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Delayed access to bilateral input alters cortical organization in children with asymmetric hearing

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ABSTRACT

Bilateral hearing in early development protects auditory cortices from reorganizing to prefer the better ear. Yet, such protection could be disrupted by mismatched bilateral input in children with asymmetric hearing who require electric stimulation of the auditory nerve from a cochlear implant in their deaf ear and amplified acoustic sound from a hearing aid in their better ear (bimodal hearing). Cortical responses to bimodal stimulation were measured by electroencephalography in 34 bimodal users and 16 age-matched peers with normal hearing, and compared with the same measures previously reported for 28 age-matched bilateral implant users. Both auditory cortices increasingly favoured the better ear with delay to implanting the deaf ear; the time course mirrored that occurring with delay to bilateral implantation in unilateral implant users. Preference for the implanted ear tended to occur with ongoing implant use when hearing was poor in the non-implanted ear. Speech perception deteriorated with longer deprivation and poorer access to high-frequencies. Thus, cortical preference develops in children with asymmetric hearing but can be avoided by early provision of balanced bimodal stimulation. Although electric and acoustic stimulation differ, these inputs can work sympathetically when used bilaterally given sufficient hearing in the non-implanted ear.

1. Introduction

Children who have one deaf ear with better hearing in their other ear are at risk for unilateral listening and abnormal cortical development because they are not candidates for cochlear implantation using standard criteria (Cadieux et al., 2013). Yet, the most effective treatment for each ear should be provided to children with hearing loss (Gordon et al., 2015). Whereas symmetric hearing loss can be treated with similar devices in each ear (two cochlear implant (CIs) for severe/profound deafness or two hearing aids (HAs) for less severe hearing impairments), children with asymmetric hearing loss may require electrical stimulation of the deaf ear with a CI and amplified acoustic sound through a HA in the better ear (Arndt et al., 2015; Cadieux et al., 2013; Ramos Macias et al., 2016). It is not clear, however, that this bimodal input (electrical CI in one ear and acoustic HA in the other) can be combined to limit unilaterally driven reorganization or promote binaural/spatial hearing in children. The concern is that electrical CI hearing completely differs from listening to amplified sound through a HA and thus could provide unbalanced or even conflicting bilateral access to sound. To test this clinical recommendation, we asked: 1) can bilateral cortical development be protected in children with asymmetric hearing loss through bimodal hearing; and 2) what factors prevent expected cortical development in children provided with bimodal hearing? We hypothesized that bimodal stimulation with limited delay restricts cortical reorganization underlying preference of one ear by providing bilateral access to sound.

Young children with asymmetric hearing loss have impaired access to bilateral sound and are at risk of developing poor sound localization and speech detection in noise (Gordon et al., 2014; Litovsky et al., 2010), as well as social, educational and language deficits (Kuppler et al., 2013; Lieu et al., 2010, 2013). These hearing difficulties and associated challenges likely reflect cortical reorganization with prolonged unilateral hearing. In children with congenital bilateral deafness, early hearing through one CI for > 2 years increases activity in the contralateral auditory cortex (Gordon et al., 2013b; Jiwani et al., 2016) and both left and right auditory cortices develop an abnormal

Abbreviations: CI, cochlear implant; HA, hearing aid; FDR, false discovery rate; BEM, boundary element model; MNI, Montreal Neurologic Institute; MRI, magnetic resonance imaging; EEG, electroencephalography; SD, standard deviations; SE, standard errors

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Table 1
Bimodal group mean ± SD demographic information and categorization by principal component analysis (PCA). Shaded regions and bolded text denote which variables significantly load to the component (factor loading > 0.3).

Variable	Left CI/right HA (n = 17)	Left HA/right CI (n = 17)	Statistics	PCA: Pattern matrix			PCA: Score coefficient matrix		
				Pre-CI		Post-CI	Pre-CI		Post-CI
				Deafness	Hearing	Hearing	Deafness	Hearing	Hearing
Duration of unilateral deafness (years)	1.2 ± 2.3	0.8 ± 0.7	$t_{(18.8)} = 0.8$, $P = 0.44$	**0.96**	−0.06	0.00	**0.47**	−0.03	−0.01
Duration of asymmetric hearing (years)	1.7 ± 2.3	1.0 ± 0.9	$t_{(21.1)} = 1.1$, $P = 0.27$	**0.97**	0.10	0.03	**0.47**	0.03	0.01
Unaided hearing loss in CI ear (dB HL)	98.4 ± 23.5	105.2 ± 19.6	$t_{(31.0)} = -0.9$, $P = 0.37$	**0.33**	**−0.75**	−0.01	**0.16**	**−0.30**	−0.02
Duration of HA use pre-CI (years)	3.2 ± 1.9	1.9 ± 1.0	$t_{(24.9)} = 2.4$, $P = 0.02$	0.03	**0.90**	−0.15	0.01	**0.35**	−0.08
Age implanted (years)	4.7 ± 2.6	3.0 ± 2.1	$t_{(30.7)} = 2.1$, $P = 0.05$	0.29	**0.88**	−0.01	0.13	**0.34**	0.00
Asymmetry in bimodal hearing (dB) (CI-HA)	7.8 ± 7.1	5.8 ± 7.3	$t_{(29.3)} = 0.8$, $P = 0.42$	−0.05	**0.53**	**0.55**	−0.03	**0.21**	**0.34**
Unaided hearing loss in HA ear (dB HL)	62.5 ± 19.9	71.7 ± 17.9	$t_{(31.7)} = -1.4$, $P = 0.17$	0.01	0.08	**0.85**	−0.01	0.04	**0.52**
Duration of CI use (years)	1.9 ± 1.3	3.4 ± 3.4	$t_{(20.5)} = -1.8$, $P = 0.090.05$		−0.34	**0.78**	0.02	−0.13	**0.47**

CI = cochlear implant; HA = hearing aid.

preference for stimulation from the hearing ear (Gordon et al., 2013b). These effects are consistent with abnormal strengthening of uncrossed pathways from the stimulated ear in unilaterally hearing cats with congenital deafness (Kral et al., 2013a, 2013b; Tillein et al., 2016). Importantly, cortical representation of the stimulated ear in children increases with delay to bilateral implantation and persists despite several years of bilateral CI use (Gordon et al., 2013b). Unilateral deprivation also reorganizes cortical networks involved in attention and executive functioning (Tibbetts et al., 2011; Wang et al., 2014; Yang et al., 2014). Given that impairments in these networks correlate with educational outcomes (Rachakonda et al., 2014), and that bilateral hearing is important for social and educational development (Lieu et al., 2013), it makes sense to avoid cortical reorganization resulting from unilateral hearing in children.

Treating asymmetric hearing loss with bimodal devices may restore bilateral access to sound, but it remains unclear how the two very different signals are processed and integrated in the cortex. Contributions from the CI could disrupt information from the better hearing ear. Sound frequencies are more poorly translated by CIs than by HAs to the auditory pathways which impairs CI users' perception of pitch and music (Gfeller et al., 2002, 2012; Hopyan et al., 2012; Limb and Rubinstein, 2012; Polonenko et al., 2017), and emotion in speech and music (Giannantonio et al., 2015; Hopyan et al., 2016; Volkova et al., 2013). On the other hand, acoustic stimulation of the non-implanted ear might be limited by deterioration of the cochleae and/or auditory neurons, affecting auditory nerve stimulation (reviewed by Korver et al., 2017). Moreover, HAs often are not capable of providing enough amplification to the basal cochlea (Stelmachowicz et al., 2004) which is the cochlear region often most affected in individuals with hearing loss (Pittman and Stelmachowicz, 2003). In addition, bimodal hearing could also be detrimental for binaural/spatial hearing by introducing large asymmetries in timing of input between the ears (direct CI stimulation of the auditory nerve is ~1.5 ms faster than acoustic input) (Polonenko et al., 2015; Zirn et al., 2015) and large mismatches in inter-aural place of stimulation which potentially compromise integration/fusion of bilateral input (Landsberger et al., 2015; Reiss et al., 2014).

To evaluate the potential benefits and limitations of bimodal hearing for bilateral auditory development, we examined cortical activity and functional outcomes in children with asymmetric hearing loss who use bimodal devices. The present findings demonstrate that bimodal stimulation can promote typical cortical activity when: 1) delay to implantation is limited and 2) bilateral access to sound through the HA and CI is balanced. When these conditions are not met, prolonged asymmetric hearing restructures auditory cortices, creating a preference for the better hearing ear. Speech perception skills depended on access to high-frequency information in each ear independently rather than on broadband-evoked aural preference measures.

2. Materials and methods

Parental/guardian written informed consent and child assent were obtained under study protocol #100000294 approved by the Hospital for Sick Children Research Ethics Board.

2.1. Participants

Sample size calculations for sufficient power ($1 - \beta \geq 0.8$, $\alpha = 0.05$) were completed a priori using G*Power v3.1.7 software (Faul et al., 2007), based on partial eta-squared values estimated from previous work (Gordon et al., 2013b, 2010). Accordingly, 50 children aged 1.3–12.9 years were recruited: 34 bimodal users (mean ± SD: 6.8 ± 3.2 years old) who wore both devices for > 6 months and 16 peers with normal hearing (6.4 ± 3.5 years old). Audiometric