

Involvement of classical anterior and posterior language areas in sign language production, as investigated by 4 T functional magnetic resonance imaging

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Abstract

To investigate the cerebral organization for language production across the particular channels supporting linguistic behavior, a functional magnetic resonance (fMRI) study was conducted in deaf native users of American Sign Language (ASL) and age-matched hearing controls. Seven native ASL speakers and 15 vocal English speaking subjects covertly performed an object naming task inside the 4T scanner using their native languages ASL or English, respectively. In subjects of both groups, classical language areas were found to be activated, including posterior Broca's area, the anterior insula, premotor cortex, and the posterior parts of the superior temporal cortex. Activations showed a predominance of the left hemisphere for both groups. In the deaf group, however, there was markedly larger involvement of the cerebellum, the inferior frontal gyrus, and the posterior insula and more robust activation in occipito-temporal and superior parietal cortices. In summary, it could be demonstrated by fMRI that native language production using ASL is associated with activation of classical language areas, although the neural organization for language processing is not identical in the two language modalities ASL and English language.

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Sign language in deaf subjects, e.g. American Sign Language (ASL), can be considered as natural language with the complex linguistic structure found in spoken language of hearing subjects, including representational levels such as phonology (sublexical structure), morphology (structure at the level of word meaning), and syntax (structure at the level of the sentence) [3]. Sign languages are not merely gestural systems, nor are they manual derivatives of the spoken language used in the surrounding community. Signed and spoken languages are comparable, then, in terms of their linguistic and psycholinguistic properties, but differ radically in terms of the way this linguistic structure is implemented in production and comprehension. Sign language makes ex-

tensive use of spatial contrasts and uses visual and manual modalities for perception and comprehension.

Lesion-based work has established that hemispheric asymmetries for language and spatial cognition in deaf life-long signers are similar to those found in hearing speaking individuals [1,13]. These lesion studies are in agreement with a functional magnetic resonance (fMRI) study of sign language comprehension demonstrating a marked bias of the left hemisphere to processing of languages independent of modality [2]. Moreover, a H₂¹⁵O positron emission tomography (PET) study showed large overlap in activation patterns during narrative production in English and in sign language [7]. There are further lines of evidence suggesting that Broca's area is involved in sign language production [8,22]. Furthermore, there is evidence that the left lateral superior temporal lobe is particularly involved in supporting sign language comprehension [18], agreeing well with studies of comprehension of spoken language.

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Taken together, these data suggest that the neural organization of signed and spoken language is surprisingly similar given the differences between the two systems and therefore that the neural organization of language is largely modality independent. The present study used fMRI at 4 T to investigate this question in more detail by examining the involvement of so-called classical language areas in sign language production for deaf participants performing a covert ASL task (object naming). Specifically, we sought to address the following questions: (1) Is Broca's area involved in production of ASL? (2) Are posterior superior temporal lobe regions which are supposed to take part in speech production in hearing individuals involved in ASL production as well? (3) Can we provide fMRI evidence for the involvement of the anterior insula (which has been suggested to be implicated in speech production, e.g. [5]), and will it also be involved in sign language production?

Seven right-handed subjects (five female) with congenital nonsyndromic deafness were included in the study (mean age 29 years, range 21–49 years). Five were born to deaf signing parents, all were exposed to ASL prelingually, and all attended a residential school for the deaf and used ASL as their primary means of communication. As controls, fifteen right-handed healthy participants (eight female; mean age 26.5 years, range 21–44 years), all of them native speakers of English, were investigated using the same study protocol; all these subjects were neurologically and neuropsychologically normal, none had any history of neurological or psychiatric disease. All subjects gave their written informed consent to participate.

The subjects underwent fMRI scanning in a Siemens/SISCO scanner operating at 4 T and equipped with a shielded head gradient set and a quadrature bird-cage head coil, at the University of Minnesota (Minneapolis, MN). Blipped multi-slice echo planar images were constantly acquired during task and reference periods (echo time, 30 ms; acquisition time, 30 ms; matrix, 64; alpha, 90°). A minimum of 27 contiguous coronal slices covered the entire brain (field of view, 200–240 mm; slice thickness, 5 mm). Structural scans were acquired axially, with a FLASH sequence (matrix, 256 × 128; 27–64 slices; 2.5–5 mm thickness, no gap; alpha, 10°; field of view, 220–256 mm). Scanner noise was constant across all conditions. Head movements were minimized as far as possible by positioning the subjects' heads in the scanner by use of a vacuum mold. Moreover, a pneumatic pressure sensor was placed next to all subjects' heads and used to record head motion data. Before 2-D Fourier transformation, a Gaussian line broadening was applied, resulting in a voxel size of approximately 5 mm³.

The activation condition comprised a word production task in which daily-life objects were visually presented on a screen outside the scanner and had to be named by the subjects; to ensure that activations could not be attributed to the participants observing their own handshapes or hearing their own voices, respectively, and in order to minimize motion-related artifacts the subjects should name

objects sub-vocally (i.e. with covert articulation). For that purpose, deaf subjects were instructed to imagine communicating with themselves by signing in analogy to covert verbal speaking. The reference condition consisted of passive viewing of size-matched grayscale images shown at the same rate as the objects, in which individual pixels were pseudo-randomly assigned a grayscale value with the luminance matching the average luminance of the objects. Stimulus presentation followed a block design in a fivefold alternation of a reference and an activation task, each of 45-s duration, i. e. an A₁B₁A₂B₂A₃ pattern where A_n denote the reference conditions and B_n denote the activation conditions.

Data were analyzed using STIMULATE software (version 5.6) by Strupp [23]. Two statistical comparisons were performed on each subject's data: Using a Student's *t*-test, (1) the B₁ activation period was compared against pooled images acquired during A₁ and A₂ reference periods, and (2) the B₂ activation period was compared against the pooled images acquired during A₂ and A₃ reference periods. For control of motion artifacts, the center of gravity in the time course for three spatial directions was plotted and, if movement exceeded a threshold of 1 mm, the data was discarded. Only pixels which showed signal changes greater in the activation periods than in the reference periods in both comparisons at the *P* < 0.01 level and which were part of a cluster of minimally four voxels within a slice were considered activated. Each activated voxel remaining after this thresholding procedure was then set to a value of 1.0, and all other pixels to a value of 0.0 to produce an activation map for each subject. These activation maps were then warped into Talairach space and superimposed as a group onto a high-contrast structural MRI image also warped to Talairach space. For anatomical identification, the coordinates from the Talairach stereotaxic grid were used. Voxels in the group data which were not activated in a majority of subjects in each sample were eliminated. Consecutively, only those clusters were regarded which were activated in at least 8 of the 15 hearing subjects or at least 4 of the 7 deaf subjects, respectively. The degree of overlap in activation in a given voxel between subjects was then color coded. By that procedure, the reduced accessibility of the individual variability in the data which is immanent in group analyses was accounted for.

As the main findings after this straight thresholding, activations in the deaf subjects were found in the anterior and posterior parts of Broca's area in the inferior frontal gyrus (IFG), corresponding to Brodmann's area (BA) 44/45, comprising the frontal operculum and in its depth the lateral aspects of the anterior insula. Thus, it could be hold that this area is indeed involved in sign language production. Furthermore, activated areas were localized in the posterior superior temporal cortex (comprising mainly BA 22) and in the precentral gyrus. In the hearing subjects, classical language areas were found to be activated, including posterior Broca's area, corresponding to BA 44/45, and the lateral anterior insula, moreover the posterior parts of the superior temporal cortex, superior temporal gyrus (STG), and

posterior temporal pole, as described previously [14]. Very robust activation was found in the premotor cortex, and the precentral gyrus was as well shown to take part in language processing, as described in previous studies on speaking subjects [19,24]. Hemispheric asymmetry of activation was found for all of the above-named areas (especially Broca's area and posterior superior temporal areas) with a clear predominance of the left hemisphere both for deaf and for hearing subjects without obvious group differences.

Besides these similarities in activation patterns, there were differences in the group activation maps. Overall, the activations in the ASL signers tended to be somewhat more scattered and less robust than in the English-speaking subjects, reflecting a larger network of regions involved and a higher interindividual variability. In the hearing subjects, the dorsal aspects of the temporal lobe showed larger activated clusters than in the deaf subjects. Moreover, activations in the ventral parts of the occipito-temporal cortices (particularly of the right hemisphere), in the superior parietal lobe (SPL) and in the supramarginal gyrus were markedly larger in the deaf participants than in the English-speaking. In the ASL users, the posterior and anterior aspects of the inferior frontal gyrus (IFG, corresponding to BA 45/46) showed a more robust involvement, and the insula was activated both in its posterior and its anterior parts in contrast to more anterior activation in the hearing group. The activations found in the superior premotor cortex were both lateral and medial for both groups, but spread more laterally in the hearing subjects. Interestingly, the significant voxel clusters in the

cerebellum were markedly larger in the deaf group. Representative rendered 3-D images of the overlays of activations onto a standard brain are given in Fig. 1A–D for the deaf and for the hearing subjects, respectively.

This is to our knowledge the first fMRI study comparing the brain organization for ASL production to that of spoken language. By that design, an experimental situation for high-resolution functional neuroimaging is created in which linguistic factors were held constant between the two language systems, whereas the sensory and motor modalities through which language production was channeled were varied. We could then compare the neural organization of the two language systems to map the contribution of modality specific factors on the neurology of language. It could be demonstrated that ASL production is associated with activation of cortical areas which are known to be involved in speech production in healthy subjects (e.g. [4,5,21]). In particular, taking the initial questions into account, Broca's area was found to be robustly activated in our sample of ASL users, as well were the posterior superior temporal cortex and the anterior insula. All these areas were activated in both the deaf and the hearing group in our study. In summary, these results confirmed the involvement of so-called classical language areas in ASL production, including posterior parts of STG [14]. These results are in agreement with the results of a recent perfusion PET study by Horwitz et al. demonstrating involvement of BA 45 in both ASL and spoken language generation [16]. Furthermore, these areas were shown to be activated during ASL

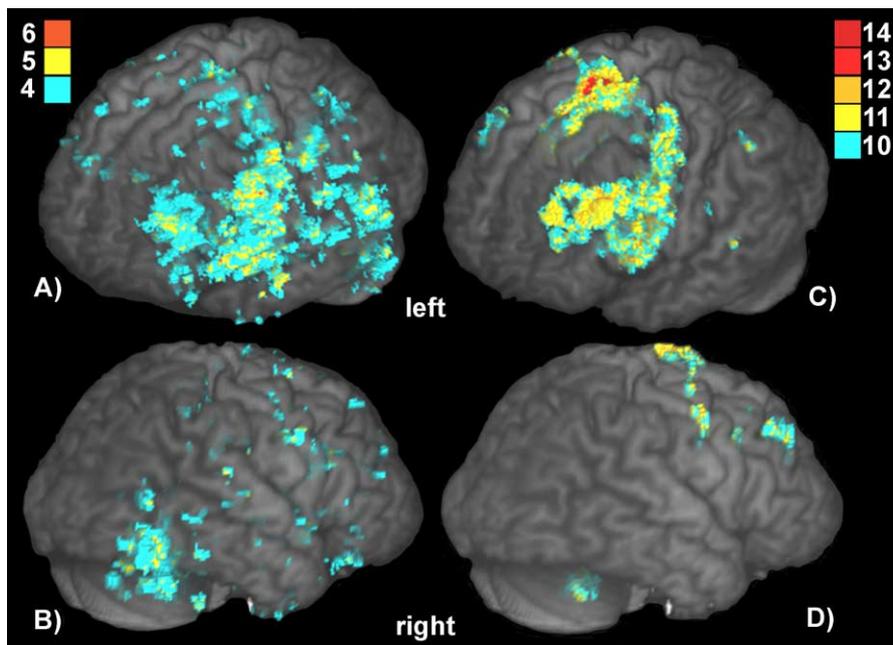


Fig. 1. Three-dimensional surface rendering of activation patterns of the word production task superimposed on a standard brain template. (A and B) ASL using subjects; (C and D) English speaking subjects. (A and C) View onto the left hemisphere, especially frontal areas including BA44/45; (B and D) view onto right hemisphere including cerebellum, occipital and parietal cortex. The color code is indexed in the colorbar for each group and denotes the number of subjects that activated jointly in this voxel after normalization (only voxels that exceeded a minimum of more than half of ASL signers or native English speakers, respectively).

comprehension as well in a previous fMRI study by Neville et al. [19].

Obviously, the cerebral activation patterns in both language modalities contained structures classically linked to language processing. With respect to Broca's area/IFG, it is well known that this region is involved in various aspects of language processing. However, it has to be noted that there is ample evidence from neuroimaging studies that Broca's area is not an exclusively language-specific module but plays a role in nonlinguistic (e.g. motor) processes as well [6]. In our study design using a reference condition without a motor component, it is not possible to differentiate if Broca's area activation in the signers might be merely due to motor planning. Anyway, a large overlap of activated clusters in IFG (BA 44/45) in both subject groups during signing and speaking, respectively, can be stated, implicating a common functional role in components of language production *sensu stricto*. With respect to the activation in the left-hemispheric anterior insula, this area has been shown to be involved in speech motor control both by neuroimaging [25] and lesion studies [10]. The present data provide evidence for its functional association with another language modality, with the same considerations concerning functional specificity for language as discussed for Broca's area.

A similar degree of language lateralization to the left hemisphere as previously described for ASL comprehension in deaf signers despite the visuospatial nature of sign language [15] could be confirmed for overt language production in the present study (in which all of the 22 subjects were right-handed). Although these findings in deaf native ASL signers agree with the results of a PET study on language lateralization in ASL [9], they are different to findings in hearing ASL-English bilinguals who acquired ASL before puberty since those showed marked right-hemispheric activation (angular gyrus) during ASL processing [20]; however, the use of ASL in these hearing bilinguals is not the same as in deaf native ASL signers. Obviously, there is large overlap in the neural basis of human language irrespective of its structure and of the modalities through which it is produced.

Differences between the underlying cerebral systems were also observed, suggesting that neural organization is not identical in the two language modalities. The cerebellum, as a motor-related but of course poly-modal brain area, exhibited markedly larger bilateral activation in ASL users, suggesting more robust recruitment of direct motor functions. However, the area with the most robust activation in the English-speaking subjects was located in the left premotor cortex. This finding is in agreement with previous studies demonstrating the major role of this area in language function, e.g. a recent intraoperative electrical stimulation study by Duffau et al. [11]. Although motor function apparently is more important in ASL, this area showed a markedly less robust activation in the deaf subjects, probably reflecting the more scattered neural network with higher interindividual variability. Moreover, the supramarginal gyrus was engaged in ASL production, in

agreement with a PET study on the processing and expression of spatial relationships within ASL [12]. The signing subjects—but not the English-speaking—showed activation in the occipito-temporal cortex which could be found bilaterally but was clearly pronounced in the right hemisphere. This finding has been described previously for deaf signers [12,17] and might reflect the greater movement component in sign language [17]. As an alternative explanation, these activated areas might reflect alterations within visual processing, particularly concerning spatial relationships, as a part of the extensive language-related network in signers. Within this extensive network involving the ventral occipito-temporal cortices and SPL, the neural representations of the visuospatial component in ASL production was demonstrated. In summary, the analysis of the brain systems involved in signed and spoken languages, despite the high degree of similarity, broadens the understanding of the neural networks underlying language generation.

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