

Modulation of mu suppression in children with autism spectrum disorders in response to familiar or unfamiliar stimuli: The mirror neuron hypothesis

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Abstract

In an early description of the mu rhythm, Gastaut and Bert [Gastaut, H. J., & Bert, J. (1954). EEG changes during cinematographic presentation. *Clinical Neurophysiology*, 6, 433–444] noted that it was blocked when an individual identified himself with an active person on the screen, suggesting that it may be modulated by the degree to which the individual can relate to the observed action. Additionally, multiple recent studies suggest that the mirror neurons system (MNS) is impaired in individuals with autism spectrum disorders (ASD), which may affect their ability to relate to others. The current study aimed to investigate MNS sensitivity by examining mu suppression to familiarity, i.e., the degree to which the observer is able to identify with the actor on the screen by using familiar versus unfamiliar actors. The participants viewed four 80 s videos that included: (1) stranger: an unfamiliar hand performing a grasping action; (2) familiar: the child's guardian or sibling's hand performing the same action; (3) own: the participant's own hand performing the same action; (4) bouncing balls: two balls moving vertically toward and away from each other. The study revealed that mu suppression was sensitive to degree of familiarity. Both typically developing participants and those with ASD showed greater suppression to familiar hands compared to those of strangers. These findings suggest that the MNS responds to observed actions in individuals with ASD, but only when individuals can identify in some personal way with the stimuli.

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1. Introduction

It has been proposed that “the bedrock on which social cognition is built is the perception that others are ‘like me’” (Meltzoff, 2007, p.126). Thus, typically developing individuals are able to see the equivalences between “self” and “other” and recognize that others behave, think, and feel things in similar ways to oneself (Meltzoff, 2007). This ability to relate and identify oneself with others is of clinical importance as it is a core impairment in the DSM-IV-TR definition of autism spectrum disorders. It has been proposed that an inability to simulate the perceptions of

others in the observer's own sensorimotor systems may underlie both the social and communicative deficits that characterize autism spectrum disorders (ASD) (Oberman & Ramachandran, 2007). Furthermore, recent studies have linked a dysfunction in the mirror neuron system (MNS), a neural system thought to underlie simulation processes, to the social deficits seen in ASD (for reviews see Oberman & Ramachandran, 2007; Williams, Whiten, Suddendorf, & Perrett, 2001). Williams et al. (2001) suggest that dysfunctional development of the MNS, possibly as a result of a combination of genetic and environmental factors, could lead to impaired self-other representations. Oberman and Ramachandran similarly bring together behavioral, functional neuroimaging, and computational findings to provide support for an underlying impairment in mirror neuron mediated simulation processes. Both papers contend that the underlying neural impairments are likely mediating the social and communication

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deficits such as imitation, theory of mind, joint attention, empathy, and language in individuals with ASD.

Mirror neurons are characterized by their unique response pattern to both performed and observed actions (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; for a review see Rizzolatti, Fogassi, & Gallese, 2001). Researchers speculate that the MNS evolved in primates to facilitate action understanding (Rizzolatti et al., 2001). In humans, this type of system may play an integral role in our ability to represent other's actions, as well as potentially the intentions and emotions that guide actions by creating a mechanism that allows observers to simulate the perception within their own motor and limbic systems (Oberman & Ramachandran, 2007). Thus, it has been speculated that through evolutionary bootstrapping this basic action understanding mechanism may have provided the foundation for the development of social skills including imitation, theory of mind, empathy, and language (Gallese, 2001).

In the original studies conducted by Rizzolatti and colleagues, it was suggested that mirror neurons are selective to animate actions (Rizzolatti & Fadiga, 1998). However, the degree to which the MNS is sensitive to socially relevant information such as the observer's connection with the observed stimulus remains unclear. One recent study (Kilner, Marchant, & Frith, 2006) aimed to explore the sensitivity of the MNS to social relevance. In this study, participants showed modulation of the parietal alpha rhythm (7–12 Hz) during the observation of hand movement, but only when the actor is facing the observer, and not when the actor is facing away. The authors suggest that this differential response reflects a filter that allows only socially relevant information to continue flowing into the more frontal mirror neuron system. Thus, perhaps the mirror neuron dysfunction reported in individuals with ASD (Bernier, Dawson, Webb, & Murias, 2007; Dapretto et al., 2005; Nishitani, Avikainen, & Hari, 2004; Oberman et al., 2005; Theoret et al., 2005; Villalobos, Mizuno, Dahl, Kemmotsu, & Müller, 2005) may be the result of a lack of social relevance in the stimuli used.

Two recent studies (Aylward, Bernier, Field, Grimme, & Dawson, 2004; Pierce, Haist, Sedaghat, & Courchesne, 2004) suggest that another cortical area, the fusiform gyrus, previously thought to be nonresponsive to faces in individuals with ASD (Hubl et al., 2003; Pierce, Müller, Ambrose, Allen, & Courchesne, 2001; Schultz et al., 2000), is found to be responsive when photos of familiar individuals are used. Both studies report increases in BOLD activity in response to familiar faces as compared to unfamiliar faces in both typically developing and ASD populations. Likewise, previous studies suggest that familiarity/expertise with the observed action modulates the activity in regions of cortex thought to contain mirror neurons (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005). Additionally, when typically developing participants are asked to view photographs of faces, regions of inferior frontal gyrus respond more markedly to the participant's own face as well as familiar faces compared to an unfamiliar face (Keenan, Wheeler, Gallup, & Pascual-Leone, 2000; Kircher et al., 2001). Finally, regions of inferior frontal gyrus and inferior parietal lobule show preferential activity to faces of self as compared to familiar other faces (Uddin, Kaplan, Molnar-Szakacs, Zaidel, &

Iacoboni, 2005). Thus, the mirror neuron system may be sensitive to the familiarity of both the kinematics of movement as well as the actor(s).

Consistent with this hypothesis, the original report of mu suppression by Gastaut and Bert (1954) reads "It [the mu rhythm] disappears when the subject identifies himself with an active person represented on the screen" (p. 439). Thus the degree of suppression of this rhythm appears to be related to the degree to which the observer identifies with the image on the screen. This sensitivity of mu suppression (reflecting sensitivity of the MNS) to socially relevant information in adults has been recently confirmed (Oberman, Pineda, & Ramachandran, 2007) and may explain how an action recognition system in the macaque may have evolved to mediate more complex social skills such as imitation, TOM, empathy and language in the human—as has previously been suggested (Ramachandran, 2000; Rizzolatti & Arbib, 1998).

Furthermore, if the MNS in ASD responds in a typical manner to observed actions performed by familiar individuals this would provide an explanation for the reported improvement in behavioral deficits when the child with ASD interacts with a parent or sibling as compared to a stranger or peer. Specifically, reports suggest that children with ASD display improved communication skills (Bernard-Opitz, 1982), increased rate of physical contact and eye contact (Kasari, Sigman, & Yirmiya, 1993) as well as improved social interaction skills (Knott, Lewis, & Williams, 1995) when interacting with a familiar as opposed to an unfamiliar individual.

The current line of research seeks to explore the role of familiarity in the modulation of the mu rhythm as an index of the mirror neuron system in typically developing children and children with ASD. The stimuli for this study included a video of a stranger performing an action, as well as videos of a familiar person (i.e., parent, guardian or sibling) and of the participant himself performing the same action. The goal was to test the hypothesis that mu suppression is sensitive to actor familiarity in both typically developing children and children with ASD. It was hypothesized that typically developing children would show greater suppression to the observation of their own as well as the familiar individual's actions when compared to a stranger performing the same action. Though previous studies have reported a lack of mu suppression to observed actions in children with ASD (Bernier et al., 2007; Oberman et al., 2005), these studies used unfamiliar actors. Thus, similar to the findings in the fusiform gyrus (Aylward et al., 2004; Pierce et al., 2004) the use of a familiar actor may elicit a more typical response.

2. Methods

2.1. Participants

Thirteen children with ASD and 13 typically developing controls participated in this study. All participants were male and ranged in age from 8 to 12 years ($M = 10.23$, $S.D. = 1.37$). All participants had normal hearing and normal, or corrected to normal, vision. ASD participants were recruited through Valerie's list, a listserv of families and professionals in the autism community. Typically developing participants were recruited from the local area. Standardized assessments of cognitive skills were administered to all children. All participants in

both groups scored within the normal range on a standardized test of intelligence (see Section 2.5). The participants in the typically developing group had no neurological or psychological disorders and were matched on chronological age and gender with a participant in the ASD group. All participants were given age-appropriate assents and parents/guardians provided written consent for their child's participation. This project was reviewed and approved by the University of California, San Diego Human Research Protections Program.

2.2. Clinical assessment

Children with ASD were diagnosed by a licensed clinical psychologist or medical doctor not associated with this research. The Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) was used to assess intellectual functioning and the Autism Diagnostic Observation Schedule—Generic (ADOS-G) (Lord et al., 2000) was used to confirm a diagnosis of autistic disorder or autism spectrum disorder. Based on the results of these assessments and clinical judgment, 7 of the 13 children met criteria for *autistic disorder*, and the remaining 6 met criteria for *autism spectrum disorder*. All participants were considered high functioning, defined as having age-appropriate verbal comprehension abilities and an intelligence quotient (IQ) greater than 80. All children were also administered the revised movement imitation test (De Renzi, Motti, & Nichelli, 1980). An imitation task was administered for several reasons. First, imitation is one of the main theorized functions of the mirror neuron system. Secondly, it is a core behavioral deficit in ASD. Finally, a recent study (Bernier et al., 2007) finds a correlation between imitation skills and mu suppression.

2.3. Stimuli

Four 80-s videos were presented. The videos consisted of: (1) stranger: an unfamiliar individual opening and closing the right hand (Fig. 1). (2) Familiar: matched to the action in the stranger's hand condition (#1) in all respects except the hand was that of the parent, guardian, or sibling of the participant. (3) Own: matched to the action in the stranger's hand in all respects except the hand was that of the participant. (4) Bouncing balls: two light gray balls on a black background moving vertically towards each other, then touching in the middle of the screen then moving apart to their initial starting position. This motion was visually equivalent to the trajectory taken by the tips of the fingers and thumb in the three hand videos, however it was not perceived as animate (Fig. 2). As the MNS is thought to be selective for animate action and though it is visually matched to the hand videos, previous studies in our labora-



Fig. 1. Stimulus 1 (stranger) was used as the unfamiliar stimulus. Also used as a model for the videos of the participant performing the same action as well as a relative (parent, guardian, or sibling) performing the same action (not shown above).

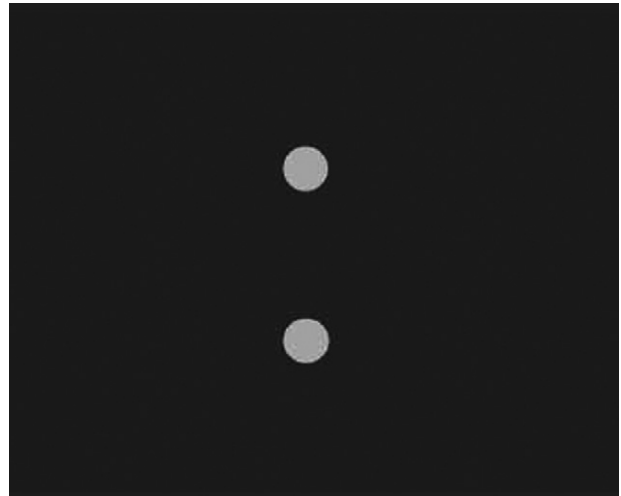


Fig. 2. Stimulus 4 (bouncing balls) was used as a baseline.

tory using this video (Oberman et al., 2005; Pineda & Oberman, 2006) elicited no reduction in mu power, the “Bouncing balls” video was used as a baseline condition.

The “Familiar” and “Own” videos were recorded during a preliminary session. These videos began with a full body shot of the actor, then zoomed into the hand to match the size and angle to that of the standard “Stranger” video. The purpose of the full body shot of the actor in the “Familiar” and “Own” conditions was to assure that the observer was able to identify whose hand was performing the action. The “Stranger” video was created prior to the study with the hand of an unfamiliar research assistant. This video did not include the preliminary full body shot as there was no need to identify whose hand was performing the action in this condition. The “Familiar” actor was the parent, guardian, or sibling that came to the study with the participant. The participants and family members were told to move their hand in a specific way to the beat of a metronome, such that these videos were matched on speed and trajectory to the “Stranger” video.

Video stimuli were presented on a 14-in. computer screen. All videos were presented at a viewing distance of 96 cm with a visual angle of approximately 17°. Brief breaks (~1–2 min) were taken between videos. To ensure that the participants attended to the video stimuli, they were asked to engage in a continuous performance task. Between three and six times during the 80-s video, the stimuli stopped moving for a period of 1–2 s. As a measure of attention to the task, participants were asked to count the number of times the stimuli stopped and report the number of stops to the experimenter at the end of the block.

2.4. Mu suppression

Previous studies in our laboratory and those of others have investigated MNS in humans through analysis of electroencephalography (EEG) mu frequency band (8–13 Hz) suppression (Altschuler, Vankov, Wang, Ramachandran, & Pineda, 1997; Altschuler et al., 2000; Bernier et al., 2007; Lepage & Theoret, 2006; Muthukumaraswamy and Johnson, 2004; Muthukumaraswamy, Johnson, & McNair, 2004; Oberman, McCleery, Ramachandran, & Pineda, 2007; Oberman, Pineda, et al., 2007; Pineda & Oberman, 2006; Pineda, Allison, & Vankov, 2000). Recent studies suggest that mu suppression can be recorded in children as young as 36 months old (Fecteau et al., 2004; Lepage & Theoret, 2006) with functional response properties similar to those found in adults. EEG is a direct measure of neuronal populations and therefore more reflective of complex computations than single unit firing and provides an inexpensive, non-invasive option that is well suited for use with clinical populations. Although the sources for mu oscillations have been identified in sensorimotor areas there are extensive interconnections with ventral premotor areas where mirror neurons are located, which appear to modulate the mu rhythm (see Pineda, 2005 for a review).

At rest, sensorimotor neurons spontaneously fire in synchrony leading to large amplitude EEG oscillations (Gastaut, 1951). When participants perform

an action but especially during the observation of an action, sensorimotor neurons are desynchronized by input from premotor mirror neurons, decreasing the power of the mu-band oscillations (Pfurtscheller, Neuper, Andrew, & Edlinger, 1997; Samelin & Hari, 1994). Studies dating back to 1954 find that, similar to mirror neurons, mu oscillations respond specifically to self-performed, observed and imagined actions (Cochin, Barthelemy, Lejeune, Roux, & Martineau, 1998; Gastaut & Bert, 1954; Pineda et al., 2000). Moreover, mirror neurons (Rizzolatti & Fadiga, 1998) and mu oscillations (Altschuler et al., 1997; Oberman et al., 2005) only respond to animate stimuli, and respond more to target-directed actions compared to non-goal-directed actions (Muthukumaraswamy et al., 2004). Finally, both mirror neurons (Buccino et al., 2001) and mu oscillations seem to respond in a somatotopic manner (Pfurtscheller et al., 1997, for a review see Pineda, 2005).

The use of mu suppression as an index of mirror neuron activity is also validated by anatomical and physiological evidence of strong cortico-cortical connections between ventral premotor cortex (i.e., pars opercularis—the region thought to contain mirror neurons) and primary sensorimotor cortex where the mu rhythm is generated and recorded (Dum & Strick, 2002; Ghosh, Brinkman, & Porter, 1987; Godschalk, Lemon, Kuyper, & Runday, 1984; Matelli, Carmarda, Glickstein, & Rizzolatti, 1986; Muakkassa & Strick, 1979; Nishitani & Hari, 2000; Shimazu, Maier, Cerri, Kirkwood, & Lemon, 2004; Tokuno & Nambu, 2000). Furthermore, preliminary evidence suggests that inhibiting inferior frontal gyrus through repetitive TMS (rTMS) leads to the absence of mu suppression (Elfenbein, Davis, Brang, Agmon, & Pineda, 2007). Thus, response of the mu rhythm to observed actions likely reflects the downstream activity of mirror neuron activity in the premotor cortex.

2.5. EEG procedure

All videos were presented twice in order to obtain enough clean EEG data for analyses. The order of presentation was counterbalanced across participants. For the “Familiar” and “Own” videos, which began with a full body shot of the actor, EEG was only analyzed for the period of time when the video was zoomed in matching the size and angle of the “Stranger” video. EEG data were collected in an electromagnetically and acoustically shielded chamber, with the child sitting in a comfortable chair. Disk electrodes were applied to the face above and below the eye, and behind each ear (mastoids). The computationally linked mastoids were used as reference electrodes. Data were collected from 13 electrodes embedded in a cap at the following scalp positions: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, T5, T6, O1, and O2, using the International 10–20 method of electrode placement. Following placement of the cap, electrolytic gel was applied at each electrode site and the skin surface was lightly abraded to reduce the impedance of the electrode–skin contact. The impedances on all electrodes were measured and confirmed to be less than 10 k Ω both before and after testing. EEG was recorded and analyzed using a Neuroscan Synamps system (bandpass 0.1–30 Hz). Data were collected for approximately 160 s per condition at a sampling rate of 500 Hz.

2.6. Data analysis

EEG oscillations in the 8–13 Hz frequency band recorded over occipital cortex are influenced by states of expectancy and awareness (Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998). Since the mu frequency band overlaps with the posterior alpha frequency band (recorded from O1 and O2) and the generators for posterior alpha tends to overwhelm that for mu, it is possible that recordings from C3, Cz, and C4 might be affected by this posterior activity. As all conditions involved visual stimuli and the eyes were open throughout the study, we would not expect a systematic difference between conditions in posterior alpha activity. Additionally, the first and last 10 s of each block of data were removed from all participants to eliminate the possibility of attentional transients due to initiation and termination of the stimulus. A 1-min segment of data following the initial 10 s was obtained and combined with the other trial of the same condition, resulting in one 2-min segment of data per condition.

Eye blinks and eye and head movements were manually identified in the EOG recording and along with other EEG artifact removed prior to anal-

ysis according to standard criteria (Goldensohn, Legatt, Koszer, & Wolf, 1999). Data were coded in such a way that these analyses were blind to the participants’ diagnosis. Data were only analyzed if there were sufficient “clean” samples with no movement or eye blink artifacts. Each cleaned set of data was further segmented into epochs of 2 s each beginning at the start of the segment. The integrated power in the 8–13 Hz range was then computed using a Fast Fourier Transform on the epoched data (1024 points). A cosine window was used to control for artifacts resulting from data splicing.

Mu suppression was calculated by forming a ratio of the power during the experimental conditions relative to the power in the ball (baseline) condition. A ratio was used to control for variability in absolute mu power as a result of individual differences such as scalp thickness and electrode impedance, as opposed to differences in mirror neuron activity. Since ratio data are inherently non-normal as a result of lower bounding, a log transform was used for analysis. A log ratio of less than zero indicates suppression whereas a value of zero indicates no suppression and values greater than zero indicate enhancement. A familiarity (stranger versus familiar versus own) \times hemisphere (left versus right) \times group (ASD versus controls) mixed model ANOVA was used. Additionally, two-tailed *t*-tests were used to compare the log suppression values of each condition to zero, using Bonferroni correction for multiple comparisons. Although data were obtained from 13 electrodes across the scalp, mu rhythm is defined as oscillations measured over sensorimotor cortex, thus only data from electrode sites C3 and C4 are presented. Two-tailed *t*-tests were also used to analyze results from the clinical tests (WASI’s full-scale IQ score, the verbal IQ score and the performance IQ score).

3. Results

3.1. Clinical testing

Two-tailed *t*-tests conducted on the WASI’s full-scale IQ score, the verbal IQ score and the performance IQ score revealed no significant group differences in any of these measures (all *ps* > 0.20). Additionally, the children with ASD had normal intelligence, as evidenced by a mean full-scale IQ above 100. Scores on the movement imitation test did show a group effect. The test was broken into four subscales (actions with objects, actions without objects, meaningful gestures, and non-meaningful gestures), with the control group performing significantly better than the ASD group on all subscales of the test, except meaningful gestures (actions with objects: $t(24) = -2.18$, $p < 0.05$; actions without objects: $t(22) = -2.40$, $p < 0.05$; meaningful gestures: $t(24) = -1.57$, $p > 0.10$; non-meaningful gestures: $t(24) = -2.21$, $p < 0.05$). Though the ASD group showed the expected impairment in imitation, this impairment was not significantly correlated with any of the EEG measures described below (all *ps* > 0.10). The mean standardized scores and standard errors for each group are presented in Table 1.

3.2. Behavioral performance

All participants performed with 100% accuracy on the continuous performance task. Participants were explicitly instructed to pay attention to the stimuli and to try to limit their eye and head movements. While not objectively measured, the ASD group appeared to followed the instructions more literally than the control group as indicated by several ASD participants having little to no eye or head movement for the entirety of the 80 s videos. Though the performance was at ceiling level for the continu-

Table 1
Results of cognitive testing

Cognitive test	ASD	Typically developing	Significance level
WASI—full scale	102.8 (15.8)	112.5 (17.3)	NS
WASI—verbal	99.9 (21.7)	110.6 (15.4)	NS
WASI—performance	106.5 (15.3)	111.7 (19.6)	NS
Imitation with objects	62.2 (17.3)	77.4 (12.9)	$p < 0.05$
Imitation without objects	73.6 (11.6)	83.4 (11.4)	$p < 0.05$
Meaningful gestures	81.0 (7.9)	87.0 (11.2)	NS
Non-meaningful gestures	65.9 (17.1)	79.7 (14.6)	$p < 0.05$

Means and standard deviations (in parentheses) for each of the experimental groups, and the results of statistical comparisons between groups, are presented. Statistical results are based on two-tailed t -tests.

ous performance task, it is inferred based on both this task and the anecdotal reports of the experimenter that any differences found in mu suppression between the two groups are not due to differences in attending to the stimuli.

3.3. EEG mu suppression

By eliminating the first and last 10 s of each block we further reduced the possibility of nonspecific effects due to movement or attention affecting our results. Additionally, analyses were run to obtain the power in the 8–13 Hz frequency in all recorded electrodes. Other than C3, Cz, and C4, no other recorded electrodes (F3, Fz, F4, P3, Pz, P4, T5, T6, O1, or O2) showed a consistent pattern of suppression. Specifically, there was no significant difference in the power in these electrodes during the experimental conditions as compared to the baseline condition. These results support the idea that the modulations of mu activity observed at C3, Cz, and C4 were not mediated by posterior alpha activity or any other nonspecific effect.

Power in the mu frequency band at scalp locations corresponding to left and right hemisphere sensorimotor cortices (C3 and C4) during the observation of a stranger's action, a familiar individual's action and the participant's own action was compared to power during the observation of the ball condition by forming the log ratio of the power in these conditions for both groups (see Fig. 3). The results revealed a significant main effect of familiarity ($F(2, 144) = 2.95, p < 0.05$). Pair-wise comparisons revealed a linear trend with the own action condition showing the greatest amount of suppression (-0.26) followed by the familiar individual's action (-0.23) with the stranger's action showing the least amount of suppression (-0.13). Though there was not a significant group by familiarity interaction, this linear trend appears to be largely driven by the ASD group's significant suppression to the familiar and own action conditions. There was no significant main effect of hemisphere ($F(1, 144) = 0.50, p > 0.48$) or group ($F(1, 144) = 0.38, p > 0.54$).

t -Tests comparing mu suppression during each of the experimental conditions to a zero baseline showed significant suppression in the typically developing control group at each electrode during all three experimental conditions (Stranger: C3 $t(12) = -2.94, p < 0.01$, C4 $t(12) = -1.83, p < 0.05$; Familiar: C3 $t(12) = -5.45, p < 0.001$, C4 $t(12) = -3.71, p < 0.01$; Own: C3 $t(12) = -3.56, p < 0.01$, C4 $t(12) = -3.28, p < 0.01$) and no sig-

nificant difference between the three conditions (both $p > 0.5$). Consistent with previous studies (Bernier et al., 2007; Oberman et al., 2005), the ASD group did not show significant suppression during the observation of a stranger's action (C3 $t(12) = -1.34, p > 0.10$; C4 $t(12) = -.11, p > 0.45$). However, the observation of a familiar individual's actions did result in significant suppression in the ASD group (Familiar: C3 $t(12) = -2.16, p < 0.05$, C4 $t(12) = -2.75, p < 0.01$; Own: C3 $t(12) = -2.66, p < 0.01$, C4 $t(12) = -5.09, p < 0.0001$). In addition, t -tests comparing suppression during the stranger condition to suppression during the familiar and own conditions revealed greater suppression during the familiar condition ($t(12) = -1.98, p < 0.05$) and own condition ($t(12) = -2.65, p < 0.01$) compared to the stranger condition for the ASD group (Fig. 3). This difference in suppression across conditions in the two groups was not due to differences in baseline mu power (C3 $t(12) = -0.64, p > 0.53$; Cz $t(12) = -1.68, p > 0.11$; C4 $t(12) = -1.20, p > 0.25$).

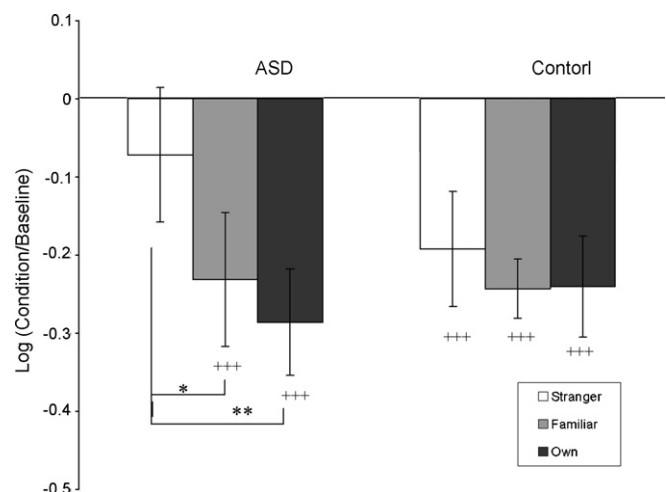


Fig. 3. Mu suppression to observed actions performed by an unfamiliar individual, a familiar individual and the participant himself. Bars represent the mean log ratio of power in the mu frequency (8–13 Hz) during the stranger (white bars), familiar (gray bars) and own (black bars) conditions, over the power in the bouncing ball condition collapsed across hemispheres for individuals with ASD and typically developing individuals. Error bars represent the standard error of the mean. For all values, a mean log ratio greater than zero indicates mu enhancement; a mean log ratio less than zero indicates mu suppression. Significant differences in suppression is indicated by asterisks: * $p < .05$, ** $p < .01$; significant suppression from 0 is indicated by plus signs: +++ $p < 0.001$.

4. Discussion

The results of the present study support the social relevance hypothesis that the mirror neuron dysfunction reported in individuals with ASD (Bernier et al., 2007; Dapretto et al., 2005; Nishitani et al., 2004; Oberman et al., 2005; Theoret et al., 2005; Villalobos et al., 2005) may be the result of a lack of social relevance in the stimuli used. These results show that familiarity modulates mu suppression, with both ASD and typically developing groups showing the greatest amount of suppression to their own movements, followed by those to a familiar individual's action, and a stranger's action showing the least amount of suppression (not significantly different than baseline in the ASD group). This is the first study to show normal mu wave suppression to observed actions in children with ASD. It is also the first study to investigate the MNS in individuals with ASD using stimuli where the actor performing the observed action is familiar to the participant.

The finding that the MNS is most active (resulting in the greatest amount of mu wave suppression) when the observed actor is familiar to the participant is consistent with the anecdotal report by Gastaut and Bert (1954) that the blocking of the mu wave occurs when an individual "identifies himself with an active person represented on the screen" (p. 439). Additionally, the finding that the children with ASD show suppression to the observed action when it is performed by a familiar individual suggests that the previous reports of impaired mu wave suppression (Bernier et al., 2007; Oberman et al., 2005) may have been the result of the observed action being performed by a stranger.

Furthermore, this pattern of results provides an explanation for the clinical observation of improvements in social skills and communication when the child with ASD interacts with a parent or sibling as compared to a stranger or peer as well as their impaired performance on the imitation task. Though we replicated the long-standing finding of impaired imitation skills in this population, perhaps if the imitation task was designed such that the child imitated the parent (instead of the experimenter) their performance would not be impaired. This is certainly a topic for future research, especially as it pertains to the active inclusion of parents in therapeutic interventions.

A set of results that speaks to the importance of stimulus familiarity in ASD, and is consistent with our findings, is that the typical neural response to faces, previously thought to be absent in this population (Hubl et al., 2003; Pierce et al., 2001; Schultz et al., 2000), is found to be intact when photos of familiar individuals are used. In a study conducted by Aylward et al. (2004) participants with autism were presented with familiar faces and cars and showed a comparable degree of activity in the FFA to typically developing individuals. In another study conducted by Pierce et al. (2004), ASD participants were presented with both stranger and familiar faces and showed greater fusiform activity in response to familiar compared to stranger faces.

Combined with previous findings (Aylward et al., 2004; Pierce et al., 2004) showing that other brain regions thought to be dysfunctional in ASD may actually be modulated by familiarity, the current observation of normal mu suppression in ASD

children to actions performed by a familiar individual suggests that the reported dysfunction in both the MNS and other regions of the brain may actually reflect an underlying impairment in identifying with and assigning personal significance to unfamiliar things, including people. This underlying impairment may manifest itself as a dysfunction in systems such as the MNS or FFA that are modulated by the ability to identify with, or assign personal or social significance to a stimulus.

The results of the current study may be indicative of a threshold effect suggesting that a greater degree of activation of the MNS is necessary in the ASD population than the typically developing population to overcome a potential reduction of mirror neurons and/or less functional MNS as a result of aberrant connectivity with more posterior regions in children with ASD. Thus, the recovery of mu suppression in the ASD population in response to the observation of actions performed by the participant himself or a familiar actor may be the result of the increased attentional or motivational salience invested in a familiar stimuli causing increased activity in the mirror neuron system in response to this category of events. It is unclear whether the effect obtained in the current study is a result of familiarity of the actor himself ("that is my hand" versus "that is a stranger's hand") or an effect of agency ("that is my own action" versus "that is a stranger's action"), however previous studies indicate that the mirror neuron system does not respond to the observation of a static image of a still (no implied action) hand (Urgesi, Moro, Candidi, & Aglioti, 2006). Thus, identity and agency might be inextricably linked when it comes to the mirror neuron system. This is an empirical question that requires further research.

Thus, to say that these systems are dysfunctional in ASD may only be partially correct. If these systems are sensitive to social relevance, and are modulated by the degree to which the observer sees the stimulus as "like me", perhaps typically developing individuals consider all people (both familiar and unfamiliar) as socially relevant agents and are able to apply this identifying tag, resulting in activation of these areas in response to the observed stimuli. In contrast, individuals with ASD may only consider familiar individuals (including themselves) as "like me" and therefore as socially relevant agents. An open question that stems from this study is the role of cognition in the sensitivity to familiarity. How does one determine what is familiar? There is, however, somewhat of a chicken and egg problem when looking at such complex systems and complex social skills in children who are 8–12 years of age. While it is possible that a dysfunctional mirror neuron system leads to a deficit in relating to unfamiliar people, it is also possible that a deficit in relating to unfamiliar people leads to a dysfunction in the development of the mirror neuron system. Clearly, more studies are necessary to address the causal issue. Additionally, since the sample in this study was solely composed of high-functioning males, the generalizability of the findings to females or lower-functioning individuals is unclear and requires further investigation.

One limitation of the present study was the differences in presentation of the videos. Unlike the familiar and own videos, the stranger video did not begin with a full body view of the stranger. Though all data were analyzed on a visually matched portion of the video wherein all three conditions only the fore-

arm and hand were visible, it is possible that not showing the full body prior to the stranger hand further hindered the ASD children's ability to draw a connection between the observed action and themselves. The stranger video was chosen in an attempt to replicate the previous finding (Oberman et al., 2005). The presentation of the full body view prior to the familiar and own videos was done in order to assure that the participants knew whom the hand belonged to and to reinforce the familiarity of these stimuli. Though this limits the interpretation of the lack of suppression in the stranger condition, it does not impact the main finding of intact mu suppression in the ASD group to observed actions under specific conditions that increase social relevance of the stimulus. Future studies are necessary to elucidate all the factors that contribute to the observer "identifying himself" with observed actions. Familiarity may be one of several factors that mediate the observer's ability to see a stimulus as "like me."

In conclusion, this study finds that the observation of actions performed by familiar individuals results in mu wave suppression in individuals with ASD, while the actions of strangers do not. This is the first study to show normal mu wave suppression during action observation in individuals with ASD. The observation that the MNS in ASD may be functioning normally under specific circumstances bodes well for therapeutic interventions aimed at improving social deficits in this population. Perhaps if one could improve the ability in children with ASD to identify with the observed unfamiliar person through behavioral, neurofeedback, or other types of training, one might improve the functioning of the MNS and alleviate some of the behavioral deficits associated with this disorder.

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