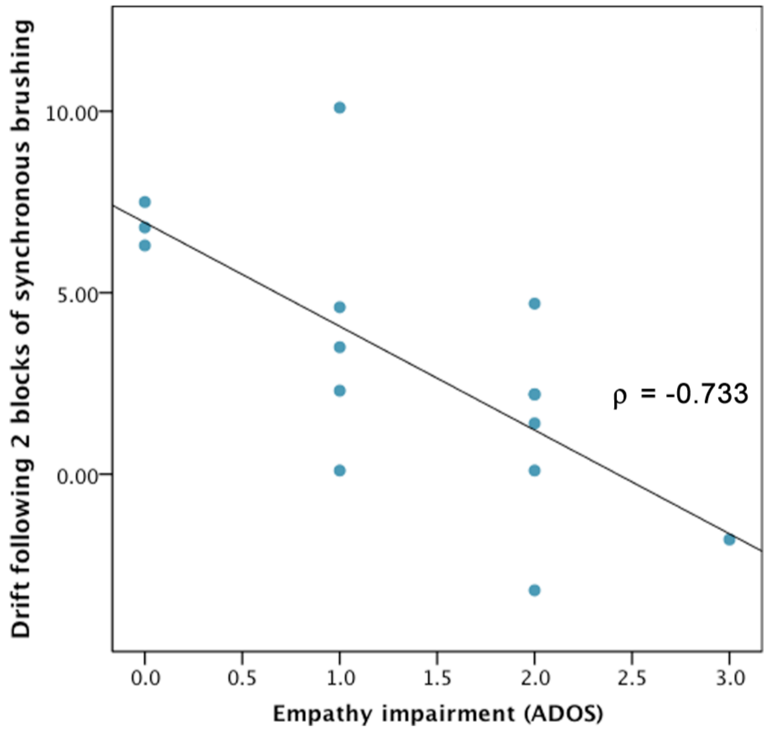


**Figure 3.**
Relation between total proprioceptive drift following 6 minutes of synchronous brushing and impairment in empathy, as measured by the ADOS, in participants with ASD.

**Table 1**

Sample characteristics

| Group | N | Age (years) | IQ | % Male | % Right-handed |
|---|---|---|---|---|---|
| ASD | 21 | 11.9 (2.8, 8–17) | 101.2 (9.3, 87–115) | 76% | 95% |
| TD | 28 | 13.4 (2.7, 8–17) | 102.7 (7.8, 85–114) | 93% | 89% |
| Test for group differences | | $t = -1.854$<br>$p = 0.073$ | $t = -0.594$<br>$p = 0.556$ | $\chi^2 = 2.72$<br>$p = 0.10$ | $\chi^2 = 0.567$<br>$p = 0.451$ |

ASD: autism spectrum disorder, TD: typically developing. Age and IQ values reflect the mean and (standard deviation, range).

## Table 2

Questions answered after each condition of the brushing experiment

| During the experiment, there were times when: |
|---|
| 1. It seemed as if I were feeling the touch of the brush in the location where I saw the rubber hand touched. |
| 2. It seemed as though the touch I felt was caused by the brush touching the rubber hand. |
| 3. I felt as if the rubber hand were my hand. |
| 4. I felt as if my (real) hand were drifting towards the right (towards the rubber hand). |
| 5. It seemed as if I might have more than one left hand or arm. |
| 6. It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand. |
| 7. It felt as if my (real) hand were turning 'rubbery'. |
| 8. It looked like the rubber hand was drifting towards the left (towards my hand). |
| 9. The rubber hand began to resemble my own (real) hand, in terms of shape, skin tone, freckles or some other visual feature. |

| − − − | − − | − | **0** | + | ++ | +++ |
|---|---|---|---|---|---|---|
| Strongly disagree | | | Unsure | | | Strongly agree |

Each question was answered using the seven-point scale depicted at the bottom. (From Botvinick and Cohen, 1998.)

## Table 3

Mean proprioceptive drift (in cm) for both groups in each condition

| Group | Asynchronous mean drift (SE) | Synchronous mean drift (SEM) |
|---|---|---|
| ASD | | |
| Block 1 | 1.06 (0.45) | 0.71 (0.46) |
| Block 2 | 0.65 (0.44) | 1.45 (0.50) * |
| TD | | |
| Block 1 | 0.47 (0.45) | 1.03 (0.28) * |
| Block 2 | 0.18 (0.34) | 0.77 (0.36) * |

*One-sample t-test $p < 0.05$.