Neuroscience Research 90 (2015) 83–89

Contents lists available at ScienceDirect

Neuroscience Research

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

The deaf utilize phonological representations in visually presented verbal memory tasks

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ARTICLE INFO

Article history:
Received 27 September 2014
Received in revised form 27 October 2014
Accepted 10 November 2014
Available online 10 December 2014

Keywords:
Deaf
Phonological representation
Visual processing
Hearing

ABSTRACT

The phonological abilities of congenitally deaf individuals are inferior to those of people who can hear. However, deaf individuals can acquire spoken languages by utilizing orthography and lip-reading. The present study used functional magnetic resonance imaging (fMRI) to show that deaf individuals utilize phonological representations via a mnemonic process. We compared the brain activation of deaf and hearing participants while they memorized serially visually presented Japanese *kana* letters (Kana), finger alphabets (Finger), and Arabic letters (Arabic). Hearing participants did not know which finger alphabets corresponded to which language sounds, whereas deaf participants did. All of the participants understood the correspondence between Kana and their language sounds. None of the participants knew the correspondence between Arabic and their language sounds, so this condition was used as a baseline. We found that the left superior temporal gyrus (STG) was activated by phonological representations in the deaf group when memorizing both Kana and Finger. Additionaly, the brain areas associated with phonological representations for Finger in the deaf group were the same as the areas for Kana in the hearing group. Overall, despite the fact that they are superior in visual information processing, deaf individuals utilize phonological rather than visual representations in visually presented verbal memory.

1. Introduction

Individuals who are congenitally deaf do not acquire spoken languages in the same way as hearing individuals. It has been shown that deaf individuals acquire spoken languages using methods that are different from hearing individuals, such as by orthography or lip-reading (Aparicio et al., 2007; Beal-Alvarez et al., 2012). However, other studies provided evidence that it is difficult for deaf individuals to acquire phonological units. They have also been shown to be inferior in their phonological abilities compared to hearing individuals (Dodd, 1979; Leybaert and Alegria, 1995; Montgomery et al., 1987).

The term "phonological unit" refers to sound information that functions in a particular language, and a phonological representation is a mental representation of the information of the sounds in the brain. Concretely, sound information that comprises words and sentences is represented in the brain when listening to words and sentences. Phonological representations reportedly occur not only when one listens to words/sentences, but also when reading them (Aparicio et al., 2007; Baddeley et al., 1981).

A number of behavioral experiments have shown that phonological representations play an important role in facilitating language processing and memorization. For instance, it has long been reported that phonological representations contribute to verbal short-term memory (Baddeley, 1986; Burgess and Hitch, 1996), especially the memory of the order of serially presented words (Nairne and Kelley, 2004; Watkins et al., 1974; Wickelgren, 1965). According to these studies, when one recalls serially presented

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Abbreviations: STG, superior temporal gyrus; MTG, middle temporal gyrus; SPM, Statistical Parametric Mapping; EPI, echo planar imaging; MNI, Montreal Neurological Institute; BA, Brodmann area; MOG, middle occipital gyrus; MFG, middle frontal gyrus.

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http://dx.doi.org/10.1016/j.neures.2014.11.004
0168-0102/© 2014 Published by Elsevier Ireland Ltd.

words that are phonologically similar, they found it is more difficult to recall these words when they are asked to do so in order. This suggests that phonological information is utilized in verbal short-term memories of order. When this phonological information does not function well as a mnemonic process, the results of order memory worsen. Besides memory, it has been reported that phonological representations are also utilized in language processing for sentence comprehension (Morita and Tamaoka, 2002).

Many behavioral studies on deaf individuals have also described that phonological representations function in these individuals when performing tasks involving languages (Charlier and Leybaert, 2000; Hanson and Fowler, 1987; Hanson and McGarr, 1989). Hanson and MaGarr showed that deaf individuals were able to judge whether or not visually presented paired words rhymed. Furthermore, they claimed that deaf individuals could understand phonological units independently of spelling recognition. For example, the words “blue” and “through” are not spelled similarly and yet deaf individuals are able to recognize that these words rhyme.

Previous studies using functional brain imaging techniques such as functional magnetic resonance imaging (fMRI) have investigated the neural correlates of phonological representations in deaf individuals. FMRI studies on hearing individuals have clarified that the left superior temporal gyrus (STG) and the left middle temporal gyrus (MTG) are associated with phonological representations. These brain areas activate when one performs tasks in which phonological representations are assumed to occur, such as when reading words and non-words and during rhyming tasks in which one judges the phonological similarity of paired words (Démonet et al., 1992; Owen et al., 2004; Rumsey et al., 1997). Previous studies on deaf individuals have shown that similar brain areas, that is, the left STG and surrounding areas, are activated for both hearing individuals and deaf individuals when phonological representations of words (in reading and rhyming tasks) are considered (Aparicio et al., 2007; Neville et al., 1998).

However, it remains unclear how deaf individuals utilize phonological representations, although behavioral and neuroscientific data have revealed that phonological representations occur in these individuals. It is especially unclear whether deaf individuals prioritize phonological information over available other sensory information when they can utilize any information. It has been reported that sensory information processing abilities besides those for auditory information in deaf individuals are different from those of hearing individuals and of signers because of auditory deprivation and the use of sign language respectively (Bolognini et al., 2012; Cattani et al., 2007; Levänen and Hamdorf, 2001). In particular, it has been described that deaf individuals have superior visual information processing abilities compared to hearing individuals. Some studies reported that signers are superior at memorizing shapes compared to non-signers, although their memorization abilities for objects are almost the same as those of hearing individuals (Cattani et al., 2007). Few studies have reported how deaf individuals (with superior visual information processing) utilize phonological representations in a circumstance where both visual and auditory information are available, e.g., understanding visually presented languages, which also have phonological information.

Using fMRI, the present study examined whether deaf individuals utilize phonological information when they memorize serially visually presented letters. Two mnemonic processes are likely utilized in the present tasks, that is, a phonological strategy in which one utilizes the sounds that letters represent, and a visual strategy in which one memorizes the shapes of letters. We hypothesized that if we obtained activation in the left STG and MTG, then this would suggest that deaf individuals preferentially utilize the phonological strategy even in a circumstance where they can utilize visual information. Based on our findings, we suggest that both hearing individuals and deaf individuals use phonological information as a mnemonic process for memorizing visually presented languages.

2. Methods

2.1. Participants

Twenty-nine subjects participated in this study. All of the participants were right-handed. The deaf group consisted of 13 congenitally deaf Japanese Sign Language (JSL) signers (6 female; mean age = 21.0 ± 1.03 years). These individuals had unaided hearing loss between 85 and 125 dB (mean = 102.7 dB). All of the deaf participants had bilingual (JSL and Japanese) education. The hearing group consisted of 16 hearing Japanese native speakers (7 female; mean age = 22.8 ± 1.56 years). The deaf and hearing groups had similar visual memory performances, as tested with the Wechsler Memory Scale-Revised (WMS-R) The visual memory scores of the two group were tested by *t*-tests ($t = 1.03$, $df = 27$, $p = 0.31$). All procedures were conducted in accordance with the ethics committees of the affiliated institutions.

2.2. Procedure

Fig. 1 shows the experimental design. Participants were asked to perform memory tasks in which Japanese *kana* letters (Kana), finger alphabets (Finger), and Arabic letters (Arabic) were used. Participants in the hearing group did not know which finger alphabets corresponded to which language sounds, whereas participants in the deaf group did, thus phonological information processing was expected to occur. All of the participants understood the correspondence between Kana letters and their language sounds. None of the participants knew the correspondence between Arabic letters and their language sounds, so this condition was used as a baseline. In each trial, 5 letters were serially presented in random order. Each letter was presented for 500 ms and there was an interval of 500 ms between letters. After a subsequent 3000 ms interval, 2 letters placed on both sides of a right arrow were presented for 4000 ms and participants were asked to answer whether the order of the letters was correct or not by pressing a button signaling “Yes” or “No.” Finally, the correct answer was presented for 1000 ms in order to keep participants motivated, followed by 3000 ms of a fixation point. Each of the three conditions was contained in a session, so that each session contained 10 Kana trials, 10 Finger trials, and 10 Arabic trials. The three conditions were repeated in the order of Kana, Finger and Arabic.

2.3. Imaging parameters and data analysis

MRI data were obtained using a MAGNETOM Sonata 1.5-Tesla system (Siemens, Germany) at Tamagawa University Brain Research Institute. Imaging conditions for echo planar imaging (EPI) were as follows: repetition time, 2000 ms; echo time, 50 ms; field of view, 192 mm; slice thickness, 6 mm; matrix, 64×64; flip angle, 90°; and voxel size, 3 mm × 3 mm × 6 mm. Each volume was composed of 20 axial slices.

Statistical Parametric Mapping software (SPM8; Wellcome Department of Cognitive Neurology, London, UK) run on Matlab R2013b (Mathworks, Natick, MA, USA) was used for image processing and statistical analysis. The following operations were performed for preprocessing. First, to reduce motion-related artifacts, Image 1s from EPI were realigned to match the first image. The first EPI image was normalized to the standard Montreal Neurological Institute (MNI) template attached to SPM8. All images were then normalized using the same normalization parameters.