



# Visual stimuli activate auditory cortex in the deaf

Eva M. Finney, Ione Fine and Karen R. Dobkins

Psychology Department-0109, University of California, San Diego, La Jolla, California 92093, USA

Correspondence should be addressed to K.R.D. ([kdobkins@ucsd.edu](mailto:kdobkins@ucsd.edu))

Published online: 12 November 2001, DOI: 10.1038/nm763

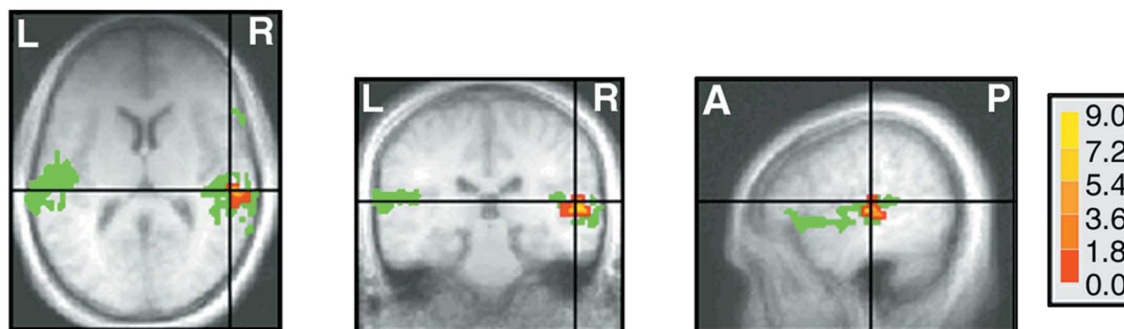
Previous brain imaging studies have demonstrated responses to tactile and auditory stimuli in visual cortex of blind subjects, suggesting that removal of one sensory modality leads to neural reorganization of the remaining modalities<sup>1-3</sup>. To investigate whether similar 'cross-modal' plasticity occurs in human auditory cortex, we used functional magnetic resonance imaging (fMRI) to measure visually evoked activity in auditory areas of both early-deafened and hearing individuals. Here we find that deaf subjects exhibit activation in a region of the right auditory cortex, corresponding to Brodmann's areas 42 and 22, as well as in area 41 (primary auditory cortex), demonstrating that early deafness results in the processing of visual stimuli in auditory cortex.

Six profoundly deaf and six hearing subjects were tested (3 females in each group; deaf,  $27.0 \pm 5.7$  years old; hearing,  $26.8 \pm 2.6$  years old). All subjects were right handed with normal or corrected-to-normal vision. All protocols were conducted in compliance with the University of California at San Diego's Human Subjects Committee Institutional Review Board. Using fMRI (AFNI software<sup>4</sup>, 1.5 T BOLD; 28 slices; TR, 4 s; voxel size,  $3 \times 3 \times 6$  mm), we defined an auditory region of interest (ROI) by measuring responses elicited by auditory stimuli (music sequences) in our hearing subjects. In Fig. 1, auditory ROIs (green regions) are plotted on an anatomical scan averaged across all deaf and hearing subjects, after transforming individual anatomies into standard Talairach and Tournoux coordinate space<sup>5</sup>. Based on Talairach and Tournoux coordinates, auditory stimuli were found to activate regions in both right and left auditory cortex, including Brodmann's areas 41, 42 and 22, although, consistent with known hemispheric asymmetries for music processing<sup>6</sup>, the total volume of the

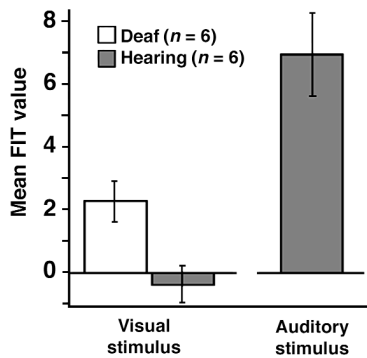
right auditory ROI ( $26.1 \text{ cm}^3$ ) was larger than that of the left ( $14.5 \text{ cm}^3$ ). Analysis of visually evoked fMRI responses was limited to within these functionally defined auditory ROIs.

Our visual stimulus consisted of a moving dot pattern (size,  $10^\circ$  diameter; speed,  $7^\circ/\text{s}$ ; dot luminance,  $590 \text{ candelas/m}^2$  against a black background; dot size,  $0.2^\circ$ ; dot density, 2.7%; percent dots moving coherently, 87%). On alternate runs, the stimulus was presented in either the right or left visual field ( $15^\circ$  eccentric to a central fixation spot). The two subject groups performed comparably on a dimming task on the motion stimulus to control for attentional state (deaf,  $91.5 \pm 12.2\%$  correct; hearing  $94.0 \pm 2.9\%$ ; deaf,  $609 \pm 107$  ms reaction time; hearing,  $654 \pm 255$  ms). Visually evoked activity within the right and left auditory ROIs was computed by correlating fMRI signal amplitude in individual ROI voxels to a reference function corresponding to the time course of the visual stimulus, after first correcting for individual subject movements in six dimensions by realigning images to a single reference image.

Visually evoked activity significantly differed between deaf and hearing subjects in the right auditory ROI (Fig. 1, colors defined in scale bar, main effect of subject group,  $F_{1,10} = 11.12$ ,  $p = 0.0038$ ), encompassing a volume of  $0.95 \text{ cm}^3$ . Although differences were also observed in the left auditory ROI, the region of effect was extremely small ( $0.054 \text{ cm}^3$ ) and did not survive stringent statistical standards for safeguarding against false positives. Within the right ROI region of main effect, the visual stimulus caused significant activation in deaf subjects (Fig. 2), with a mean functional intensity (FIT, which reflects the magnitude of activation) value of  $2.26 \pm 1.37$  ( $p = 0.0049$ ), whereas no significant activation occurred in hearing subjects (mean FIT,  $-0.31 \pm 1.30$ ,  $p = 0.59$ ). In comparison, the mean FIT value produced by auditory stimuli in these same voxels within hearing subjects was  $6.90 \pm 2.65$  ( $p = 0.0069$ ). Based on Talairach and Tournoux coordinates, this region of visual activation in the deaf corresponds to Brodmann's areas 42 and 22 (secondary and association auditory areas, respectively), which includes part of the planum temporale. In addition, several voxels ( $0.22 \text{ cm}^3$ , ~23% of the total region of effect) fell within area 41 (primary auditory cortex), which encompasses the medial portion of Heschl's gyrus. We also cross-checked these coordinates against probabilistic atlases<sup>7,8</sup> and confirmed that our region of effect included both A1 and the planum temporale. There was no



**Fig. 1.** Visual stimuli activate auditory cortex in the deaf. Shown is an anatomical scan averaged across all deaf and hearing subjects. Auditory regions of interest (ROIs, green regions) and voxels activating differentially in deaf versus hearing subjects in response to the visual motion stimulus (colors defined in scale bar) are shown on axial (left), coronal (middle) and sagittal (right) sections of an averaged anatomical brain, transformed into the standard stereotaxic space of Talairach and Tournoux<sup>5</sup>. The area of visual responsiveness falls within Brodmann's areas 41, 42 and 22 in the right auditory ROI. Crosshairs highlight a voxel within the area of main effect that maps to Brodmann's area 41 (primary auditory cortex). Scale bar indicates the functional intensity (FIT) value, or magnitude of activation. L, left; R, right; A, anterior; P, posterior side of brain.



**Fig. 2.** Mean activation in deaf versus hearing subjects to visual stimuli. Mean functional intensity (FIT) values, corresponding to magnitude of activation, for deaf (white bars) and hearing (gray bars) subjects within the area of main effect shown in Fig. 1. Visual stimuli produced significant activation in deaf but not hearing subjects. For comparison, auditory-evoked activity in this region of hearing subjects is also shown. Error bars denote standard errors of the means.

main effect of visual field or interaction between visual field and subject group within this region.

In a second version of these experiments, we collected fMRI responses when subjects were instructed to ignore the motion stimulus and instead perform a dimming task on the fixation spot. Here, deaf and hearing subjects differed significantly ( $F_{1,10} = 4.09, p = 0.036$ ) within a region of the right auditory ROI (0.54 cm<sup>3</sup>, a subset of the region of difference obtained from the attend condition) that mapped onto area 42. Deaf subjects exhibited significant activity in this region (FIT coefficient,  $2.85 \pm 2.91, p = 0.031$ ) and, as before, hearing subjects did not (FIT coefficient,  $0.175 \pm 1.43, p = 0.78$ ). The smaller region of effect observed under the ignore condition is consistent with the general tendency for sensory cortical areas to activate less strongly to ignored than attended stimuli<sup>9,10</sup>. Nonetheless, the fact that visual activation in auditory cortex was observed in deaf subjects even when the motion stimulus was ignored attests to the robustness of the cross-modal plasticity effect.

Related to the present findings, results from previous fMRI and positron emission tomography studies have suggested that the auditory regions in which we found visual activation in the deaf include areas that may also be involved in visual language processing in both deaf and hearing subjects. Specifically, Brodmann's areas 42 and 22 in deaf subjects are activated to visual images of sign language<sup>11,12</sup>, and these same areas are activated in hearing subjects during a silent lip reading task<sup>13</sup> (and during auditory speech tasks<sup>13</sup>). In addition, there has been previous suggestion that these auditory areas may be used for processing purely visual (that is, non-linguistic) stimuli in the deaf. However, these earlier studies used techniques with poor spatial resolution, such as electroencephalography, that could not distinguish whether visual responses in deaf subjects originated from auditory cortex or nearby visual areas<sup>14</sup>.

In sum, the results of the present study using fMRI demonstrate the recruitment of auditory cortex in the deaf for the processing of purely visual stimuli. The cross-modal plastic-

ity observed in the present study appeared predominantly in the right auditory cortex. Because our experiment used moving visual stimuli, this hemispheric asymmetry may simply reflect a predisposition for motion processing in the right auditory cortex. This possibility is supported by the finding that in hearing subjects, the right auditory cortex (specifically, the planum temporale) is specialized for processing auditory motion<sup>15</sup>. Thus, right auditory cortex in the deaf, devoid of its normal auditory input, may come to serve motion processing in the visual modality. Remarkably, the reciprocal result has recently been reported in blind subjects. Here, responses to moving auditory stimuli are observed predominantly in the right visual cortex of the blind<sup>2</sup>, again suggesting a predisposition toward motion processing in the right hemisphere. Most importantly, our demonstration of cross-modal plasticity in deaf subjects, in conjunction with that observed in the blind, attests to the robust ability of the human brain to reorganize in response to the removal early in development of input from one sensory modality.

ACKNOWLEDGEMENTS

Supported by an NSF grant to K.R.D. and an NRSA grant to E.M.F. We thank G. Boynton and M. Sereno for helpful discussions, G. Brown, L. Eyles Zorrilla, P. Goldin and S. Tapert for assistance with data analysis, and D. Cai for assistance with subject recruitment.

RECEIVED 11 JUNE; ACCEPTED 17 OCTOBER 2001

1. Sadato, N. *et al.* *Nature* **380**, 526–528 (1996).
2. Weeks, R. *et al.* *J. Neurosci.* **20**, 2664–2672 (2000).
3. Kujala, T. *et al.* *Trends Neurosci* **23**, 115–120 (2000).
4. Cox, R. W. *Computers and Biomedical Research* **29**, 162–173 (1996).
5. Talairach, J. & Tournoux, P. *Co-Planar Stereotaxic Atlas of the Human Brain* (Thieme Medical, New York, 1988).
6. Christman, S. *Cerebral Asymmetries in Sensory and Perceptual Processing* (Elsevier Science B.V., 1997).
7. Westbury, C. F. *et al.* *Cereb. Cortex* **9**, 392–405 (1999).
8. Rademacher, J. *et al.* *Neuroimage* **13**, 669–683 (2001).
9. Martinez, A. *et al.* *Nat. Neurosci.* **2**, 364–369 (1999).
10. Gandhi, S. P. *et al.* *Proc. Natl. Acad. Sci. USA* **96**, 3314–3319 (1999).
11. Petitto, L.A. *et al.* *Proc. Natl. Acad. Sci. USA* **97**, 13961–13966 (2000).
12. Nishimura, H. *et al.* *Nature* **397**, 116 (1999).
13. Calvert, G. A. *et al.* *Science* **276**, 593–596 (1997).
14. Neville, H. J. *Ann. NY Acad. Sci.* **608**, 71–91 (1990).
15. Baumgart, F. *et al.* *Nature* **400**, 724–726 (1999).