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Research paper

Cortical cross-modal plasticity following deafness measured using functional near-infrared spectroscopy

Rebecca S. Dewey [a, b, *], Douglas E.H. Hartley [a, b, c]

[a] Otology and Hearing Group, Division of Clinical Neuroscience, School of Medicine, University of Nottingham, Nottingham, NG7 2UH, UK
[b] National Institute for Health Research (NIHR) Nottingham Hearing Biomedical Research Unit, 113 The Ropewalk, Nottingham, NG1 5DU, UK
[c] MRC Institute of Hearing Research, University Park, Nottingham, NG7 2RD, UK

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A B S T R A C T

Evidence from functional neuroimaging studies suggests that the auditory cortex can become more responsive to visual and somatosensory stimulation following deafness, and that this occurs predominately in the right hemisphere. Extensive cross-modal plasticity in prospective cochlear implant recipients is correlated with poor speech outcomes following implantation, highlighting the potential impact of central auditory plasticity on subsequent aural rehabilitation. Conversely, the effects of hearing restoration with a cochlear implant on cortical plasticity are less well understood, since the use of most neuroimaging techniques in CI recipients is either unsafe or problematic due to the electromagnetic artefacts generated by CI stimulation. Additionally, techniques such as functional magnetic resonance imaging (fMRI) are confounded by acoustic noise produced by the scanner that will be perceived more by hearing than by deaf individuals. Subsequently it is conceivable that auditory responses to acoustic noise produced by the MR scanner may mask auditory cortical responses to non-auditory stimulation, and render inter-group comparisons less significant. Uniquely, functional near-infrared spectroscopy (fNIRS) is a silent neuroimaging technique that is non-invasive and completely unaffected by the presence of a CI. Here, we used fNIRS to study temporal-lobe responses to auditory, visual and somatosensory stimuli in thirty profoundly-deaf participants and thirty normally-hearing controls. Compared with silence, acoustic noise stimuli elicited a significant group fNIRS response in the temporal region of normally-hearing individuals, which was not seen in profoundly-deaf participants. Visual motion elicited a larger group response within the right temporal lobe of profoundly-deaf participants, compared with normally-hearing controls. However, bilateral temporal lobe fNIRS activation to somatosensory stimulation was comparable in both groups. Using fNIRS these results confirm that auditory deprivation is associated with cross-modal plasticity of visual inputs to auditory cortex. Although we found no evidence for plasticity of somatosensory inputs, it is possible that our recordings may have included activation of somatosensory cortex that masked any group differences in auditory cortical responses due to the limited spatial resolution associated with fNIRS.

1. Introduction

The loss of one sensory modality can lead to neural plasticity of cortical areas associated with the remaining modalities. There is mounting evidence from human imaging studies to suggest that auditory and tactile stimulation can activate visual cortex in blind subjects (Kujala et al., 1995; Sadato et al., 1996; Cohen et al., 1997; Roder et al., 1997; Weeks et al., 2000). Also studies have investigated plasticity in the auditory cortex of deaf individuals using functional magnetic resonance imaging (fMRI; Finney et al., 2001; Auer et al., 2007; Karns et al., 2012; Vachon et al., 2013) and magnetoencephalography (MEG; Finney et al., 2003). One such study (Finney et al., 2001) found visual motion evoked activity in the right auditory cortex of early-deaf individuals. This predominately right-sided activation of auditory cortex in response to moving visual and/or tactile stimulation has been confirmed in

Abbreviations: CI, cochlear implant; fNIRS, functional near infrared spectroscopy; HbO, oxygenated haemoglobin; HbR, deoxygenated haemoglobin

* Corresponding author. NIHR Nottingham Hearing Biomedical Research Unit, Ropewalk House, 113 The Ropewalk, Nottingham, NG1 5DU, UK. Tel.: +44 (0) 115 8232638; fax: +44 (0) 115 8232618.
E-mail addresses: rebecca.dewey@nottingham.ac.uk (R.S. Dewey), douglas.hartley@nottingham.ac.uk (D.E.H. Hartley).

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other fMRI studies (Sadato et al., 1996; Auer et al., 2007; Vachon et al., 2013). Together, these studies suggest that deafness is associated with cross-modal plasticity within auditory cortex, predominately on the right side, however, Karns et al. (2012) found bilateral activation of auditory cortex to visual and tactile stimulation in deaf individuals. Unlike previous studies that used bilateral stimulus presentation (Sadato et al., 1996; Finney et al., 2001; Auer et al., 2007; Vachon et al., 2013), Karns et al. (2012) presented visual and somatosensory stimuli to the right eye only, which may partially account for the inconsistency of results across studies.

Evidence suggests that cross-modal plasticity in auditory brain regions following deafness may be an important factor in understanding and predicting how much benefit an individual might subsequently receive from a cochlear implant (CI; Lee et al., 2001; Giraud and Lee, 2007; Lee et al., 2007; Strelnikov et al., 2013; Sandmann et al., 2015; Song et al., 2015; Strelnikov et al., 2015). However, we currently have limited techniques for assessing the effects of CIs on neural plasticity, since testing with positron emission tomography (PET) is restricted (Johnsrude et al., 2002) due to cumulative effects of radionuclide exposure. Furthermore, fMRI is not safe to perform in these individuals and brain recordings using electroencephalography (EEG) and magnetoencephalography (MEG) are often distorted by electrical artefacts associated with CI stimulation. It is also important to consider the potential confounding effect of background acoustic noise associated with fMRI that cannot be matched between deaf and hearing participants, and the effect of techniques such as sparse sampling (Hall et al., 1999) on the resulting temporal signal to noise ratio of functional images due to the acquisition of fewer samples/reduction of temporal resolution. Specifically, acoustic noise from the gradient coils will be perceived more by hearing than by deaf participants. Therefore it is conceivable that any group differences in responses to non-auditory stimulation will be confounded by the differences in sensory experience during stimulation of all sensory modalities.

Functional near-infrared spectroscopy (fNIRS) non-invasively measures changes in cortical concentration of oxy-haemoglobin (HbO) and deoxy-haemoglobin (HbR), from which neuronal activity can be inferred. Also fNIRS provides silent recordings that are free from magnetic and electrical artefacts, and thus is highly suited to auditory research and is safe for repeated use in CI recipients (Sevy et al., 2010). Further, it is possible to measure functional responses to auditory stimulation in auditory cortex using fNIRS (Ohnishi et al., 1997; Minagawa-Kawai et al., 2002; Remijn and Kojima, 2010; Sevy et al., 2010; Plichta et al., 2011).

To our knowledge, the current study is the first to use fNIRS to assess auditory cortex responses to auditory and non-auditory stimulation in profoundly-deaf participants and normally-hearing controls. The primary aim of this study was to determine whether high-contrast moving visual stimuli and vibrotactile stimulation of the palms and fingers of both hands induced responses consistent with cross-modal plasticity in profoundly-deaf individuals using fNIRS. We predicted that the right temporal lobe of profoundly-deaf individuals would exhibit greater responses to non-auditory sensory stimulation, compared with normally-hearing controls.

2. Materials and methods

2.1. Participants

Profoundly-deaf volunteers (n = 30; 12 male and 18 female) were recruited to the study *via* local deaf clubs and audiology departments. Although inclusion criteria for participants in this group were based on current CI candidacy criteria within the UK (NICE, 2009), namely unaided pure-tone air-conduction thresholds of $\geq$90 dB SPL at 2 and 4 kHz in both ears, pure-tone air conduction thresholds were measured across four frequencies in both ears (0.5, 1, 2 and 4 kHz in both ears; pure-tone audiometry was performed in accordance with BS EN ISO 8253-1). Of the 30 deaf participants, 27 had pure-tone averages (PTAs) of $\geq$90 dB SPL at 0.5 and 1 kHz and the three remaining participants had thresholds ranging from 15 to 90 dB SPL at these two frequencies. Thus some participants may have perceived the broadband auditory stimuli that were used in our study, particularly those with residual low frequency hearing. Aside from meeting the UK audiometric criteria for CI candidacy, the participant group was intentionally heterogeneous, since subjects were not screened for inclusion based on any particular aetiology of hearing loss. Profoundly-deaf participants were asked about their deafness, including the aetiology of deafness, age at onset and duration of deafness and hearing aid experience (Table 1). Onset of deafness ranged from birth to 29 years of age, and duration of deafness ranged from 20 to 59 years. Unless otherwise stated, all measures of dispersion are reported as standard deviation of the mean. The mean age at onset of deafness was 2 $\pm$ 5 years and the mean duration of deafness was 39 $\pm$ 12 years. Hearing aid use also varied widely across the group, ranging from none at all to full-time bilateral aiding. Mean duration of hearing aid experience was 31 $\pm$ 17 years. All testing was performed unaided and no participant had a CI at the time of testing.

Normally-hearing volunteers (n = 30; 12 male and 18 female) were recruited *via* posters around the University of Nottingham. Normally-hearing individuals had pure-tone air conduction thresholds of $\leq$20 dB SPL at 0.5, 1, 2 and 4 kHz in both ears. Profoundly-deaf and normally-hearing participants had no known cognitive or psycho-motor impairments and none reported any active external or middle ear disease.

All participants included in the study were aged between 18 and 60 years old. The profoundly-deaf group were aged 41 $\pm$ 11 years, ranging from 20 to 59 years, while the normally-hearing control group were aged 34 $\pm$ 13 years, with a range of 18–60 years. There was small but statistically-significant difference in age between the two groups ($p = 0.02$). However, preliminary data analysis showed no significant correlation between the age of our normally-hearing participants and their auditory cortical response to visual stimulation ($p = 0.89$, $R^2 = 0.0006$; data not shown). Therefore there was no evidence to suggest that the small difference in mean age between the groups would influence our results. All participants were able to understand instructions in spoken or written English and/or British Sign Language (BSL) and reported normal or corrected-to-normal vision. BSL interpreters were used as and when requested by the participant, particularly when obtaining written informed consent, with 23 out of the 30 profoundly-deaf participants using BSL as a preferred communication method (see Table 1). The majority of participants in the normally-hearing and profoundly-deaf groups were right handed. Although there were 4 left-handed individuals in the profoundly-deaf group and none in the normally-hearing group, there were no significant group differences in handedness quotient scores. Neuroimaging data from all participants were analysed in the same way, regardless of handedness, as we had no basis for a handedness-dependent hypothesis. The study was approved by the National Research Ethics Service Nottingham Committee (Ref: 12/EM/0016).

2.2. Stimuli

The paradigm consisted of recording responses to auditory, visual and somatosensory stimulation separately. In each sensory modality, responses to two, separately presented stimuli were compared to a common baseline condition. The common baseline