Neural Correlates of Motion Processing through Echolocation, Source Hearing and Vision in Blind Echolocation Experts and Sighted Echolocation Novices

Thaler1, L., Milne2, J.L., Arnott3, S.R., Kish4, D. & Goodale2, M.A.

Author Affiliations:

1Department of Psychology, Durham University, Durham, UK
2The Brain and Mind Institute, The University of Western Ontario, London, Ontario, Canada
3The Rotman Research Institute, Baycrest, Toronto, Ontario, Canada
4World Access for the Blind, Encino, California, United States

Corresponding Author:
Lore Thaler
Dept. of Psychology, Durham University
Science Site, South Road
Durham DH1 3LE
United Kingdom
Tel 0044 191 3343290
Mail lore.thaler@durham.ac.uk

Number of figures: 7
Numbers of tables: 2

Wordcount abstract: 250
Wordcount introduction: 535
Wordcount discussion: 2778

Running Head: Neural Correlates of Echo Motion Processing

Keywords: fMRI, Human, Cortex, Neuroplasticity, audition
We have shown in previous research that motion processing through echolocation activates temporal-occipital cortex in blind echolocation experts. Here we investigated how neural substrates of echo-motion are related to neural substrates of auditory source-motion and visual motion. Three blind echolocation experts and twelve sighted echolocation novices underwent fMRI scanning while they listened to binaural recordings of moving or stationary echolocation or auditory source sounds located either in left or right space. Sighted participants brain activity was also measured while they viewed moving or stationary visual stimuli. For each of the three modalities separately (echo, source, vision) we then identified motion sensitive areas in temporal-occipital cortex and in the planum temporale (PT). We then used a region of interest (ROI) analysis to investigate cross-modal responses, as well as laterality effects. In both sighted novices and blind experts we found that temporal-occipital source-motion ROIs did not respond to echo-motion and echo-motion ROIs did not respond to source motion. This double-dissociation was absent in PT ROIs. Furthermore, temporal-occipital echo-motion ROIs in blind, but not sighted, participants showed evidence for contralateral motion preference. Temporal-occipital source-motion ROIs did not show evidence for contralateral preference in either blind or sighted participants. Our data suggest a functional segregation of processing of auditory source-motion and echo-motion in human temporal-occipital cortex. Furthermore, the data suggest that the echo-motion response in blind experts may represent a reorganization rather than exaggeration of response observed in sighted novices. There is the possibility that this reorganization involves the recruitment of ‘visual’ cortical areas.
Some people, just like certain bats and marine mammals, can echolocate by making mouth-clicks and listening to the returning echoes (Schenkman and Nilsson 2010; Stoffregen and Pittenger 1995; Teng and Whitney 2011). Echolocation can be learned by both blind and sighted people with normal hearing (Ammons et al. 1953; Teng and Whitney 2011; Worchel and Mauney 1951). Previous behavioural research has shown that people are sensitive to echo-motion (Rosenblum et al. 2000; Thaler et al. 2011), and in a previous functional magnetic resonance imaging study, we found that echoes from moving as compared to stationary surfaces elicited an increase in activation in temporal-occipital cortex in blind echolocation experts (Thaler et al. 2011). Human temporal-occipital cortex harbours visual motion area MT+, as well as areas sensitive to auditory source motion (Saenz et al. 2008), however. Consequently, here we addressed the question how neural substrates of echo-motion, auditory source-motion, and visual motion in temporal-occipital cortex are related. We also investigated the planum temporale (PT) because of its involvement in the processing of spatial sound movement (e.g. Griffiths and Warren 2002; Krumbholz et al. 2005a).

Blind people are more sensitive to acoustic reverberations than sighted people, even when they do not consciously echolocate (Dufour et al. 2005; Kolarik et al. 2013). To ensure that we would investigate echolocation processing in the blind at a uniformly high skill level, we recruited three blind echolocation experts to participate in the study. Furthermore, we recruited twelve sighted participants who had been trained in an echolocation task in the context of the current study. Including sighted participants not only allowed us to investigate echo-motion areas in the sighted brain, but also enabled us to compare the source and visual motion areas we identified with those reported previously in the literature. Brain activity was measured with fMRI while participants listened to binaural recordings of moving or stationary echolocation or source sounds located either in left or right space. Sighted participants’ brain activity was also measured while they saw moving or stationary visual stimuli. For each of the three modalities separately (echo, source, vision), we then
identified motion sensitive areas in temporal-occipital cortex and the PT. Subsequently, we used a region of interest analysis to investigate cross-modal activity, as well as laterality effects. We found in both blind and sighted participants that source-motion areas in temporal-occipital cortex did not respond to echo-motion, and that echo-motion areas did not respond to source-motion. This double-dissociation was absent for ROIs in the PT. We also found that temporal-occipital echolocation areas in blind experts, but not in the sighted novices, showed a preference for echo-motion in contralateral space. Temporal-occipital source-motion areas did not show contralateral preference in either group. The data suggest that echo-motion and source-motion are processed in different temporal-occipital brain areas in both blind and sighted people. The laterality data, in particular, suggest that the echo-motion response in the blind experts may represent a reorganization rather than an exaggeration of the response observed in the sighted novices. There is the possibility that this reorganization in the blind experts may be related to the involvement of ‘visual’ cortical areas for the processing of echoes that has been reported previously (Arnott et al. 2013; Thaler et al. 2011).

2. Materials and Methods

All testing procedures were approved by the ethics board at Durham University and the University of Western Ontario, and participants gave written informed consent prior to testing. All experimental procedures conformed with The Code of Ethics of the World Medical Association as stated in the Declaration of Helsinki (1964). The consent form was read to participants, and the location to sign was indicated through tactile and visual markers. Software used to conduct testing was programmed using Psychophysics Toolbox 3.08 (Brainard 1997), Matlab (R2009a, The Mathworks, Natick, MA, USA) and C/C++. fMRI data were analyzed using Brain Voyager QX version 2.3 (Brain Innovation, Maastricht, The Netherlands) and Matlab. Sound editing was performed with Adobe Audition version 1.5 software (Adobe Systems, San Jose, CA,
USA). Sound equalization was performed with filters provided by the headphone manufacturer (Sensimetrics, Malden, MA, USA).

2.1. Participants

Three blind, male echolocation experts (B1-B3) participated in the study. B1 (29 yrs) had lost sight gradually from birth due to Glaucoma. Since early childhood (approx 3 yrs) B1 had had only bright light detection. At time of testing he was completely blind. B1 reported to have used echolocation on a daily basis since he was 12 years old. B2 (44 yrs) had lost sight due to retinopathy of prematurity. He reported to have started to use echolocation when he was in his early twenties, but stopped using it between 34 and 40 years of age because during this time bad health required him to use a wheelchair which was pushed by another person. At age 40 he resumed using echolocation on a daily basis. B3 (age 42 yrs) was enucleated at one year of age because of retinoblastoma. He reported to have used echolocation as long as he can remember. At time of testing, all echolocation experts reported using mouth-click based echolocation on a daily basis. Twelve sighted echolocation novices (six female) aged 20-43, participated in the study as well. All novices reported not having used or trained echolocation before the study.

2.2. Experimental Stimuli

2.2.1. Sound Stimuli - Setup and Recording Procedure

All auditory stimuli were recorded in the Beltone Anechoic Chamber at the National Centre for Audiology in London, Ontario, Canada, measuring 5.5 m high x 7.0 m wide x 3.7 m deep, and equipped with a 125 Hz cut-off wedge system on the walls and ceiling. The chamber floor was covered in foam baffles. The participant stood on a pedestal so that his head position was aligned with the centre of the chamber. Ambient noise recordings indicated a background noise (i.e., ‘noise
Recordings of the entire session’s audio were acquired via in-ear binaural omni-directional microphones (Sound Professionals-TFB-2; ‘flat’ frequency range 20 – 20,000 Hz) attached to a portable Edirol R-09 digital wave recorder (16-bit, stereo, 44.1 kHz sampling rate). Microphones were placed directly at the opening of the echolocator’s left and right auditory canals and held in place by a soft rubber ‘horn-shaped’ housing that conformed to the shape of the concha. During recording, participants held their head stationary and faced straight ahead. Recordings were made separately for B1 and B2. B3 could not participate in the recording sessions for logistical reasons.

Echolocation Sounds: Similar to our earlier study (Thaler et al. 2011), echo stimuli were created by recording echolocation clicks and subsequent echoes as the participant was presented with a sound-reflecting object. Thus, echolocation recordings contained both clicks and click echoes. The object was a plastic bowl (diameter 28.5 cm, depth 11 cm) covered in aluminium foil. The object was presented at ear level with the concave surface facing the echolocator, and it could be located either to the left or to the right of the participant, and it could either be moving or stationary (Figure 1, top). To create conditions in which a sound-reflecting surface was moving silently to the right or left of the participant, the object was moved around the participant by the experimenter (LT). To minimize the sounds and echoes generated by the experimenter herself, the experimenter was located as far behind from the participant as the size of the anechoic chamber permitted (approx. 1.5 m), and used a 0.8 cm diameter, 2 m long metal rod to position the sound reflecting surface next to the participant. Specifically, the sound reflecting surface was attached to the end of the metal rod protruding towards the participant, while the experimenter manually held the other end. For stationary conditions the experimenter positioned the surface in a fixed position approx. 60° from straight ahead to the right or to the left of the participant’s head at a distance of approx 80 cm. For moving conditions the experimenter smoothly moved the surface either the left or the right side of the participants head. For right motion conditions, the motion trajectory started at 60° to the right of straight ahead at a distance of approx. 80 cm. The surface then started to move counter-clockwise...
on a roughly circular arc centred on the participant’s head, until it reached 20° to the right of straight ahead, at which point it reversed direction to clockwise. At 100° to the right of straight ahead it reversed direction again from clockwise to counter-clockwise. Thus, the azimuth of the sound reflecting surface changed, but its radial distance remained constant at 80 cm (see Figure 1, top).

During a motion trial the surface traversed each of the two extreme points (20° and 100° of straight ahead) ~3 times, resulting in ~5 traversals of an 80° arc, averaging a motion speed of ~40° per second. The motion trajectory was mirror-symmetric for left-motion conditions. For each of the four conditions (left-moving, left stationary, right moving, right stationary) recordings were made as follows: First the surface was placed at its starting position. Then, the participant (either B1 or B2) started to make short (approx. 4 ms), broadband echolocation clicks at a rate of approx. 2-2.5 Hz with his head held stationary and straight ahead. Then the experimenter either held the surface in place (stationary conditions) or started moving the surface (moving conditions). The experimenter vocally signalled the participant the end of the trial, at which point the participant stopped making echolocation clicks. High-quality stereo recordings (16-bit, 44.1 kHz) of the entire sessions’ audio were acquired with the in-ear microphones and saved for off-line editing. B1 and B2 participated in separate recording sessions.

Source Sounds: Spatial conditions for source sound stimuli matched those in echolocation conditions (Figure 1, bottom). They were also generated in the same way as echolocation stimuli. There were only two differences. One, instead of a sound-reflecting surface, a loudspeaker (Hewlett Packard Mini USB-Powered Laptop Speakers, Model NN109AA#ABA) playing clicking sounds (see Sound Editing) was mounted to the tip of the steel rod. Two, the participant remained entirely silent during a trial.

2.2.2. Sound Stimuli - Sound Editing
Echolocation: Two unique sound sequences were extracted from the recordings for each spatial condition. Each of these sequences was 10 s in duration. The total number of sequences used in the Echolocation Experiment was 16 (4 conditions × 2 echolocators × 2 exemplars), and there were 4 sequences for each experimental condition (right moving, right stationary, left moving, left stationary). Sequences contained between 19 and 21 clicks, and there was no systematic difference in the number or duration of clicks across conditions. The average acoustic energy of echolocation sounds (in dB RMS) was -41.6 (SD=1.5) in left moving, -39.5 (SD=3.0) in left stationary, -42.0 (SD=1.7) in right moving, and -39.9 (SD=3.7) in right stationary conditions. The average difference in acoustic energy (in dB RMS) between right and left channels in moving and stationary conditions was 0.6 and 1.7, respectively. This difference is small because both microphones pick up energy mostly from the direct click signal which is similar for both microphones. The intensity differences between moving and stationary stimuli were due to the fact that participants B1 and B2 generated mouth clicks at different levels in the different conditions. We did not rescale our stimuli to match average intensity across conditions for two reasons. First, we wanted to avoid systematic differences in background noise present in our recordings. Second, it has been estimated that the Weber fraction (ΔI/I) for discriminating differences in sound intensity for transients such as clicks is at best 0.25, and at worst exceeds 1 (Raab and Taub 1969). Thus, even the largest difference in sound intensity in our stimuli was well below threshold.

Source Hearing: To create stimuli for source conditions, we played modified clicking sounds through loudspeakers. The modified clicking sounds were the same as those used in our previous study (Thaler et al. 2011). The clicking sounds had been recorded while no sound reflecting surface had been present (‘empty’ clicks). They had been recorded in the same anechoic chamber, but in the ears of an echolocator not involved in the current study (participant EB in Thaler et al. 2011). From these recordings we extracted three unique click sequences (each containing approximately 5 - 6 clicks at a rate of approx. 2.5 Hz). Subsequently, the stereo sound was transformed into a mono
sound by randomly choosing either the left or right channel track. Finally, the mono-track waveform samples were inverted and reversed. To record source sounds, the sounds created this way were played through loudspeakers in a continuous loop and recorded in either B1 or B2’s ears in the four different spatial conditions. Two unique sound sequences were extracted from the recordings for each spatial condition. Each of these sequences was 10 s in duration. The total number of sequences used in the source Experiment was 16 (4 conditions × 2 echolocators × 2 exemplars), and there were 4 sequences for each experimental condition (right moving, right stationary, left moving, left stationary). The average acoustic energy of source sounds (in dB RMS) was -39.5 (SD=0.2) in left moving, -39.4 (SD=0.4) in left stationary, -39.7 (SD=0.5) in right moving, and -39.8 (SD=0.6) in right stationary conditions. The average difference in acoustic energy (in dB RMS) between right and left channels in moving and stationary conditions was 10.9 and 11.2, respectively.

2.2.3. Visual Stimuli

Participants viewed a display that showed a circular red fixation target (0.5° visual angle diameter) in three different conditions: baseline (in front of a black background), stationary: (in front of a pattern of white random dots, diameter 0.1° visual angle, spaced on average 1° of visual angle apart, that flickered at 1 Hz) and moving (in front of pattern of white random dots, diameter 0.1° visual angle, spaced on average 1° of visual angle apart, that translated smoothly across the visual field and changed direction of motion randomly every second). The active display area subtended 20° x 13° of visual angle.

2.3. MRI scanning

Imaging for B3 and S1-S5 was performed at Durham University Neuroimaging Facility (James Cook University Hospital, Middlesbrough, United Kingdom). Imaging for B1 and B2 was performed at the Robarts Research Institute (London, Ontario, Canada). In both facilities we used a 3-Tesla, whole-body MRI system (Magnetom Tim Trio; Siemens, Erlangen, Germany) with a 32-channel head coil.
2.3.1. Set-Up and Scanning Parameters

*fMRI Echolocation and Source Hearing:* Audio stimuli were delivered over MRI-compatible insert earphones (Sensimetrics, Malden, MA, USA, Model S-14). Participants adjusted the sound level to their own comfort. Earphones were encased in replaceable foam tips that provided a 20–40 dB attenuation level (information provided by the manufacturer). Further sound attenuation was attained by placing foam inserts between the head rest and the listener's ears. To minimize background noise, the MRI bore's circulatory air fan was turned off during experimental runs. A single-shot gradient echo-planar pulse sequence in combination with a sparse-sampling design (Hall et al. 1999) was used for functional image acquisition. Repetition time [TR] was 12 s (10 s silent gap+2 s slice acquisition). We used a FOV of 211 mm and 64×64 matrix size, which led to in-slice resolution of 3.3×3.3 mm. Slice thickness was 3.5 mm and we acquired 38 contiguous axial slices covering the whole brain in ascending order. Echo time [TE] was 30 ms and Flip-Angle [FA] was 78°.

*fMRI Vision (Sighted Only):* Visual stimuli were viewed through a first-surface mirror mounted on top of the head coil and were shown at a spatial and temporal resolution of 1920 x 1200 pixels and 60 Hz, respectively, on a 24-inch MRI compatible LCD display (BOLDscreen for fMRI; Cambridge Research Systems, Kent, United Kingdom) located behind the head-coil in the bore. fMRI scanning parameters were the same as the echolocation experiments, with exception of a 2-s TR related to the continuous scanning procedure.

*Anatomical Images:* Anatomical images of the whole brain were acquired at a resolution of 1×1×1 mm using an optimized sequence (MPRAGE).

2.3.2. Functional Paradigms
Echolocation: Each run contained silent baseline and experimental trials. Experimental trials contained 10 s of echolocation sounds. This was followed by a 50 ms 1200 Hz tone. The participant was instructed to indicate his response with a key press after he heard the tone (see behavioural paradigm below). Functional scans started 10 s after the run had started and lasted 2 s. The next trial started after scanning had ended. Silent baseline trials differed from experimental trials in that the 2 s functional scan occurred after 10 s of silence. No beep was provided and no key-presses were produced. Participants listened to echolocation recordings from both B1 and B2 and from all four spatial conditions, i.e. Stationary-Right, Stationary-Left, Moving-Right, Moving-Left (see Experimental Stimuli for more details). Thus, there were eight experimental conditions total.

Stimulus presentation order was balanced using a clustered Latin square design, such that each run contained eight clusters, each cluster contained all four spatial conditions using recordings from the same person (i.e. B1 or B2). The order of conditions within each cluster was chosen such that every spatial condition was preceded by every other spatial condition in a run. The recordings from B1 and B2 were alternated. A cluster of four spatial conditions was always preceded by a silent baseline trial and each run began and ended with a silent baseline trial. Thus, there were 41 trials per run (9 silent+ 8×4 experimental) and the duration of each run was 41×12 s. Each participant performed five runs.

Source Hearing: Source runs were identical to echolocation runs with the only exception that experimental trials contained 10 s of source sounds, instead of echolocation sounds. Each participant performed 5 runs.

Vision (Sighted Only): Each run contained baseline, stationary and moving conditions. Each condition was shown in blocks of 16 seconds and in fixed order, such that baseline always preceded stationary blocks, and stationary blocks always preceded moving blocks. Each run began and ended with a
baseline block. The total number of blocks in each run was 25 (8 moving, 8 stationary and 9 baseline). Hence, the duration of each run was 25 x 16 s and the number of functional volumes acquired in each run was 200. Each participant performed one run.

Order of Experiments:

All participants ran the experiments in the following order: Echolocation, Source Hearing, Vision (Sighted only).

2.4. Behavioural Paradigms

2.4.1. During MRI

Echolocation: Participants were asked to keep their eyes closed during the duration of the experiment. The basic paradigm was a 1-interval-4-alternative forced choice (AFC) paradigm. The participant listened to the echolocation sound and judged the spatial properties of the sound reflecting surface (right moving, right stationary, left moving, and left stationary). The participants indicated their responses on an MR compatible keypad by pressing the key located under his right index, right middle, right ring or right little finger, respectively.

Source Hearing: The paradigm and response collection was the same as in echolocation conditions. The only difference was that the participant judged the spatial properties of a source sound, instead of a sound-reflecting surface.

Vision: The participants’ task was to direct their gaze at the fixation target.

2.4.2. Before MRI
Behavioural testing before MRI was conducted in a quiet room. Sounds were presented using the same headphones as during MRI scanning and participants adjusted the level to their own comfort.

*Experts:* Before MRI scanning B1-B3 made themselves familiar with the sounds by listening to them and receiving feedback about the spatial properties of the sound from the experimenter (LT). In addition, B1-B3 each performed one full run without feedback in both echolocation and source hearing conditions.

*Novices:* Before MRI scanning sighted participants completed two echolocation practice sessions on two separate days, each of which took approx. 40 minutes. Within each practice session participants listened (with their eyes closed) to 160 echolocation sounds from both B1 and B2 in block-randomized order. After each sound participants were prompted to indicate which spatial condition they perceived (i.e. Stationary-Right, Stationary-Left, Moving-Right, Moving-Left), regardless of the sound having been recorded with B1 or B2. Participants indicated their response by pressing a key on a computer keyboard. After they had given their response they received feedback about the spatial condition they had listened to. In addition, at the end of each practice session they each performed one full run without feedback. Immediately before MRI scanning participants made themselves familiar with the sounds by listening to them and receiving feedback about the spatial properties of the sound.

2.5. fMRI Data Analysis

2.5.1. Pre-Processing and Coregistration

In the beginning of each functional run, the system went through three functional scans without saving data to disk (this is scanner manufacturer default programming for functional sequences). Subsequently, acquisition of functional data started. The first volume acquired in the beginning of
each auditory run had served the purpose to initialize the stimulus presentation software, but it was not used for functional data analysis. For visual runs, all volumes were used for functional data analysis. Each run was subjected to Slice Scan Time Correction (Tri-linear sinc), temporal High-Pass Filtering (cut-off at 2 sines/cosines) and 3D Motion correction (Sinc). For quality assessment we inspected the motion parameters estimated for within-run motion for each run. This inspection revealed that motion estimates did not exceed 1° rotation and 1 mm translation within any given run. Furthermore, motion parameter estimates appeared drift-like and uncorrelated with the paradigm. To align the functional to the anatomical data for each participant, we first used 3D motion correction to align each volume within a run to the functional volume closest to the anatomical scan. The functional volume closest to the anatomical scan was co-registered to the anatomical scan of that same participant. The anatomical for each participant was then transformed into standard stereotactic space (Talairach and Tournoux 1988). Prior to group analyses, data were smoothed with a 6mm FWHM Gaussian kernel; however, ROI definition and analyses for individual participants were conducted using unsmoothed data.

2.5.2. Functional Analysis

2.5.2.1. Whole Brain Analyses

**BOLD activity related to echolocation stimulation as compared to silence:** To obtain activity related to echolocation processing as compared to a silent baseline for each participant, we applied a GLM with the stick-predictor “Sound” (maximum and minimum values 1 and 0, respectively) to the z-transformed time courses of runs obtained in echolocation experiments (5 runs per participant). To determine where BOLD activity during echolocation trials exceeded that during silent baseline trials, we isolated voxels where the beta value of the ‘Sound’ predictor was significantly larger than zero. For sighted participants, group data were analyzed using the RFX GLM approach, and the
significance threshold for evaluation of results in volume space was set to $p<.001$. To control the rate of type-I errors in the statistical map, we applied a cluster size threshold (Forman et al. 1995). Cluster threshold values were estimated in volume space using the BrainVoyager Cluster Threshold Estimator Plugin (Goebel et al. 2006). For blind participants the sample size ($n=3$) was too small to apply an RFX analysis. Thus, we ran a fixed effects GLM for each individual participant and evaluated consistency of activations across participants by computing probability maps. To obtain probability maps, each participant’s individual activity map was thresholded at $p<.1$ (Bonferroni correction; individual voxel threshold $p<.000002$). Then, overlap of individual thresholded maps was computed as a percentage. One hundred percent overlap for a given voxel signifies that all three participants showed significant activity for this voxel.

**BOLD activity related to source hearing as compared to silence:** To obtain activity related to source hearing as compared to a silent baseline for each participant, we analysed the time-course data obtained in source sound experiments (5 runs per participant) in the same way as the echolocation data.

**BOLD Activity related to visual stimulation as compared to darkness:** To obtain activity related to general visual processing we applied a GLM with one predictor ‘light’ to the z-transformed time courses of runs obtained in the vision experiment (1 run per participant). The predictor was obtained by convolving a boxcar function that indicated the presence of the event with the standard 2-gamma HRF. To determine where BOLD activity during vision trials exceeded that during dark baseline trials, we isolated voxels where the beta value of the ‘Light’ predictor was significantly larger than zero. Group data were analyzed using the RFX GLM approach, and the significance threshold for evaluation of results in volume space was set to $p<.001$. To control the rate of type-I errors in the statistical map, we applied a cluster size threshold (Forman et al. 1995). Cluster threshold values...
were estimated in volume space using the BrainVoyager Cluster Threshold Estimator Plugin (Goebel et al. 2006).

2.5.2.2. ROI Analyses

Definition of echo-motion ROIs: To obtain activity related to processing of moving echoes as compared to stationary echoes for each participant individually, we applied a fixed effects GLM with stick-predictors “right moving”, “left moving”, “right stationary” and “left stationary” to the z-transformed time courses of runs obtained in echolocation experiments (five runs per participant). Each participant’s individual GLM results were then subjected to a conjunction analysis, i.e. (right moving + left moving > 0) AND (right moving + left moving > right stationary + left stationary), the significance threshold for which was set to 0.05 (voxelwise). Echo-motion ROIs were defined by selecting voxels around the ITS/LOS junction, or in the planum temporale (PT) for which the value of the contrast was significant. Table 2 shows centre-of-gravity Talairach coordinates for echo-motion ROIs.

Definition of source-motion ROIs: ROIs for source conditions for individual participants were defined by analyzing each participant’s data from functional runs obtained in source conditions in the same way as the echolocation data. Table 2 shows centre-of-gravity Talairach coordinates for source-motion ROIs.

Definition of vision-motion ROIs: To obtain activity related to processing of visual motion for each participant individually, we applied a fixed effect GLM with two predictors, i.e. “moving” and “stationary” to the z-transformed time courses of runs obtained in visual motion experiments (one run total). Predictors were obtained by convolving a boxcar function that indicated the presence of the event with the standard 2-gamma HRF. The GLM was run as a fixed effect model for each
The GLM results were then subjected to a conjunction analysis, i.e. (moving > 0) AND (moving > stationary). Visual motion ROIs were defined by selecting voxels around the ITS/LOS junction, or in the PT for which the value of the contrast was significant. In temporal-occipital cortex voxels were selected using both a liberal voxelwise p<.05 threshold, and more conservative Bonferroni corrected p<.05 threshold, where the correction was computed based on all voxels in the functional volume. Table 2 shows centre-of-gravity Talairach coordinates for vision-motion ROIs.

Analysis of Contralateral Preference: To determine activity for echo-motion or source-motion from the right or left side of space, we applied a GLM with stick-predictors “left motion”, “left stationary”, “right motion” and “right stationary” to the time courses of runs obtained in echo and source experiments (five runs per experiment per participant). Predictors as well as the time course for each voxel were z-transformed before the analysis, resulting in normalized beta values. The GLM was run as a fixed effect model inside each left and right echo- and source-motion ROI for each participant. From this analysis we were able to compute beta values related to left and right moving and stationary conditions separately for each voxel. To determine if there was a right or left motion preference in left or right ROIs, we computed the contrast value for moving as compared to stationary conditions for each voxel within each ROI separately for right and left space conditions. For blind participants, we then subjected these values to a factorial ANOVA with ‘Space’ and ‘Hemisphere’ as independent factors, separately for echo- and source-motion ROIs. Technically, we could have used the number of beta values to determine error degrees of freedom (df) for each ANOVA, but this would have resulted in different df for the error terms (and thus differences in statistical power) between participants and ROIs. To avoid this, we determined df based on the number of times an event had occurred. For example, in echo-motion ROIs, ‘left motion’, ‘right motion’, ‘left stationary’ and ‘right stationary’ each occurred 40 times resulting in 160 independent events and 156 df for the error term to compute the ANOVA. The same applies to the ANOVA applied to source ROIs. In this way we could use data obtained from all voxels inside each ROI to
determine interaction effects between ‘Space’ and ‘Hemisphere’ for each blind participant individually.

For sighted participants, we computed moving as compared to stationary responses for right and left space conditions and for right and left ROIs in the same way as for blind participants. Instead of assessing the significance of effects for each participant individually, however, data were analyzed on the group level using repeated measures ANOVA, with ‘Space’ and ‘Hemisphere’ as within-subject factors.

3. Results

3.1. Behaviour

Participant’s behavioural task during fMRI scanning was to judge the spatial properties (right moving, right stationary, left moving, left stationary) of the sound reflecting surface (echolocation task) or the sound source (source task). Participants’ behavioural performance (percentage correct) is shown in Table 1. Chance performance would have been 25%. Chi-square tests were conducted separately for each participant and task. For B1 and B2 performance was also analyzed separately for when they listened to their own sounds (i.e. B1 to B1 and B2 to B2) and to the sounds of the other person (i.e. B1 to B2 and B2 to B1). This was done to assess the potential role played by listening to sounds obtained with an alien (other person) or familiar (own) head related transfer function (HRTF). All participants in all conditions performed significantly better than chance (p<.001). Thus, all sighted as well as all blind participants were able to perform both the echolocation and source motion tasks significantly better than chance. To evaluate if sighted novices performed differently from blind experts, we compared percentage correct values between novices and experts separately for source and echo conditions. Results were consistent across tests, and showed that experts performed better than novices in the echolocation task (t-test for independent samples:...
t(13)=3.9591; p=.0016), but that there was no difference between experts and novices in the source task (t-test for independent samples: t(13)=0.9294; p=.3696). Sighted participants’ performance did not differ between left and right space conditions for either source sounds (paired samples t-test: t(11) =1.961; p=.0757), or echo sounds (paired samples t-test t(11) = 1.0998; p=.2949). Neither did B1-B3 performance differ between left and right space (see Chi-square test results in Table 1). Interestingly, sighted participants were more accurate for stationary as compared to moving echo sounds (paired samples t-test: t(11) =3.704; p=.0035). This can be explained by our sighted participants’ bias to report ‘stationary’ in echo conditions (mean: 57.1%, SD: 9.1). This bias was significantly different from 50% (one-sample t-test; t(11) = 2.717; p=.02). Sighted participants were equally accurate for stationary as compared to moving source sounds (paired samples t-test: t(11)=1.746; p=.1087). Performance of B1-B3 did not differ between stationary and moving condition for either echo or source sounds (see Chi-square test results in Table 1).

All the t-tests were followed up with non-parametric Wilcoxon rank sum or Wilcoxon signed rank tests, and exactly the same story emerged. Finally, performance for B1 and B2 did not differ when they listened to their own sounds (i.e. B1 to B1 and B2 to B2) or to the sounds of the other person (i.e. B1 to B2 and B2 to B1) (see chi-square test results in Table 1). Thus, the use of an alien vs. familiar HRTF most likely did not affect performance in our study. There is the possibility, however, that B1 and B2 might still have benefited from getting accustomed to their own sounds and this might have helped in interpreting the sounds of the other person. This was not the case for B3, however, and therefore might be the reason for B3’s lower accuracy in the echolocation task.

3.2. Overall Activity – Whole Brain Analysis

The top row in Figure 2 shows slice views of sighted participants’ BOLD activity in echolocation, source hearing and visual conditions, in blue, green and red, respectively. The columns correspond to different transverse slices, and Talairach z-coordinates are indicated above each column. It is
evident that high consistency in sighted participants’ auditory and visual activations (i.e. high levels of statistical significance) are found in Heschl’s gyrus and occipital cortex. This was expected since Heschl’s gyrus and occipital cortex contain primary auditory and visual cortices, respectively.

The middle row in Figure 2 shows slice views of blind participants’ BOLD activity echolocation, and source sound conditions, in blue and green, respectively. It is evident that highest consistency in blind participants’ auditory activations (i.e. 100% overlap of individual activation maps) are found in Heschl’s gyrus. This was expected since Heschl’s gyrus contains primary auditory cortex. Two out of the three blind participants, i.e. B1 and B3, (66.7% overlap) also show activation in occipital cortex at the chosen significance threshold. The occipital activations are more extensive for echolocation conditions (in blue) as compared to source sound conditions (in green).

The bottom row in Figure 2 shows the activations found in the sighted participants in vision conditions and in the blind participants in echo and source conditions superimposed. It is evident that areas of highest consistency in occipital cortex during visual stimulation in sighted participants’ partially overlap with blind participants’ echo and source activations in occipital cortex. Previous studies have shown that blind people can exhibit BOLD activation in ‘visual’ occipital brain areas in response to auditory stimulation (for review see Bavelier and Neville 2002; Merabet and Pascual-Leone 2010). Activations in other brain areas also overlap between blind and sighted (e.g. parietal cortex), but the activation patterns within each group are less consistent. In their entirety the overall auditory and visual activations in blind and sighted participants are consistent with what has been reported previously in the literature.

3.3. Modality Specific Motion Activity – ROI Analysis

Table 2 (top rows) reports locations and sizes of echo-motion, source-motion and vision-motion ROIs in temporal-occipital cortex. In addition, Figure 3 illustrates echo- and source-motion ROIs in temporal-occipital cortex in the three blind echolocation experts. In temporal-occipital cortex echo-
motion ROIs could be defined for only eight out of the twelve sighted echolocation novices, and for three of these in only one hemisphere. In contrast, bilateral echo-motion ROIs could be defined for all three echolocation experts. Talairach coordinates of echo-motion ROIs obtained in sighted participants and blind participants in the current study correspond well to those obtained in two other blind echolocation experts under slightly different experimental conditions (participants EB and LB in Thaler et al. 2011; coordinates reproduced in Table 2). Source-motion ROIs could be defined for all blind and ten sighted participants. For two sighted participants source-motion ROIs could be defined only in the right or left hemisphere, respectively. Vision-motion ROIs could be defined bilaterally for all sighted participants at p<.05. At p<.05 (Bonferroni corrected) vision-motion ROIs could be defined bilaterally for eleven of the twelve sighted participants, and for one participant in only one hemisphere.

Table 2 (bottom rows) reports locations and sizes of echo-motion, source-motion and vision-motion ROIs in the PT. In the PT, echo-motion ROIs could be defined for all blind experts and all sighted novices, but for three of the sighted novices only in one hemisphere. Source-motion ROIs could be defined for all blind and sighted participants, but for one sighted participant only in one hemisphere. Coordinates of source-motion ROIs correspond well to those reported previously for sighted participants (e.g. Krumbholz et al. 2005a). Vision-motion ROIs could be defined for all sighted participants, but for one participant only in one hemisphere.

We used ROI analyses to compute both intra-modal and cross-modal responses. The analysis of intra-modal responses measures the sensitivity of an ROI towards motion in the modality used to define the ROI (e.g. vision-motion response in the vision-motion ROIs) and can serve as a ‘benchmark’ level of activity, since from the way ROIs were defined it was expected that intra-modal motion responses should be significant (Kriegeskorte et al. 2009; Vul et al. 2009). The analysis of cross-modal responses measures the sensitivity of an ROI towards motion in another modality (e.g.
vision-motion response in echo-motion ROIs). Thus, this analysis will tell us to what degree ROIs are functionally separate. Figure 4 shows the results of the ROI analysis of intra- and cross-modal responses. The left, middle and right panels show activations in source-motion, echo-motion, and vision-motion ROIs, respectively. Top and bottom rows show results for temporal-occipital and PT ROIs, respectively. Vision-motion ROI results are shown for ROIs defined at p<.05, but the same results were obtained for ROIs defined at p<.05 (Bonferroni corrected). Bars indicate ROI responses to motion in the three different modalities. As expected, intramodal responses are significant in all ROIs, and intramodal responses yield largest effects in each ROI.

With regard to cross-modal responses in temporal-occipital cortex, source-motion ROIs do not show a significant response towards echo-motion in any of the participants, and echo-motion ROIs do not show a significant response to source motion in either sighted or blind participants. Both echo- and source-ROIs in sighted participants, however, show a significant visual motion response. In contrast, vision-motion ROIs do not show a significant cross-modal response to either source- or echo-motion. This suggests that visual-motion signals can drive echo- and source-motion ROIs in temporal-occipital cortex, but neither echo- nor source-motion signals can drive vision-motion ROIs in the same region of the brain. In the PT, echo-motion ROIs show a significant response to source motion, but source-motion ROIs do not show a significant response towards echo-motion. Both echo- and source-motion ROIs in the PT of sighted participants show a significant visual motion response, and vision-motion ROIs also show a significant response for source motion.

In summary, in temporal-occipital cortex, echo- and source-motion ROIs are functionally dissociated in both blind and sighted brains. In contrast, there is no functional dissociation in the PT, because echo-motion ROIs are driven by source-motion signals. In both the PT and temporal-occipital cortex – perhaps not surprisingly - the strong visual activation encroaches on both echo- and source-motion ROIs in the sighted brains.
To investigate potential differences in ROIs between blind and sighted participants, we compared the size, x (absolute value), y, and z coordinates of temporal-occipital and PT echo-and source-motion ROIs between the two groups of participants using independent samples tests. We found that echo-motion ROIs in temporal-occipital cortex were significantly larger for the blind experts (average = 563 voxels) than the sighted novices (average = 95 voxels) (t(17)=4.065; p = .001). Furthermore, source-motion ROIs in temporal-occipital cortex were shifted 6.5 mm more medial in the blind than the sighted, and this difference was significant (t(22) = 3.359; p = .003). These results were confirmed using non-parametric Wilcoxon rank sum tests. No other comparisons between the two groups of participants were significant.

To investigate potential differences in spatial location between echo- and source-motion ROIs in temporal-occipital cortex we compared their x (absolute value), y, and z coordinates using paired-sample tests across all participants. We did not find any significant differences.

To investigate potential differences in spatial location between temporal-occipital echo- and source-motion ROIs on the one hand, and vision-motion ROIs on the other, we compared their x (absolute value), y, and z coordinates. For the sighted participants we used paired-samples tests, whereas for the blind we used independent samples tests. For sighted participants, we found that source-motion ROIs were located 8.4 mm more anterior (t(17) = 5.799; p < .001) and 6.1 mm more lateral (t(17) = 4.861; p < .001) than vision-motion ROIs. Echo-motion ROIs were located 10.4 mm more anterior than vision-motion ROIs (t(12) = 4.436; p = .001). These results were confirmed using non-parametric Wilcoxon signed rank tests. We did not find any significant differences for the blind participants.

3.4. Laterality – ROI Analysis
Figure 5 shows the results from the laterality analysis for all participants and ROIs. The ANOVA results are indicated next to each panel. Results of pairwise comparisons with independent samples (blind) and paired samples (sighted) t-tests computed between left and right-space conditions within left and right hemisphere ROIs are indicated as well.

It appears that with regard to source-motion the results are similar across blind and sighted participants for both temporal-occipital and PT ROIs, namely that there is a tendency for a preference for source motion in left space in both left and right hemisphere ROIs, though the left preference is reduced in the left hemisphere for ROIs in the PT. However, with regard to echo-motion the pattern of results is different. Specifically, in temporal-occipital ROIs all blind participants show preference for echo-motion in contralateral space, i.e. a stronger response for moving as compared to stationary echoes in left space in right hemisphere ROIs, and a stronger response for moving as compared to stationary echoes in right space in left hemisphere ROIs. Although the ANOVA interaction effects, as well as the independent samples t-tests, are only significant for B1 and B3, the trend is the same for B2. In contrast, sighted participants do not show this contralateral preference but a general preference for motion in left space in temporal-occipital ROIs. In fact, it appears that sighted participants’ lateralization for echo-motion in temporal-occipital ROIs is quite similar to their lateralization for source-motion in temporal-occipital ROIs. In sum, the processing of echo-motion in temporal-occipital ROIs in the blind echolocation experts shows clear evidence for a contralateral preference. No such effect was observed for processing of echo-motion in the PT, or for processing of source-motion in the blind. Moreover, neither echo-motion nor source-motion showed evidence of a contralateral preference in the sighted in any ROI.

Previously, it has been shown that brain activity in the PT as measured with fMRI is stronger for motion signals coming from contralateral space (Krumbholz et al. 2005b). Importantly, those authors evaluated the magnitude of the lateralized motion response against the magnitude of a response to a non-lateralized stationary stimulus, i.e. a sound that was not lateralized to the same hemisphere.
The results of the analysis of contralateral preference shown in Fig.5, however, were computed by evaluating the magnitude of a response to a lateralized motion stimulus against the magnitude of the response to a stationary stimulus lateralized to the same hemisphere. Thus, the left-lateralization for source motion in the PT shown in Fig.5 does not contradict previous reports. To see if we could replicate the contralateral preference for source motion in PT when the response to a lateralized source motion stimulus is evaluated against a response to a sound not lateralized to the same hemisphere, we also computed left and right motion responses *per se* for all ROIs. As can be seen in Fig. 6, we did indeed replicate the Krumbholz et al. (2005b) result of contralateral preference for source motion in the PT of sighted participants. It is also evident that the left preference for echo-motion persists in the PT of sighted participants, while there is no clear preference in temporal-occipital cortex ROIs. The results of the blind participants agree with those in the sighted, with the important difference that blind experts still show a contralateral preference for echo-motion in temporal-occipital ROIs.

In sum, our laterality data are consistent with previous findings about lateralization of source motion in the PT. They also highlight, that blind echo experts show contralateral activity in temporal-occipital echo-motion ROIs.

4. Discussion

Previous behavioural research has shown that people are sensitive to echo-motion (Rosenblum et al. 2000; Thaler et al. 2011). With regard to the underlying neural mechanisms, we have shown previously that echoes from moving as compared to stationary surfaces lead to an increase in activity in temporal-occipital cortex in blind echolocation experts (Thaler et al. 2011). Here, we followed up on this work and investigated how temporal-occipital brain areas involved in echo-motion processing are related to those involved in processing of auditory source-motion and visual motion in blind echolocation experts and sighted echolocation novices. We also investigated the
potential role played by the PT, because of its involvement in the processing of sound motion (Griffiths and Warren 2002; Krumbholz et al. 2005a). To take into consideration individual variability in brain anatomy we used functional localization methods and region of interest analyses.

4.1. Processing of Auditory Source Motion and Visual Motion - Relation to Previous Results

The relative centre-of-gravity coordinates for temporal-occipital visual and source-motion areas that we find in our sighted participants (Table 2) appear to be consistent with what has been previously reported in the literature (i.e. Poirier et al. 2005, 2006; Saenz et al. 2008). With regard to the functional properties of visual and source motion areas there is an ongoing debate as to what degree visual motion area MT+ is sensitive to sound motion. While some evidence supports the idea of an auditory motion response in area MT+ (Poirier et al. 2005, 2006), other evidence does not (Saenz et al. 2008). It has been suggested that seemingly contradictory results may be due to differences in data analysis, i.e. analysis of spatially averaged data vs. ROI analysis (Saenz et al. 2008). In our current study we used functional localizer methods and ROI analyses similar to those used by Saenz et al (2008), and consistent with their results we also found that sighted participants' visual motion areas were not driven by auditory motion (Figure 4, bottom panel). In addition, we found that there was a difference in centre-of-gravity coordinates between (sighted) vision and (sighted) source-motion ROIs in temporal-occipital cortex. In summary, consistent with previous studies using a similar type of analysis (Saenz et al. 2008) our data suggest that source and visual motion areas in temporal-occipital cortex can be separated in the sighted brain.

Previous research involving participants who lost sight early in life, but regained sight as adults (i.e. sight-recovery patients), has shown that blindness leads to source motion activation in area MT+ (Saenz et al. 2008). In our blind participants we cannot localize area MT+. Based on Saenz et al. (2008), however, one would predict that our blind participants, in contrast to our sighted participants, may recruit ‘visual’ areas for the processing of source motion. Consistent with this

26
hypothesis, centre-of-gravity coordinates for temporal-occipital ROIs did not differ between (sighted) vision areas and (blind) source areas, but they did differ between sighted (vision) and sighted (source) areas, and between (sighted) source and (blind) source areas.

Apart from investigating cross-modal responses, we also analysed the laterality of responses to source motion, and our data are consistent with previous findings about lateralization of source motion in the PT (Krumbholz et al. 2005b).

In sum, our current results with regard to the processing of auditory source motion and visual motion agree with previous data reported in the literature.

4.2. Independence of Echo-Motion and Source-Motion Processing

We found that temporal-occipital source-motion ROIs do not show a significant response towards echo-motion in any of the participants, and temporal-occipital echo-motion ROIs do not show a significant response to source-motion. Thus, echo- and source-motion ROIs in temporal-occipital cortex dissociate. This suggests that echo- and source-motion are processed in separate brain areas in temporal-occipital cortex. There was no double-dissociation in the PT. Since we obtained the same result in sighted novices and blind experts, this likely represents a general principle of echolocation processing in people, and suggests the existence of a neural specialization of areas in temporal-occipital cortex for echo-motion processing. When we compared centre-of-gravity coordinates between temporal-occipital echo- and source-motion areas, however, we did not find any significant location differences on the group level. Thus the functional separation of ROIs on the individual level did not translate into a spatial segregation on the group level. In a way, the finding of a functional dissociation is surprising because both source- and echo-motion signals are mediated through hearing. The shared activation in the PT is suggestive of shared aspects of sensory processing. For example, the PT is not just sensitive to auditory motion, but to auditory space in general (e.g. Arnott et al. 2004; Deouell et al. 2007). This shared aspect between the echo and source stimuli might be
mediated in the PT. The dissociation in temporal-occipital cortex could then be understood considering that source- and echo-motion may still be computed based on different acoustic signals. In our study we used azimuthal auditory motion, while radial distance remained constant. It follows that the distance dependent echo-pulse delay or the related repetition pitch, both of which are important aspects of radial echo-motion processing, are unlikely to be relevant in the context of our study. For source-motion, azimuthal motion of the sort we employed here is carried mainly through inter-aural timing differences (ITD) and inter-aural level differences (ILD) induced by the source sound itself. Binaural differences in spectrum (i.e. head shadow) also play a role, though this effect is much reduced as compared to ITD and ILD. Motion trajectories of the loudspeaker and the sound reflecting surface were the same. Thus, if one considers the echo by itself, the same changes in binaural cues would characterize both source- and echo-motion and thus not be a good basis for explaining the neural differences we observed. One could argue, however, that binaural echo-motion cues are different from binaural source-motion cues because the former include both click and echo (e.g. see Papadopoulos et al. 2011 for an analysis of binaural cues for human echolocation). Furthermore, there are spectral cues that participants could have used for processing of azimuthal echo-motion, but not source motion in our study, and that may be responsible for the difference in brain activity we observed. Specifically, the human mouth is not a perfectly omnidirectional sound emitter, and in particular high-frequency content drops off with increasing azimuth (e.g. Dunn and Farnsworth 1939). It follows that spectrum of echoes varies systematically with azimuth. Figure 7 illustrates this effect using waveplots and frequency spectra of echoes from a surface placed at 20° and 60° to the right with respect to straight ahead. As expected, the high frequency content of echoes reaching the right ear (i.e. echoes reaching the ear via direct path unimpeded by head-shadow) decreases as the surface moves away from the straight ahead. This source of information is absent in source-motion conditions. Therefore, these differences in cues are a good basis for explaining the neural differences we observed.
These differences in the cues used for echo- as compared to source-motion might also be used to explain performance differences between sighted novices and blind experts. Specifically, spatial information in echo-conditions is carried through the echo, which occurs in close temporal proximity to the click. Therefore, one potential reason for sighted participants’ inferior performance in our study might be that they have poorer temporal resolution as compared to the blind experts. In that case, sighted participants’ informative echo signal would be more ‘diluted’ by increased temporal smear with the uninformative click signal. Support for this idea comes from a study showing increased temporal resolution (as measured with evoked potentials) for successive clicks in blind people who were ‘good obstacle avoiders’ (i.e. blind people who supposedly used echolocation) as compared to sighted people (Arias, et al., 1993).

To the best of our knowledge, it has not yet been explicitly investigated in other echolocating species if source- and echo-motion are processed by the same neural circuits. This is the case even for bats, where there is considerable research on processing of static and dynamic aspects of both source sounds and echolocation sounds. Of particular relevance in the investigation of processing of dynamic source sound in bats is a study by Wilson and O’Neill (1998) investigating effects of auditory source motion on receptive fields in bat inferior colliculus. They found that receptive fields shifted with direction of motion, basically biasing localization towards direction of apparent motion. Though no direct comparison between echo-motion and source-motion was made, the authors suggested that source-motion-induced receptive field shifts might be part of a predictive hunting strategy where spatial information from echolocation is processed alongside spatial information from source sounds, suggesting perhaps some sort of parallel processing. Future research is needed to investigate these issues further.

In our study, the azimuth of the sound reflecting surface changed, but its radial distance remained constant. Our choice was influenced by the tradition to present azimuthal motion in the investigation of auditory source motion. In the investigation of echo-motion, motion presented along the radial axis, i.e. motion in depth, has received widespread attention. In the bat auditory
system, target distance and radial relative velocity are encoded by neurons sensitive to Doppler-shifted echoes, or specific pulse-echo delay combinations (e.g. Covey and Casseday 1999; Neuweiler et al. 1980; Riquimaroux et al. 1991; Wenstrup and Portfors 2011). It has also been suggested that even human listeners may be able to exploit changes in pulse-echo delay and/or repetition pitch in radial motion (Rosenblum et al. 2000). In sum, there are strong precedents for presenting echo-motion along a radial axis, but this aspect of echo-motion processing is left unexplored in the present study.

4.3. Neural Reorganization for Echo-Motion Processing in Blind Echolocation Experts

Behavioural data showed that blind and sighted participants performed equally well in the source task, but that blind echo experts performed better than sighted novices in the echo task. Temporal-occipital echo-motion ROIs were significantly larger in the blind experts than the sighted novices. Furthermore, the blind experts showed contralateral preference for processing of echo-motion in temporal-occipital cortex, and this was absent in the sighted novices. This pattern of results, in particular the laterality data, suggests that the echo-motion response in the blind experts may represent a reorganization rather than an exaggeration of the response observed in the sighted novices.

It could be argued that the contralateral bias that we observed reflects differences in spatial attention. Effects of attention on brain activity have been shown for both visual and auditory sensory cortices (Gandhi et al. 1999; Lipschutz et al. 2002; Petkov et al. 2004). Thus, although we cannot rule out this explanation, it would still be remarkable that all three echolocation experts show attentional modulation in a contralateral fashion for echo-motion.

Another issue to keep in mind is that even though sighted novices were able to perform the echolocation task significantly better than chance, they still made errors (Table 1). Accordingly, the functional echo-motion data from the sighted novices is ‘contaminated’ by inaccurate trials, which
may affect the laterality data. At the same time, however, laterality results in echo-motion ROIs, though not indicative of contralateral preference, are highly reliable and, in addition, strongly resemble those in source-motion ROIs. Furthermore, sighted and blind participants performed equally well in the source task. This suggests that lack of statistical power and/or behavioural performance may not be an issue in the context of the laterality analysis for echo-motion ROIs.

The question arises what the nature of the neural reorganization in blind echo experts is. We would argue that the contralateral preference of temporal-occipital echo-motion ROIs may signify the recruitment of visual pathways for the processing of echo-motion in the blind echolocation experts. We have found in previous research that blind echolocation experts have a relative increase in BOLD signal in occipital cortex (incl. calcarine cortex) during the presentation of echolocation sounds as compared to echo-less control sounds (Thaler et al. 2011). We have also shown that there may be a topographic representation of object shape in the calcarine cortex of an early blind echolocator (Arnott et al. 2013; Thaler et al. 2011). These data suggest that visual cortical areas are recruited for echolocation in blind experts.

In the current study, only B1 and B3 showed activity in posterior occipital/calcarine cortex during the presentation of echo-sounds (Figure 2). There are various potential explanations for this; for example, differences in B2’s visual experience before vision loss, differences in continuous use of echolocation (i.e. B2 temporarily stopped using echolocation in adulthood for health reasons) and/or neural plasticity in adulthood. Importantly, however, all three blind echolocation experts showed robust activity in temporal-occipital cortex for echo-motion (Figure 3, Table 2). This pattern of results in combination with B2’s high level of behavioural performance (Table 1) suggests that activity in calcarine cortex may play a task-dependent role for echolocation performance in the blind, and in particular that echo-motion processing might rely on activity in temporal-occipital cortex, rather than calcarine cortex.
In the current study, centre-of-gravity coordinates of temporal-occipital (blind) echo-motion ROIs did not differ significantly from those of (sighted) visual motion (i.e. MT+) ROIs. Furthermore, contralateral preference is considered a typical processing characteristic of visual motion area MT+ (e.g. Huk et al. 2002), and we found evidence for contralateral preference in temporal-occipital echo-motion ROIs in the blind experts. In combination with previous findings (Arnott et al. 2013; Thaler et al. 2011) the data suggest the involvement of visual cortical areas, and more specifically area MT+, in the processing of echo-motion in blind echolocation experts.

4.4. Effects of Blindness vs. Echolocation Expertise

As stated in the introduction, blind people are more sensitive to acoustic reverberations than sighted people, even when they do not consciously echolocate (Dufour et al. 2005; Kolarik et al. 2013). It was for this reason that we investigated echolocation processing in the blind at a uniformly high skill level in a sample of three blind echolocation experts. Below, we discuss potential implications this may have in the context of our study.

With regard to the independence of echo-motion and source-motion processing in temporal-occipital cortex we obtained the same result in sighted novices and blind experts. This suggests that neither blindness nor expertise play a role here, which is strong evidence for the idea that independence of echo-motion and source-motion processing in temporal-occipital cortex represents a general principle of echolocation processing in people.

With regard to the neural reorganization for echo-motion processing in blind echolocation experts, our data do not allow us to conclusively distinguish if this is due to either blindness or expertise, or both. As mentioned above, previous research has shown that blind people are generally more sensitive to acoustic reverberations (Dufour et al. 2005; Kolarik et al. 2013). This might suggest that blindness per se, rather than expertise, may drive the neural reorganization we observe. Consistent with this idea, we did not observe systematic relationships (i.e. correlations) between behavioural
performance in the echo-motion task and the degree of contra-laterality that was exhibited (i.e. the magnitude of the F-value for the interaction effect) in our sample of blind echolocation experts (also compare data for B1-B3 in Table 1 and Figure 5). We did also not find any evidence for such a relationship in our sample of sighted participants. At the same time, however, it is important to consider that the effects of blindness and echolocation expertise may never be fully dissociated, because - as stated above - blindness may always result in generally stronger reliance on sound echoes. In sum, our data suggest that the response to echo-motion in blind echolocation experts is the result of neural reorganization. Future research is needed to further investigate the roles that blindness and expertise play in this reorganization.

4.5. Left Lateralization

We observed that the contrast between moving and stationary source conditions was generally bigger for motion signals from left space (Fig.5). There was no difference in behavioural performance between left and right space conditions in our study. There is the possibility, however, that the left-lateralization we observed is related to superior motion processing in left space as measured with psychophysical methods (Hirnstein et al. 2007).

4.6. Conclusion

Our data suggest a functional segregation of processing of source- and echo-motion in human temporal-occipital cortex. Furthermore, when considered in combination with previous results, our data are consistent with the idea that the echo-motion response in the brains of blind echo-experts may be the result of neural reorganization involving visual cortical areas. Finally, the finding that we were able to define echo-motion areas in eight out of twelve sighted echo novices brains, suggests that echolocation may be more ingrained into the human perceptual capacities than previously
thought, and that this might be an inherent opportunity that the brains of blind echolocation experts can capitalize upon.

Acknowledgments

We thank Wolfgang Ferber, Juan Ruiz and Adam Shaible for their help in the conduction of this research. We thank Cristiana Cavina-Pratesi and Jason Connolly and two anonymous reviewers for comments on a previous version of this manuscript.

Grants

This work was supported by a grant from Durham University Neuroimaging Centre (LT).


Figure Legends

Figure 1 – Illustration of the experimental conditions. In each condition binaural recordings were made in the ears of participants B1 and B2. In echo conditions they made clicks while a sound-reflecting surface was present. In source conditions they remained silent while clicks were played through a loudspeaker. Recordings were made in an anechoic chamber. For more details see section ‘Materials and Methods’.

Figure 2 – Transverse slice views of sighted and blind participants BOLD activity in auditory and visual conditions superimposed on participants’ average brain. Talairach z-coordinates are indicated above each column. **Top row:** RFX Results for sighted participants (n=12) in visual and auditory conditions. **Middle row:** Results for blind participants (n=3) in auditory conditions. **Bottom row:** Results from sighted and blind participants superimposed. There were only three blind participants. Thus, to demonstrate consistency across blind participants, activity is shown in the form of probability maps (in percentage overlap) overlaid on participants’ average brain (Talairach space, left-is-left). One hundred percent overlap for a given voxel signifies that all three participants showed significant activity for this voxel. Probability maps are thresholded so that only those voxels are shown for which activity overlapped for at least two individual maps. This corresponds to a 66.7% overlap threshold for the blind sample. Map values between the lower threshold and 100% were obtained using linear interpolation. LGN: Lateral Geniculate Nucleus; Occ/Calc: Occipital cortex/Calcarine Cortex; HG/PT: Heschl’s gyrus/Planum temporale; PPC: Posterior Parietal Cortex; IPS: Intraparietal Sulcus; SPL: Superior Parietal Lobule.

Figure 3 – Illustration of Regions of Interest (ROIs) obtained for source and echo motion conditions in temporal-occipital cortex in three blind echolocation experts. ROIs are shown superimposed on each participant’s brain (Talairach space, left-is-left). The different panels correspond to different transverse slices, and Talairach z-coordinates are indicated above each panel. Details of individual ROI sizes and locations are reported in Table 2.

Figure 4 – Results of cross-modal analysis in source, vision and echo ROIs in the Planum Temporale (PT) and Temporal-Occipital Cortex (TOC). Coordinates and sizes of ROIs are summarized in Table 2. Bars indicate the average contrast value for beta weights in moving as compared to stationary conditions. Error bars indicate standard errors. Significance was determined using one-sample t-tests (two-tailed). For blind participants tests were computed for each individual separately based on the FX GLM results so that for each test df = 196. For sighted participants, tests were computed on the group level, so that for each test df = n-1. * = p <.05, ** = p < .01, *** = p < .005.

Figure 5 – Results of laterality analysis in source and echo ROIs in the Planum Temporale (PT) and Temporal-Occipital Cortex (TOC). ROI details are summarized in Table 2. Bars indicate the average normalized beta value for moving as compared to stationary conditions. For blind participants B1-B3 error bars indicate variances. For sighted participants error bars indicate standard errors of the mean, and small inset bars denote the average difference between left and right space conditions within each ROI. ANOVA results are summarized to the right of each panel. Data of blind participants B1-B3 were analyzed for each individual separately using factorial ANOVA, where the degrees of freedom for the effect and error terms were 1 and 156, respectively, for all tests. Significance between left and right-space conditions within ROIs was determined using independent samples t-tests (two-tailed, df=78). Data of sighted participants were analyzed on the group level using repeated measures ANOVA. The group analysis could only be conducted for those participants who had echo and/or source ROIs in both hemispheres, which is why numbers of subjects differ across analysis. Sp = Main Effect of Space; HS = main effect of hemisphere; Sp x HS = Interaction effect, * = p <.05, ** = p < .01, *** = p < .005.
Figure 6 – Results of secondary laterality analysis in source and echo ROIs in the Planum Temporale (PT) and Temporal-Occipital Cortex (TOC). The analysis shown here was computed based on the average normalized beta value in moving conditions. In contrast, the laterality analysis shown in Fig.5 was computed based on the average normalized beta value in moving as compared to stationary conditions. For blind participants B1-B3 error bars indicate variances. For sighted participants error bars indicate standard errors of the mean, and small inset bars denote the average difference between left and right space conditions within each ROI. ANOVA results are summarized to the right of each panel. Data of blind participants B1-B3 were analyzed for each individual separately using factorial ANOVA, where the degrees of freedom for the effect and error terms were 1 and 156, respectively, for all tests. Significance between left and right-space conditions within ROIs was determined using independent samples t-tests (two-tailed, df=78). Data of sighted participants were analyzed on the group level using repeated measures ANOVA. The group analysis could only be conducted for those participants who had echo and/or source ROIs in both hemispheres, which is why numbers of subjects differ across analysis. Sp = Main Effect of Space; HS = main effect of hemisphere; Sp x HS = Interaction effect, * = p < .05, ** = p < .01, *** = p < .005.

Figure 7 – Illustration of the effects of azimuth on level and spectrum of sound echoes. Waveform plots (top) and frequency spectra (bottom) of click and echoes for binaural recordings made in the presence of a sound reflecting surface at 20° or 60° to the right of straight ahead (compare Figure 1). High-frequency content of echoes is reduced in 60° as compared to 20° conditions. Frequency content of clicks is similar in the two conditions. The headphones used in our experiment only went up to 10 kHz. Parts of the spectrum not audible in our experiment are greyed out.
Table 1 — Summary of participants’ behavioural performance (percentage correct) in all conditions. For sighted participants we report the mean and standard deviation (in parentheses) across subjects. Sound recordings had been made with B1 and B2. Thus, for B1 and B2 we also analyzed how they performed when listening to their own or to the other person’s sounds. For more performance details please see ‘Results’. For more details about participants (e.g. case histories) please see ‘Participants’.

<table>
<thead>
<tr>
<th>Source</th>
<th>Echo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Sighted (n=12)</td>
<td></td>
</tr>
<tr>
<td>93.5% (7.2)</td>
<td>50.9% (17.3)</td>
</tr>
<tr>
<td>Left: 92 (7.4)</td>
<td>Left: 52.1 (17.7)</td>
</tr>
<tr>
<td>Right: 95.1 (8)</td>
<td>Right: 49.6 (17.9)</td>
</tr>
<tr>
<td>Moving: 91.3 (11)</td>
<td>Moving: 47.3 (18.7)</td>
</tr>
<tr>
<td>Stationary: 95.7 (4.7)</td>
<td>Stationary: 54.5 (17.5)</td>
</tr>
<tr>
<td>B1 (Glaucoma)</td>
<td></td>
</tr>
<tr>
<td>96.9%</td>
<td>96.3%</td>
</tr>
<tr>
<td>Self (n=80): 96.3</td>
<td>Self (n=80): 95.0</td>
</tr>
<tr>
<td>Other (n=80): 97.6</td>
<td>Other (n=80): 97.6</td>
</tr>
<tr>
<td>$\chi^2(1,155) = .006; p = .936$</td>
<td>$\chi^2(1,154) = .026; p=.872$</td>
</tr>
<tr>
<td>Left (n=80): 96.3</td>
<td>Left (n=80): 98.8</td>
</tr>
<tr>
<td>Right (n=80): 97.6</td>
<td>Right (n=80): 93.8</td>
</tr>
<tr>
<td>$\chi^2(1,155) = .006; p = .936$</td>
<td>$\chi^2(1,154) = .104; p = .747$</td>
</tr>
<tr>
<td>Moving (n=80): 97.6</td>
<td>Moving (n=80): 93.8</td>
</tr>
<tr>
<td>Stationary (n=80): 96.3</td>
<td>Stationary (n=80): 98.8</td>
</tr>
<tr>
<td>$\chi^2(1,155) = .006; p = .936$</td>
<td>$\chi^2(1,154) = .104; p = .747$</td>
</tr>
<tr>
<td>B2 (Retinopathy of Prematurity)</td>
<td></td>
</tr>
<tr>
<td>99.4%</td>
<td>98.8%</td>
</tr>
<tr>
<td>Self (n=80): 100</td>
<td>Self (n=80): 97.6</td>
</tr>
<tr>
<td>Other (n=80): 98.8</td>
<td>Other (n=80): 100</td>
</tr>
<tr>
<td>$\chi^2(1,159) = .006; p = .937$</td>
<td>$\chi^2(1,158) = .025; p = .874$</td>
</tr>
<tr>
<td>Left (n=80): 98.8</td>
<td>Left (n=80): 100</td>
</tr>
<tr>
<td>Right (n=80): 100</td>
<td>Right (n=80): 97.6</td>
</tr>
<tr>
<td>$\chi^2(1,159) = .006; p = .937$</td>
<td>$\chi^2(1,158) = .025; p = .874$</td>
</tr>
<tr>
<td>Moving (n=80): 100</td>
<td>Moving (n=80): 100</td>
</tr>
<tr>
<td>Stationary (n=80): 98.8</td>
<td>Stationary (n=80): 97.6</td>
</tr>
<tr>
<td>$\chi^2(1,159) = .006; p = .937$</td>
<td>$\chi^2(1,158) = .025; p = .874$</td>
</tr>
<tr>
<td>B3 (Retinoblastoma)</td>
<td></td>
</tr>
<tr>
<td>96.3%</td>
<td>82.5%</td>
</tr>
<tr>
<td>Left (n=80): 93.8</td>
<td>Left (n=80): 90</td>
</tr>
<tr>
<td>Right (n=80): 98.8</td>
<td>Right (n=80): 75</td>
</tr>
<tr>
<td>$\chi^2(1,154) = .104; p = .747$</td>
<td>$\chi^2(1,132) = 1.091; p = .296$</td>
</tr>
<tr>
<td>Moving (n=80): 92.5</td>
<td>Moving (n=80): 80</td>
</tr>
<tr>
<td>Stationary (n=80): 100</td>
<td>Stationary (n=80): 85</td>
</tr>
<tr>
<td>$\chi^2(1,154) = .234; p = .629$</td>
<td>$\chi^2(1,132) = .121; p = .728$</td>
</tr>
</tbody>
</table>
Table 2 – Centre-of-gravity coordinates (Talairach Space) and sizes of regions of interest (ROIs) for source motion, echo motion and visual conditions in Temporal-Occipital Cortex (TOC) and the Planum Temporale (PT). For sighted subjects (Ss) we report means and SD (in Parentheses) computed across individual subject ROIs. For sighted subjects ROIs could not be defined for all subjects and hemispheres in echo and source conditions at the defined statistical threshold. Thus, the number of ROIs used to compute group statistics (n) are provided. For visual motion conditions we report statistics for TOC ROIs defined at p<.05 and defined at p<.05 (Bonferroni corrected). Diagonal lines indicate that participants did not take part in that experimental condition. Data for EB and LB were collected in Thaler et al. (2011) and are shown for comparison only.
<table>
<thead>
<tr>
<th></th>
<th>TOC Source ROIs (p&lt;.05)</th>
<th>TOC Echo ROIs (p&lt;.05)</th>
<th>TOC Vision ROIs (p&lt;.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#vox x y z</td>
<td>#vox x y z</td>
<td>#vox x y z</td>
</tr>
<tr>
<td>Ss</td>
<td>LH (n=9)</td>
<td>LH (n=6)</td>
<td>LH (n=12)</td>
</tr>
<tr>
<td></td>
<td>408 (315)</td>
<td>90 (100)</td>
<td>7461 (2692)</td>
</tr>
<tr>
<td></td>
<td>-46 (3.2)</td>
<td>-45 (6.9)</td>
<td>-41 (3.9)</td>
</tr>
<tr>
<td></td>
<td>-60 (9.5)</td>
<td>-57 (10.6)</td>
<td>-68 (7.6)</td>
</tr>
<tr>
<td></td>
<td>7 (6)</td>
<td>6 (5.8)</td>
<td>3 (6.5)</td>
</tr>
<tr>
<td></td>
<td>RH (n=9)</td>
<td>RH (n=7)</td>
<td>RH (n=12)</td>
</tr>
<tr>
<td></td>
<td>472 (673)</td>
<td>99 (80)</td>
<td>6257 (2408)</td>
</tr>
<tr>
<td></td>
<td>50 (4.7)</td>
<td>47 (5.4)</td>
<td>43 (4.4)</td>
</tr>
<tr>
<td></td>
<td>-57 (6.1)</td>
<td>-55 (4.4)</td>
<td>-66 (7.7)</td>
</tr>
<tr>
<td></td>
<td>6 (5.2)</td>
<td>9 (2.7)</td>
<td>5 (5)</td>
</tr>
<tr>
<td></td>
<td>LH (n=6)</td>
<td>RH (n=10)</td>
<td>RH (n=12)</td>
</tr>
<tr>
<td></td>
<td>408 (315)</td>
<td>90 (100)</td>
<td>7461 (2692)</td>
</tr>
<tr>
<td></td>
<td>-46 (3.2)</td>
<td>-45 (6.9)</td>
<td>-41 (3.9)</td>
</tr>
<tr>
<td></td>
<td>-60 (9.5)</td>
<td>-57 (10.6)</td>
<td>-68 (7.6)</td>
</tr>
<tr>
<td></td>
<td>7 (6)</td>
<td>6 (5.8)</td>
<td>3 (6.5)</td>
</tr>
<tr>
<td></td>
<td>RH (n=9)</td>
<td>RH (n=7)</td>
<td>RH (n=12)</td>
</tr>
<tr>
<td></td>
<td>472 (673)</td>
<td>99 (80)</td>
<td>6257 (2408)</td>
</tr>
<tr>
<td></td>
<td>50 (4.7)</td>
<td>47 (5.4)</td>
<td>43 (4.4)</td>
</tr>
<tr>
<td></td>
<td>-57 (6.1)</td>
<td>-55 (4.4)</td>
<td>-66 (7.7)</td>
</tr>
<tr>
<td></td>
<td>6 (5.2)</td>
<td>9 (2.7)</td>
<td>5 (5)</td>
</tr>
</tbody>
</table>

B1 LH  128  -45 -60 -3  487  -35 -74 -1

RH  1151  38 -65 0  342  47 -77 3


RH  79  42 -67 6  424  49 -65 4

B3 LH  2449 -42 -59 7  389 -41 47 11

RH  1701  45 -62 -1  1391  53 -52 14

EB LH  1030  -49 -54 9

RH  678  47 -57 6

LB LH  622  -53 -55 2

RH  517  -47 -59 9

PT Source ROIs (p<.05)                   PT Echo ROIs (p<.05)                   PT Vision ROIs (p<.05)

<table>
<thead>
<tr>
<th></th>
<th>#vox x y z</th>
<th>#vox x y z</th>
<th>#vox x y z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ss</td>
<td>LH (n=12)</td>
<td>LH (n=9)</td>
<td>LH (n=12)</td>
</tr>
<tr>
<td></td>
<td>572 (625)</td>
<td>202 (319.7)</td>
<td>1822 (1781)</td>
</tr>
<tr>
<td></td>
<td>-53 (5.8)</td>
<td>-46 (7)</td>
<td>-50 (5.2)</td>
</tr>
<tr>
<td></td>
<td>-31 (7.1)</td>
<td>-36 (6.2)</td>
<td>-36 (5.3)</td>
</tr>
<tr>
<td></td>
<td>12 (4.5)</td>
<td>15 (3.3)</td>
<td>17 (4)</td>
</tr>
<tr>
<td></td>
<td>RH (n=11)</td>
<td>RH (n=12)</td>
<td>RH (n=11)</td>
</tr>
<tr>
<td></td>
<td>872 (964)</td>
<td>294 (472)</td>
<td>1688 (1512)</td>
</tr>
<tr>
<td></td>
<td>56 (3.6)</td>
<td>57 (6.1)</td>
<td>54 (6.3)</td>
</tr>
<tr>
<td></td>
<td>-30 (8.5)</td>
<td>-32 (6.3)</td>
<td>-33 (6.7)</td>
</tr>
<tr>
<td></td>
<td>13 (3.6)</td>
<td>14 (5)</td>
<td>18 (4.3)</td>
</tr>
</tbody>
</table>

B1 LH  464 -48 -24 -9  34 -49 -28 13

RH  281  47 -31 10  60  62 -31 17

B2 LH  399 -53 -28 11  604 -50 -36 17

RH  274  57 -30 10  104  47 -42 15

B3 LH  1074 -52 -27 14  79 -52 -31 14

RH  855  57 -34 16  727  60 -31 18