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# From viewing of movements to understanding and imitation of other persons' acts: MEG studies of the human mirror-neuron system

Riitta Hari and Nobuyuki Nishitani

## Abstract

For successful social interactions, humans continuously monitor, and often imitate, motor acts, postures, and gaze of their co-citizens. Recent data suggest that this type of intention reading and action imitation could be supported by 'mirror neurons', first identified in the monkey frontal lobe. We have characterized, with whole-scalp magnetoencephalographic (MEG) recordings, the human mirror-neuron system (MNS), which seems to consist of several cortical areas activated in a clear temporal sequence. Observation of orofacial gestures activated in both hemispheres and within about 250 ms, first the visual cortex, then the superior temporal sulcus (STS) region, the inferior parietal cortex, Broca's area, and finally the primary motor cortex. Activation of Broca's area was significantly stronger during on-line imitation than execution or observation of finger and mouth movements. Activation of somatosensory cortices was also modified during action viewing. Studies of the human MNS raise intriguing questions about the functional relationship between speech production and orofacial/hand gestures, and also emphasize the importance of motor functions in human cognition. Future studies should address the generality and abnormalities of the human MNS.

## 23.1 Introduction

Humans monitor other subjects' motor-act-based intentions continuously, automatically, and without effort. This very human behavior, essential for successful social

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interactions, could be supported by a 'mirror-neuron system' (MNS) that provides shared representations for action execution and representation.

Since the pioneering findings of 'mirror neurons' in the monkey frontal cortex by the Parma group (Di Pellegrino *et al.* 1992; Gallese *et al.* 1996; Rizzolatti *et al.* 1996), attempts have been made to find similar neuronal behavior in the human brain. We have followed the millisecond-range activation sequences of the human MNS with whole-scalp magnetoencephalography (MEG; Hari *et al.* 2000). We will therefore start our chapter with a brief presentation of the basics of the MEG method. We will then discuss our MEG data on the human MNS, ending with some speculative statements of the role of the MNS in human behavior.

### 23.2 MEG as a tool to study human brain function

Postsynaptic neuronal currents, arising in synchronously activated cortical pyramidal cells, produce extremely tiny magnetic fields, only about  $10^{-9}$  times the steady magnetic field of the Earth. These fields, mainly generated by currents in fissural cortex, can be measured with sensitive superconducting quantum interference devices (SQUIDs) totally non-invasively outside the head. To locate the activated areas in the brain, it is often useful to consider the local neuronal activation as a current dipole. The purpose of MEG recordings is then to identify and locate the dipoles accurately in the brain, and to follow changes in their strengths as a function of time.

The magnetic field outside the head is first picked up with superconducting flux transformers, i.e. wire loops, the shapes of which are crucial for the shape of the measured field patterns. When the source can be well described as a single current dipole, recordings with a magnetometer (a single coil) or an axial gradiometer (two coils wired in opposite directions, one close to and the other a few centimeters above the scalp) show the largest signals a few centimeters away from the dipole, symmetrically on both sides. Instead, recordings with a planar gradiometer, consisting of a figure-eight coil wired in the same plane (such as used in studies of this chapter), show the strongest signals just above the current dipole at the site of the steepest field gradient (Hämäläinen, *et al.* 1993; Hari 1999).

The next step is to find the site of the current dipole by means of a least-squares fit to signals measured (preferably simultaneously) at several sites above the scalp. In the first visual evaluation of the data, the strongest signals measured with planar gradiometers point directly towards the most probable source locations, greatly facilitating the subsequent analysis of complex field patterns. Finally, a multi-dipole model can be constructed by adding all local sources to the model, and by taking into account the signals of all sensors at all time points.

The current-dipole model is well suited for studies of local discrete activation areas, whereas distributed source models may be preferred for proper description of very complex current distributions (Uutela *et al.* 1999). However, it should be emphasized

that the analysis method affects the results: applying a distributed model to a point-like source will indicate distributed activity, and vice versa. The localization accuracy of the source models naturally depends on the signal-to-noise ratio.

The requirement of measuring the magnetic field pattern at the same time all over the whole head has led to rapid development of multichannel neuromagnetometers during the past two decades. Figure 23.1 shows our helmet-shaped MEG device, comprising 306 sensors; 204 sensors are planar gradiometers and the remaining 102 are magnetometers (VectorView™, Neuromag Ltd). With the emergence of whole-scalp neuromagnetometers, MEG recordings have been increasingly applied for exploration of human cognitive functions, including 'motor cognition', as the MNS studies below will demonstrate.

Skull and scalp distort the electric potential distributions (and thus EEG) but are transparent for magnetic signals, so that the MEG pattern is restricted to a more local area than the corresponding EEG distribution. MEG measurements are often advantageous when multiple sources are to be resolved. For example, the distinction between the primary and the secondary somatosensory cortices is easy with MEG but, due to the overlapping potential distributions, tedious with EEG (Hari *et al.* 1984; Kaukoranta *et al.* 1986).

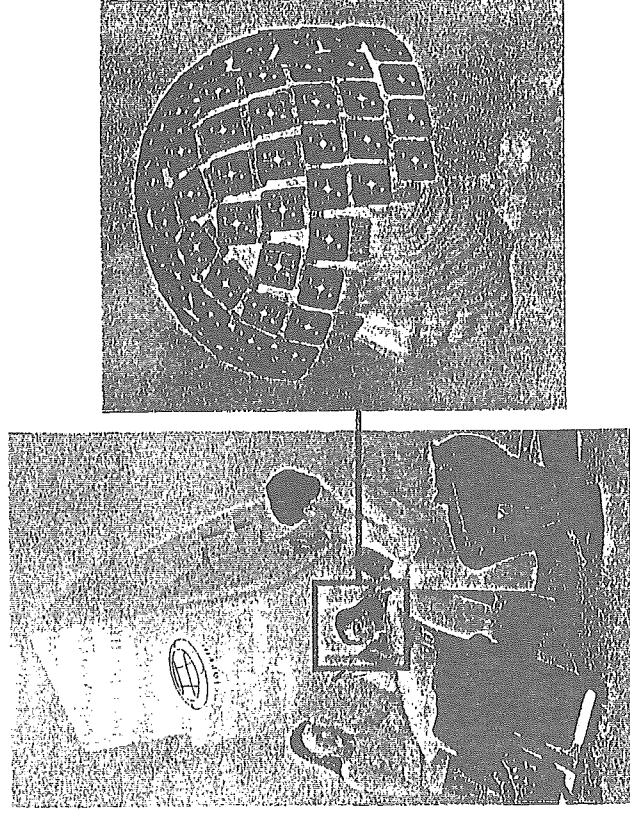


Fig. 23.1 Preparation of a subject for MEG measurement with a 306-channel neuromagnetometer. The sensor array of the device is shown on the right (courtesy of Mika Seppä).

In a sphere, radial currents affect only the potential distribution. For accurate EEG modeling, the electric conductivities of skull and scalp should be known. Both MEG and EEG signals reflect neural activation directly, and not blood flow or metabolism.

The advantages of MEG in human brain research (Hari *et al.* 2000) include—besides non-invasiveness and the excellent temporal resolution—the very good replicability of the signals, even over months, and the possibility of obtaining quantitative information on activation strengths (net intracellular currents) in local neuronal populations. The selectivity of MEG to activation of fissural cortex can be considered an advantage as well, because these areas are difficult to reach with other means, including intracranial recordings. Moreover, the complete source configuration can be more easily resolved if the tangential (fissural) parts of the currents are identified first by MEG.

Because of the non-uniqueness of the inverse problem, the MEG and EEG source analyses require human interaction and are rather demanding for a beginner. Another limitation (common with fMRI and PET but not with EEG) is that the subject has to keep his or her head immobile during the recording.

### 23.3 Social brains and mirror neurons

Much of the previous and highly important animal and human electrophysiological work on sensory functions has been carried out with rather artificial stimuli, such as tone pips, flashing checkerboard patterns, or electric pulses delivered on the skin. However, such elementary stimuli are rarely encountered in everyday life. Instead, other humans provide us with strong and continuous 'social stimulation' and we certainly have 'social brains' that have been tuned to help us to get along among our co-citizens.

Seeing other people's movements may influence the observer's own motor system and even result in unintended imitation. This phenomenon can be experienced while just viewing athletic performance, and noticing that one's own knee rises at the same time as does the athlete's knee. Similarly, students of body language have frequently noted that humans easily imitate another person's postures. One candidate for a brain system supporting this type of copying and imitation of movements and postures is the neuronal network forming the MNS.

Several years ago, Rizzolatti and coworkers found neurons in area F5 of the monkey frontal cortex that were activated both when the monkey acted himself, taking a raisin from a tray, and when he viewed another monkey or the human experimenter making the same act (Di Pellegrino *et al.* 1992; Gallese *et al.* 1996; Rizzolatti *et al.* 1996). These 'mirror neurons', more jovially 'monkey see, monkey do neurons' (Carey 1996) seem to match action representation with action execution. They thereby could form a link between the sender and the receiver of a motor-act-based message: two persons can communicate effectively only if they share a common code or possess similar mechanisms to perceive, and act in, the world.

We have been interested in finding, by means of MEG, evidence about the existence of a human MNS which, at its simplest level, should fulfill the following requirements.

1. The system's functional state should change when the subject herself makes a movement.
2. The functional state should be modulated to the same direction as in (1), but most likely less vigorously, when the subject just views another person making a similar movement. In this situation the subject has no requirement for subsequent reproduction of the movement and her own muscles should be relaxed.
3. Modulation, probably even stronger than during (2), would be expected to occur when the subject imitates on-line (as simultaneously as possible) the motor acts of the other person.

A transcranial magnetic stimulation (TMS) study was the first to show modulation of pathways from the human primary motor cortex to the spinal level while the subject viewed another person's motor acts (Padiga *et al.* 1995). However, this study did not pinpoint the exact level (cortical versus subcortical/spinal) where the effect of viewing took place. Thus our MEG study, reported below (Hari *et al.* 1998), was the first one to demonstrate that action viewing affects the primary motor cortex. A more recent TMS study has confirmed this proposal (Strafella and Paus 2000). The early human imaging studies by means of positron emission tomography (PET) demonstrated involvement of Broca's area in the human MNS, activated when the subject observed the examiner using a precision grasp to enclose an object (Grafton *et al.* 1996).

### 23.4 Motor cortex and the MNS

In our first MNS-related MEG study (Hari *et al.* 1998), we tried to find out whether the human primary motor cortex, M1, would be activated when subjects just view another person's motor acts. To probe the functional state of M1, we monitored modulation of the motor cortex 20-Hz MEG rhythm (Hari and Salmelin 1997). Movements of either the left or the right hand suppress this rhythm, with slightly contralateral dominance; the movements are followed by 'rebounds'—increases in the level of the MEG rhythm (Nagamine *et al.* 1996). Electric stimuli applied to median nerves at the wrists are also followed by clear rebounds of the 20-Hz rhythm, and this increase likely reflects an inhibitory state of the motor cortex (Salmelin and Hari 1994). The relationship between the rebound and motor cortex inhibition is also supported by TMS results of decreased excitability in the motor cortex with a time course similar to that of the 20-Hz rebound (Chen *et al.* 1998).

In addition to source analysis that indicates that the main origin of the 20-Hz rolandic activity is in the precentral motor cortex (Salmelin and Hari 1994; Hari *et al.* 1998; see insert of Fig. 23.2), strong further evidence about the generation of the rhythm in M1 derives from studies demonstrating oscillatory cortico-muscular coupling at about 20-Hz during isometric contraction of different muscles (Conway *et al.* 1995; Salenius *et al.* 1997; Hari and Salenius 1999). The generators of the maximally coherent

MEG signals agree with the location of the individual M1 cortex, evaluated anatomically and functionally in each individual (Salenius *et al.* 1997) and by stimulations during neurosurgical operations (Mäkelä *et al.* 2001).

Figure 23.2 (left) shows our three experimental conditions: resting, acting, and viewing. During all conditions, the left and right median nerves of the subject were stimulated alternately to vary the level of the motor-cortex rhythm in a well-controlled manner (see above). During acting, the subject manipulated a small object with the fingers of

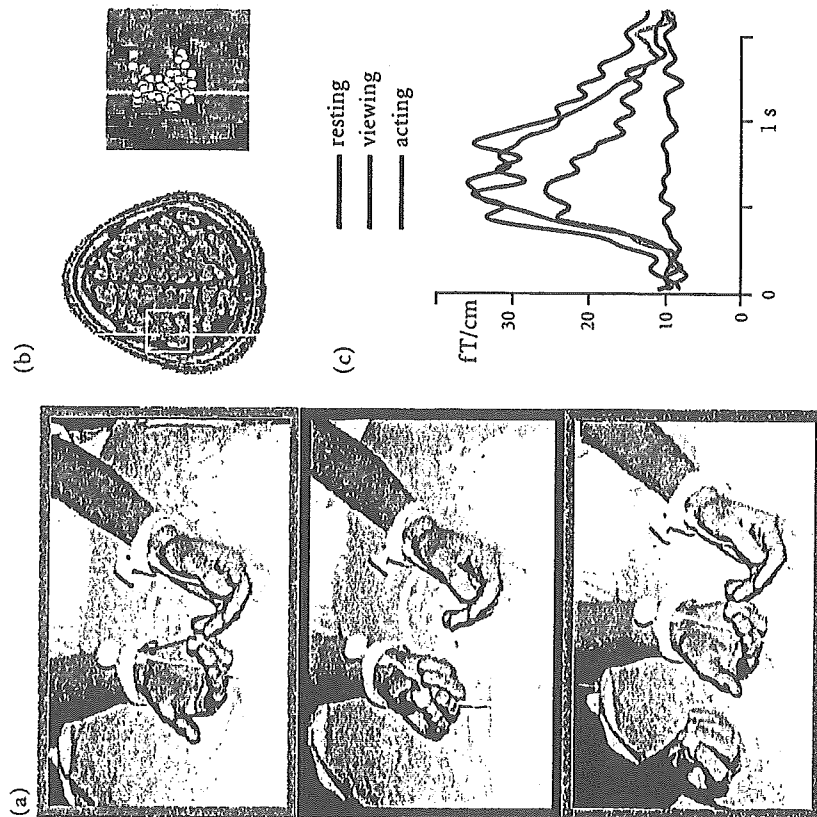


Fig. 23.2 (a) Experimental conditions during an action viewing experiment (from top to bottom: resting, acting, and viewing). (b) Sources of the unaveraged 20 Hz oscillations in the left rolandic area. The locations of the dipoles (circles) agree with activation of the 'hand knob' (Yousry *et al.* 1997) of the precentral primary motor cortex. (c) Level of the left-hemisphere 20-Hz motor-cortex rhythm after right median nerve stimuli (presented at time zero) during all conditions; two repetitions of the same stimulation are shown for the rest condition. (Adapted from Hari *et al.* 1998.)

her right hand, and in the viewing condition she viewed the experimenter to perform similar movements. An important new experimental approach was to have a real person performing the movements in the subject's field of view, instead of some video presentation of the stimuli. In fact, a later study showed the effects of interest to be 15–20% stronger for motor acts presented live than those seen on a video (Järveläinen *et al.* 2001).

Figure 23.2c shows that stimulation of the right median nerve was followed by a typical 20-Hz rebound in the left hemisphere: the 20-Hz level increased to its maximum within 500 ms after the median nerve stimulus (presented at time zero). This rebound reflects changes in the M1 cortex, as discussed above. When the subject was herself manipulating the small object, the rebound (inhibition of M1) was totally abolished, as was expected because the movements required activation of the M1 cortex. Interestingly, the rebound was also significantly suppressed when the subject just viewed another person's manipulation movements without moving herself. It is important to note that surface EMG did not show any increase of muscle activity during action viewing.

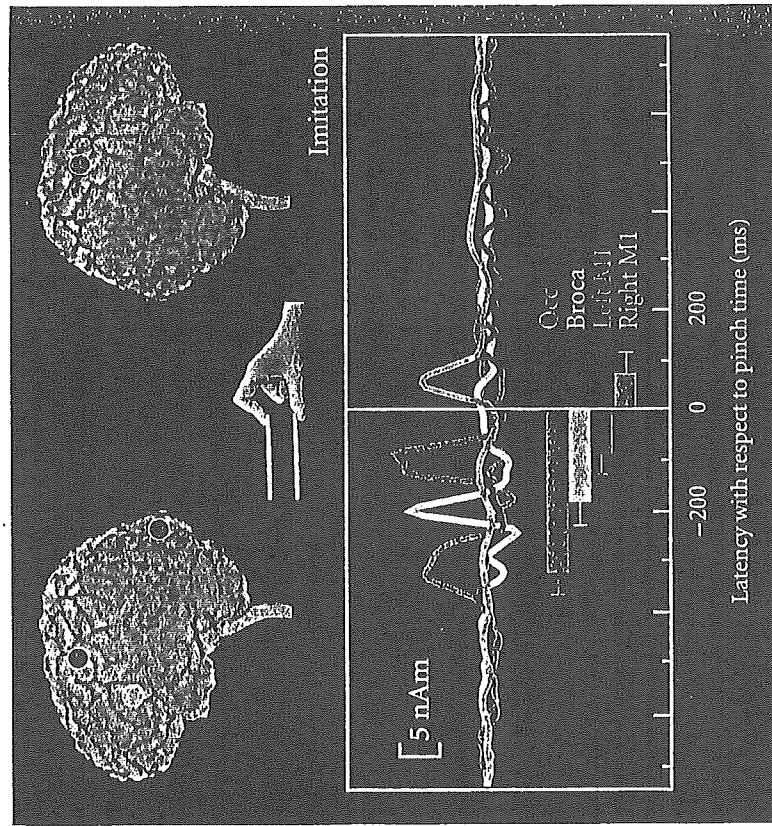
These data indicate that the human primary motor cortex is activated when the subject just views another person's actions. The motor cortex thus fulfills our requirements (1) and (2) for a MNS, and we can suggest it to be a part of the human MNS.

### 23.5 Temporal sequence during pinching

Because modulation of the 20-Hz motor-cortex rhythm reflects changes in M1 only, it is not of much use for monitoring inter-areal cortical dynamics during action viewing. In the next MNS study we therefore recorded brain activity time-locked to hand movements. The subject either himself stretched his right arm and hand towards a manipulandum, ending the movement with a pinch of the tip (see insert of Fig. 23.3), or he imitated on-line similar movements made by the experimenter (who was again performing live in the measurement chamber in the subject's field of view), or only observed the experimenter's movements.

Figure 23.3 shows examples of responses of a single subject in the imitation condition (Nishitani and Hari 2000). The first activation occurred in the posterior visual areas about 400 ms before the subject pinched the top of the manipulandum (and thereby released a trigger pulse for signal averaging). The next main activation occurred in Broca's area and was followed by signals in the left motor cortex, and finally in the right motor cortex some 200 ms later.

These brain regions were activated both during action execution and observation, and they can thus be considered parts of the human MNS. The relative timing of the visual cortex, but not of the other brain areas, differed between the conditions because the visual stimulus, the experimenter's or the subject's hand, appeared into the subject's visual field at different stages of the movement sequence, depending on the task. A similar sequence of activation was seen in other subjects, and the



**Fig. 23.3** Averaged MEG responses of a single subject during the imitation condition in the pinching experiment. Different colors in the traces, bars, and brain locations refer to visual cortex (Occ), Broca's area (Broca), and the left and right primary motor cortices (M1). The mean  $\pm$  SEM latencies of eight subjects are given below the traces. The time zero refers to the time when the reaching movement ended with a pinch at the tip of the manipulandum. (Adapted from Nishitani and Hari, 2000.)

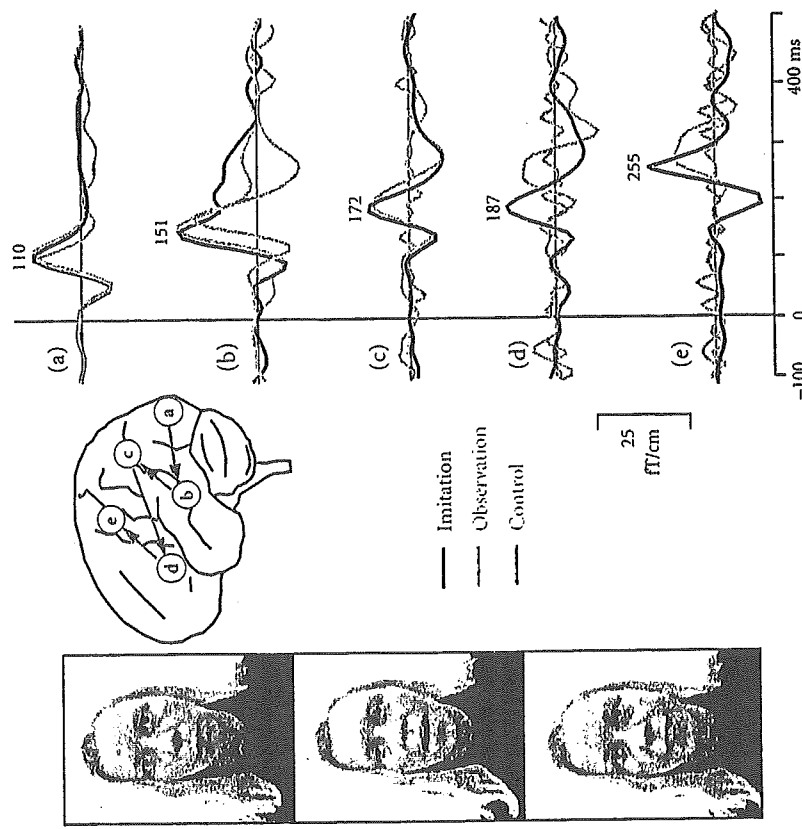
sequence was similar in the imitation and observation conditions. Activation in Broca's area and in the left primary motor cortex was significantly stronger during imitation than during the other conditions (Nishitani and Hari 2000). Thus either the same cells fired more vigorously during imitation than during viewing and execution, or the neurons activated by viewing and execution were closely intermingled in a small area.

### 23.6 Frozen orofacial gestures

The above data indicate that many types of hand actions can activate the human MNS. In monkeys, the mirror neurons of the F5 region are also activated by orofacial gestures.

We therefore wondered whether still pictures of lip forms, frozen orofacial gestures, only implying motion, could also activate the human MNS. In one session, the subject was asked to imitate the lip forms immediately after having seen them in the picture, and in the other session the subject had to view the pictures without any requirement for subsequent production of the movements.

Figure 23.4 shows brain responses from a single subject while he imitated the lip forms (red traces). The signals illustrate a clear prolongation of the response latencies



**Fig. 23.4** Averaged MEG responses of a single subject to observation and imitation of lip forms, shown on the left, and to viewing of landscapes (control). The signals were picked up from five locations, corresponding approximately to the visual cortex, the superior temporal sulcus, the inferior parietal lobe, Broca's area, and the primary motor cortex, respectively. The numbers give the peak latencies of the responses. The schematic brain picture in the middle indicates the assumed sequence of activation based on the response latencies. (Nishitani and Hari, unpublished data from a Finnish subject in a study very similar to that of Nishitani and Hari 2002.)

from sensor location a to location e. Because the signals were recorded with planar gradiometers, this temporal order could correspond to progression of activation from the occipital visual cortex to the superior temporal sulcus (STS), then to inferior parietal area, to Broca's region, and finally to the left primary motor cortex. This order of activation, occurring in 200–250 ms, has been confirmed by source analysis in 10 Finnish (Nishitani and Hari, unpublished) and in 10 Japanese subjects (Nishitani and Hari 2002).

A very similar sequence of activation was also seen when the subject just observed the lip forms (green traces). Interestingly, the control stimuli of landscapes activated the occipital and temporal-lobe regions (areas a and b), similarly to the lip form stimuli, but thereafter these blue traces did not show any significant activation, suggesting clear stimulus-specificity of the activation pattern.

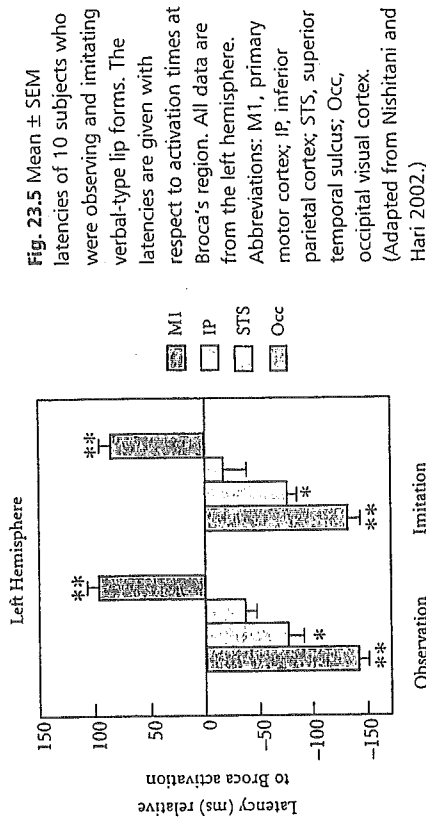
It is again important to note that a surface electromyogram from mouth muscles was silent during the observation condition, whereas during imitation and execution (not shown in Fig. 23.4 but reported by Nishitani and Hari 2002) it reflected real mouth movements, as expected.

The STS region activated in our subjects (mean Talairach coordinates:  $x$  from  $\pm 49$  to  $\pm 55$ ,  $y$  from  $-43$  to  $-48$ , and  $z$  from 10 to 13) agrees with locations related to social perception (Allison *et al.* 2000) and with areas activated during reciprocal imitation (Decety *et al.* 2002). The STS area activated in our study was in the left hemisphere, about 15 mm more anterior to landscapes than to faces.

Monkey studies have remained indecisive about the activation routes from the STS, where neurons with mirror properties have also been observed, to the inferior frontal cortex, as there are no direct pathways between these areas. Our timing data (see also the mean data in Fig. 23.5) suggest that the human STS area involved in the MNS is connected to the inferior frontal cortex (Broca's area) via the inferior parietal lobe. However, to present the correspondence between the human and monkey STS areas is still poorly understood. Whereas the monkey mirror neurons in STS region are located in the anterior part of the STS region (STPa; Perrett *et al.* 1990), the human MEG activation was observed in the middle or posterior STS. Of course it is possible, and even likely, that the mirror-neuron systems differ between monkeys and humans.

We would also like to be cautious about the conclusiveness of the exact activation sequence derived from the timing of peak activations at different brain areas. One reason is that microelectrode recordings in monkeys have demonstrated considerable temporal overlap in activations of different visual cortices that are anatomically considered to represent hierarchical stages of visual processing (Schmolesky *et al.* 1998).

Before making a strong claim about activation of Broca's region by just viewing lip forms, we should rule out the possibility that the activation was elicited by the inferred verbal content of the lip forms. If that were the case, activation in Broca's area could be considered speech-related rather than addressed to the human MNS. We therefore



**Fig. 23.5** Mean  $\pm$  SEM latencies of 10 subjects who were observing and imitating verbal-type lip forms. The latencies are given with respect to activation times at Broca's region. All data are from the left hemisphere. Abbreviations: M1, primary motor cortex; IP, inferior parietal cortex; STS, superior temporal sulcus; Occ, occipital visual cortex. (Adapted from Nishitani and Hari 2002.)

also compared activations triggered by neutral faces and by faces with verbal and non-verbal lip forms (Nishitani and Hari 2002).

Neutral faces activated the primary motor cortex in none of our subjects and weak activation was seen Broca's region in only 3 out of 10 subjects. Instead, both verbal and non-verbal lip forms activated Broca's region and the M1 cortex in a very similar manner, with slightly stronger sources to verbal than non-verbal lip forms in the left hemisphere, and vice versa in the right hemisphere. We are thus confident that the observed activation in Broca's region is not explained by linguistic or verbal content of the stimuli.

### 23.7 Problem of agency

The existence of the human MNS, which all the above data suggest, means that overlapping brain areas may be activated during action execution and observation. This leads to the problem of agency: how does the subject know that she made a certain motor act and not only saw it, provided that the corresponding brain activation patterns are very similar? This may sound a ridiculous question, but is not trivial at all because misattribution of one's own acts is possible. For example, patients with some psychiatric disorders may address their own actions to external agents and experience that they are under 'alien control'.

In the healthy human brain, the problem of agency may be solved by first sending an efference copy (corollary discharge) from the movement preparation areas to other brain areas to inform them about the forthcoming consequences of the acts. Then the feedback provided by proprioceptive and other somatosensory afferents during own movements can be compared with the expectations tuned by the efference copy.



We have observed that parts of the somatosensory cortical network demonstrate behavior that may contribute to the sense of agency. When median nerve stimuli were used to probe the functional state of the primary and secondary somatosensory cortices, SI and SII, responses of SI were increased and responses of SII decreased both when the subject manipulated a small object with the fingers of her right hand and when she saw another person performing similar movements (Avikainen *et al.* 2002); however, as the only exception, the responses of the left SI cortex were suppressed during the subject's own manipulation movements.

These data imply that the cortical somatosensory network, and especially the primary somatosensory cortex contralateral to the moving limb, could help in resolving the agent of a motor act. A recent study on a haptically deafferented patient suggests that subjects cannot become aware of their actions on the basis of efference copies only, but that they might be aware of the result of the comparison process (Fournier *et al.* 2002). Of course, the execution and observation conditions differ also in the sense that activation of the primary motor cortex is under threshold during observation but over threshold during execution, and this difference certainly affects the awareness of own action as well.

## 23.8 Role of the MNS in human behavior?

### 23.8.1 Imitation

The strengthening of activation during imitation in Broca's area (Talairach coordinates:  $x$  from  $\pm 42$  to  $\pm 50$ ,  $y$  from 15 to 22, and  $z$  from 12 to 14 in our studies) is interesting and would support the role of the MNS in imitation behavior. Imitation is essential for the learning of many motor skills. Children learn by watching adults and other children, developing under continuous social feedback. Fortunately for the child's development, imitation seems highly rewarding: healthy children greatly enjoy both imitating and being imitated themselves.

One can copy movements and motor acts without understanding their meaning, as happens when a flock of birds escapes from a lake following the first frightened bird. However, true imitation goes beyond copying of action patterns and is more flexible, resisting, for example, changes in the physical environment (Gattis *et al.* 2002). Imitation is likely to be guided by a set of hierarchically organized goals which compete with each other if the processing capacity of the actor is limited (Gattis *et al.* 2002). Therefore imitation cannot be based on a direct sensory-motor mapping only, but rather requires some degree of action recognition and understanding. The MNS might provide such a sophisticated mechanism that helps to recognize and understand motor acts of other persons (Gallese 2001).

Imitation skills are abnormal in many autistic subjects, who imitate less and in a different manner than healthy subjects (Williams *et al.* 2001). If a healthy person is asked to imitate another person face-to-face, she typically prefers to imitate as in mirror; this

preference is seen already in small children. In our recent behavioral study with a pen-cup task (Wohlschläger and Bekkering 2002), Asperger and high-functioning autistic subjects did not benefit from the mirror-image pose of the person to be imitated (Avikainen *et al.* 2003). The autistic group made considerably more errors than the control group in selecting the correct grip and correct hand for the imitation in the mirror-image position but were equally accurate as the control subjects in imitating in crossed-over fashion (with anatomical rather than spatial correspondence with the person to be imitated). The relationship of the deficit in mirror-image imitation to possible dysfunctions of the MNS remains to be shown. It is interesting that the autistic subjects seemed to be normally reading the goals of other subjects' acts, as they achieved the end-point of the movement (the cup) as accurately as the control subjects. The end-points of actions are considered to be at the top of the set of goals guiding the imitation behavior (Gattis *et al.* 2002) and thus could be the last ones to be disturbed in case of deteriorating imitation behavior.

### 23.8.2 Mind-reading skills

Besides imitation, another possible role for the human MNS could be involvement in 'mind reading' skills, i.e. computation of other people's intentions continuously and automatically, based on observed and understood movements, postures, and gaze. These skills are essential for social communication and seem to be defective in, for example, autism and schizophrenia. Studies of the MNS might therefore provide novel insights into the pathophysiology of these brain disorders.

### 23.8.3 Representation of hand and orofacial gestures in Broca's area

One fascinating puzzle arising from the available MNS data is the representation of hand and orofacial gestures in the speech production area. In this context it is of interest to note that Brodmann's area 44, i.e. a part of Broca's area, is considered the human homologue of the monkey mirror-neuron area F5 (Passingham 1993; Petrides and Pandya 1994; Matelli and Luppino 1997). Moreover, Broca's area is not only a speech-production area but can be activated in association of various hand actions; for example, when stroke patients try to use their paralyzed hand or when people mentally imagine hand grasping (for references, see Gallese *et al.* 1996). Thirdly, there are close connections between speech-related gestures and speech production, which are often even considered as outlets of the same thought process (Goldin-Meadow 1999).

Speech-related gesturing seems to be independent of whether others are able to see the gestures or not. Thus humans gesture while speaking in phone, and even congenitally blind persons gesture—and while speaking with persons whom they know to be blind as well (Iverson and Goldin-Meadow 1998)! In stutterers, speech-related hand gestures may freeze at the time of stuttering whereas speech-unrelated hand movements continue (Mayberry and Jaques 2000). Interestingly, hearing babies born to deaf

parents may not babble aloud with their mouths but, instead, silently with their hands, so that the hand movements then contain the proper speech rhythm. (Petitto *et al.* 2001).

Thus abundant evidence points towards rather intimate connections between speech-related gestures and speech production, and the co-representation of these two functions in Broca's region is in full agreement with suggestions about common evolutionary roots of gestures and speech. For example, Rizzolatti and Arbib (1998), in the framework of the MNS, speculated that hand and orofacial gestures—rather than sounds—might have served as the precursors of human language. This proposal was not without precedents, but is now grounded, on a feasible neurophysiological basis.

The evolution of Broca's region first for gestural communication and only later for speech is supported by findings that this area is larger in the left than the right brain half of great apes, who do not speak (Cantalupo and Hopkins 2001).

### 23.9 Future studies

One interesting question for future studies is whether the human MNS functions extend beyond pure motor behavior. Modulation of the SI and SII cortices (Avikainen *et al.* 2002), discussed above, supports such a possibility. Interestingly, recent intracranial recordings have shown that the human anterior cingulate cortex can react to thermal pain perceived by the subject and also to mere viewing of another subject receiving similar stimuli (Hutchinson *et al.* 1999). It is thus tempting to speculate that the human MNS might comprise a general and socially important mechanism to allow intentions, emotions, and even the intensity of pain to be matched and communicated between individuals.

Studies of the human MNS could provide insights into brain disorders that manifest themselves as abnormal imitation or mind-reading skills, such as autism and schizophrenia. Studies of the 'social brain' will certainly provide exciting challenges for the whole neuroscience community.

### Acknowledgements

Supported by the Academy of Finland, the Sigrid Jusélius Foundation, the Human Frontier Science Program Organization Grant RG 39–98 (P.I. Vittorio Gallese), and Grant-in-Aid for Scientific Research (B) 15 300111 from JSPS.

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特集 言語機能の脳内メカニズム

## 言語野の進化

西谷 信之

神経研究の進歩

第47巻 第5号 別刷  
2003年10月10日 発行

医学書院

## 特集 言語機能の脳内メカニズム

### 言語野の進化\*

西谷 信之\*\*

われわれの日常のソーシャル・コミュニケーションは、主として言語により確立されている。ヒトの言語機能においては、ブローカ野の発見以来、優位半球の後下前頭葉に存在する「運動性言語野」が、言語表出に重要な位置を占めていると考えられてきた。ヒトにおける最近の神経科学的研究により、古典的な言語表出機能に加えて、非言語情報処理における興味ある知見が得られ、後下前頭部の機能が再考されつつある。後下前頭部の前駆体は、言語や会話に関連する表情や手指の動作の理解に重要な役割を果たすとともに、個々の意思疎通の進化に本質的な役割を担ってきたのではないかと考えられる。

キーワード：ブローカ野，模倣，ミラー・ニューロン・システム，ヒト

#### はじめに

哺乳類が約2億年前に発生したのち、約5~6千万年前に霊長類の祖先が出現したとされる(Schick & Toth, 1993)。その後二足歩行のヒトが約400万年前に出現し、道具として石を使用し始めたのが約250万年前と考えられている。しかし発声器官の構造から、言葉を喋る能力は未だ獲得されていなかったと推定されている。その後、約50万年を経て脳の急激な膨張が生じているが、当時のヒト科に属する霊長類(archaic Homo sapiens)の出現まで、約150万年ほどを要している。このarchaic Homo sapiensは、サルやチンパンジーなどの類人猿と同様に、咽頭が高位に位置し、母音形成に必要な共鳴腔としての咽頭腔・口腔が狭いことが知られ、その結果発生音は、奇声や擬音程度のものであったと推測されている(Dingwall, 1979)。しかしその後10万年ほど前にまで至ると、現在のわれわれ Homo sapiens sapiens にかなり近似した頭蓋底および

構音器官の構造を持つようになり(Lieberman, 1991)、なんらかの語音の発生が可能であったのではないだろうかと考えられている。そして、このような構造の進化に呼応する形で、中枢神経系も進化したものと考えられる(図1)。

#### I. 言語領域の機能

ヒトの言語領域は、1861年にフランスの外科医P. Broca(1824-1880)が報告して以来、優位半球の後下前頭部[ブローカ野, Brodmann area (BA) 44/45]が運動性言語野、さらには1874年のC. Wernicke(1848-1905)により、左側頭葉の後部上側頭部(ウェルニッケ野)が、感覚性言語野として理解されてきた。その後の研究により、ブローカ野の機能として、言語表出に関わるのみならず、単語想起、命名、統辞処理などの機能が明らかにされてきた(Wise et al, 1991; Salimelin et al, 1994; Stromswold et al, 1996)。一方、ウェルニッケ野の機能として単語の意味処理、単語の

2003年7月25日受稿

\* Evolution of language area.

\*\* 国立身体障害者リハビリテーションセンター感覚機能系障害研究部感覚認知障害研究室(〒359-8555 所沢市並木4-1) Nobuyuki NISHITANI: Cognitive Functions Section, Department of Rehabilitation for Sensory Functions, Research Institute, National Rehabilitation Center for Persons with Disabilities, 4-1 Namiki, Tokorozawa-shi, Saitama 359-8555, Japan.

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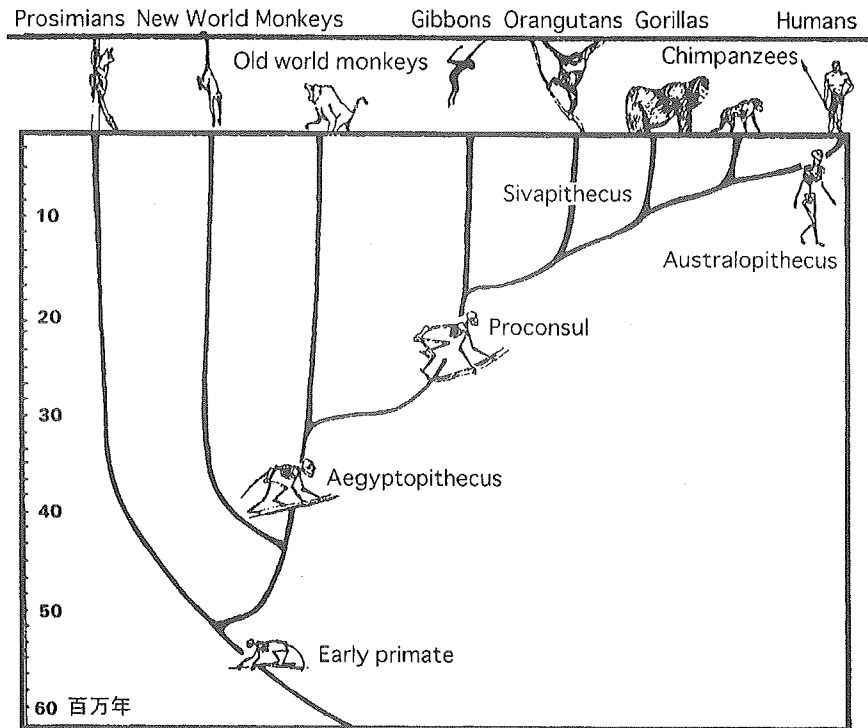


図1 霊長類の進化 (Schick & Toth 1993 より改変)

音韻処理などが明らかにされている (Demonet et al, 1992; Fitch et al, 1997)。これら言語に関連した機能に関する研究は膨大な数に上る。詳細は他書を参照されたい。はたして、この大脳皮質領域は、ヒトの進化の過程において、固有の機能と言語関連機能が連携するに至ったのであろうか、言語機能をヒトが獲得する以前では、その本来の固有の機能はいかなるものであったのであろうか。それを直接的に証明することは不可能ではあるが、最近の非言語情報に関連する研究が、その手懸りを与えてくれているようである。

## II. 新たな脳機能研究の知見から

日常のソーシャル・コミュニケーション確立のために、ヒトは言語情報に加えて非言語情報を併用している。そこで Nishitani & Hari は、言語とは無関係な手指の動きを観察または模倣した場合、ならびに自らその動作を行う場合に、その動作に関連する脳磁場活動部位と、その時間的変化について明らかにした (Nishitani & Hari, 2000)。この記録では、検者が検査室内の被験者の右側に位置し、標的に向かって右手を伸展し把握する反復動作を行う。被験者には、その動作の観察、右手による模倣、あるいは被験者自らのペースによる同様の手の動作を行う (実行) よう指示をした。

検者もしくは被験者が標的先端を指先で把握する瞬間を起点とし、脳活動の評価を行った。図2は、一人の被験者の模倣課題での脳活動を示している。標的先端の把握より約350ミリ秒前に、最初の活動が後頭部に認められた。次にブローカ野、[特にブロードマン44野, Brodmann area (BA) 44], さらに左側運動野、そしてさらに約100ミリ秒遅れて右側運動野が活動するのが認められた。同様の領域の活動は、観察と実行課題においても認められた。この活動様式は、他の被験者においても同様であった。また観察と模倣課題においては、脳の活動部位とその時間的關係は同様であった。さらにブローカ野と左側運動野は、他の課題時に比べて、模倣課題において有意に大きく活動していることが明らかになった。この結果は、ブローカ野と運動野の模倣における役割を強調しているものと考えられた。

次に、ブローカ野と運動野のこのような活動は、実際の動作の観察、模倣等においてのみに認められるのか否かを明らかにするために、口唇形状のみを変化させた顔の静止画像を呈示し、その観察、模倣、さらには同様の口唇形状を被験者自ら構成する (実行) 課題時の脳活動を明らかにした (Nishitani & Hari, 2002)。図3左は、実際に用いた口唇形状の異なる顔写真で、

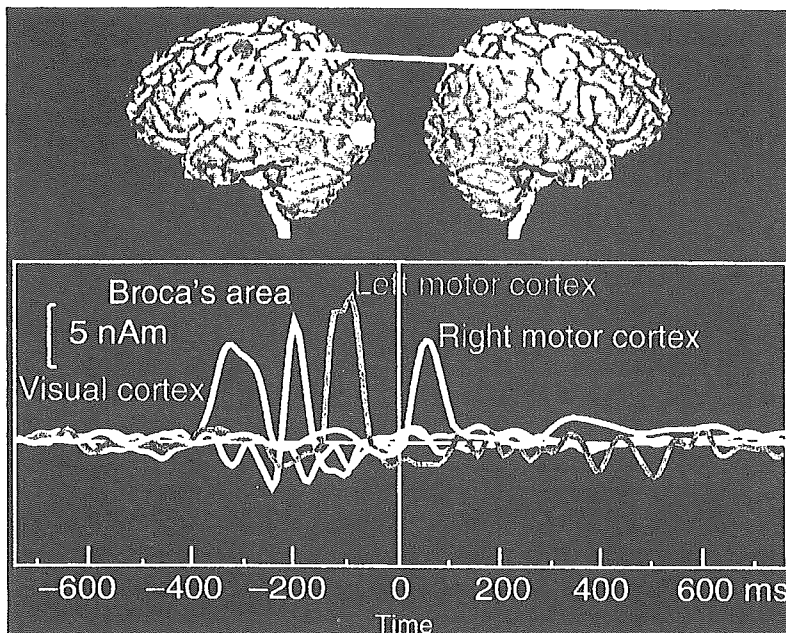


図2 標的先端の反復把握動作の模倣課題における一健常被験者の脳磁場活動部位と活動の大きさの時間的变化 (Nishitani & Hari 2000 より改変)

上段および下段は、それぞれ言語変換容易な、および困難な口唇形状である。中段は対照として用いた写真である。被験者には、記録の事前に口唇形状を呈示しているが、上段の写真が母音の口唇形状であるか否かは説明を行っていない。観察、模倣課題時での活動は、後頭部視覚野、上側頭溝、下頭頂部、ブローカ野（主に BA44、一部 BA45）、そして一次運動野の順に認められた。この全過程は、220-250 ミリ秒であった。ここでブローカ野と一次運動野の活動時間の差は、手指の観察・模倣の場合よりも、口唇のそれの方が、30-40 ミリ秒短かった (Nishitani & Hari, 2000, 2002)。この結果は、ブローカ野と運動野口唇領域との連携が手指とのそれに比べて密接であることを示唆するものである。一方、対照として呈示した不動の口唇の観察課題では、各種口唇形状の観察、模倣と同様に被験者全員で後頭部視覚野、上側頭溝と下頭頂部で活動が認められたのに対して、それ以降の脳部位では有意な活動を認めなかった。図3右は、左半球ブローカ野および右半球の相同部位における、観察と模倣課題での活動強度の関係を示している。これによると、上述した結果と同様に、口唇形状の異なる顔写真の観察においても、あたかも自らが実行している場合と同様に、左半球ブローカ野および右半球の相同部位が活動していることが明らかになった。次に口唇形状の模倣課題において

は、他の課題と比較し、有意に左半球ブローカ野および右半球の相同部位の活動は亢進していた。いずれの課題においても、左半球では、言語化可能な口唇形状に対する課題のほうが、言語化不可能なそれに対するより優位で、右半球ではその逆の傾向を認めた。両側半球の同活動とも若干の差を認めたが、言語要因による活動強度の有意差は認められなかった。

手指の形状に対する観察、模倣の課題下においても、両側半球において口唇形状の観察、模倣課題と同様の結果が示された (Nishitani & Hari, 2001)。さらに日本手話 (Japanese Sign Language : JSL) とアメリカ手話 (American Sign Language : ASL) のそれぞれ独自の手形から選択した手指形状を刺激とし、手話を知らない健聴者と JSL のみを知る日本人聾啞者 (Japanese signer : JS) に呈示し、その観察と模倣課題における両半球の活動を比較した。JS が JSL を観察、模倣する場合は、左半球のブローカ野と運動野の活動が、また逆に ASL に対する場合や健聴者の場合では、右半球の両部位の活動が有意であった。この結果はブローカ野と運動野における両側半球の機能分化を示唆するものである。

以上のようなブローカ野の活動は、動作やそれを示唆する視覚情報の観察、模倣および実行で認められるだけでなく、聴覚情報においても同様に認められた

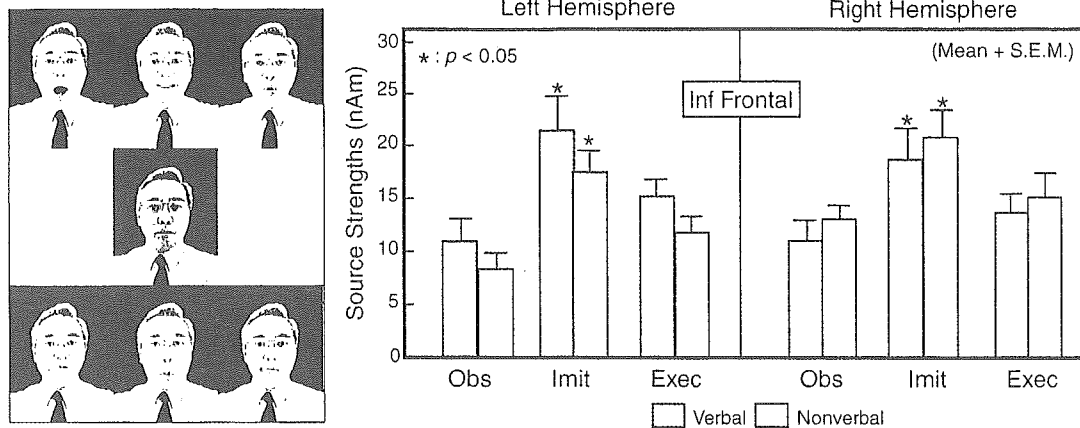


図3 口唇形状の観察、模倣課題、および自ら同様の口唇形状を作成した場合における刺激写真と左右後下前頭部の磁場活動の大きさ

Occ: Occipital cortex, STS: superior temporal sulcus, IPL: Inferior parietal lobule, M1: Primary motor cortex (Nishitani & Hari 2002 より改変)。

(Nishitani & Hari, 2003b)。図4は、語音、トーン、さらに不協和音を、聴取した場合と、それを擬似的に「模倣」し、語音もしくは擬音を発する場合のブローカ野の磁場活動を、Minimum Current Estimates (Uutela et al, 1999) を用いて示したものである。語音の聴取および特に模倣においては、ブローカ野が強く活動しているのがわかる。これに対して、トーンおよび不協和音に対しては、語音よりは弱いものの、聴取、模倣においてブローカ野の活動が認められた。ここで興味深いのは、このトーンや不協和音に対する聴取や模倣では、その主たる活動領域が、語音のそれに比べて、やや後方に位置していることである。これらの活動領域を頭部MRI画像上に重畳すると、語音に対する主活動部位はブローカ野前方部 (BA45) であるのに対して、トーンや不協和音では、ブローカ野の後方部 (BA44) であることが明らかになった。

### III. ヒト後下前頭弁蓋部 (BA44) と三角部 (BA45)

ヒト後下前頭葉の弁蓋部 (BA44) と三角部 (BA45) の細胞構築は異なることが明らかにされている。すなわち、BA44 は第5層の錐体細胞が多く存在し、その直後に位置する運動前野や運動野のそれに類似しているのに対して、BA45 ではその分布は少ない。さらにこのBA44の細胞構築は、サル前頭部F5領域と類似していることが示されている (Matelli & Luppino, 1997; Petrides & Pandya, 1994; Rizzolatti & Arbib, 1998; Rizzolatti et al, 2001; Tomaiuolo et al, 1999)。

次に、この後下前頭部のBA44とBA45の機能の相違を、Nishitaniはダイナミック磁気共鳴分光法を用いて、神経化学物質代謝の変化を非侵襲的に評価することで明らかにした (Nishitani, 2003a, 2003c)。この記録においては、言語化容易な手指の形状と変換不可能・困難な手指の形状の写真の観察に用い、それらの観察と模倣を課題とした。それによると、対照として用いた握りこぶしの写真の観察・模倣に比べて、言語性要因に関係なく、BA44とBA45で、コリン複合物質とクレアチン複合物質の代謝が有意に上昇しているのを認めた。さらにBA45では言語化が容易な手指の観察・模倣では、言語化が困難な手指の観察・模倣に比べて、有意にコリンおよびクレアチン複合物質の代謝が亢進していたのに対して、BA44では手指の形状に関係なく、観察、模倣両課題で代謝が有意に亢進していることが明らかになった。また観察と模倣との比較では、これまでの脳磁場研究の結果と同様に、刺激手指の言語性要因に関係なく、BA44とBA45ともに、模倣課題時に代謝の有意な亢進を認めた。以上の結果は、細胞構築学的に異なるBA44とBA45は、機能的にも異なることを示唆したものである。

### IV. サル・ミラー・ニューロン

サルにおける同様の神経活動が明らかにされている。Rizzolattiら (1996) は、サルの前頭葉領域F5の細胞群が、サル自身が餌を取り上げるなどの動作をしているときに加えて、他のサルや検者が同様の手の動作を行っているのを観察しているときにも活動すること



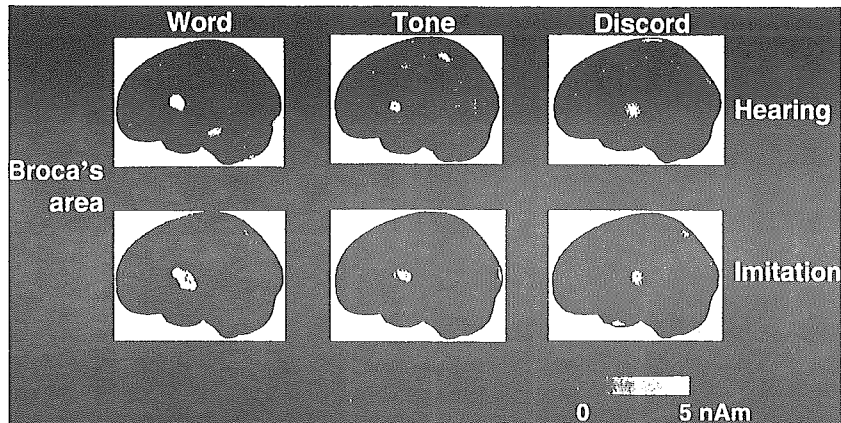


図4 3種類の音(語音, トーン, 不協和音)の聴取, 模倣におけるブローカ野の活動 Minimum Current Estimates により脳磁場活動を評価したもの(Nishitani & Hari 2003bより改変)。

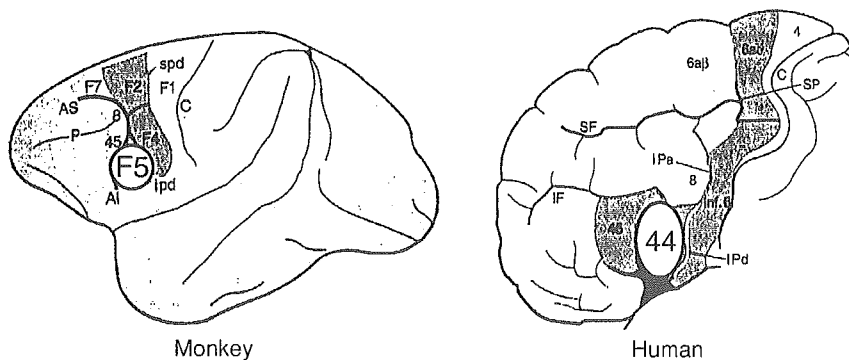


図5 サルとヒトの前頭部地図  
サル F5 野とブローカ野(その中で BA44)とは細胞構築学的に近似している。

を明らかにした。この F5 に存在するニューロン群は、他者の動作を観察しているとき、あたかも自らが同様の動作を行っているかのように活動することから、“ミラー”ニューロン・システム(Mirror Neuron System: MNS)と呼ばれた。このサルにおける神経細胞群の活動に関する詳細は、本特集の他稿を参照されたい。そしてそのヒト MNS の首座は、一連の研究からブローカ野および一次運動野(Fadiga et al, 1995; Hari et al, 1998; Nishitani & Hari, 2000, 2001, 2002, 2003b)にあるのではないかと考えられている。一方、サルの腹側運動前野に電気刺激を加えると、サルの手指や口唇が動くことが知られている(Preuss et al, 1996)。このように、細胞構築学的に両者が近似していることに加えて、サルならびにヒトにおける機能研究の結果から、サル F5 領域とヒトブローカ野、特に BA44 が相同部位では

ないかと考えられるのである。

#### V. ヒト・ミラー・ニューロン・システムとブローカ野

手や口唇のジェスチャーの観察, 模倣に関連した脳活動と言語機能, 発話との関連はいくつかの研究や事実により支持される。上述したように、サル前頭部 F5 領域への電気刺激により、手指や口唇の動きが誘発される(Preuss et al, 1996)。第2に、サル前頭部 F5 領域とヒトブローカ野は、細胞構築学的ならびに機能的に相同部位である(Matelli & Luppino, 1997; Petrides & Pandya, 1994; Rizzolatti & Arbib, 1998; Rizzolatti et al, 2001; Tomaiuolo et al, 1999)。第3に、例えば脳梗塞患者がその麻痺側の手指を使用しようとするとき、口唇も同時に動くことが認められるように、ブローカ

野は発話関連領域であるのみでなく、様々な手指の動作に連動して活動する(Gallese et al, 1996)。第4には、身振りと言話の密接な関係を挙げられる。この場合、第三者がその身振りを見ているか否かは関係ない(Iverson & Goldin-Meadow, 1998)。また吃音者においては、吃音が生じているときは発話に関連した手の動作は停止し、発話に関連のないそれは可能であるという(Mayberry & Jaques, 1998)。これらの事実、ブローカ野と口唇や手指の動作の関連を支持すると考えられる。

ここでCantalupo & Hopkinsら(2001)が、興味ある研究を報告している。言語優位半球における神経解剖学的な優位性が、少なくとも約500万年前のgreat apesに既に認められ、ヒトの進化の過程で唯一出現したものではないというものである。このBA44の左右不同は、great apesの発声に伴う身振りの創生と関連しているのかも知れない。そして、遂にはこの機能はHomo sapiens sapiensの言語表出システムの発達に関わることになり、後下前頭部の脳溝形成が促進され、その結果BA45の拡大がもたらされたのであろうと考察している。この研究結果は、BA44の前駆体が、コミュニケーション機能の進化の過程で中心的位置を占めていたとする、われわれの考察を支持するものである。

ヒトの動作や表情の観察は、コミュニケーションの形成の第1段階であると考えられる。小児は大人や他の小児の動作などを見て学習する。その結果、社会生活に欠くことのできない技術を習得していく。ヒトは、たとえばはじめ動作の意味するところを理解することが不可能であっても、動作を真似ることができる。このようにMNSは、他人の動作の根底にある意図を理解するための複雑なメカニズムを、ブローカ野を舞台にして構築しているのではないかと考えられる。そしてMNSにより、運動・動作に基づくメッセージの送り側と受け取り側の連携が形成され、生来保有している内的プロセス(学習)を介して、ソーシャル・コミュニケーションを確立してきたものと考えられる(Mataric & Pomplum, 1998)。さらに石器時代から、Homo sapiens sapiens出現までの進化の過程で、コミュニケーションの一手段として言語を獲得し、その中心的役割を果たし、そして現在もその役割を担っているのが、ブローカ野であり、またBA44ではないかと考えるのである。

#### おわりに

ヒト後下前頭部の最近の見解に基づき、言語野の進

化について述べた。ヒトは集団における他者との関係維持のために、言語による意思疎通の手段を獲得した。その言語機能の中核は後下前頭部に存在するが、言語獲得以前には、後下前頭部の前駆体は、意思疎通に重要な役割を果たす他人の行為・動作、および動作に繋がる意図の理解を担っていたのではないかと考えられた。またこの機能は言語獲得後の現代のヒトにも存在し、動作の模倣を通じ、新たなスキルの獲得と新たな脳機能の進化を促してきたのではないかと考えられた。

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**Abstract**

Evolution of language area

*Nobuyuki Nishitani*

from

*Cognitive Functions Section, Department of Rehabilitation for Sensory Functions, Research Institute, National Rehabilitation Center for Persons with Disabilities, 4-1 Namiki, Tokorozawa-shi, Saitama 359-8555, Japan.*

We establish daily social-communication, mainly with language, in addition to non-verbal information such as facial expression and gesture. As for the language function of human, since Broca's area was discovered, "motor language field" located in the infero-posterior frontal area has been considered to play an important role in verbal expression. Recent neuroscience researches have shown the interesting knowledge in the non-verbal processing and the function of the infero-posterior frontal area has been reconsidered. It is suggested that the precursor of Broca's area has played a crucial role in understanding facial expression and hand gestures in relation to language and speech, and had an essential role in the human evolution of the inter-individual communication.

*(Received : July 25, 2003)*

Shinkei Kenkyu no Shinpo (Advances in Neurological Sciences), Vol. 47, No. 5, pp701-707, 2003.  
IGAKU-SHOIN Ltd., Tokyo, Japan.

特集 第38回脳のシンポジウム【高次脳機能解析法と機能局在】

## MEGによる高次脳機能研究

西谷 信之 柴崎 浩

神経研究の進歩

第47巻 第6号 別刷

2003年12月10日 発行

医学書院