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Research Paper

Contralateral routing of signals disrupts monaural level and spectral cues to sound localisation on the horizontal plane

Adam J. Pedley [a], Pádraig T. Kitterick [b, c, *]

[a] Medical Research Council, Institute of Hearing Research, The University of Nottingham, University Park, NG7 2RD, UK
[b] NIHR Nottingham Biomedical Research Centre, Ropewalk House, 113 The Ropewalk, Nottingham, NG1 5DU, UK
[c] Otology and Hearing Group, Division of Clinical Neuroscience, School of Medicine, University of Nottingham, Nottingham, NG7 2UH, UK

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ABSTRACT

Objectives: Contra-lateral routing of signals (CROS) devices re-route sound between the deaf and hearing ears of unilaterally-deaf individuals. This rerouting would be expected to disrupt access to monaural level cues that can support monaural localisation in the horizontal plane. However, such a detrimental effect has not been confirmed by clinical studies of CROS use. The present study aimed to exercise strict experimental control over the availability of monaural cues to localisation in the horizontal plane and the fitting of the CROS device to assess whether signal routing can impair the ability to locate sources of sound and, if so, whether CROS selectively disrupts monaural level or spectral cues to horizontal location, or both.

Design: Unilateral deafness and CROS device use were simulated in twelve normal hearing participants. Monaural recordings of broadband white noise presented from three spatial locations ($-60°$, $0°$, and $+60°$) were made in the ear canal of a model listener using a probe microphone with and without a CROS device. The recordings were presented to participants via an insert earphone placed in their right ear. The recordings were processed to disrupt either monaural level or spectral cues to horizontal sound location by roving presentation level or the energy across adjacent frequency bands, respectively. Localisation ability was assessed using a three-alternative forced-choice spatial discrimination task.

Results: Participants localised above chance levels in all conditions. Spatial discrimination accuracy was poorer when participants only had access to monaural spectral cues compared to when monaural level cues were available. CROS use impaired localisation significantly regardless of whether level or spectral cues were available. For both cues, signal re-routing had a detrimental effect on the ability to localise sounds originating from the side of the deaf ear ($-60°$). CROS use also impaired the ability to use level cues to localise sounds originating from straight ahead ($0°$).

Conclusions: The re-routing of sounds can restrict access to the monaural cues that provide a basis for determining sound location in the horizontal plane. Perhaps encouragingly, the results suggest that both monaural level and spectral cues may not be disrupted entirely by signal re-routing and that it may still be possible to reliably identify sounds originating on the hearing side.

1. Introduction

Individuals who have access to hearing in one ear only, such as those with single-sided deafness (SSD), do not have access to the binaural cues that facilitate accurate localisation in the horizontal plane (Moore, 2012) and therefore display severely-impaired spatial hearing abilities (Colburn, 1982; Slattery and Middlebrooks, 1994). The acoustic diffraction of sound by the head ('head-shadow effect') can provide a basis for relatively crude judgements about the location of a sound based on its level when listening monaurally. Studies have also suggested that some monaural listeners adapt to use the effects of the outer ears (pinnae) on incoming sounds that are primarily a cue to vertical elevation (Wightman and Kistler, 1997) to distinguish sounds from

* Corresponding author. NIHR Nottingham Biomedical Research Centre, Ropewalk House, 113 The Ropewalk, Nottingham, NG1 5DU, UK.
E-mail addresses: adam.pedley@nottingham.ac.uk (A.J. Pedley), padraig.kitterick@nottingham.ac.uk (P.T. Kitterick).

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different locations in the horizontal plane (Shub et al., 2008; Kumpik et al., 2010; Rothpletz et al., 2012). However, even with the use of these cues their localisation abilities remain severely-impaired relative to binaural listeners (Humes et al., 1980; Wazen et al., 2005). Substantial inter-individual variability in monaural localisation ability has been observed (van Wanrooij and van Opstal, 2004) that may relate to the presence of high-frequency hearing loss in the remaining ear (Agterberg et al., 2014).

A common audiological intervention for those with SSD is a Contralateral Routing Of Signals (CROS) hearing aid (Harford and Barry, 1965; Kitterick et al., 2014). A CROS aid comprises two hearing aid-like devices. One aid is worn on the non-hearing ear and acts as a satellite microphone for the second aid worn on the hearing ear. The acoustic coupling of this second aid is selected to be as transparent as possible to minimise occlusion of the hearing ear. The aim of this re-routing of acoustic information is to provide the listener with greater access to sound by overcoming the head shadow effect, and in doing so to aid the ability to understand speech in background noise (Hol et al., 2005). However, because the process of fitting a CROS aid attempts to minimise any differences in the acoustic signature of sounds located towards the non-hearing and hearing ears (Pumford, 2005), it possible that a well-fit CROS aid could severely restrict the availability of monaural level and spectral cues. However, empirical research does not support this conclusion.

Systematic reviews have identified six studies that have evaluated the impact of CROS use on localisation in the horizontal plane (Peters et al., 2015; Kitterick2016). Five of the six studies found no difference in localisation performance between monaural and CROS listening configurations (Arndt et al., 2011; Bosman et al., 2003; Hol et al., 2005; Hol et al., 2010; Niparko et al., 2003). However, their small sample sizes limited their statistical power to detect changes in localisation (Kitterick et al., 2016). Only one study found that the localisation abilities of CROS device users were significantly worse than those of monaural listeners (Lin et al., 2006). No study has differentiated between the effects of CROS on level or spectral cues. The conflicting nature of this evidence and the use of inconsistent methods for assessing localisation means that it is not possible to conclude whether CROS use impairs localisation ability or not (Kitterick et al., 2016).

As individuals with SSD rate spatial hearing as one of the most important listening skills that they would like to improve (McLeod et al., 2008), the current study aimed to resolve the question of whether CROS use affects localisation in the horizontal plane and if so, whether it disrupts the use of monaural level and spectral cues, or both. Although previous studies have demonstrated that acute effects of monaural listening on localisation can be induced by occluding one ear of normal hearing participants (McPartland et al., 1997; Kumpik et al., 2010; van Wanrooij and van Opstal, 2004; Irving and Moore, 2011), the current study used monaural recordings to simulate unilateral deafness to exercise precise experimental control over the CROS fitting methodology and to minimise individual variability in high-frequency hearing thresholds that could influence access to spectral cues (Agterberg et al., 2014). It was hypothesised that: 1) with training, participants would be able to discriminate sounds from three spatially-separated locations using both monaural level cues and spectral cues; 2) by eliminating any variability in CROS fitting across participants and by ensuring the sample size was sufficiently large to achieve adequate statistical power it would be possible to demonstrate that CROS use disrupts the availability of these monaural cues and can degrade localisation performance; 3) CROS-related effects would only occur when the device was switched on as they arise due to the re-routing of signals rather than any occlusion of the hearing ear.

2. Methods and materials

2.1. Sample size

The required sample size was determined based on an *a priori* power analysis conducted using the G*Power software (Faul et al., 2007). Pilot testing with four participants suggested that the size of the effect of CROS use on monaural localisation accuracy was 1.25 standard deviations based on the specific spatial discrimination task used in the present study. To detect an effect of this size with 95% power and at $\alpha = 0.05$ using a paired-sample *t*-test would require 9 participants. To account for attrition across three testing sessions, 12 participants were recruited to allow for a 25% drop-out rate whilst still achieving the desired statistical power.

2.2. Participants

Twelve normal-hearing adults (mean age 21.6 years, range 19–24 years) were recruited to participate. All participants reported no history of hearing problems and had pure-tone average thresholds ≤20 dB Hearing Level (HL) bilaterally, averaged across octave frequencies from 125 to 8000 Hz inclusive (mean threshold 7.2 dB HL, range 1.4–11.8). Participants received financial compensation for their participation. The study received ethical approval from the School of Psychology, University of Nottingham and all participants gave informed consent prior to data collection.

2.3. Stimuli recordings

Monaural recordings were made of broadband noises presented from loudspeakers located at −60°, 0°, and +60° azimuth in an anechoic chamber, where negative angles denote locations to the left of straight ahead. The noises were generated using the Matlab software package (Mathworks, Natick MA) by generating 20-sec long samples of Gaussian-distributed random noise, calculating their fast Fourier transform (FFT), setting the amplitude of components lower than 200 Hz and above 12 kHz to zero, and finally calculating the inverse FFT. This specific range of frequencies was chosen as it represented the bandwidth over which it was possible to exercise control over the output of the loudspeakers in order to achieve a flat frequency response at the listening position (Seeber et al., 2010). A pre-emphasis filter was generated for each loudspeaker by recording Maximum-Length Sequences (MLS) (Rife and Vanderkooy, 1989) at the listening position; i.e. at the point equidistant from the three loudspeakers. The filters not only ensured a flat frequency response but also equalised the output levels of the loudspeakers and synchronised the arrival times of the first wavefronts at the listening position. The pre-emphasised noises were presented using an external audio interface (MOTU 24I/O) and power amplifiers (RA150, Alesis).

Recordings of the noise stimuli were made in the right ear canal of a model listener using a probe tube microphone (Etymotic Research Inc. ER-7C Series B Clinical Probe Tube Microphone System) while they sat at the listening position. Therefore, the three spatial locations (−60°, 0°, and +60°) corresponded to the deaf side, the centre, and the hearing side, respectively. The microphone body was secured using a headband and the probe tube was inserted so that its tip was between 15 and 20 mm from the entrance of the right ear canal. The signals were high-pass filtered (3-pole Butterworth filter with −1–dB cut-off at 20 Hz) and amplified (+40 dB gain) using a battery-powered pre-amplifier (G.R.A.S. 12AK 1-Channel Power Module). The conditioned signals were sampled at 44.1 kHz with 16-bit quantization using the same external audio interface.

Three sets of monaural recordings were made. 'Unaided'

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