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White matter structure in the right planum temporale region correlates with visual motion detection thresholds in deaf people

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ABSTRACT

The right planum temporale region is typically involved in higher-order auditory processing. After deafness, this area reorganizes to become sensitive to visual motion. This plasticity is thought to support compensatory enhancements to visual ability. In earlier work we showed that enhanced visual motion detection abilities in early-deaf people correlate with cortical thickness in a subregion of the right planum temporale. In the current study, we build on this earlier result by examining the relationship between enhanced visual motion detection ability and white matter structure in this area in the same sample. We used diffusion-weighted magnetic resonance imaging and extracted the measures of white matter structure from a region-of-interest just below the grey matter surface where cortical thickness correlates with visual motion detection ability. We also tested control regions-of-interest in the auditory and visual cortices where we did not expect to find a relationship between visual motion detection ability and white matter. We found that in the right planum temporale subregion, and in no other tested regions, fractional anisotropy, radial diffusivity, and mean diffusivity correlated with visual motion detection thresholds. We interpret this change as further evidence of a structural correlate of cross-modal reorganization after deafness.

1. Introduction

In a the typical human brain, the planum temporale region (PTR) is involved in processing higher-order sensory features of audition (e.g. Hickok and Saberi, 2012). This area is typically defined as consisting of the superior temporal plane posterior to Heschl's sulcus, and the adjacent posterior superior temporal gyrus (Hickok and Saberi, 2012), although its boundaries are controversial (Westbury et al., 1999). In people who are born deaf, this structure responds instead to visual motion stimuli, such as moving dots (Dewey and Hartley, 2015; Fine et al., 2005; Finney et al., 2001; Sadato et al., 2005), gratings (Shiell et al., 2015a), and hands and/or lips (Cardin et al., 2013; Petitto et al., 2000; Sadato et al., 2005). This cross-modal reorganization is thought to reflect a takeover of the deprived auditory cortex by the visual modality, in order to support compensatory enhancements to visual abilities.

Consistent with this idea, a relationship between cross-modal activity and visual abilities has been identified in an animal model of deafness, the congenitally deaf cat (Lomber et al., 2010). Deaf cats are better than hearing cats at both detecting visual motion and localizing peripheral visual targets (Lomber et al., 2010). These behavioural enhancements rely on cross-modal activity, such that in deaf cats but not in hearing, visual performance is impaired when specific regions of the auditory cortices are deactivated (Lomber et al., 2010). Similar enhancements to visual abilities may also exist in deaf people. In a recent experiment from our lab, visual motion detection thresholds were measured in adults who were profoundly deaf from birth or early life, and compared to those of hearing adults (Shiell et al., 2014). Deaf participants had lower (i.e. enhanced) detection thresholds than hearing participants (Shiell et al., 2014), consistent with the

Abbreviations: PTR, planum temporale region; HGS, Heschl's gyrus and sulcus; FA, fractional anisotropy; RD, radial diffusivity; AD, Axial diffusivity; MD, mean diffusivity; MRI, magnetic resonance imaging; DWI, diffusion-weighted magnetic resonance imaging; WM, white matter; GM, grey matter; TBSS, tract-based spatial statistics

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behavioural results from deaf cats (Lomber et al., 2010).

As a follow-up to this behavioural finding, we conducted a second experiment to investigate the potential relationship between enhanced visual motion detection abilities and cross-modal structural reorganization of auditory regions (Shiell et al., 2015b). Using magnetic resonance imaging (MRI), we measured cortical thickness in the right PTR, the region of the auditory cortex that shows cross-modal activity for visual motion stimuli in the deaf (Cardin et al., 2013; Dewey and Hartley, 2015; Fine et al., 2005; Finney et al., 2001; Petitto et al., 2000; Sadato et al., 2005; Shiell et al., 2015a). We found that the cortical thickness of this area correlated with visual ability, such that thicker cortex was associated with better visual motion detection thresholds. We interpreted this finding as evidence of this area's involvement in compensatory vision after deafness, and as an indication of how grey matter (GM) structure is altered in this phenomenon (Shiell et al., 2015b). In the current paper, we build on this association between visual ability and cross-modal reorganization, by exploring the potential relationship between behaviour and white matter (WM) structure. Following the hypothesis that a region of the right PTR reorganizes after deafness to support enhanced visual motion detection abilities, we predicted that the structure of WM in this region would change to reflect this plasticity.

WM structure in deaf people has been extensively studied with magnetic resonance imaging (MRI), but, to our knowledge, not within the context of compensatory visual enhancements. Rather, most of the documented changes in WM within auditory regions have been attributed to the degeneration of WM structure. For example, researchers have uncovered a decreased volume of WM in deaf people in Heschl's gyri (Emmorey et al., 2003; Kim et al., 2009; Hribar et al., 2014; Shibata, 2007) and the left superior temporal gyrus (Shibata, 2007), although these results are not always replicated (Leporé et al., 2009; Li et al., 2013; Penhune et al., 2003).

In addition to measures of WM volume, the structure of WM in deaf people has been investigated using diffusion-weighted MRI (DWI). With DWI, a diffusion tensor model can be fit at each voxel in order to derive several measures that describe how water is constrained by the microstructure of the underlying brain tissue (Alexander et al., 2007). In WM, these measures are typically interpreted as being influenced by axon density, diameter, myelination, and the proportion of crossing fibres (Beaulieu, 2013). One of these measures, known as fractional anisotropy (FA), captures the relative strengths of water diffusion along all three axes of the diffusion tensor. FA has been used extensively to characterize individual differences in WM structure (Johansen-Berg, 2010). A standard approach for examining FA, known as Tract-based Spatial Statistics (TBSS), involves aligning diffusion-weighted images according to the regions of highest FA in the brain, and applying voxel-wise statistics (Smith et al., 2006). With this technique, previous studies have identified decreased FA in auditory regions of deaf people in various regions of the superior temporal lobe (Li et al., 2012; Miao et al., 2013), but none of these studies investigated how changes in WM integrity might be related to compensatory visual ability.

In the current paper, we used DWI to investigate the relationship between WM structure in the right posterior superior temporal gyrus and visual motion detection thresholds in deaf people. Building on our earlier finding (Shiell et al., 2015b), we sampled the WM directly below a GM region-of-interest (ROI) in the right PTR taken from our earlier study. We reasoned that this ROI approach will sample WM tracts that terminate in cross-modally reorganized GM, and will thus maximise the likeliness of identifying WM structure that is associated with cross-modal reorganization.

2. Methods and materials

The study was approved by the Research Ethics Board of the Montreal Neurological Institute, and all participants gave informed written consent. A sign language interpreter was present throughout all testing sessions to translate (either *Langue des Signes Québecoises* or American Sign Language) between the experimenter and participant.

2.1. Participants

All participants took part in two earlier studies in our lab. (Shiell et al., 2015b, 2014). Participants were eleven adults (5 men and 6 women; mean age = 28.2 years old; age range = 21–37 years old) with bilateral and profound deafness. Two participants confirmed hereditary congenital deafness, eight had unknown congenital etiologies, and one became deaf at six months of age due to meningitis. Participants had a hearing loss of greater than 90 dB HL at 500, 1000, 2000, and 8000 Hz in both ears, except for four participants, who could sense 500 Hz at 80 or 85 dB HL but not at higher frequencies. All participants used hearing aids during their childhood but stopped during their adolescence or earlier, and used sign language as their primary language of communication. Six participants learned sign language from interaction with deaf family members, and five participants learned sign language in school around the age of five years old. These latter participants used a combination of signed French, home signs, and gestures to communicate prior to this. Because our hypothesis concerned the relationship between behaviour and anatomy within the deaf population, it did not require a comparison between deaf and hearing groups, and thus hearing participants were not included.

2.2. Visual motion detection task

Visual motion detection thresholds were measured during our earlier study (Shiell et al., 2014). In this task, participants maintained central fixation while viewing two simultaneously presented sinusoidal gratings (grating size: $6° \times 6°$, spatial frequency: 0.33 cycle/°, Michelson contrast: 50%). The gratings were presented for 500 ms in the left and right visual fields, centered at $-10°$ and $+10°$. In each trial, one of the two gratings was randomly selected to move while the other remained stationary. Participants pressed a button to indicate which of the two gratings was moving, and guessed if they were uncertain. The speed of the motion varied between trials according to an adaptive staircase procedure (Kaernbach, 1991). Fixation was monitored with an Eyelink 1000 eye tracker (SR Research, Mississauga, ON, Canada), and trials were discarded from the staircase if fixation was broken. The staircase terminated after 15 reversals, which were averaged to give the threshold measure for that run. Runs in which participants broke fixation in more than 18% of the trials (representing 2 standard deviations above the mean number of times that fixation was broken across all participants and runs) were discarded. Participants completed 8 runs, and the median threshold across these runs was used as the final threshold measure.

2.3. Magnetic resonance imaging

Scanning occurred on a 3-T Siemens Trio scanner with a 32-channel head coil, at the McConnell Brain Imaging Centre of the Montreal Neurological Institute. For each participant, we acquired a high-resolution T1-weighted MPRAGE image (1.0 mm isotropic resolution, 176 slices, 256×256 matrix, TR/TE = 2300/2.98), and a diffusion-weighted image via a single-shot spin-echo-planar sequence (2.0 mm isotropic resolution, 72 slices, $b = 1000$ s/m^2,