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Observation–execution matching system for speech: a magnetic stimulation study

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Observation of limb movements in human subjects resulted in increased motor-evoked potential (MEP) amplitude elicited by magnetic stimulation of motor cortex in the muscles involved in that movement, suggesting that an observation–execution matching (OEM) system exists in humans. We investigated whether the OEM system is activated by speech gestures presented in the visual and auditory modalities. We found that visual observation of speech movement enhanced MEP amplitude specifically in muscles involved in production of the observed speech. In contrast, listening to the sound did not produce MEP enhancement. The findings suggest that the OEM system may be modality specific. It may be involved in action recognition in the visual modality, but is not responsible for perception of simple items of sound. *NeuroReport* 12:1341–1344 © 2001 Lippincott Williams & Wilkins.

Key words: Action recognition; Mirror neuron; Observation–execution matching system; Speech perception; Transcranial magnetic stimulation

INTRODUCTION

Single cell recordings from the frontal cortex in monkeys have identified a group of neurons in the F5 area (rostral part of inferior area 6) [1] that discharge during specific goal-related movements such as grasping or manipulating [2]. Other neurons in the same area become active when the monkey is presented with three-dimensional objects that match the type of grip coded by the neuron [3]. More recently [4], a subset of F5 neurons known as mirror neurons has been identified. These neurons become active when the monkey makes a goal-directed movement and when it observes similar movements made by others. Neurons with similar properties have also been reported in the posterior parietal cortex (area 7a) of monkeys [5]. These mirror neurons are thought to constitute part of an observation–execution matching (OEM) system.

There is also evidence for an OEM system in humans. A study using transcranial magnetic stimulation (TMS) of the motor cortex during observation of grasping movement found a significant increase in motor-evoked potential (MEP) amplitude in the muscles used for the execution of the same action [6]. Investigations using PET [7,8] have found significant activation of the left inferior frontal gyrus (Broca's area), the left superior temporal sulcus and the inferior parietal lobule during observation of grasping behavior in humans. Neuromagnetic recordings have confirmed activation of the left inferior frontal cortex and the primary motor cortex during observation of hand reaching movements [9,10]. These findings suggest that an OEM system for action recognition of limb gestures exists in humans, similar to the mirror neuron system in monkeys. The OEM system in humans involves Broca's area, the analog of area F5 [11–13] in the monkey premotor cortex.

The functional role of the mirror neuron or OEM system has been argued extensively. Some researchers have suggested that these neurons generate an internal representation of movement, which may be involved in motor learning by imitation or understanding of the observed action [4,14]. The OEM system may also be involved in conscious or unconscious [16] recognition and differentiation of specific types of action from numerous other similar types of action [15]. Given recent reports of Broca's area involvement in speech perception [17,18], it has been speculated [4,6,10,14] that an OEM system may play a role in the retrieval of articulatory gesture as suggested by the motor theory of speech perception. According to this theory [19,20], listeners perceive speech because they are aware of how sounds are produced by their own articulators. These articulatory (or phonetic) gestures are objects of speech perception represented in the brain as invariant motor commands. There is no direct evidence to support this hypothesis.

In the present study, we investigated whether an OEM system can be observed for articulatory movements associated with speech and examined the specificity of this system. We also tested whether auditory speech stimulus can activate the OEM system and the effects of non-congruent information in the visual and auditory modality. We used speech sounds /ba/ and /ta/ because production of /ba/ activates lip muscles whereas production of /ta/

involves the tongue and the jaw but not lip muscles. Our first hypothesis is that visual observation of speech movement will increase MEP amplitude in the muscles involved in the execution of the same movement, similar to observation of limb movements [6]. Thus, visual observation of speech movement /ba/ and not /ta/ is expected to increase MEP amplitude in lip muscles. Our second hypothesis is that the OEM system helps to retrieve speech gesture from an auditory signal as suggested by the motor theory of speech perception [4,6,10,14]. Listening to speech sound /ba/ is predicted to increase MEP amplitude in lip muscles.

SUBJECTS AND METHODS

Subjects: We studied 11 normal volunteers. The results from one of the authors in a pilot study were excluded since he had extensive exposure to the auditory and visual stimuli and was not naive to the purpose of the experiment. One additional subject was screened but the experiments could not be conducted because we were unable to activate the contralateral orbicularis oris muscle by TMS without activating the ipsilateral facial nerve which produced responses that overlapped with MEPs from TMS. Therefore, results from nine normal volunteers (four women and five men, mean age 27.5 years, range 23–33 years) were analyzed. All subjects gave written informed consent. The protocol was approved by the University Health Network Research Ethics Board.

EMG recordings: Recordings were made from the right orbicularis oris with disposable adhesive disk (silver–silver chloride) electrodes. One electrode was placed at the angle of the mouth and another electrode was on the upper lip, midway between the midline and the angle of the mouth. The signal was amplified (model 2024F Intronix Technologies, Bolton, Ontario, Canada), filtered (2 Hz–5 KHz), digitized (at 5 KHz, Micro 1401, Cambridge Electronics Design, UK) and stored in a laboratory computer for offline analysis. For each subject we confirmed that the orbicularis oris muscle was activated only when producing /ba/ and not when producing /ta/.

Transcranial magnetic stimulation: TMS was performed with a 7 cm figure-of-eight coil and a Magstim 200 stimulator (The Magstim Company, Dyfed, UK). The coil was placed at the optimal position for eliciting motor evoked potentials (MEPs) from the right orbicularis oris muscle. The optimal position was marked on the scalp to ensure identical placement of the coil during the experiment. The handle of the coil pointed backward and perpendicular to the presumed direction of central sulcus. The direction of the induced current was posterior to anterior and was optimal to activate the motor cortex trans-synaptically [21]. The motor threshold was determined at rest to the nearest 1% of the stimulator's output and was the minimum intensity required to evoke MEP amplitudes of $> 50 \mu V$ in $\geqslant 5$ of 10 trials. Since TMS can activate the ipsilateral facial nerve, we carefully distinguished volume-conducted response due to left facial nerve stimulation from MEPs elicited by cortical stimulation. Responses were accepted as MEPs if there was no visible ipsilateral (left) facial twitch, considerable trial-to-trial variation in amplitude character-

istic of MEPs and marked enhancement with voluntary muscle activation.

The stimulus intensity for TMS was set at 4–5% below the resting motor threshold for the orbicularis oris muscle. With subthreshold stimulation MEPs were rarely elicited. This resulted in a low and stable baseline and is also most suited to detect small increases in MEP amplitude associated with increased corticospinal excitability [22]. However, reduced corticospinal excitability cannot be detected with subthreshold TMS.

Stimulus conditions and procedure: The subjects were seated in front of a computer screen and asked to maintain relaxation of facial muscles. EMG silence was monitored on a computer screen and via speakers at high gain. Five conditions were tested: (1) visual /ba/ consisting of a video of the face of a person producing the /ba/ sound once every 2 s with the sound muted, (2) visual /ta/ with a video of the face of a person producing the /ta/ sound presented once every 2 s with the sound muted, (3) auditory /ba/ consisting of the /ba/ sound presented once every 2 s with a blank screen, (4) synchronized auditory /ba/ and visual /ba/, (5) synchronized auditory /ba/ and visual /ta/. The last stimulus presents non-congruent information in the auditory and visual modality (McGurk stimulus) and is identified by most listeners as /da/ (McGurk effect). Each test condition was preceded by a baseline condition where the static face of the person producing the stimuli was presented. Eight TMS pulses delivered 5.1 s apart were applied in each test or baseline condition. The TMS pulses were not time-locked to the visual or auditory stimuli. Testing was done in four blocks and each block consisted of 48 TMS pulses with three test and three baseline conditions. In the first block the test conditions were auditory /ba/, visual /ba/ and synchronized auditory and visual /ba/. In the second block auditory /ba/, visual /ta/ and synchronized auditory /ba/ and visual /ta/ were presented. The first and second blocks were then repeated once. Within each block the conditions were presented in random order. The subjects were naïve to the purpose of the experiment and were asked to pay attention to the stimulus. They were questioned about the stimulus sequence and the nature of the stimuli between runs to ensure that they paid attention during testing.

In four of the nine subjects we also investigated the effects of speech stimuli on the excitability of the corticospinal projection to hand muscles. Surface EMG recordings were made from the right abductor pollicis brevis (APB) muscle. The coil was placed over the hand area of the motor cortex and the stimulus intensity adjusted to 5% below resting motor threshold for the APB muscle. The experimental setup and stimulus conditions were otherwise identical to that of the main experiment.

Data analysis: Peak-to-peak MEP amplitude was measured for each trial offline. MEP response to the first TMS pulse for each test or baseline condition was discarded to avoid the effects of transition between conditions. For each condition, mean MEP amplitude was expressed as a percentage of the mean baseline MEP immediately preceding that condition in the same experimental run and the results

from two blocks were averaged. A repeated measure analysis of variance (ANOVA) was conducted with MEP amplitude as the dependent variable and test conditions as the repeated measure. If the effect of test condition was significant, *post-hoc* comparisons using Fisher's protected least significant difference (PLSD) was performed to detect differences between test conditions. Differences were considered significant at $p \leqslant 0.05$.

RESULTS

We were able to activate the right orbicularis oris muscle at rest in all the subjects included in the study. The resting motor threshold was $63 \pm 3.7\%$ (mean $\pm$ s.e.) for the right orbicularis oris muscle and $36 \pm 2\%$ for the right APB muscle.

Examples of single trials across different conditions from one subject are shown in Fig. 1. Figure 2 summarizes the effects of different test conditions on MEP amplitude for the orbicularis oris muscle. Group variance across conditions was compared using Mauchly's test of sphericity and found to be homogeneous. ANOVA showed a significant effect of test conditions on MEP amplitude ($p = 0.003$, $F = 4.395$, df $= 5$). *Post-hoc* tests showed that visual /ba/ ($p = 0.001$) and auditory-visual /ba/ ($p = 0.04$) were the
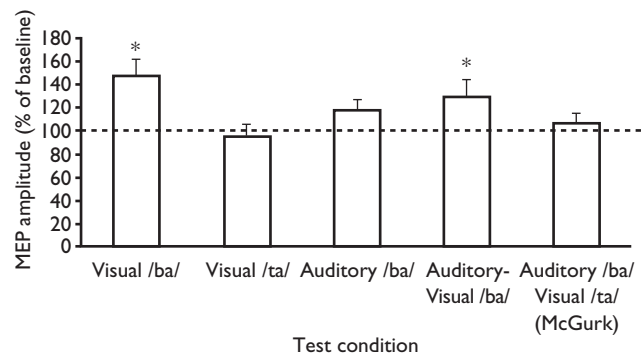
Fig. 2. MEP amplitude expressed as percentage of the baseline immediately preceding the test condition for each of the five test conditions (data from nine subjects). Error bars represent standard error. The visual /ba/ and auditory-visual /ba/ differed significantly (*) from the baseline (indicated by the dotted line).

only conditions with significantly increased MEP amplitude compared to the baseline. The visual /ba/ condition differed significantly from the visual /ta/ ($p = 0.0003$), auditory /ba/ ($p = 0.029$) and McGurk ($p = 0.004$) conditions but not the auditory-visual /ba/ condition. The auditory-visual /ba/ condition differed significantly from the visual /ta/ condition ($p = 0.02$) only. The differences between conditions were consistent across subjects.

The McGurk stimuli was identified as /da/ by seven of the nine subjects. Two others failed to form a fused auditory percept of /da/ and reported hearing the auditory /ba/ and seeing the video /ta/ distinctly. Repeat analyses excluding the two subjects who did not show the McGurk effect yielded identical results. The test conditions had no significant effect on the MEP amplitude of the APB muscle elicited by stimulation over the hand area of the motor cortex.

DISCUSSION

As predicted by our first hypothesis, the OEM system was activated by visual observation of the speech movement /ba/. This activation appeared to be specific for the muscles involved in the production of the movement. There was no increase in the MEP amplitude in the APB muscle with stimulation of the hand area of the motor cortex. Moreover, there was no significant increase in MEP amplitude in the orbicularis oris muscle with the visual /ta/ stimulus. Production of the /ta/ sound involves jaw opening with tongue movements but does not activate the orbicularis oris muscle. These results are similar to findings during observation of hand and arm movements where the pattern of MEP facilitation closely reflects the pattern of muscle activity when executing the observed movement [6].

The increased MEP amplitude in the orbicularis oris muscle during movement observation is probably mediated by cortico-cortical connections linking the premotor and motor cortex [9]. This is supported by demonstration of left inferior frontal cortex activation preceding activation in primary motor cortex by 100–200 ms during action observation in a recent study using neuromagnetic recordings [10]. However, we cannot rule out the involve-
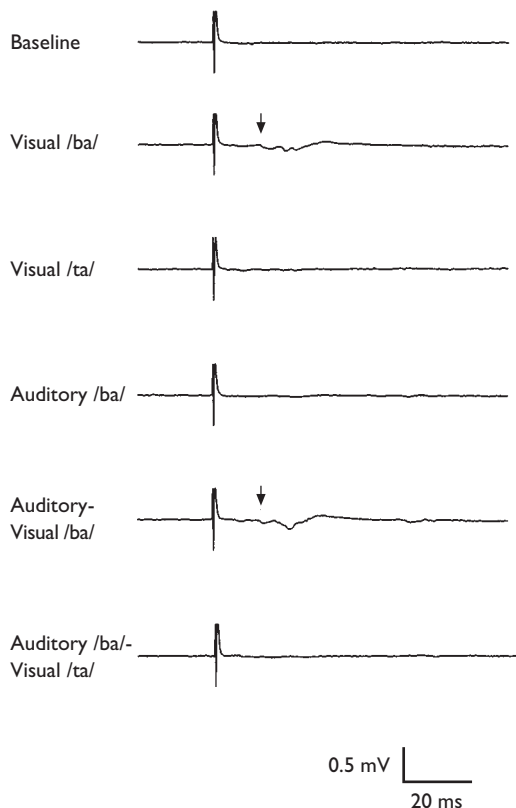

Fig. 1. Examples of single trials recorded from the right orbicularis oris muscle for the different test conditions from one subject. Since subthreshold TMS was used, the majority of baseline trials did not produce MEPs. The arrows point to MEP onset in the Visual /ba/ and the Auditory-visual /ba/ condition.

ment of direct and indirect connections between the premotor cortex and the facial nerve nucleus in the brain stem.

Contrary to our second hypothesis, the auditory /ba/ stimulus did not cause significant MEP enhancement compared to the baseline condition, suggesting that the OEM system is not activated by speech presented in the auditory modality. As the auditory /ba/ stimulus was correctly and easily identified by all subjects, our findings do not support the hypothesis that the OEM system underlies sub-threshold activation or covert retrieval of related gestures necessary for speech perception as suggested by various researchers based on the motor theory of speech perception. Whether more difficult listening tasks can lead to MEP enhancement will require further study. Since neither the visual /ta/ nor the auditory /ba/ stimuli alone elicited significant MEP facilitation, it was not surprising that the presentation of non-congruent McGurk stimulus did not elicit any significant change in MEP amplitude.

Our findings have implications for the functional significance of MEP enhancement mediated by the OEM system. It has been suggested that enhancement in MEP amplitude could be due to automatic, covert retrieval of the action [4,14,15]. However, a significant difference in MEP facilitation for visual /ba/ condition compared to the auditory /ba/ condition suggests that if the OEM system is related to covert retrieval of the action from the subject's repertoire, this retrieval is modality specific. Auditory stimuli do not activate this process. More specifically related to speech stimuli is the possible contribution of covert, sub-vocal rehearsal (also referred to as articulatory recoding or rehearsal) to the observed MEP enhancement. Sub-vocal rehearsal has also been implicated as an essential component of auditory short-term memory [23]. Since it is unlikely that sub-vocal articulatory rehearsal is active only in the visual /ba/ condition, it does not account for the pattern of MEP facilitation across conditions observed in our study.

CONCLUSION

Observation of speech movement leads to MEP facilitation specific to the muscles involved in the production of the observed speech, supporting the existence of an OEM system for speech gestures presented in the visual modality. These results are similar to that reported for observation of limb movement in humans and monkeys. The OEM system may be modality specific and is not involved in the perception of simple sound stimuli.

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