Neuroscience Letters 461 (2009) 65–68

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Gaze-related mimic word activates the frontal eye field and related network in the human brain: An fMRI study

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ARTICLE INFO

Article history:
Received 14 March 2009
Received in revised form 7 June 2009
Accepted 11 June 2009

Keywords:
fMRI
Active gaze
Mimic word
Frontal eye field

ABSTRACT

This is an fMRI study demonstrating new evidence that a mimic word highly suggestive of an eye gaze, heard by the ear, significantly activates the frontal eye field (FEF), inferior frontal gyrus (IFG), dorsolateral premotor area (PMdr) and superior parietal lobule (SPL) connected with the frontal–parietal network. However, hearing a non-sense words that did not imply gaze under the same task does not activate this area in humans. We concluded that the FEF would be a critical area for generating/processing an active gaze, evoked by an onomatopoeia word that implied gaze closely associated with social skill. We suggest that the implied active gaze may depend on prefrontal–parietal interactions that modify cognitive gaze led by spatial visual attention associated with the SPL.

Recent neuroimaging studies unveiled brain mechanisms bridging language and implied action [15]. Action verbs could activate specific brain areas related with perception and gaze [14]. For example, generation of action words activated an area in the middle temporal gyrus anterior to the area involved in the perception of motion while generation of color words selectively activated a brain area in the ventral temporal lobe anterior to the area involved in the subjective perception of color in humans [7].

Mimic words (imitate actions) related with a mental state such as laughter also selectively stimulate specific brain areas connected with the perception of laughter and smile. Osaka et al. [10] used fMRI to show that laughter modules using mimic words highly suggestive of laughter, heard by the ear with the eyes closed, significantly activated the extrastriate visual cortex near the inferior occipital gyrus in which the laughing face could easily be represented. However, whether a mimic word expressing active gaze, for example gazing restlessly or fixing one's eyes on someone without averting one's gaze, had an effect on the brain region involved in manipulating the mind's active gaze has not previously been investigated.

An active mimic word could essentially be defined as sound symbolism used to describe various human emotions and psychological states. A rough English equivalent would be, for example, "butterflies in the stomach". The role of active onomatopoeia (formation of a word from a sound associated with that being named) in the Japanese language is a very critical because Japanese has a very limited number of verbs. Therefore, one role of mimic words is to fill in the gap and provide a means for concise expression when a sufficiently descriptive verb does not exist. Such words make the language very vivid and instantly conjure up images in the mind of a native Japanese speaker, thus producing a strong synaesthetic effect. Japanese is uniquely rich in this type of expression, which is frequently used in daily conversation, magazines and newspapers, especially for headlines, because of its brevity and power to project vivid imagery including active gaze [3]. The expressions are classified into categories of different sensory and emotional expressions such as laughter, gazing and other more cerebral states. Osaka et al. [9] suggested that onomatopoeia forms unique action words that express various human conscious states and classified, using multidimensional scaling based on rated subjective intensity, the six top onomatopoeia words inducing gaze into Euclidian space. The uniqueness of this type of expression frequently represents a peculiar Japanese way of expressing feelings and/or mentality [3]. Although there is a considerable amount of knowledge about the neural representation of gaze perception, little is known about higher cognitive brain function with regard to gaze in connection with language function. Some mimic words involve very salient gaze components and sounds of gaze-related onomatopoeia can convey a subjective quality of gaze related to one's intentional stance [6].

The perception of gaze is a critical social skill for the people since it could reflect the internal mental states of others and thus it provides clues to interpret another person's thought process. Further, the direction of gaze is an excellent guide to the focus of another person's attention. Although, the present experiment is not directly associate with social cognition, but investigated the social brain's

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0304-3940/$ – see front matter
doi:10.1016/j.neulet.2009.06.023

representation of onomatopoeia. Perett et al. [13] investigated the neuronal responses of the macaque monkey's superior temporal sulcus (STS) that were tuned to the profile view of a face with an averted gaze. Recent findings on eye gaze suggest that information about gaze as social eye-contact is not processed in a unified fashion in any single area of the brain [1]. Rather, a highly cognitive sense of one's own gaze toward other people seems to be prepared and generated over distributed a frontal–parietal network in the maintenance of gaze information in which information about specific features, such as looking around restlessly and/or staring at someone repeatedly. Interestingly, recent neuroimaging studies of social neuroscience demonstrated that the human STS (defined as being the areas of adjacent cortex on the surface of the superior and middle temporal gyri and adjacent cortex on the surface of the angular gyrus) were activated by observing other people's gaze direction [2,5] while that during one's own intentionally motivated active gaze has not been investigated. The current study investigated the STS involvement on the mental representation of the active gaze-related words. Furthermore, how these features are linked to create internal gaze representing intentional stance was investigated here using mimic words that are strongly characterized by implied gaze. We presented the participant's ear with onomatopoeia words that are highly suggestive of various modes of gazing and looking to study whether these words activate not the auditory cortex but the cortex related to the listener's implied gaze. We hypothesized that a word-driven active gaze generation task would be excellent for testing the gaze-related region, because gaze-associated mimic words have specific sounds indicating implied gaze and would demand extensive processing devoted to gaze representation. We used fMRI to measure brain activity associated with gaze realization through the generation of a mental image of the gaze described by the word and compared fMRI activations between words that implied gaze and control words that implied no-gaze (non-sense syllables).

In the present experiment, twenty healthy college students or graduates aged 20–27 (11 females and 9 males) served as participants. Participants were recruited as paid volunteers from the Psychology Department of Kyoto University. Participants with chronic pain were excluded. Informed consent in accordance with the protocol approved by the Advanced Telecommunication Research (ATR) Institute Review Board was obtained from each participant before participating in this fMRI experiment. ATR is the site of our data collection.

We obtained behavioral indices of gaze and control conditions: Six Japanese gaze-evoking mimic words were selected from the top six high frequency words (mean judgment for evoking active gaze was 95% or more based on 290 responses) for generating one's gaze due; words were "gyoro-gyoro" for open one's eye widely and look sharply around, "maji-maji" for fix one's eye on someone without averting one's gaze, "jiro-jiro" for gaze at someone repeatedly and unreservedly, "shige-shige" for stare continuously, "kyoro-kyoro" for looking around nervously, "chira-chira" for repeatedly looking at someone for short period of time. These six words were selected based on previous scaling studies ($n = 290$) using multidimensional scaling and a method of magnitude estimation for affective gaze [10]. Observers were asked to assign numbers (from 1 to 100) according to the strength of their psychological impression of active gaze imagination of the vividness (average evaluation score = 50) using magnitude estimation analysis [8]. We employed six non-sense syllables having no gaze-related association value selected from a standard non-association table [17], which were the same as those used as the control condition in a previous onomatopoeia study [10]: These nonsense syllables were "rhini-rhini", "heyu-heyu", "sonu-sonu", "mena-mena, "runi-runi", and "nuhe-nuhe", each of which consisted a repeated syllable that has no meaning. In the previous study, we confirmed that these six non-sense syllables functioned as a valid control condition. The other concern is that how the activation will be, if the participants heard the onomatopoeia words which is not related to active gaze? Our previous study [9] also confirmed that different onomatopoeia activated different specific brain areas depending on its content.

We employed a block design and introduced two conditions: gaze and control conditions. Each participant performed four sessions: In each session all conditions were tested. In the gaze block, six onomatopoeic words were presented. Each word was presented for 2-s followed by 3-s inter-stimulus intervals. In the control block, six non-sense syllables, i.e., having no gaze-related association, with a similar syllable length as the gaze-associated words, were presented in the same time sequence as words in the gaze block. During the tasks, participants were instructed to form mental images of affective gaze corresponding to each gaze-related word stimulus, while keeping their eyes closed and maintaining their eyes in a fixated position throughout the entire condition. We asked the participants to make imagery of themselves gazing upon something. Eye fixation for each participant during imagery task was confirmed in the pre-session using eye movement recording apparatus. In the control condition, the participants were just required to listen to the non-sense syllables. The order of word presentation was counterbalanced across sessions and participants in order to avoid possible habituation of repeated word/nonword presentations. Our previous study showed that this procedure is valid for approximately four sessions [10]. During the session, participants were asked to listen to words/non-words presented to both ears through an air-driven earphone system.

Whole brain imaging data were acquired on a 1.5 T whole-body MRI scanner (Marconi Magnex Eclipse) using a head coil. Head motion was minimized with a forehead strap. For functional imaging, we used a gradient-echo echo-planar imaging sequence with the following parameters: TR 3 s, TE 55 ms, flip angle 90°, FOV 22 cm by 22 cm and pixel matrix 64 by 64. Sixteen contiguous, 6 mm thick slices with a 1.2 mm gap were obtained on the axial plane for each participant. After collection of the functional images, T1-weighted images (154 slices with no gap) using a conventional spin echo pulse sequence (TR = 12 ms; TE = 5 ms; flip angle 8°, FOV = 22 cm × 22 cm, and pixel matrix = 256 × 256) were collected for anatomical co-registration at the same locations as functional images.

After image construction, functional images were analyzed using SPM2 (Wellcome Department of Cognitive Neurology, London, UK). Five initial images were discarded from the analysis to eliminate non-equilibrium effects of magnetization. All functional images were realigned to correct for head movement. We selected images with less than 1 mm movement within runs when the images were corrected. The functional images were normalized and spatially smoothed with an isotropic Gaussian filter (6-mm full width-half maximum). Low frequency noise and differences in global signal were removed. Data were modeled using a box-car function. Single participant data were analyzed with a fixed-effects model while group data were analyzed using a random effects model.

Fig. 1 and Table 1 show the activated brain areas (control and gaze > control) and coordinates (uncorrected, $p < .001$), respectively. As Table 1 shows, cortical areas including the frontal–parietal regions were activated under the active gaze condition, while only the bilateral primary auditory cortex (BA22; −48, −8, −2 and 52, −8, −2) is activated under the control condition (Fig. 1 upper panel). The activation of restricted bilateral primary auditory cortex suggests that non-sense words had recognized as meaningless sound as compared with meaningful onomatopoeia words which activated more extended areas. In fact, we observed more extended activation areas, including the same primary auditory areas, and left supramarginal and superior temporal gyrus which involves the function associated with word comprehension. We subtracted the control from gaze (gaze > control) and obtained significant values in the fol-

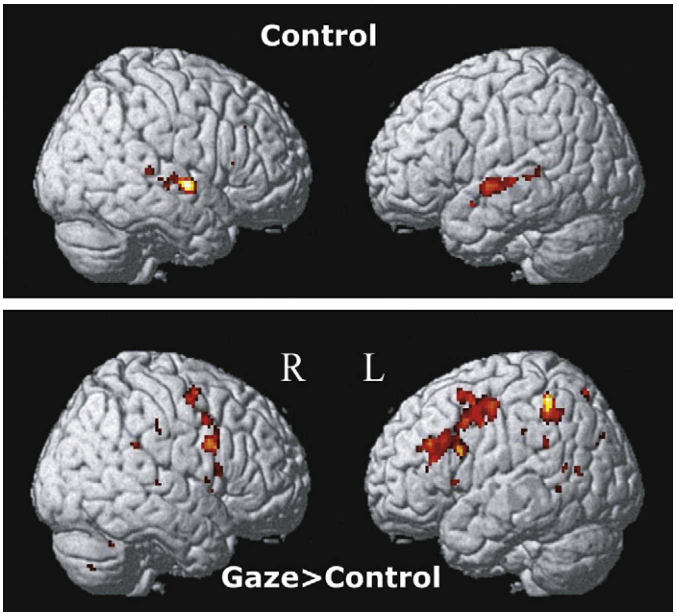

Fig. 1. Activated brain areas under gaze > control (control activation subtracted from gaze activation) (lower panel) and activated area under control (upper panel).

lowing areas: Left frontal eye field (FEF) close to precentral gyrus, left superior parietal lobule (SPL), left dorsolateral premotor cortex (PMdr) area in the middle frontal gyrus, left inferior parietal lobule (IPL) and right inferior frontal gyrus (IFG) while there were no significant activations seen in the reverse contrast (control > gaze).

Both the left FEF close to the precentral gyrus and left SPL appeared closely related to the implied gaze. Human FEF has been postulated to represent the major region involved in internal gaze control, and is, according to the recent study, located either in the vicinity of the precentral sulcus and/or in the depth of the caudalmost part of the superior frontal sulcus [12]. The FEF was more active during the delay when the direction of the memory-guided saccades was known compared to when it was not known throughout the delay in spatial working memory task [4]. It is likely that the FEF can maintain language-driven gaze intentions with sustained activity that likely reflects the active representation of the gaze. Therefore, the FEF–SPL dorsal network is likely to maintain directional information through the shifting and maintenance of spatial attention.

Interestingly enough, activation of the STS was not observed in the present study which suggested that the neuronal basis of one's own implied gaze is independent of the perception of another person's eye gaze. Our observation of left FEF activation strongly suggests that the FEF to anticipate the corresponding areas so as to guide active gaze shifts. The new evidence presented here is that the FEF is activated by mimic word related to active gaze and not by visual input from the visual cortex. Activation of the FEF could be a form of spatial rehearsal, similar to the way that Broca's area (BA44) is thought to support verbal rehearsal with subvocal motor articulation that refresh phonological representations (gaze-related words) stored in posterior parietal cortex [11]. Thus, the FEF could possibly refresh the spatial gaze representations stored in the IPL (BA40) via activation of FEF.

Table 1
Region of activation gaze > control.

Brain region activated	Brodmann's area	Coordinates			*T* value
		x	*y*	*z*	
	Gaze > control				
FEF	BA6	−40	−7	48	4.6
IFG	BA44	52	11	25	4.54
PMdr	BA6	−26	10	51	4.14
IPL	BA40	−35	−42	45	4.5
SPL	BA7	−12	−70	56	3.9

Note: uncorrected $p < .001$. *Abbreviations*: FEF = frontal eye field; IFG = inferior frontal gyrus; PMdr = dorsal premotor: SPL = superior parietal lobule.

The PMdr is the rostal part of the lateral premotor cortex, which is closely interconnected with the prefrontal cortex and is located in the superior precentral sulcus adjoining the superior frontal sulcus and dorsomedial to the FEF. Thus PMdr is independent of immediate movement and is assumed to have cognitive functions such as preparation for motor responses under mental operation tasks [4].

Thus, the SPL in connection with the FEF and PMdr may potentially play a shared role with the focusing of attention accompanied by active gaze [8]. Aided by the left SPL, activity of the left FEF was strengthened. Following the top-down cooperation among these regions, internal active gaze driven by mimic words could easily be performed.

The other interesting result obtained was activation of the right IFG where a memory retrieval system seems to work in the working memory. Tulving et al. [16] reported hemispheric encoding/retrieval asymmetry based on their PET study. They proposed a left IFG activation for memory encoding and right IFG activation for memory retrieval. According to this theory, the role of the right IFG would be to retrieve gaze representation (evoked by onomatopoeia) from the phonological store in the IPL and transmit the information to the frontal–parietal network including the FEF and SPL. Thus, the right IFG coupled with the FEF and related attentional network seems to work together to produce implied gaze.

In summary, an onomatopoeia word highly suggestive of active gaze, heard by the ear, significantly activated gaze control areas (FEF) driven by the spatial attention modulating area (SPL and PMdr), while non-sense words that did not imply active gaze under the same task did not activate this area in humans. This suggests that mimic words representing active gaze could effectively stimulate the neuronal network to prepare gaze.

Acknowledgements

This work was supported by JSPS Grant #19203032(A). The authors thank Takashi Ikeda and Daisuke Matsuyoshi are thanked for their help in collecting the data.

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