

# EEG evidence for mirror neuron activity during the observation of human and robot actions: Toward an analysis of the human qualities of interactive robots

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## Abstract

The current study investigated the properties of stimuli that lead to the activation of the human mirror neuron system, with an emphasis on those that are critically relevant for the perception of humanoid robots. Results suggest that robot actions, even those without objects, may activate the human mirror neuron system. Additionally, both volitional and nonvolitional human actions also appear to activate the mirror neuron system to relatively the same degree. Results from the current studies leave open the opportunity to use mirror neuron activation as a ‘Turing test’ for the development of truly humanoid robots.

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## 1. Introduction

A great deal of robotics research has recently investigated issues surrounding the creation of robots that are able to socially interact with humans and other robots [7,8,36]. Some recent work has focused on developing anthropomorphic “humanoid” robots for optimal social-communicative interactions with humans. Models have been developed stressing the importance of different processing strategies (i.e., purely sensory vs. embodied vs. a combination of both) [6,24,38,43]. As a result, several of these models draw on findings in the fields of developmental psychology [23,35] and cognitive neuroscience [7,32,37,38]. Perhaps the most influential contribution to this area derives from the discovery of an action

observation/execution network known as the ‘mirror neuron’ system.

Single unit studies indicate that neurons in area F5 of the macaque premotor cortex, which are indistinguishable from neighboring neurons in terms of their motor properties, also discharge in response to observed actions [17, for a review see 57]. That is, when a monkey observes another individual performing an action that is part of its own motor repertoire, these ‘mirror neurons’ fire, creating the basis for a neural observation/execution matching system. These single unit studies also show that the macaque mirror neuron system is selective for object-directed actions [21]. Functionally, it has been suggested that this system may allow the monkey to perform both an on-line automatic execution of the action and an off-line internal simulation of the observed action. Such a simulation may play a critical role in one’s ability to understand the movements of other individuals, an ability that is critical for social interaction [22] and particularly relevant for the development of “humanoid” interactive robots.

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Individual neurons have not been directly studied in the same way in humans. However, the existence of an analogous system in the homologous brain region (Broca's area/Brodmann's area 44) has received strong support from multiple indirect population-level measures, including transcortical magnetic stimulation (TMS) [18], functional magnetic resonance imaging (fMRI) [30] and electroencephalography (EEG) [15,39,44,51,52]. Though this system seems to be functionally and anatomically analogous, one notable difference between the monkey F5 system and the human mirror system is that the monkey system only responds to actions with target objects whereas the human system will respond, albeit to a lesser extent, to pantomimed [9,40] and intransitive actions [18]. Additionally, recent work has uncovered populations of neurons with similar properties in the parietal cortex [9,40], as well as the superior temporal sulcus [12,47]. These results suggest that the frontal mirror neuron system may be part of a broader action observation/execution network [19,45].

Previous studies in our laboratory [1,44,51] and those of others [39,15] have investigated the mirror neuron system in humans through analysis of EEG mu frequency band oscillations. At rest, sensorimotor neurons spontaneously fire in synchrony [23], leading to large amplitude EEG oscillations in the 8–13 Hz (mu) frequency band. When subjects perform an action, these neurons fire asynchronously, thereby decreasing the power of the mu-band EEG oscillations [49]. Over the past 50 years there have been several theories relevant to the function of the mu rhythm [for a review 50]. Most recently, results of several studies have uncovered various properties of mu suppression that directly link it to the frontal mirror neuron system. First, mu power recorded from electrodes at scalp locations C3 and C4 is reduced by self-initiated movement and observed movement [3,15,23,45]. Importantly, similar to mirror neuron activity, the mu wave does not respond to non-biological directional motion such as bouncing balls [1,44]. Furthermore, analogous to previous fMRI studies of the mirror neuron system [9], the presence of an object increases mu wave suppression as compared to pantomimed actions [40].

Since the mu rhythm is generated by activity in sensorimotor areas [23], and mirror neurons are located in premotor cortex [17], it has been hypothesized that the mu rhythm may specifically index downstream modulation of primary sensorimotor areas by mirror neuron activity [40]. Additionally, the frontal mirror neuron system is the only network in the region of sensorimotor cortex that has been identified as responding to observed hand actions. Taken together, these results suggest that mu wave suppression to observed actions can be used as a selective measure of activity of this system.

The discovery of mirror neuron activity in humans has resulted in extensive experimental research as well as theoretical papers on the role of the mirror system in human imitative [57], social [22], emotional [13], and cognitive [54,56] behaviors. Mirror neuron activity has

also been implicated in disorders of social cognition (i.e. autism spectrum disorders) [16,42,44,62,64].

Based on the extant findings, researchers have begun to develop dynamic neural network models based on the human mirror neuron system to be used with interactive robots. Of particular relevance to the current study is research conducted by Ito and Tani [32], who developed a neural network model for deferred imitation for use by an entertainment robot (Sony's 'QRIO'). The purpose of this neural network was to create a more naturalistic human–robot interaction by having the robot mimic the synchronization patterns naturally present in human interactions and, therefore, increase the time humans spent interacting with the robot. A recent review [7] describes the development of a “socially intelligent” robot (Leonardo). The robot's physical and cognitive architecture are based on previous research in simulation and the mirror neuron system, which enable it to not only imitate, but also to understand the human interactant's emotions, based on facial expressions. Although not directly evaluated in these experiments, the implication is that the human mirror neuron system may be activated as a result of the human interactant anthropomorphizing these robots. Indeed, by activating the human mirror neuron system humanoid robots could potentially tap into the powerful social motivation system inherent in human life, which could lead to more enjoyable and longer lasting human–robot interactions.

Ito and Tani's as well as Breazeal's work address two important aspects of a robot that might influence the activation of the mirror neuron system in a human interactant: (1) the temporal aspects of social interaction (e.g. simple dance-like imitation sequences); (2) the cues used by humans to determine when and how spontaneous switching of roles (e.g. modeler vs. imitator) can and should occur during a social interaction. Research with human subjects has shown that these are important aspects of behavior during social interactions [e.g., 2,11,58]. Other aspects of a stimulus shown to be important for the perception of human or biological movement include physical shape [27,46], the temporal properties of the physical body [53], the temporal and spatial properties of its motion [4,5,14,25,28], and the topography of the motion [10,41]. Furthermore, the volitional nature of the actions may also be an important factor in the perceived ‘humanness’ of a stimulus [55]. In fact, a recent study by Iacoboni and colleagues [29] indicated that the activity in the mirror neuron system was modulated based on both whether the observed action was embedded in a context and the specific intention of that action. It has been proposed by Gallese [20] that the observation/execution matching system provided by the mirror neuron system may allow humans to have a “shared manifold” for more internal states such as goals and intentions.

The goal of this study was to characterize the specific properties of stimuli that produce activation of the human mirror neuron system, with an emphasis on properties that

are critically relevant for the perception of humanoid robots. Since it is unclear whether robot actions suppress the mu wave, Experiment 1 determined whether the observation of an action performed by a robot hand with human-like characteristics (i.e., four fingers and opposable thumb) is sufficient to activate this biological action perception system. Since the presence of a target object appears to modulate the mu rhythm when observing human actions [40], Experiment 1 also examined the capacity for robot actions with and without target objects to differentially activate the human mirror neuron system. This study has clear implications for both the neural basis of robot action perception and the flexibility of the mirror neuron system. Experiment 2 examined the influence of volition during the observation of human actions. If the mu wave were differentially modulated by volitional actions, this would provide further support for the role of mirror neurons in the understanding of the intentions of others and thus the creation of a theory of other minds. This study may also lead to a better understanding of the critical features necessary for successful development of an interactive humanoid robot.

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Subjects

Our original sample consisted of 20 undergraduate students, recruited through the UCSD Psychology Department Subject Pool, who received class credit for their participation. Three subjects' data were excluded from analysis due to technical problems with the EEG apparatus, resulting in a final sample of 17 subjects (13f, 4m) ages 18–23 ( $M = 19.6$ ,  $SD = 1.50$ ). Four subjects were left-handed based on a self-report measure. The project protocol was reviewed and approved by the UCSD Human Research Protections Program and all subjects gave written consent.

#### 2.1.2. Procedure

EEG data were collected during three conditions: (1) *watching video of a robot picking up a ball* (Fig. 1, Experiment 1a). Subjects viewed a black and white video of a mechanical, five-fingered, robot arm which appeared to be mechanically driven, but in reality was controlled by a human experimenter outside of camera view. The arm was seen reaching toward, grasping, and picking up a ball. Care was taken to assure that the stimulus had the correct kinematics (both spatial and temporal) and phasic properties of typical goal-directed actions. (2) *Watching video of a robot opening and closing its hand with no object present* (Fig. 1, Experiment 1b). Subjects viewed a black and white video of the same robot arm reaching out and mimicking a grasping action. The basic visual properties of this video were matched to those of the object-directed robot stimulus except for the presence of a ball. (3) *Watching visual white noise* (Fig. 1, Experiment 1c). In this video, full-screen television static was presented as a baseline condition. All videos were 80 s in length and were viewed at a distance of 96 cm. In both of the videos, robot movement occurred at a rate of 1 Hz. All conditions were presented twice to obtain enough clean EEG data for analyses. The order of the conditions was counterbalanced across subjects.

To ensure that subjects attended to the video during the experimental conditions, they were asked to engage in a continuous performance task. Between four and six times during each of the 80-s videos, the stimuli stopped moving for one cycle (a period of 1 s). Subjects were asked to count the number of times this occurred and report it to the experimenter at the end of each video session.

#### 2.1.3. EEG data acquisition

Disk electrodes were applied to the face above and below the left eye and behind each ear (mastoids). Average activity of the linked mastoids was used as a reference. Data were collected from 13 electrodes embedded in a cap, at the following scalp positions: F3, Fz, F4, C3, Cz, C4, P3,

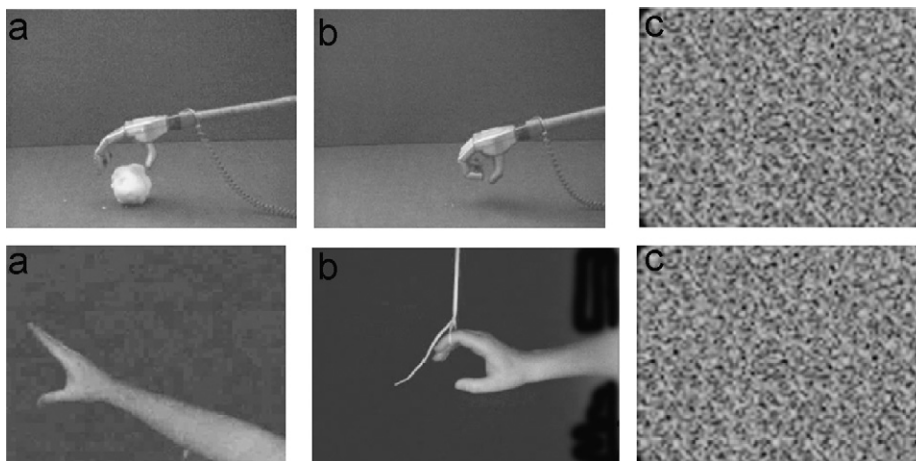


Fig. 1. Frames from the videos used in Experiment 1: (a) robot picking up a ball, (b) robot opening and closing its hand with no object, (c) baseline, visual white noise and Experiment 2: (a) volitional hand action, (b) nonvolitional hand action, (c) baseline, visual white noise.

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 5 k $\Omega$  both before and after testing. Once the electrodes were in place, subjects were seated inside an acoustically and electromagnetically shielded testing chamber.

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.

#### 2.1.4. Data analysis

EEG oscillations in the 8–13 Hz frequency band recorded over occipital cortex are influenced by states of expectancy and awareness [34]. Therefore, the first and last ten seconds of each block of data were removed from all subjects in order 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 blink and eye and head movements were manually identified in the EOG recording, and artifacts during these intervals were removed prior to analysis using traditional methods [26]. For each cleaned segment the integrated power in the 8–13 Hz range was computed using a fast Fourier transform. Data were segmented into epochs of 2 s beginning at the start of the segment. Fast Fourier transforms were performed on the epoched data (1024 points). A cosine window was used to control for artifacts resulting from data splicing.

Power in the mu frequency band at scalp locations corresponding to left and right sensorimotor cortex (C3 and C4) during the observation of robot hand actions with and without objects was compared to power during the baseline (visual white noise) condition. This was done by computing the log ratio of the power in these conditions. Although data were obtained from electrodes across the scalp, mu rhythm is defined as oscillations measured over sensorimotor cortex, thus only data from C3 and C4 are presented. 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 brain 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 a value greater than zero indicates enhancement.

To test the effect of the presence of an object on mu wave suppression during robot action observation, we used a statistical model based on previous research by Muthukumaraswamy and colleagues [40]. Actions with and without objects were compared using a two-way (object by hemisphere) repeated measures ANOVA.

We further examined whether robot action observation had a significant effect on mu suppression. For this purpose, we utilized statistical procedures previously implemented by several research groups designed to evaluate changes in mu power from a baseline condition [3,44,48,51]. *T*-tests were performed to examine suppression as indicated by a log ratio significantly less than 0 in left and right hemisphere electrodes (C3 and C4) during the experimental conditions.

## 2.2. Results

### 2.2.1. Behavioral performance

All subjects performed with 100% accuracy on the continuous performance tasks. We thus infer that any differences found in mu suppression are not due to differences in attending to the stimuli.

### 2.2.2. Mu suppression

A 2 (target object present vs. absent) by 2 (left vs. right hemisphere) within-subjects factorial analysis of variance revealed no significant main effects of presence of a target object (Fig. 2:  $F(1,16) = 0.744, p > 0.40$ ) nor hemisphere ( $F(1,16) = 2.148, p > 0.16$ ), nor a significant presence of target object by hemisphere interaction ( $F(1,16) = 0.096, p > 0.76$ ).

*T*-tests comparing mu suppression during each of the experimental conditions to zero showed significant suppression from baseline in mu oscillations over both the left and right hemispheres during the object-directed movement condition (Fig. 2a: C3  $t(16) = -2.75, p < 0.007$ ; C4  $t(16) = -2.00, p < 0.03$ ). During the no object condition, subjects showed significant suppression over the left hemisphere (Fig. 2b: C3  $t(16) = -2.85, p < 0.006$ ), and

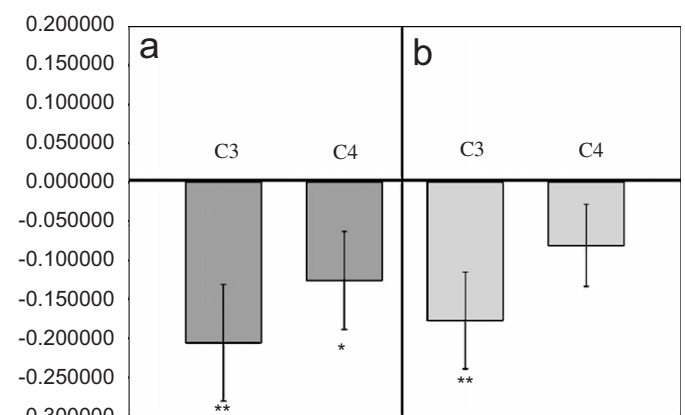


Fig. 2. Mu suppression to experimental conditions in Experiment 1. Bars represent the mean log ratio of power in the mu frequency (8–13 Hz) during the robot actions with (a) and without (b) objects conditions, over the power in the baseline condition for scalp locations C3 and C4. Error bars represent 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 suppression is indicated by asterisks, \* $p < 0.05$ , \*\* $p < 0.01$ .



marginally significant suppression over the right hemisphere (Fig. 2b: C4  $t(16) = -1.54$ ,  $p = 0.0603$ ).

### 2.3. Discussion

Results from this study suggest that EEG mu power is suppressed by robot actions both with and without target objects. Since the mu frequency band overlaps with the posterior alpha frequency band (recorded from O1 and O2) and the generator for posterior alpha can obscure that for mu, it is possible that recordings from C3 and C4 might be affected by this posterior activity. Other than central leads, no other electrodes showed a consistent pattern of suppression in the frequency band of interest, indicating that the mu suppression observed in C3 and C4 were not mediated by posterior alpha activity.

We found no significant difference in the extent of suppression between the object-directed and non-object directed conditions. This lack of difference is surprising given the previous results of Muthukumaraswamy and colleagues [40] who investigated mu wave suppression to observation of object-directed and pantomimed actions. These researchers found significantly more suppression to the observation of object-directed human movements as compared to mimed actions. However, the results of the current study suggest that suppression to robot actions may not distinguish between actions with and without objects.

It is possible that the high-density acquisition system that Muthukumaraswamy and colleagues used is more sensitive to modulations in mu amplitude than the system utilized in the current study. Muthukumaraswamy et al. used averages of 8 individual electrodes per hemisphere to index suppression whereas our suppression values were derived from one electrode per hemisphere (C3 and C4). Muthukumaraswamy and colleagues also used individually defined 2 Hz frequency bands based on topography as their measure of the mu wave and averaged discrete trials of visual stimuli while we defined the mu band more extensively as any EEG activity falling within 8–13 Hz and averaged a block of repeatedly performed actions.

An alternative explanation for the differences between the current results and those reported by Muthukumaraswamy and colleagues may have been related to the subject's ability to attribute mental states to the observed actions. Muthukumaraswamy and colleagues suggest that their subjects were able to both infer somatosensory activation (see [33]) and attribute goals to the performer of the object-directed actions. In our study, the subjects may have had difficulty attributing either somatosensory or higher order cognitive processes such as goals to robots (as suggested by Itakura [31]). Despite this lack of differentiation based on the presence of an object, it is promising for the field of robotics that actions performed by a human-like robot, even those without a clear and visible goal, may be sufficient to activate the mirror neuron

system, a system previously thought to be selective for biological actions.

## 3. Experiment 2

### 3.1. Method

#### 3.1.1. Subjects

Our sample consisted of 20 subjects (13f, 7m) ages 18–39 ( $M = 21.2$ ,  $SD = 4.43$ ). Three subjects were left-handed. Subjects were recruited through the UCSD Psychology Department Subject Pool and received class credit for their participation. This project was reviewed and approved by the UCSD Human Research Protections Program, and all subjects gave written consent.

#### 3.1.2. Procedure

EEG data were collected during three conditions: (1) *watching video of a hand moving volitionally* (Fig. 1, Experiment 2a). Subjects viewed a black and white video of an experimenter opening and closing the right hand. (2) *Watching video of a hand being moved by a string* (Fig. 1, Experiment 2b). Subjects viewed a black and white video of an experimenter's hand being pulled open and closed by a string. The basic visual properties of this video were matched to those of the volitional hand stimulus. (3) *Watching visual white noise* (Fig. 1, Experiment 2c). Full-screen television static was presented as a baseline condition. All videos were 80 s in length and viewed at a distance of 96 cm. Both of the hand videos moved at a rate of 1 Hz. As in Experiment 1, all conditions were presented twice in order to obtain enough clean EEG data for analyses and the order of the conditions was counter-balanced across subjects.

To ensure that subjects attended to the video stimuli during the experimental conditions, the same continuous performance task described in Experiment 1 was used. All EEG data acquisition and analyses were conducted in the same manner as Experiment 1.

#### 3.1.3. Data analysis

Power in the mu frequency band at scalp locations corresponding to sensorimotor cortex (C3 and C4) during the observation of volitional and nonvolitional action conditions was compared to power during the baseline (visual white noise) condition by forming the log ratio of the power in these conditions. To test the effect of volition on mu wave suppression during human action observation, we used the same statistical model implemented in Experiment 1. The volitional and nonvolitional hand movement observation conditions were compared in a two-way (volition by hemisphere) repeated measures ANOVA.

Furthermore, we examined whether both the volitional and nonvolitional conditions resulted in significant mu wave suppression. As in Experiment 1,  $t$ -tests were performed to examine suppression as indicated by a log ratio significantly

less than 0 in left and right hemisphere electrodes (C3 and C4) during the experimental conditions.

### 3.2. Results

#### 3.2.1. Behavioral performance

Similar to Experiment 1, all subjects performed with 100% accuracy on the continuous performance tasks. Therefore, we infer that any differences found in mu suppression are not due to differences in attending to the stimuli.

#### 3.2.2. Mu suppression

A 2 (volitional vs. nonvolitional) by 2 (left vs. right hemisphere) within subjects factorial analysis of variance revealed no main effect of volition (Fig. 3:  $F(1,19) = 0.012$ ,  $p > 0.91$ ) nor hemisphere ( $F(1,19) = 0.604$ ,  $p > 0.44$ ), nor a significant volition by hemisphere interaction ( $F(1,19) = 1.066$ ,  $p > 0.31$ ).

*T*-tests comparing mu suppression during each of the experimental conditions to zero showed significant suppression from baseline in mu oscillations over both the left and right hemispheres during both the volitional (Fig. 3a: C3  $t(19) = -4.65$ ,  $p < 0.0001$ ; C4  $t(19) = -3.46$ ,  $p < 0.001$ ) and nonvolitional (Fig. 3b: C3  $t(19) = -3.40$ ,  $p < 0.002$ ; C4  $t(19) = -2.96$ ,  $p < 0.004$ ) hand movement conditions.

### 3.3. Discussion

Results indicate that EEG power in the mu spectrum recorded over left and right sensorimotor cortex is suppressed during the observation of human action regardless of whether that action is volitional or nonvolitional. As in Experiment 1, other than central leads, no

electrodes showed a consistent pattern of suppression in the frequency band of interest. These results indicate that the modulations of mu activity observed at C3 and C4 were not mediated by posterior alpha activity. The findings suggest that volition is not a necessary property for activation of the mirror neuron system during the observation of human actions. Further, volition may not be necessary for naturalistic social interaction, thus may not be a property that researchers will have to incorporate into their humanoid robots. However, it is also possible that the overrepresentation of human actions in natural situations as volitional may lead to a persistence in the activation of the mirror neuron system during the viewing of human actions—even nonvolitional actions. If so, this may be considered a form of priming that cannot be overcome in the 2-min presentation used in this study. Prolonged exposure to the observation of nonvolitional biological actions on the order of hours or days might result in a reduction of mu suppression to such actions.

### 3.4. Additional analyses

To test the effect of ‘humanness’ of the stimulus on mu wave suppression, the responses during the volitional hand movement observation condition in Experiment 2 and the robot action without object condition in Experiment 1 were compared with a two-way (‘humanness’ by hemisphere) between subjects ANOVA. There was no significant main effect of humanness (Fig. 4:  $F(1,35) = 1.266$ ,  $p > 0.27$ ), however, there was a significant hemisphere effect ( $F(1,35) = 4.425$ ,  $p < 0.05$ ). There was no significant

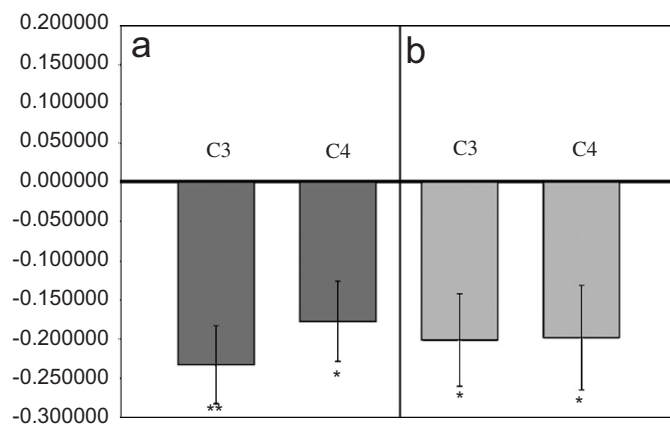


Fig. 3. Mu suppression to experimental conditions in Experiment 2. Bars represent the mean log ratio of power in the mu frequency (8–13 Hz) during the volitional hand movement (a) and nonvolitional hand movement (b) conditions, over the power in the baseline condition for scalp locations C3 and C4. Error 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 suppression is indicated by asterisks, \* $p < 0.005$ , \*\* $p < 0.0001$ .

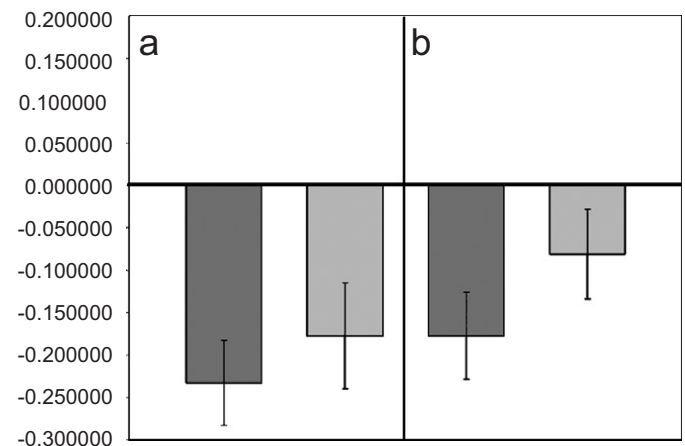


Fig. 4. Post hoc comparison of the average mu suppression during the action without an object robot hand movement condition of Experiment 1 and volitional human hand movement condition of Experiment 2. Dark gray bars represent the mean log ratio of the power in the volitional hand movement condition over the power in the baseline condition, while light gray bars represent mean log ratio of the power in the action without object robot condition over the power in the baseline condition for scalp locations C3 (a) and C4 (b). Error bars represent the standard error of the mean. There was not a significant main effect of humanness on mu wave suppression.

interaction ( $F(1,35) = 0.322, p > 0.57$ ). In order to determine whether the hemisphere effect was driven by either the robot or human condition, pair-wise  $t$ -tests with alpha corrections were conducted on left hemisphere versus right hemisphere robot and left hemisphere versus right hemisphere human separately. There was no significant effect for either group. (robot:  $t(16) = 1.42, p > 0.17$ ; human:  $t(19) = 1.65, p > 0.11$ ).

These findings, showing that human movement and robot movement suppressed the mu wave to relatively the same extent, suggests that there may not have been a difference in mirror neuron activation to the robot relative to the human stimuli. Previous work has suggested that non-biological stimuli do not activate the mirror neuron system [17]. However, such a conclusion may need to be amended, as it appears that an inanimate robot (albeit with human-like physical properties) can also activate this system.

### 3.5. General discussion

In this study, the properties of stimuli that would modulate mirror neuron activity were examined, with an emphasis on those properties relevant to human–robot interaction. Experiment 1 found that observation of actions performed by robots both with and without target objects resulted in suppression of the mu wave. This finding indicates that robot actions may be able to activate the mirror neuron system, previously thought to be specifically selective for biological actions. Additionally, no evidence was found of a difference in magnitude of mirror neuron activity between the object and no object conditions. An alternative explanation for the apparent inconsistency with the human literature may be a result of the observer having difficulty attributing somatosensory activity or goals to the robot stimuli. However, because there were many methodological differences between the previous human study and the current robot study, it is possible that other factors may have played a role in the lack of modulation based on the presence of a goal. In Experiment 2, the effect of volition on mirror neuron activity to observation of human actions was investigated. It was found that the mu wave was suppressed to both volitional and nonvolitional actions, with no significant difference in the suppression between conditions. These findings indicate that the mirror neuron system is not selective for volitional actions performed by human hands.

As both human and robot actions are extremely complex, complexity of movement may also be a factor in modulation of the mu wave. For this reason, previous studies of mu wave suppression [1,15,44] have used non-biological stimuli matched for complexity as a control. In these studies power in the mu wave was not suppressed to the non-biological stimuli indicating that the suppression was not simply a result of the complexity of human action. That being said, future research should compare suppression during animate

or robot actions to that of inanimate complex motion stimuli matched for low-level properties.

To our knowledge, Tai and colleagues [61] are the only other group that has attempted to investigate mirror neuron activity during the observation of robot actions. In their study, subjects watched both an experimenter and a robot performing grasping actions. When observing the human making a grasping action, glucose metabolism (as measured by Positron Emission Tomography (PET)) was increased in the area of the premotor cortex indicating activity of the mirror neuron system. Alternatively, when subjects observed the robot making the action, no such activity was present. The apparent discrepancy between Tai et al.'s study and the current study can be explained by differences in stimulus presentation and interpretation of findings.

Single unit macaque mirror neuron studies indicate that the mirror neuron system activates to observation of object-directed actions, but does not respond when the action is performed indirectly—by using a tool [21]. Gallese and colleagues' interpretation of this finding was that mirror neurons were selective to direct hand–object interactions. However, Tai and colleagues reinterpreted this finding as evidence for mirror neuron selectivity for biological action. In the Tai et al. study, the robot was explicitly controlled by a button press by the experimenter, in clear view of the subject, essentially turning the robot into a tool. A human did not explicitly control our robot hand; In fact, all possible steps were taken to make the robot appear to be autonomous. Based on Gallese and colleagues' data, one would predict no mirror neuron activation to Tai and colleagues' stimuli (indirect actions). However, by utilizing stimuli that depict direct actions of robots, we were able to examine the possible role of the mirror neuron system to the observation of autonomous robot actions.

Results from the current studies leave open the opportunity to utilize mu suppression and functional imaging techniques such as fMRI and PET as tools for examining the capacity of a given humanoid robot for activating the social/biological perception system in human observers (including the mirror neuron system). Researchers, such as Ito and Tani [32], Breazeal and colleagues [6–8], and Littlewort and colleagues [36], who are developing anthropomorphic robots, may be most successful if their robots are able to tap into the powerful social interaction system inherent in humans. Future research should utilize mu wave suppression and other measures of mirror neuron activity as a *neural* “Turing test” [59,60,63] for assessing whether humans perceive the robot anthropomorphically. The results of such studies could be useful for the analysis and development of future interactive robots, and further our understanding of both physical characteristics (like the presence of five fingers, or a human-like face) and behavioral characteristics (such as volition, imitation, and language) that may facilitate prolonged robot–human interactions.

Future research should also focus on the degree to which experience with robots that have human-like physical and behavioral characteristics activate social perception systems in the human brain. Particular attention should be focused on which properties of robot stimuli are necessary or sufficient to activate the mirror neuron system in human observers. Experimental designs may include studies of robot actions during synchronous versus asynchronous social robot-human interactions, studies during observation of human-like and non-human-like robot facial actions, studies during observation of anthropomorphic versus non-anthropomorphic hand actions (e.g., five-fingered versus three-fingered), studies during observation of symbolic versus asymbolic gestures, etc. Due to limitations on movement during neuroimaging, it may be useful to implement priming paradigms, as well (e.g., live synchronous versus asynchronous human subjects–robot interactions followed by neuroimaging during observation of simple robot actions).

As the spatial resolution of EEG is low, it is difficult to exclude the possibility that our findings are a result of activity in other regions affecting the mirror neuron system, such as the superior temporal sulcus (STS) and area MT/V5, as opposed to direct modulation of the mirror neuron system itself. Additionally, based on the results of the current study, it appears that the effect of properties such as volition and target presence may be relatively small and, as such, techniques such as fMRI and PET, which have better spatial resolution than EEG, may have greater power to tease apart the differential effects of these properties on the modulation of the mirror neuron system specifically. If so, the results of future studies could be highly successful in quickly advancing the development of more human-like robots.

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