

**Neuroimaging studies of crossmodal plasticity and
language processing in deaf people.**

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Introduction

In this short chapter we focus on just two questions in the domain of cortical imaging of language and sensory processing. First, to what extent do cortical circuits that subserve spoken language in hearing people also support spoken language processing, in the form of speechreading, in people born profoundly deaf? Second, do the cortical circuits for processing a visible language such as sign language involve auditory processing regions and do these networks differ between deaf and hearing signers?

Before these questions can be answered, it is important to realise just how variable the world of the deaf child can be compared with that of a hearing child. The child born deaf may be deprived of not one but two human faculties. Since most human languages are spoken, the loss of hearing can have major

consequences for successful acquisition. Sensitivity to heard speech has been demonstrated as early as the second trimester of foetal development (Mehler & Christophe, 1994), and spoken language development is heavily dependent on adequate auditory function throughout childhood. If hearing is lost, for example, by infectious disease such as meningitis within the first five years, its impact on spoken language development can be immense (Bedford et al, 2001).

Furthermore, the great majority of deaf children are born to hearing parents, and may therefore be deprived of a critical feature of the ecology of language development - a salient informative communicative context shared by child and caregivers (Vygotsky, 1962, 1978). However, approximately 5-10% of the deaf population are born to deaf parents, the majority of whom use a signed language within the home. Thus, these deaf children are raised with exposure to a visuo-spatial language, which possesses all the cognitive, linguistic and communicative requirements of a human language (Klima & Bellugi, 1979; Sutton-Spence & Woll, 2000). Moreover, this language is not related in any significant way to the spoken language of the host community. The signed language development of Deaf children of Deaf parents (DoD) follows the characteristic course, both in timing and structure, of spoken language acquisition in hearing children (eg Bellugi & Fischer, 1972; Klima & Bellugi, 1979; Liddell, 1980; Sacks, 1989; Petitto et al, 2001).

Before considering the neural systems supporting processing of signed languages in native users, we will explore an aspect of language processing in deaf people from a hearing home (DoH) which has, until very recently, been relatively neglected in studies of the cognitive neuroscience of language: This is speechreading. Hearing people make use of visible speech actions; in fact, they cannot avoid it (McGurk & MacDonald, 1976, and Section C of this volume). Deaf people are exposed to speech and its visible effects. Nevertheless, skill at speechreading varies enormously from one deaf child to another. The root cause of this variability must be associated with the reduced input specificity of seen compared with heard speech. This can be demonstrated convincingly in terms of phonological structure. Speech that is seen but not heard can deliver only a small subset of the phonological categories available to the hearing perceiver of speech (see eg Summerfield, 1987). But for a profoundly deaf child born into a hearing family speechreading may be the only means to access to the language that surrounds her. Although earlier tests suggested otherwise (eg Mogford 1987), careful recent tests of lipreading show that a proportion of people born deaf can become adept at spoken language processing and may be more skilled than the best hearing individuals at following silent lipread speech (Bernstein, Demorest & Tucker, 2000). Our work has explored how cortical circuits for speechreading become organised in people born profoundly deaf. These are people for whom a spoken, not a signed, language was the first language available in the home.

Seeing Speech: cortical correlates of silent speechreading in hearing and deaf individuals

Calvert et al (1997) were the first group to explore the cortical substrates for the processing of seen silent speech in a hearing population using fMRI. Participants were given a simple speechreading task: ‘Watch the face speaking random numbers between 1 and 9, and rehearse them silently to yourself’. Silent speechreading activated extensive visual cortical regions including V5/MT, occipito-temporal regions. In addition parts of the auditory speech processing system within the lateral temporal lobe were activated bilaterally at the group level. In particular activation was observed in posterior parts of the superior temporal gyrus (STG), extending both ventrally into the superior temporal sulcus (STS) and superiorly onto the superior temporal plane, incorporating the tip of Heschl’s gyrus (BA42; see Figure 1).

figure 1 about here

The most striking aspect of the study was that it demonstrated that parts of auditory cortex defined functionally as those regions of superior temporal cortex that were activated by heard speech, could also be activated by watching the silent speaker. This was unexpected since these areas had been considered to be specific to acoustic processing; they were in the regions that have been labelled as primary (A1) and secondary (A2) auditory cortex (see Luria, 1972). Activation was not

extensive within A1, and given the spatial resolution of fMRI, appeared to be confined to the parabelt rather than core regions of auditory cortex (Hackett et al, 2001). These are the cytoarchitectonic Brodmann areas (BA) 41 and BA 42. Activation was robust, and replicable (MacSweeney et al, 2000; 2001; 2002a; Campbell et al, 2001). Figure 2 illustrates the relative locations of these superior temporal regions. Two questions arose from these findings: First, was activation in auditory cortex specific to seen (silent) speech or did it extend to non-linguistic lip movement? Second, would the pattern be replicated in people born profoundly deaf?

figure 2 about here

To address the first of these questions we compared speechreading with perception of mouth movements that could not be construed as speech – facial actions such as chewing. Many of the same regions were activated by both types of facial movement, including STS and posterior parts of STG (Calvert et al., 1997; Campbell et al, 2001). However, speechreading activated superior lateral temporal regions (ie auditory cortex) to a greater extent than watching facial gurns. This activation was bilateral, whereas activation by facial gurns in these areas was right-lateralised. Do deaf people show a similar pattern when they watch speech? Does activation occur in regions corresponding to those activated by heard speech in hearing individuals? We tested six deaf adults using the same

tasks. All were profoundly deaf from birth, had hearing parents, and their main mode of communication with hearing people was spoken English. All had attended schools where spoken English was the medium of instruction. They were as good as the hearing group at identifying lipspoken vocabulary items. Despite this, their pattern of cortical activation differed significantly from that of the hearing group (see Figure 3; MacSweeney et al, 2001, 2002a). Specifically, there was no suggestion that left superior lateral temporal regions were activated consistently across this group when performing the speechreading perception task. Deaf individuals showed activation in different regions of the left lateral temporal cortex, however the focal location of these activations was inconsistent across individuals and no lateral superior temporal activation was detected at the group level. Our interpretation of this lack of consistency in location of temporal activation was that it directly reflected the deaf participants' lack of experience of auditory correlates of visible speech. In hearing individuals, associations between vision and audition in speech are consistent throughout development. Functional imaging studies suggest that the STS may support audiovisual speech binding for normally occurring heard and seen speech, and can then modulate back-projections to sensory cortex. In hearing people, activation of STS is time-linked to activation in both sensory cortices when presented with coherent audiovisual speech. We have suggested that this is the mechanism that is responsible for

activation in auditory processing regions when hearing people watch silent speech (Calvert et al, 1999, 2000).

In deaf people, even when behavioural measures suggest equivalent or superior skills to those of hearing controls, long-term absence of hearing has led to a change in the cortical associations that develop when speech is identified by eye. Instead of recruiting regions that support acoustic processing, regions that were consistently activated across participants included the posterior cingulate and parahippocampal gyrus (see Figure 3; MacSweeney et al, 2001, 2002a). This network of regions may be involved in integrating remembered events with online processing. Posterior cingulate, in particular, may perform a binding function, similar to that of the STS in hearing people, but in this case, between visual analysis of seen speech and memories of previous encounters of that item. The deaf group also activated visual processing regions within the left lingual gyrus (V2/VP regions of visual cortex). Such activation can be observed for reading written words (eg Kuriki et al, 1998) and can also show variable lateralisation as a function of the attentional requirement to detect local (left-sided) or global (right-sided) visual target structure (Fink et al, 1997). Involvement of this region in speechreading in deaf people, however, was a new finding and it suggests that this area is indeed modifiable by language associations. In support of this, Giraud et al (2001), using PET, report that deaf adults of mixed aetiology, who have

received a cochlear implant show activation in visual cortex when they are trying to *hear* lexical speech contrasts, with no visual input at all. They speculate that this activation, which was most marked in visual region V2, may reflect associations established in deaf people, prior to implant and restoration of acoustic function, between watching speech movements and the lexical correlates of seeing speech.

figure 3

Thus our studies and data from others suggest that visual cortical regions might reorganise following early hearing loss. It has been suggested that posterior cortical regions may become relatively more active in the brains of deaf compared to hearing people, driven by the functional needs of the deaf person to ‘make vision work in place of hearing’ (and see Emmorey, 2001 for further discussion). The extent to which such reorganisation may reflect structural changes in the visual system, and/or differences in the allocation of attentional resource, is a topic of intense study. Although it has not been possible to demonstrate advantages for low-level contrast sensitivity in deaf people (Finney & Dobkins, 2001), attention to motion in the visual periphery can sometimes be detected more readily by deaf signers than hearing nonsigners and is accompanied by specific electrophysiological signatures (eg Neville & Lawson, 1987; see Neville & Roder, this volume). In addition, a left-hemisphere advantage for visual

movement detection in deaf signers, which is absent or reversed in hearing populations, is reliably reported (Neville & Lawson, 1987, Bosworth & Dobkins, 1999). Bavelier et al (2001) have shown that moving flow-field patterns requiring attention to spatial or featural aspects of the display generated relatively greater activity in the left- MT/MST visual processing regions, in deaf compared with hearing people. Moreover, activation was enhanced when attention was required to detect peripheral visual movement. As originally suggested by Neville and Lawson (1987), these effects may reflect early exposure to sign language, leading to enhanced attentional processing to visual movement (Bavelier et al 2000, 2001; Bosworth & Dobkins, 2002).

While some reorganisation of parts of visual cortex and their projections to and from (visual) association cortex may be predicted as a compensatory or learned aspect of cognition in deafness, the fate of auditory cortex in the absence of hearing is less clear. When measured prior to the implantation of a cochlear hearing aid, auditory cortex in deaf people is generally hypometabolic (Okazawa et al, 1996; Lee et al, 2001). Lee et al (2001) report a correlation between degree of hypometabolism in auditory cortex and effectiveness of speech processing post-implant in prelingually deaf people. The less active the resting metabolism of the auditory cortical regions tested pre-implant, the better post-implant (speech) hearing appeared to be. They suggest that speech processing following

acoustic prosthesis must therefore depend on resistance to colonisation from other modalities (such as visual input) in auditory cortex. We will return to this inference in our closing remarks. But is there direct evidence that auditory cortical regions in deaf people are modifiable, so that they become sensitive to inputs other than sound? Neurophysiological and behavioural studies of congenitally deaf cats suggest not. Studies by Klinke and colleagues (see Klinke et al, 1999) suggest that reafferentation of auditory inputs (from cochlear excitation) is the only means by which responsiveness in auditory cortex can be attained. Without this, “afferent input...remains rudimentary.”

Vibrotactile activation of auditory cortex? - ‘feeling’ speech

A MEG study by Levänen, Jousmaki and Hari (1998) reported frequency-specific activation in auditory cortex in an elderly deaf man when he received vibrotactile stimulation of the fingers and palm of the hand. Activation was observed first in somato-sensory cortex and somewhat later in auditory cortex. Auditory cortex activation was not observed in hearing controls. In the Tadoma method of speechreading, which was originally developed for deaf-*blind* people, the perceiver senses as well as sees speech by resting his hand on the mouth, shoulder and clavicle of the speaker. In this way the resonant body vibrations consequent to vocal cord vibration can be picked up. For the sighted deaf speechreader, mouth movements are visible, but information about voicing

patterns, which cannot reliably be gleaned from lip-patterns, can still be usefully picked up by feeling clavicle vibrations. Moreover, this type of vibrotactile information appears to combine naturally with seen speech, so that ‘tacto-visual’ speech illusions, similar to the McGurk audio-visual speech illusion for hearing listeners, can be generated (Fowler & Dekle, 1991). It is unclear from Levänen et al’s report whether their deaf participant, from a family including deaf members, was a practised Tadoma-user, or whether he ever had useable hearing - for example in the first year or two of life. Had that been the case, then activation in auditory processing regions could have occurred through established associations of vibrotactile processing with seen and heard speech. Levänen & Hamdorf (2001) also report greater behavioural sensitivity to vibro-tactile stimulation in deaf than hearing individuals, but there are no further reports of deaf individuals showing vibrotactile-related activation in auditory cortex. It should further be noted that MEG does not yet allow sufficiently good resolution to confirm that *primary* auditory cortex was activated by vibrotactile perception, given the proximity of primary somatosensory cortex to Heschl’s gyrus (see figure 2).

Conclusions: silent speechreading by deaf adults

Speechreading (lipreading) is a window into the world of speech for the person born deaf. The highly skilled deaf lipreader may closely resemble the hearing person in their reliance on verbal strategies for memory rehearsal and in

their perceptual sensitivity to phonetic structure in a range of language processing tasks, including reading (eg Leybaert, 2000; Leybaert et al, 1998 for such behavioural evidence in deaf speechreaders who are also exposed to phonetic manual cues). Nevertheless, there are clear indications that deaf and hearing speechreaders use different cortical resources. Hearing people show activation in superior temporal cortex, including primary and secondary auditory regions and the STS, when speechreading. In contrast, only one deaf participant showed speechreading related activation in the region that would be classified as secondary auditory cortex in hearing people (MacSweeney et al., 2001). As a group, the deaf participants did not reliably activate these regions but made relatively greater use of visual processing systems, especially within the left lingual gyrus, which may be modulated by posterior cingulate activity. Reports of non-acoustic activation of primary auditory cortex by vibro-tactile stimulation in deaf people require more detailed localisation studies and replication. To date, it seems that speech-related activation within regions corresponding to primary auditory cortex can only be reliably observed when seen and heard speech have been experienced by the perceiver. Whether the same is true of a signed language input will now be discussed.

Signed language processing systems

Only very few cases of sign-language aphasia in deaf adults have been reported (e.g., see Poizner et al, 1987; Corina 1998). These case studies suggest that the organisation of processing systems supporting signed languages is strikingly similar to that for spoken language (e.g., Hickok et al, 1996). Lesions to the left hemisphere, in Broca's area within the left inferior frontal lobe, and Wernicke's area (left posterior superior and middle temporal gyri, incorporating the supramarginal gyrus) have similar effects on signed language processing as they would on speech processing in hearing people. Neuroimaging studies concur that sign *production* implicates Broca's area, just as speech production does in hearing people (McGuire et al, 1996, Corina & McBurney, 2001) and, in a complementary way, Wernicke's area is activated when meaningful sign language is perceived (Söderfeldt et al, 1994,1997; Neville et al, 1998; Nishimura et al, 1999; Petitto et al, 2000). There is currently some debate concerning the degree of lateralisation of sign language perception in relation to speech lateralisation (see Neville et al, 1998; Paulesu & Mehler, 1998; Hickok et al. 1998; Rönnberg et al, 2000; Corina & McBurney 2001; MacSweeney et al, 2002b), which will not be elaborated here. There is agreement, however, that not only does the processing of signed languages activate regions involved in spoken language processing, including Wernicke's and Broca's areas, but also that there may be cortical

regions recruited to sign-language processing which are unlikely to be recruited to processing speech. For example, we have shown that the parietal lobes may be specifically involved in processing signed sentences which are spatially demanding (MacSweeney et al., 2002c). In contrast, these regions were not differentially activated in hearing people perceiving audiovisual spoken English versions of the same sentences. Thus there are likely to be subtle differences in processing systems used for signed and spoken languages. However, for the purposes of this chapter we will focus on the issue of whether signed languages may recruit auditory processing regions.

Auditory cortex: when can it be activated by visual stimuli?

Pioneering cortical imaging studies of sign language processing have all showed activation in superior temporal regions (Söderfeldt et al., 1994,1997; Neville et al, 1998; Levänen et al, 2001). None of these studies made explicit claims concerning activation of brain regions analogous to auditory cortex in hearing people, in people born profoundly deaf. However some recently published reports have done so.

Nishimura et al. (1999), using PET, reported that sign-language stimuli could activate superior temporal regions, corresponding to auditory cortex in hearing people, in a man born profoundly deaf. This work explicitly distinguished between regions corresponding to primary (A1) and secondary (A2) auditory

cortex. The authors found reliable activation by sign language only in A2-analogue regions and not within Heschl's gyrus (A1). Also using PET, Petitto et al (2000) furthered this finding, reporting activation of secondary auditory cortex in Deaf native signers, but not hearing non-signers, during perception of ASL signs. Furthermore, they reported the same pattern of activation for phonologically structured nonsense signs. On the basis of these data, the authors made the strong claim that superior temporal regions, including secondary auditory cortex, were *specifically* activated by phonologically structured input – regardless of whether this was delivered auditorily through speech or visually through a signed language. Activation in this region was suggested to reflect the segmental structure – the phonology – of the language. Our own findings partly support Petitto's claims, but they also suggest further patterns.

When compared with viewing a still image of a person, our studies suggest that observing British Sign Language (BSL) sentences generated activation in the same region reported by Petitto et al, extending to the posterior superior temporal gyri bilaterally, in deaf native signers (MacSweeney et al., 2002b). In a further study, we have also observed activation in these regions when deaf participants watched meaningless arm and hand-movements, based on the tic-tac signalling system used by bookmakers and their assistants to signal betting odds on the racetrack (MacSweeney et al., in prep). These displays do not

comprise sequences that can be interpreted as signed language. Superior temporal regions that support heard speech analysis in hearing people have indeed become sensitive to sign language input, but this sensitivity may extend to *all* potentially meaningful brachial and manual gestures.

A recent fMRI study by Finney et al., (2001) suggests that such activation may extend even beyond biological motion such as that of the hands and arms. They reported activation in cortical regions corresponding to primary auditory cortex when a group of prelingually deaf people viewed a simple moving dot pattern. Activation of auditory cortex by such abstract visual input cannot be explained by possible early acquired associations between sight, sound and touch for speech, as in the case of vibrotactile activation in Levänen et al's (1998) case study.

Animal data suggest acoustic specificity for primary auditory cortex (Klinke et al, 1999). Thus the findings of Finney et al of visual activation in primary auditory cortex in people born deaf raise important questions regarding the degree of cross-modal plasticity of A1 and its functional role(s). As figure 2 indicates, primary auditory cortex is a difficult region to localise - whatever the means of neuroimaging. The transverse temporal gyrus (Heschl's gyrus) is located within the superior plane of the temporal lobe. This region is adjacent to a number of non-acoustic regions in the superior and inferior plane. Individuals

vary in the extent, inclination, number of duplications and gyral architecture of Heschl's gyrus (see Leonard et al 1998). Therefore mapping activation across different brains into a standardised space (as in Finney et al's study) may not be satisfactory when attempting to localise primary auditory cortex, as a functional region, at the group level. A further consideration is that the anatomy of this region in congenitally deaf people has not yet been explored. Thus there may be structural differences in this region between congenitally deaf and hearing populations of which we are not yet aware.

In our study (MacSweeney et al., in prep) we examined the claim that activation from a moving visual display (BSL and TicTac) might extend into primary auditory cortex. Using each individual's high resolution structural image we were able to locate Heschl's gyrus in each participant and look for corresponding activation within this region. There were no participants in whom the main focus of activation fell within Heschl's gyrus. Rather, in the majority of participants, the main focus of activation within this region was posterior to Heschl's gyrus in the planum temporale. However in one participant out of nine, this posterior activation did incorporate a medial posterior portion of Heschl's gyrus, the analogue of primary auditory cortex in hearing people. A more robust finding from this analysis however, was that in half of our participants this activation included the tip of Heschl's gyrus at its junction with superior temporal

gyrus, the analogue region of secondary auditory cortex. Thus our studies to date suggest that in deaf people secondary auditory cortex analogue region is sensitive to varieties of visual movement, and not, as hypothesised by Petitto et al (2001), just to sign-structured input. However, with regard to activation within the medial portion of Heschl's gyrus, the pattern is still unclear. We have observed limited activation in this region in one of our deaf participants. Interestingly, there are also preliminary reports of activation of this region in *hearing* people during observation of moving dot patterns (Bavelier & Neville, 2002). Therefore the degree of cross-modal plasticity of this assumed unimodal area is, as yet, far from fully understood.

Native signers: the role of hearing status

One remaining question is whether the visual activation observed in auditory regions in deaf native signers is related to early sign language knowledge or hearing status? In all our studies of BSL perception a consistent finding is that, compared with deaf people of similar sign background, hearing offspring of Deaf parents show reduced activation in superior temporal regions, including auditory cortex. While in deaf people auditory regions can become specialised for visual processing, in people with intact auditory function these regions remain dedicated to speech – even when it is not the first language to be acquired (MacSweeney et al., 2002b). Under these circumstances, sign language ‘struggles to compete’

within auditory cortex, with heard and spoken language, despite its early acquisition. Thus congenital deafness rather than sign language knowledge appears to account for the recruitment of auditory cortices to visual motion processing. To test this hypothesis further it would be necessary to explore conditions under which auditory cortices are activated in congenitally profoundly deaf late learners of a signed language, a group not yet explored in neuroimaging studies of sign language processing.

Cortical plasticity of auditory speech processing regions in profound prelingual deafness : Conclusion

Lee et al (2001) conclude their study of auditory cortex metabolism in deaf patients pre- and post- cochlear implant with a strong claim:

“If cross-modal plasticity (*eg for sign language*) restores metabolism in the auditory cortex before implantation, prelingually deaf patients will show no improvement in hearing function... The resting cortical metabolism of untreated (*sic*) prelingually deaf patients represents a usurping by cross-modal plasticity, which deters the improvement of hearing capability and the restoration of normal function in the auditory temporal cortices after cochlear implantation” (p.150).

In this statement Lee et al appear to be advocating early cochlear implantation and/or restricting exposure of a deaf child to a signed language in order to preserve the auditory function of auditory cortex. In our opinion this

contentious issue requires much more extensive research - especially in relation to age of implantation and language mastery pre-implantation. Our work does find evidence that auditory processing regions are reserved for spoken language processing in hearing people, even when a signed language was the first to be acquired. Hearing and deaf groups could be readily distinguished by activation in these regions. However, the evidence for the 'usurping' of primary auditory cortex by other modalities in people born deaf is far from clear. Animal studies do not conform with Lee et al.'s suggestions. Klinke et al (1999) have failed to find activation in primary auditory cortex in the congenitally deaf cat in response to visual or tactile input. In particular, in our own studies, in the absence of perceived acoustic structure, auditory-analogue regions do not develop a consistent specialisation for speechreading of a spoken language. Furthermore, although we have observed partial activation of Heschl's gyrus in some deaf participants we have not yet observed focussed and robust activation by visual stimulation in the medial portion of Heschl's gyrus - the region which, in hearing people, would be delineated as A1. Future studies with more deaf participants, and with enhanced imaging resolution should enable us to obtain more authoritative information.

More generally, while in hearing people superior temporal regions support not only speech but a range of complex acoustic analyses contributing, for

example, to voice timbre and musical analysis (eg Belin et al, 2000; Griffiths et al, 1998); so in deaf people, these regions may support a range of non-sign, but complex, patterns of visual movement processing. These may include moving checkerboard and flow patterns (Bavelier et al, 2001; Finney et al, 2001), and also a range of biological movement patterns including gestural patterns. The role of the STS in the analysis of communicative gesture in hearing people is well established (see Allison et al, 2000, for review). But our speculation here goes beyond this both functionally and anatomically: it is possible that the disposition of the brain of the person born deaf for mastering signed language may be associated with a reconfiguring of language cortex in the superior, posterior parts of the lateral temporal cortex to subserve the analysis of many varieties of non-linguistic visual movement.

The close correspondence in patterns of cortical activation for speech in hearing people and for sign in deaf people strongly supports the view that language makes use of cortical substrates involved in processing communicative gesture. Such gesture patterns, whether vocal or manual, may have characteristics suited to the processing specialisation of the superior posterior temporal regions, especially within the left hemisphere. The elaboration of those characteristics in humans and in other primates may ultimately clarify how and why language may evolve in all sentient human populations, irrespective of their hearing status.

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Figure 1 Speechreading and listening to speech.

Group median activation maps for hearing subjects. Three contiguous transaxial scans ($n=7$). Blue indicates regions activated by hearing speech; pink indicates regions activated by watching silent speech. Yellow regions are activated both by heard and seen speech. These overlap areas are in auditory cortex on the superior surface of the temporal lobe

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Figure 2 Schematic of the superior temporal plane (STP) of the human left hemisphere, 'unfolded' to show relative positions of primary (dark, including Heschl's Gyrus;HG) and secondary auditory cortex, (PT,Tpt - lighter), on the superior surface of the posterior part of the superior temporal gyrus. The positions of the superior temporal sulcus (STS) and other associative auditory regions (lightest) are also shown.

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Figure 3 Activation by speechreading in hearing and deaf subjects.

The top row of four contiguous axial images shows median activation by silent speechreading in hearing subjects ($n=6$). Superior temporal gyri were activated

bilaterally, extending into auditory cortex. The lower four images show corresponding slices for deaf subjects (n= 6). Activation in the deaf subjects is in right insular/ frontal regions, the parahippocampal gyri bilaterally and the posterior cingulate. There is no activation in auditory cortex-analogue regions.

Adapted from MacSweeney et al, 2001

Figure 1

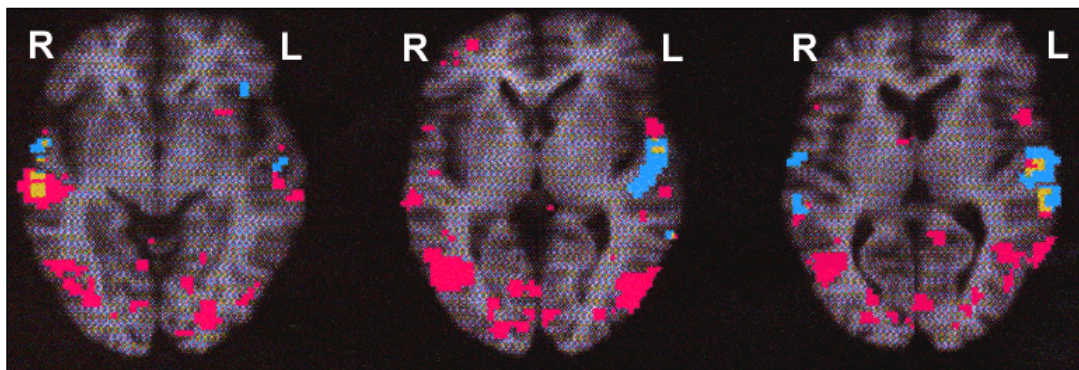


Figure 2

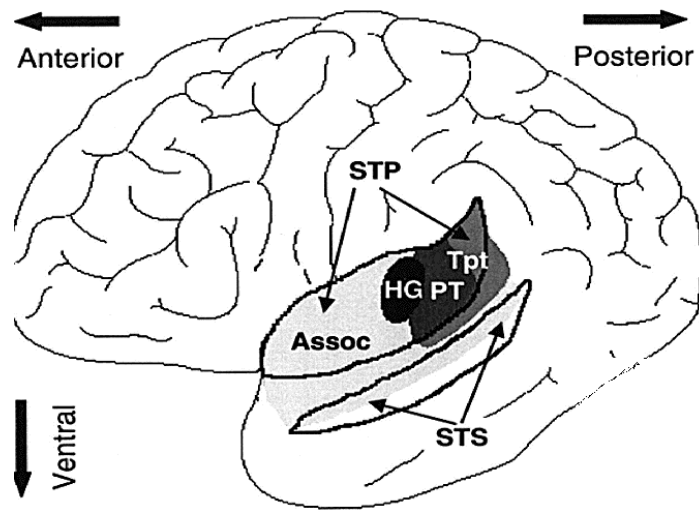


Figure 3

