

Title: Effects of handedness and viewing perspective on Broca's area activity

Short title: Broca's area and observer's motor experience

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Abstract

Given that we understand observed action via a sensorimotor link that maps the action onto our motor representations, activity of the mirror neuron system may depend on the sensory and motor features of that action. To investigate this hypothesis, we recorded the activity of Broca's area (BCA) in right-handed subjects during observation of chopstick use via near-infrared spectroscopy. Subjects watched the right- or left-handed action recorded from the first- or third-person perspective. Results show that the handedness of the observed action influences BCA activity, but the viewing perspective does not. We conclude that the motor aspect of the observed action is critical for BCA activation because this aspect is more relevant for simulating the observed action than the visuospatial aspect.

Keywords

Action observation; Broca's area; Handedness; Hierarchy; Language; Mirror neuron system; Music; Perspective; Syntax

Introduction

Broca's area (BCA) is typically known for its role in linguistic processing, but it also contributes to planning, imitation and observation of action. BCA activity is influenced by the visual appearance of an observed action. Specifically, Brodmann area (BA) 44, a part of BCA, encodes features of an observed action, such as trajectory and hand shape [1, 2]. The direct-matching hypothesis [3] holds that we understand an observed action by mapping the visual representation of the action onto our motor representation of the same action. Because motor representation is generated via physical experience (for example, the sensorimotor link between a hand motion and the vision of this hand-arm posture), the activity of the mirror neuron system may be affected by the sensory and motor aspects of the kinematic features of an observed action. A recent study showed that in monkeys trained to grasp food with a tool, most of the hand-grasping mirror neurons in F5 (the monkey homologue of human BA 44 [4]) become active while observing the grasping of food with novel tools the monkey had never used [5]. But, as the authors mention, the question of whether the BCA (or F5) activity is due to the sensory aspect or to the motor aspect of the observed action has not been clarified.

If motor representation is shaped through a sensorimotor link, people's BCA activities will be determined by their sensory experiences of how they usually see their own body parts when performing an action. This visual aspect of an observed action (e.g., the viewing perspective) may influence the observer's BCA response. However, Jackson et al. [6] found no differential BCA activity

during imitation and observation of intransitive limb motions seen from the first-person perspective (1PP) versus the third-person perspective (3PP). As the authors of this study mention, BCA probably did not exhibit an effect of perspective because it is minimally responsive to simple intransitive actions. Thus, if the subjects had observed transitive, meaningful actions from different perspectives, perspective effects would likely have appeared in BCA.

Similarly, if motor representation is shaped through a sensorimotor link, people's BCA activities will be determined by their motor experiences of how they usually move their body parts when performing an action. This motor aspect of an observed action (e.g., handedness) may influence the observer's BCA response. Johnson-Frey et al. [7] found that the activity of BCA (BA 44) during a pantomime of tool use with the dominant hand was somewhat different from that during a pantomime performed by the non-dominant hand. In this case, the use of simple tools (such as a hammer or pliers) was pantomimed, which may have minimized the effects of handedness because the use of such tools does not require much practice and could be performed with either hand. Thus, if tools requiring more practice and greater hand preference had been used for the pantomime, the results of this experiment might have shown the effects of handedness more clearly.

What remains unclear from these studies is whether and how sensory and motor aspects of the observed action, such as handedness and viewing perspective, influence BCA activity in response to viewing a previously acquired

action. Indeed, behavioral evidence indicates that the mental representation of others' behavior is affected by both perspective taking and the handedness of action [8]. Here, to determine whether the sensory or motor aspect is more relevant to BCA activity, we investigated BCA activity while right-handed subjects observed, from either the 1PP or the 3PP, chopstick use performed using either the right or the left hand. We expected that 1PP observation of right-handed action would robustly resonate with the observer's own motor representation and elicit high BCA activity. Varying handedness and perspective allowed us to examine which of these factors is more relevant to BCA activity. Although our subjects could not use chopsticks with their left hands, if visuospatial experience is the critical factor driving the BCA response, then the 1PP observation of left-handed action should elicit high BCA activity because subjects' own hand-arm postures are usually seen only from the 1PP when using chopsticks. In contrast, although one's own chopstick use is rarely observed from the 3PP, if motor experience is the critical factor driving the BCA response, then the 3PP observation of right-handed action should elicit high BCA activity because our subjects could only use chopsticks with their right hands.

Methods

Subjects

Nine healthy, right-handed adults (six males and three females, aged 23–40 years) who were able to use chopsticks skillfully only with their right hand participated in this study. Handedness was checked using the Edinburgh

Handedness Inventory [9] (mean laterality quotient, 87.0; range, 77.8–100; median, 84.6). Written informed consent to take part in this study was obtained following procedures approved by the Ethical Committee of the Primate Research Institute, Kyoto University.

Stimuli

The stimulus set for this study consisted of video clips in which an actor moved colored sugarplums from one saucer to another at a pace of one piece of candy per second. First, the actor's performance was filmed simultaneously by two digital video cameras: one filmed the action from the 1PP, and the other from the 3PP. Each movie (640 x 480 pixels, 30 frames/s) was cut into 10-s clips, after which eight 10-s clips were chosen. Then, two different 10-s clips were combined to make four 20-s stimulus movies. To exclude unpredictable effects due to the starting position of the arm and make the transition between clips smooth, 0.5-s fade-in and -out periods were added to the beginning and end of each 10-s clip. Finally, these 20-s movies were flipped horizontally, resulting in four types of movies (two handedness x two perspectives) that were generated from an identical performance. Subjects viewed the movies from the 1PP (as if the subjects were actually manipulating the objects with either their own right [R1 condition] or their own left [L1 condition] hand) and from the 3PP (as if they were watching another person manipulate the objects with either the right [R3 condition] or the left [L3 condition] hand). Example static pictures from the four conditions are shown in Figure 1 (see Supplemental Video 1 for additional details). Stimuli were presented at the center of a 17-inch LCD monitor placed

approximately 70 cm from the subject's head.

Fig. 1 around here

Procedure

Each experimental session consisted of 16 trials. Each stimulation period lasted 20 s, during which any 1 of 16 movies (4 movies x 4 conditions) was presented. The length of the inter-stimulus interval was 30 s. All four combinations of hand and perspective conditions were presented four times in a pseudo-random order. Every condition was presented once in four successive trials, and the same hand or perspective condition was presented in no more than three consecutive trials. Subjects were instructed to watch the video clips carefully during the stimulation period, paying attention to the action while gazing at the fixation point at the center of the monitor. The beginning of each stimulus movie was accompanied by a tone. Subjects were asked to open their eyes gently when they heard the tone and close their eyes gently when the stimulus movie disappeared. Thus, subjects' eyes were closed during the rest period. The entire experiment lasted approximately 15 min.

Near-infrared spectroscopy (NIRS) measurements

We used an NIRS instrument (ETG-100, Hitachi Medical Corporation, Tokyo, Japan) to measure changes in oxygenated hemoglobin (oxy-Hb) concentration

during the task. An NIRS shell was placed over the left inferior frontal region. We measured responses from the channel that was determined as a point between the optode nearest to F7 (in the international 10–20 system) and its posteriorly adjacent optode. Because F7 on the scalp projects onto the cortical surface at BA 45/47 [10, 11], our results presumably reflected activity from BCA. The sampling rate was 10 Hz. NIRS recording is more tolerant of body movements and blinking than functional magnetic resonance imaging (fMRI) and electrophysiological recording, which allows subjects to perform tasks more comfortably and under fewer bodily constraints but comes at the expense of the advantages of the other procedures (e.g., high temporal- and spatial-resolution recording and depth recording). NIRS data are highly consistent with fMRI data [12].

Cortical responses for each trial were stimulus-locked and extracted from continuously sampled oxy-Hb data. Pulsatory fluctuations were removed from the results by smoothing the oxy-Hb time series backward in time with a 5-s moving window. Baseline drift was then corrected by linear interpolation between the time point of task onset and the time point of stimulus onset of the next trial. The time series data were then averaged over trials for each condition. Finally, a mean oxy-Hb value per time point within a peri-stimulus period (a 20-s time window from 5 s after stimulus onset to 5 s after stimulus offset) was calculated for each condition. Before NIRS data were compared across conditions, the signal for each condition was standardized individually by dividing the mean oxy-Hb value within the peri-stimulus period in each condition

by the root mean square of the mean oxy-Hb values across all four conditions to eliminate the influence of inter-subject variance on inter-condition variance in each subject. The standardized signal values were then submitted to a Wilcoxon signed-rank test to survey the general effects of handedness of the actor ([R1 + R3] vs. [L1 + L3]), perspective of observation ([R1 + L1] vs. [R3 + L3]) and their interaction ([R1 + L3] vs. [L1 + R3]) on cortical responses. The significance level was set to 5%. To investigate the specific effects of handedness (R1 vs. L1 and R3 vs. L3), perspective (R1 vs. R3 and L1 vs. L3) and interaction (R1 vs. L3 and R3 vs. L1), *post-hoc* analyses were performed using a Wilcoxon signed-rank test. For each of these comparisons, the significance level was set at 2.5%.

Results

Cortical activations could be categorized into three patterns. Three typical examples of the averaged time series data and the mean oxy-Hb value within the peri-stimulus period (insets) are shown in Figure 2. In four subjects, the mean signal intensity was positive only for right-handed actions that were observed from the 1PP (R1 condition; Fig. 2a, subject DH shown). Three subjects showed a positive mean value for right-handed actions that were independent of perspective (R1 and R3 conditions), whereas the signals were weak or negative for left-handed actions (Fig. 2b, subject DK shown). The remaining two subjects exhibited negative values under all conditions (Fig. 2c, subject TH shown).

Fig. 2 around here

Next, standardized signal values were compared between conditions (Fig. 3). Statistical analysis revealed that observations of right-handed and left-handed actions resulted in different BCA activities ($n = 9$, $Z = 2.310$, $p = 0.021$). Subsequent comparisons revealed a significant difference in BCA activity between the R1 and L1 conditions ($n = 9$, $Z = 2.310$, $p = 0.021$, Fig. 3a) and a marginally significant difference between the R3 and L3 conditions ($n = 9$, $Z = 2.073$, $p = 0.038$, Fig. 3b). Although there was an overall difference in the BCA activity between the 1PP and 3PP observations ($n = 9$, $Z = 2.073$, $p = 0.038$), *post-hoc* analysis did not show a difference in BCA activity between either the R1 and R3 conditions ($n = 9$, $Z = 1.836$, $p = 0.066$, Fig. 3c) or the L1 and L3 conditions ($n = 9$, $Z = 1.125$, $p = 0.260$, Fig. 3d). Given that there were overall effects of handedness and perspective but no significant interaction between them ($n = 9$, $Z = 1.007$, $p = 0.314$), one might expect that the R1 action recruited BCA to a greater extent than the L3 action ($n = 9$, $Z = 2.310$, $p = 0.021$); however, the difference between the R3 and L1 actions was not significant ($n = 9$, $Z = 0.889$, $p = 0.347$).

Fig. 3 around here

Discussion

Each of our subjects had used chopsticks with their right hands for more than 20 years. Thus, their motor representation of chopstick use was established by right-handed action viewed from the 1PP. As expected, their BCAs responded most strongly to actions viewed as if the subjects were actually performing the acts themselves. BCA activity seemed to be determined by an interaction of sensory and motor aspects of an observed action. However, the high BCA response to 1PP observation of right-handed action generalized to 3PP observation of right-handed action but not to 1PP observation of left-handed action. Therefore, the motor aspect of the observed action is more relevant to BCA activity than the visuospatial aspect. This conclusion is supported by recent studies showing that F5 neurons in monkeys respond to the use of tools the monkeys have never seen [5] and that 1PP observation of food grasping actions activates only slightly more F5 neurons than 3PP observation, although about 3/4 of F5 mirror neurons exhibit perspective-dependent activity [13].

The macaque F5 receives its major input from multisensory regions of the inferior parietal lobule (IPL), and this fronto-parietal connection is supposed to be involved in transforming visual information into action [14]. Previous studies have demonstrated that right IPL activation is stronger in conditions of 3PP imagery and imitation trials than 1PP [6], indicating a role for this region in visuospatial analysis [15]. On the contrary, left IPL activation is stronger during 1PP simulation than it is under 3PP conditions, indicating a role for this region in

action simulation [6, 15]. Therefore, BCA activity during observation of previously learned actions, concurrent with enhanced activity of the left IPL, is thought to reflect action simulation processes based on pre-existing motor representations [16]. Although we did not record the IPL activity, the BCA activity observed in our study was likely accompanied by an activation of the left IPL and is thus likely related to action simulation rather than visuospatial analysis. Further supporting the relationship between BCA activity and action simulation are our findings that BCA activity was generally greater in 1PP than 3PP observation and that BCA activity was determined mainly by motor aspects of the observed action. In sum, we argue that the observation of previously acquired actions generates action planning based on the observer's own motor representation and, accordingly, that the motor aspects (i.e., handedness) of the observed actions are more relevant to BCA activity than its visuospatial aspects (i.e., viewing perspective or hand-arm posture).

Before we reached the conclusion that the motor aspects of observed actions readily activate motor representation in BCA, we had to rule out several possibilities. First, our results showed marginally greater BCA activation to 3PP observation of right-handed actions than left-handed actions. However, a previous study reported that BCA and the corresponding cortex of the right hemisphere are more active during 3PP imitation of left-handed actions (in this study, subjects moved a finger that was in the same location of a finger they observed a model move) than 3PP imitation of right-handed actions (when subjects moved the same finger that the model moved) [17]. Despite the

difference in task types between this study and the present study (i.e., observation versus imitation), this discrepancy may be due to the task demand. Because increased BCA activity in their study was associated with stronger activity of the right IPL, their task probably required spatial analysis of the position of the moved finger, while our action observation task implicitly required an action simulation. Thus, our results and those of the other study probably show BCA activities that are associated with different mechanisms. However, all we asked of our subjects was to view the movies. If we had explicitly asked the subjects to simulate the observed action or to judge the direction in which the hand moved a piece of candy, the BCA activity we observed may have been somewhat different.

Second, our subjects generally showed greater BCA responses to right-handed than left-handed actions. One may suspect that the observed handedness effect reflected cortical activity induced by a contralateral effector. However, studies in the monkey suggest that visuomotor neurons in F5 are responsive to actions that share the same goal but are performed with different effectors. In contrast, the activities of neurons in the primary motor and parietal cortices are determined by elementary movements and the laterality of the effector [18, 19]. Therefore, although we recorded BCA activity only from the left hemisphere, the observed handedness effect within BCA was likely related to the observers' motor representation rather than the contralateral hand movement itself.

Finally, the BCA activity reported here could have been induced by internal

vocalization. However, BCA activity varied across conditions even though the intention, goal and meaning of the action were the same, and the global appearance of the observed actions was very similar across conditions. Thus, we assume that differential BCA activity across conditions was not related to internal speech. In sum, the BCA activity we found was related to the observer's motor representation and was more sensitive to the motor aspect than the sensory aspect of the observed action.

How does BCA, an area typically known for its role in linguistic processing, represent observed actions? Recent studies have demonstrated that BCA processes the rapid segmentation and hierarchical sequencing of elements in both language and music domains [20 - 22]. Such principles are also inherent to meaningful actions, such as tool use [23]. For instance, the action of using chopsticks is organized from meaningful segments (e.g., picking up, holding, moving and releasing food), which are abstracted from an ongoing chain of individually meaningless movements of the tool, objects, fingers and arm. It has been suggested that BCA and the corresponding cortex of the right hemisphere are involved in online processing of the hierarchical sequence during the planning and observation of action [24, 25]. Thus, we speculate that the BCA activation observed in our study represents a domain-general 'syntactical' processing of hierarchically organized body movements underlying chopstick use.

Conclusion

Our findings suggest that, when observing a previously acquired action, the motor aspect of the observed action is more relevant to the observer's motor representation and thus induces a stronger BCA activation than the visuospatial aspect. Such BCA activity is supposed to be involved in simulating how one would organize one's own body movements to achieve the observed action.

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Figure legends

Figure 1. Static examples of stimulus movies.

Examples of the combinations of two handedness and two perspective conditions are shown. Subjects were shown the movies in color (see supplemental video).

Figure 2. Typical examples of the NIRS results.

Time series data of oxy-Hb signal for three typical subjects are shown across time after stimulus onset. Shaded areas indicate the stimulus period. Plots in the insets represent the mean oxy-Hb value within the peri-stimulus period. See text for details.

Figure 3. Comparison of results between conditions.

Comparison of standardized signal values between right- vs. left-handedness conditions for the 1PP (a) and 3PP (b) observations and between the 1PP vs. 3PP conditions for right-handed (c) and left-handed (d) actions. Points from the same subject are connected.

Supplemental video 1. Examples of stimulus movies.

Four types of 10-s clip are shown in order: a right-handed action seen from the first-person perspective (R1), a left-handed action seen from the first-person perspective (L1), a right-handed action seen from the third-person perspective (R3) and a left-handed action seen from the third-person perspective (L3). In an actual trial, two different clips of the same condition were combined to make a

20-s stimulus movie.

Figure 1.

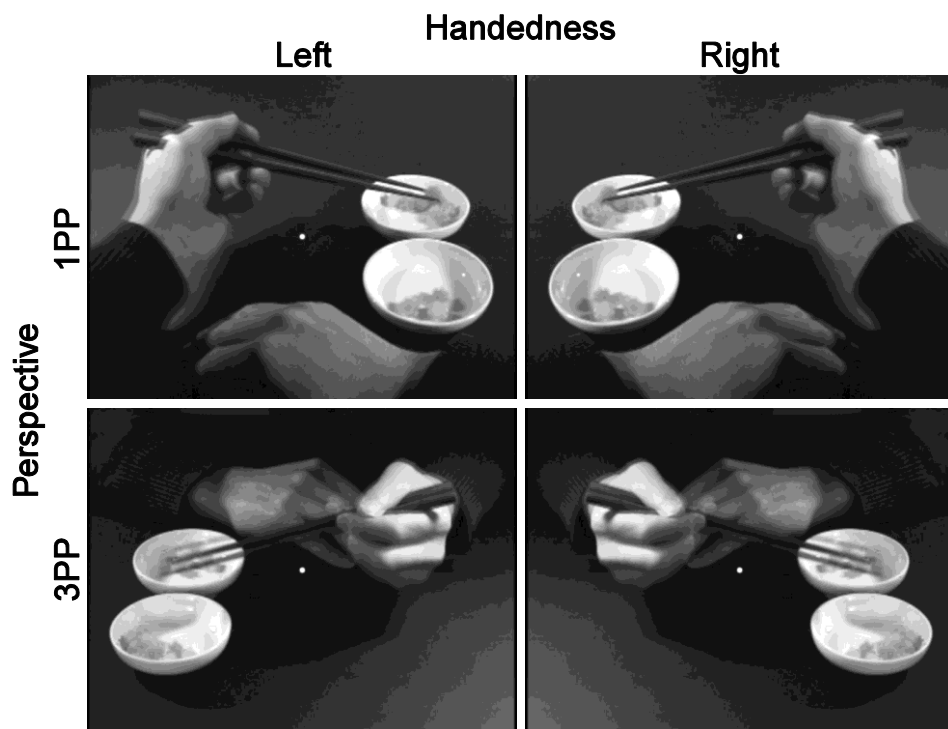


Figure 2.

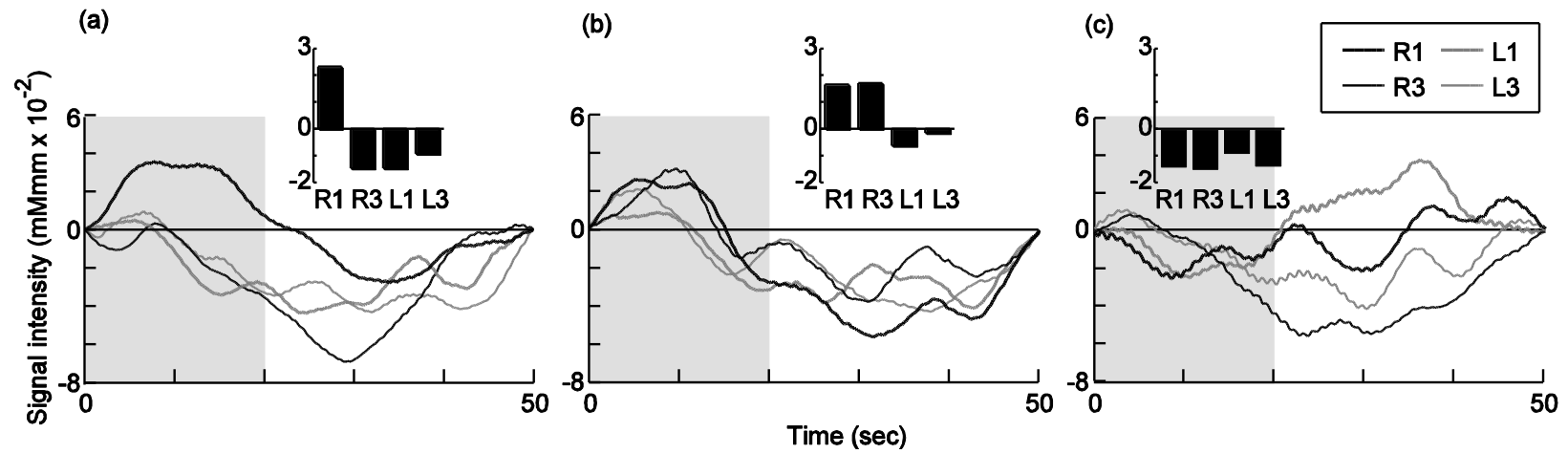


Figure 3

