

# Brain activity related to action- and non-action related sounds in a three-dimensional sound reproduction system

Koichiro Tsuchida<sup>1</sup>, Kanako Ueno<sup>1,2</sup>, Sotaro Shimada<sup>1,2</sup>

<sup>1</sup>School of Science and Technology, Meiji University, Kanagawa, Japan

<sup>2</sup>CREST, Japan Science and Technology Agency, Saitama, Japan

## Abstract

The mirror neuron system (MNS) is the brain region that is activated when seeing the sight or hearing the sound of another's action. We investigated whether the mirror neuron system shows differential activation for action-related and non-action-related sounds and whether it is susceptible to the quality of the sounds. In this experiment, we used a three-dimensional sound field reproduction and recording system based on the boundary surface control principle (BoSC). Mu-rhythms of EEG over the sensorimotor cortex (Fz, Cz, C3 and C4 electrodes) were recorded throughout the experiment. The results showed significant differences between action-related and non-action-related sounds at Cz and C3 through 62-ch loudspeakers. We found a significant difference between 1-ch and 62-ch loudspeakers when subjects listened to action-related sounds. These results confirm that the mirror neuron system is activated in a three-dimensional sound reproduction system when we listen to action-related sounds.

**Keywords** - Mirror neuron system, BoSC system, Electroencephalography (EEG),  $\mu$ -suppression

## 1 Introduction

The mirror neuron system (MNS) is found in area F5 of the monkey premotor cortex [1]. Other monkey mirror neuron areas include the inferior parietal lobule (in particular the prefrontal gyrus but also intraparietal areas) and the prefrontal cortex [2]. The MNS is activated both when the monkey performs an action and when he observes a similar action made by another monkey or by the experimenter. In the human brain, the MNS includes the inferior frontal cortex (opercular region), the primary motor cortex and the rostral-most region of the superior parietal lobe [3]. Action-related sounds can be also recognized by the MNS. Neurons that discharge when the animal performs a specific action and when it hears an action-related sound were found in monkey premotor cortex [4]. Most of these neurons also discharge when the monkey observes the same action. These audiovisual mirror neurons code actions independently of whether these actions are performed, heard, or seen; that is, the MNS is activated when hearing the sound of another's action [4].

The mu rhythm is measured using electroencephalography (EEG). It is defined as the 8–13 Hz frequency range and is thought to be the result of synchronous discharges by resting neurons in the sensorimotor area of the brain, usually measured over the somatosensory cortex [5, 6]. Suppression occurs when these neurons receive input, particularly during motor act preparation [7]. This phenomenon is called mu suppression, and can be used as a proxy marker of mirror neuron activation.

In this experiment, using mu-suppression as a reference, we investigated whether the mirror neuron system shows differential activation for action-related and non-action-related sounds and whether it is susceptible to the quality of the sounds. To create a highly realistic massive 3D sound field, various auditory displays and sound reproduction systems have been invented [8, 9, 10]. In this experiment, we used a three-dimensional sound field reproduction and recording system based on the boundary surface control principle [11] to record and reproduce sounds with a higher quality.

## 2 Method

### 2.1 Subjects

Sixteen healthy subjects participated in the experiment (14 male, 2 female, aged  $22.1 \pm 0.68$ , mean  $\pm$  SD). All subjects reported normal hearing and all but two were right-handed. Written informed consent was obtained from all subjects. Their anonymity was assured and they had the right to leave the study at any time. The experiments were approved by the ethics committee of the School of Science and Technology, Meiji University, and conducted according to the principles and guidelines of the Declaration of Helsinki.

### 2.2 BoSC system

In this study, we used the boundary surface control (BoSC) sound reproduction system that enables us to record and reproduce a sound field area.

Ise proposed the boundary surface control principle (BoSC principle) [12]. By integrating the Kirchhoff-Helmholtz integral and inverse system, the BoSC system can accurately reproduce a three dimensional (3-D) sound field surrounded by a closed boundary surface. The BoSC system comprises the BoSC microphone system (Fig. 1) and the reproduction room (Fig. 2). First, the BoSC microphone system records the sound pressure on the surface of a volume defined by the BoSC microphone array. Next, the recorded signals are convoluted with a set of inverse filters. Finally, a loudspeaker array accurately recreates the sound field in other locations by reproducing the convoluted signals. In the BoSC system, the inverse filters are determined by an inverse system of a transfer function matrix measured between each loudspeaker and microphone pair.

The BoSC microphone array has the same configuration as a C80 fullerene. Seventy omnidirectional microphones (DPA 4060BM) installed at the nodes of the fullerene except 10 nodes of downside position are used for the recording. The diameter of the microphone array is about 46 cm. The reproduction area in the BoSC system is the inner region enclosed by the microphone array. Therefore, the system can reproduce a 3-D sound field surrounding the listener's head.



Fig. 1. C80 fullerene structure microphone array to record a 3D sound field with 80 nodes having intervals of around 8 cm. 70 omni-directional microphones are installed on each node position except 10 nodes of downside part.



Fig. 2. Loudspeaker system to reconstruct a 3D sound field recorded by a C80 fullerene-structured microphone array that consists of a dome structure and a support pillar. The dome structure part has four mounting racks and six full-range units, and 16, 24 and 16 units are installed on them, respectively.

The loudspeaker array has the oval dome structure consists of four racks, and full-range loudspeaker units (FOSTEX FE83E) are installed on each rack. The loudspeaker array is set in a soundproofing room to reduce the external noise. In the room, a chair on a hydraulic lift is installed to adjust the height of a listener's ears.

### 2.3 Stimuli

All auditory stimuli were recorded by the microphone array. The sounds of hands clapping, tearing up a sheet of paper, and balling up a sheet of paper were prepared as action-related sounds for this study, as well as the sounds of a metronome, shredding a sheet of paper, and flushing the toilet, as non-action-related sounds. The recording data were converted to wav files using MATLAB software and reproduced using NUENDO software.

### 2.4 Procedure

All participants were involved in the same two-hour experiment. The subjects listened to the sound stimuli in the 3D sound field reproduction room under low-lighting conditions to avoid external auditory and visual nuisance. The hydraulic lift and the chair raised the subject's head into the 3D sound field reproduction area. The subjects sat still during all trials and listened carefully during the task period. They were instructed to do nothing during the rest period.

The experimental sounds lasted for 4 s. Each sound was presented 20 times in a pseudo-randomized order. The inter-stimulus interval was set at 4 s. The experiment consisted of two sessions: the 1-ch and 62-ch sessions. In the 1-ch session, the sound was reproduced from one loudspeaker in front of subject. In the 62-ch session, the sound was reproduced by all (62-ch) loudspeakers installed in the reproduction room to realize the 3D sound field. The sound pressure level of stimulus was adjusted at the center of the microphone array to eliminate the level differences between 1-ch and 62-ch stimuli. The duration of each part of the experiment (1ch/62ch) was about 16 minutes. After the experiment, all subjects filled out questionnaires. The order of experimental conditions (1-ch or 62-ch) was counterbalanced across subjects.

### 2.5 Electrophysiological recording and Analysis

EEG (g.USBamp, g.tec, Inc, Australia) measurements were performed throughout the experiment (band-pass filters: 0.5-30 Hz, notch filters: 50 Hz, data acquisition: A/D converter with 16 bits resolution and a sampling frequency of 512 Hz) referenced to the ear lobe. Statistical analysis and plotting were then performed using MATLAB software (The MathWorks, Natick, MA) for signal processing and statistical analysis, respectively. The EEG recordings were conducted according to the 10/20 international system of electrode placement. Four bipolar channels were used and the electrodes were placed at the C3, C4, Cz and Fz positions, where sensorimotor activity would most likely be presented (Fig. 2). The ground electrode was positioned at Fpz and the reference electrode at A2. Bipolar electrooculography (EOG) was also measured. EOG artifacts were removed from the recorded data using independent component analysis (ICA). The resulting data were transformed by a continuous Morlet wavelet transform. Attenuation of EEG power in the mu frequency range (7-12 Hz) over the motor area reflects the activity in the motor area and is regarded as mirror neuron system activation during the hearing of sounds in this study.

### 3 Result

Cz and C4 showed significant activation to action-related sounds in the 1-ch session (Cz:  $t=2.36$ , C4:  $t=1.76$ ,  $p<0.05$ ). Cz, C3 and C4 showed significant activation to action-related sounds in the 62-ch session (Cz:  $t=4.83$ , C3:  $t=3.09$ , C4:  $t=1.84$ ,  $p<0.05$ ).

We found a significant difference between action-related and non-action-related sounds in the 62-ch session at Cz and C3 (Cz:  $t=3.63$ , C3:  $t=2.36$ ,  $p<0.05$ ) but we did not find a significant difference between action-related and non-action-related sounds in the 1-ch session. Figure 4 depicts the attenuation rate results at C3.

We also found a significant difference between 1-ch and 62-ch sessions when subjects listened to the action-related sounds at Cz ( $t=1.83$ ,  $p<0.05$ ) but not for the non-action-related sounds.

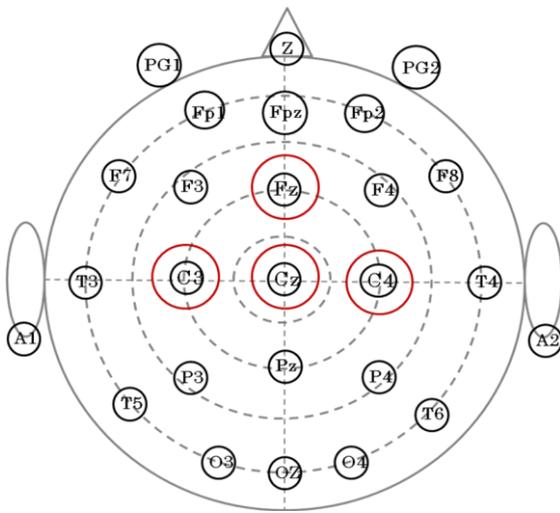


Fig. 3. Positions of the 10/20 system where electrodes were placed

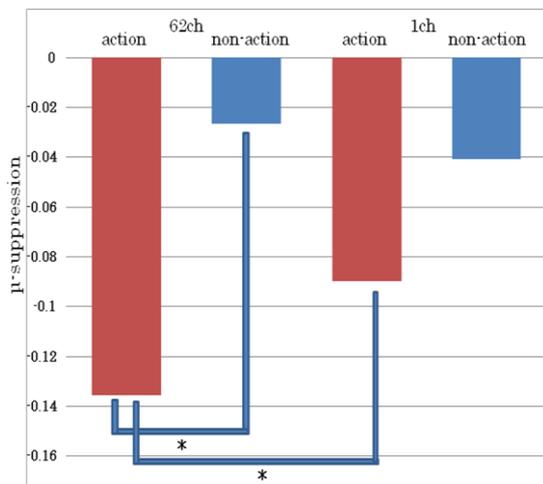


Fig. 4.  $\mu$ -suppression at Cz (red: action-related sound blue: non-action-related sound).  
\*: significant difference ( $P<0.05$ ).

### 4 Discussion

Our results showed that attenuation of the mu rhythm ( $\mu$ -suppression) was observed when the subjects heard action-related sounds, while it was not evident when hearing non-action-related sounds. Moreover, this attenuation was

significantly larger in the 62-ch loudspeaker condition, which creates a more realistic sound field, than in the 1-ch condition. These results indicate that the MNS is activated for action-related sounds and that this activation is enhanced for more realistic sounds.

Our result is consistent with previous studies that have shown MNS activation to action-related sounds [4]. Mu-suppression has been repeatedly observed during motor tasks and interpreted as MNS activation [7]. In addition, our study revealed that MNS activation to action-related sounds was enhanced for more realistic sounds. The sound pressure levels were equivalent between the 62-ch and 1-ch conditions, so that the difference in the degree of MNS activation was not due to physical characteristics of the sound stimuli. Rather, we consider that MNS activation to action-related sounds was affected by the presence and/or realistic sensation of the sound. Previous studies showed that MNS activity was greater in response to a live real person than to a televised person [13]. This result suggests that we can measure the degree of realistic sensation or 'kansei' by assessing the MNS activation to human action perception in various naturalistic situations.

### Acknowledgements

This research was supported by a CREST grant from the Japan Science and Technology Agency, and JSPS KAKENHI Grant Numbers 25700015 and 22240026.

### References

- [1] G. Rizzolatti, L. Fadiga, V. Gallese and L. Fogassi, Premotor cortex and the recognition of motor actions, *Cognitive Brain Research*, 3, 131-141, 1996.
- [2] G. di Pellegrino, L. Fadiga, L. Fogassi, V. Gallese and G. Rizzolatti, Understanding motor events: a neurophysiological study, *Experimental Brain Research*, 91, 176-180, 1992.
- [3] M. Iacoboni, RP. Woods, M. Brass, H. Bekkering, JC. Mazziotta and G. Rizzolatti. Cortical Mechanisms of Human Imitation, *Science*, 286, 2526-2528, 1999.
- [4] E. Kohler, C. Keysers, MA. Umiltà, L. Fogassi, V. Gallese and G. Rizzolatti, Hearing sounds, understanding actions: action representation in mirror neurons, *Science*, 297, 846-848, 2002.
- [5] WN. Kuhlman, Functional topography of the human mu rhythm, *Electroencephalography and Clinical Neurophysiology*, 44 (1), 83-93, 1978.
- [6] KL. Anderson and M. Ding, Attentional modulation of the somatosensory mu rhythm, *Neuroscience*, 180, 165-180, 2011.
- [7] G. Pfurtscheller, C. Brunner, A. Schlögl and FH. Lopes da Silva, Mu rhythm (de)synchronization and EEG single-trial classification of different motor imagery tasks, *NeuroImage*, 31, 153-159, 2006.
- [8] J. Blauert, Spatial hearing: the psychophysics of human sound localization-revised edition, The MIT Press, London, England, 1997.
- [9] J. Garas, Adaptive 3D sound systems, Kluwer Academic Publisher, 2000.
- [10] S. Takane, A new theory for high definition virtual acoustic display named advise, *Acoustical Science and Technology*, 24, 5, 276-283, 2003.
- [11] S. Enomoto, Y. Ikeda, S. Ise and S. Nakamura, Three-dimensional sound field reproduction and recording systems based on boundary surface control principle, *Proceedings of the 14th International Conference on Auditory Display*, 24-27, 2008.
- [12] Ise, S. "A principle of sound field control based on the kirchhoff-helmholtz integral equation and the theory of inverse systems". *Acoustica*, 85, 78-87 (1999).
- [13] S. Shimada and K. Hiraki. Infant's brain responses to live and televised action. *NeuroImage*, 32, 930-939, 2006.