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Review article

Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications

Hannah Glick, Anu Sharma*

Department of Speech, Language, & Hearing Science; Institute of Cognitive Science, University of Colorado at Boulder, 2501 Kittredge Loop Road, 409 UCB, Boulder, CO 80309, USA

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ABSTRACT

This review explores cross-modal cortical plasticity as a result of auditory deprivation in populations with hearing loss across the age spectrum, from development to adulthood. Cross-modal plasticity refers to the phenomenon when deprivation in one sensory modality (e.g. the auditory modality as in deafness or hearing loss) results in the recruitment of cortical resources of the deprived modality by intact sensory modalities (e.g. visual or somatosensory systems). We discuss recruitment of auditory cortical resources for visual and somatosensory processing in deafness and in lesser degrees of hearing loss. We describe developmental cross-modal re-organization in the context of congenital or pre-lingual deafness in childhood and in the context of adult-onset, age-related hearing loss, with a focus on how cross-modal plasticity relates to clinical outcomes. We provide both single-subject and group-level evidence of cross-modal re-organization by the visual and somatosensory systems in bilateral, congenital deafness, single-sided deafness, adults with early-stage, mild-moderate hearing loss, and individual adult and pediatric patients exhibit excellent and average speech perception with hearing aids and cochlear implants. We discuss a framework in which changes in cortical resource allocation secondary to hearing loss results in decreased intra-modal plasticity in auditory cortex, accompanied by increased cross-modal recruitment of auditory cortices by the other sensory systems, and simultaneous compensatory activation of frontal cortices. The frontal cortices, as we will discuss, play an important role in mediating cognitive compensation in hearing loss. Given the wide range of variability in behavioral performance following audiological intervention, changes in cortical plasticity may play a valuable role in the prediction of clinical outcomes following intervention. Further, the development of new technologies and rehabilitation strategies that incorporate brain-based biomarkers may help better serve hearing impaired populations across the lifespan.

Contents

Abbreviations: CI, Cochlear implant, cochlear implantation; CAEPs, Cortical auditory evoked potentials; CVEPs, Cortical visual evoked potentials; CSSEPs, Cortical somatosensory evoked potentials; SSD, Single-sided deafness

* Corresponding author.
E-mail address: anu.sharma@colorado.edu (A. Sharma).

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1. Introduction

The human cortex demonstrates an exquisite capacity for neuroplasticity over the course of the lifespan, capable of adapting to intrinsic and extrinsic forces during development and adulthood, to alterations in sensory input, insult, injury, and learning. Cross-modal plasticity is one such form of cortical neuroplasticity. Cross-modal plasticity can occur as a result of decreased or abnormal sensory input, whereby cortical regions of the deprived modality become vulnerable to the recruitment by the remaining, intact sensory modalities. Intra-modal plasticity is another form of cortical plasticity, whereby brain changes are induced within a particular cortical area as a result of increased or decreased input to that sensory system. Auditory deprivation, as in hearing loss or deafness, may result in cortical cross-modal plasticity, whereby the auditory cortex is recruited for visual or somatosensory processing (Allman et al., 2009; Buckley and Tobey, 2010; Campbell and Sharma, 2016, 2014; Chen et al., 2016; Doucet et al., 2006; Finney et al., 2003; Finney, 2001; Gilley et al., 2008; Giraud and Lee, 2007; Giraud et al., 2001; Kim et al., 2016; Lee et al., 2007; Levänen and Hamdorf, 2001; Meredith and Lomber, 2011; Sharma et al., 2016, 2015; Stropahl et al., 2015). Similar phenomena are well documented in the visual neuroscience literature, in which blindness results in the recruitment of visual cortex for somatosensory (vibrotactile) and auditory processing (see Lazzouni and Lepore, 2014 for a review).

In this review, we will describe current evidence of cross-modal and intra-modal plasticity in hearing impaired populations across the lifespan, with particular focus on how these brain changes may relate to clinical behavioral outcomes. We will discuss the wide range of variability in speech perception outcomes observed in hearing impaired populations, and how cross-modal and intra-modal changes within the sensory cortices may contribute to this variability. As a field, we are beginning to gain a better understanding of other downstream effects of hearing loss, such as compromises in neurocognitive abilities (e.g. working memory deficits) and changes in social-emotional regulation, in both adults and children (Kral et al., 2016). Recently, untreated hearing loss has been linked to increased risk of cognitive decline among older adults, though the potential causal mechanisms underlying this relationship are poorly understood (Contrera et al., 2016; Lin et al., 2011a, 2011b, 2014; Mick et al., 2014; Peelle et al., 2011).

2. Developmental sensitive periods and cross-modal plasticity

In children, auditory deprivation leads to delayed or abnormal development of the central auditory pathways, particularly if deprivation occurs during a sensitive period, or an established time window of approximately 3.5 years during which alterations in sensory input (e.g. deafness or hearing loss) can lead to profound and long-term impacts on the brain (See Kral and Sharma, 2012; Sharma et al., 2009, 2002 for discussion on the sensitive period for cortical maturation in deaf children). Animal studies suggest that auditory deprivation, especially that which is allowed to continue beyond the sensitive period, alters connectivity within the auditory system, between sensory systems and between the auditory system and higher-order neuro-cognitive centers resulting in significant deficits in brain and behavior (including sequence processing, working memory, executive functioning and concept formation) (Kral et al., 2016). One form of the afore-mentioned change in cortico-cortico connectivity is cross-modal re-organization between the auditory system and other sensory systems (e.g. vision). Animal studies suggest that sensory repurposing of auditory cortices appears to occur in higher-order sensory cortices as opposed to primary auditory cortices (Kral and Sharma, 2012; Kral et al., 2003). A recent paper (Land et al., 2016) examined visual responsiveness in a higher-order auditory cortical area (dorsal zone or DZ), which has been implicated in cross-modal re-organization (Lomber et al., 2010). A small number of visually responsive neurons were found in DZ in congenitally deaf cats. However, the vast majority of neurons in DZ showed auditory responsivity. Further, the visual and auditory neurons formed distinct populations that did not interact, suggesting that visual cross-modal re-organization does not decrease auditory responsiveness in congenitally deaf cats. Thus, while cross-modal recruitment of higher-order auditory areas is likely involved in closing developmental sensitive periods in deafness (Kral and Sharma, 2012; Kral, 2007), it appears that auditory responsivity is maintained despite cross-modal re-organization by vision (Land et al., 2016).

2.1. *Visual and somatosensory cross-modal plasticity in deaf cochlear implanted children*

Cross-modal re-organization by vision has been observed in developing and adult animals and humans with congenital or pre-lingual onset of deafness (Neville and Lawson, 1987; Buckley and Tobey, 2010; Dewey and Hartley, 2015; Doucet et al., 2006; Finney et al., 2003; Finney, 2001; Lee et al., 2001, 2007; Lomber et al., 2010). In congenitally deaf cats, for example, it appears that enhanced peripheral localization abilities observed in these animals is sub-served by the posterior auditory field (Lomber et al., 2010). That is, while the deaf cats show enhanced peripheral visual abilities compared to normal hearing cats, the temporary deactivation of the posterior auditory cortex leads to a depression in these abilities. Similarly, enhanced visual motion detection appears to be sub-served by dorsal auditory cortex (Lomber et al., 2010). More recently, increased performance in visual motion detection abilities has been shown in humans with pre-lingual hearing loss onset (Hauthal et al., 2013; Shiell et al., 2014; Shiell et al., 2016).

Like deaf cats, cross-modal cortical re-organization by the visual modality has been documented in congenitally deaf children fitted with CIs. In a recent study by our laboratory, cortical visual evoked potentials (CVEPs) were recorded using 128-channel high-density EEG in a group of CI children ($n = 14$) and an age-matched group of normal hearing children in response to a radially modulated visual grating stimulus giving the effect of apparent motion (see Campbell and Sharma, 2016 for details and methodology used). In the group of CI children, the average age of first implant was 3.12