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Review Article

Plasticity in bilateral superior temporal cortex: Effects of deafness and cochlear implantation on auditory and visual speech processing

Carly A. Anderson [a, b, *], Diane S. Lazard [c, d], Douglas E.H. Hartley [a, b, d, e]

[a] National Institute for Health Research (NIHR) Nottingham Hearing Biomedical Research Unit, Ropewalk House, 113 The Ropewalk, Nottingham, NG1 5DU, United Kingdom
[b] Otology and Hearing Group, Division of Clinical Neuroscience, School of Medicine, University of Nottingham, Nottingham, NG7 2UH, United Kingdom
[c] Institut Arthur Vernes, ENT Surgery, Paris, 75006, France
[d] Nottingham University Hospitals NHS Trust, Derby Road, Nottingham, NG7 2UH, United Kingdom
[e] Medical Research Council (MRC) Institute of Hearing Research, The University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

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ABSTRACT

While many individuals can benefit substantially from cochlear implantation, the ability to perceive and understand auditory speech with a cochlear implant (CI) remains highly variable amongst adult recipients. Importantly, auditory performance with a CI cannot be reliably predicted based solely on routinely obtained information regarding clinical characteristics of the CI candidate. This review argues that central factors, notably cortical function and plasticity, should also be considered as important contributors to the observed individual variability in CI outcome. Superior temporal cortex (STC), including auditory association areas, plays a crucial role in the processing of auditory and visual speech information. The current review considers evidence of cortical plasticity within bilateral STC, and how these effects may explain variability in CI outcome. Furthermore, evidence of audio-visual interactions in temporal and occipital cortices is examined, and relation to CI outcome is discussed. To date, longitudinal examination of changes in cortical function and plasticity over the period of rehabilitation with a CI has been restricted by methodological challenges. The application of functional near-infrared spectroscopy (fNIRS) in studying cortical function in CI users is becoming increasingly recognised as a potential solution to these problems. Here we suggest that fNIRS offers a powerful neuroimaging tool to elucidate the relationship between audio-visual interactions, cortical plasticity during deafness and following cochlear implantation, and individual variability in auditory performance with a CI.

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* Corresponding author. NIHR Nottingham Hearing Biomedical Research Unit, Ropewalk House, 113 The Ropewalk, Nottingham, NG1 5DU, United Kingdom.
E-mail addresses: carly.anderson@nottingham.ac.uk (C.A. Anderson), dianelazard@yahoo.fr (D.S. Lazard), douglas.hartley@nottingham.ac.uk (D.E.H. Hartley).

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1. Introduction

1.1. Variability in cochlear implant outcome

Over the past few decades, continued developments in cochlear implantation have enabled many individuals with severe-to-profound sensorineural hearing loss to benefit substantially from a cochlear implant (CI). Benefits provided by a CI can include greater awareness of environmental sounds (Cooper, 2006; Summerfield and Marshall, 1995), better quality of life (Damen at al., 2007; Klop et al., 2007; UK Cochlear Implant Study Group, 2004), improved psychological well-being (Knutson et al., 1998; Olze et al., 2011; Rembar et al., 2009), and significant improvements in auditory speech perception (Lazard et al., 2010a; Summerfield and Marshall, 1995; UK Cochlear Implant Study Group, 2004). However, evidence from multiple studies consistently suggests that there is pronounced variability in speech perception abilities across adult CI recipients, even in quiet listening conditions (Blamey et al., 2013; Gantz et al., 1993; Holden et al., 2013; Lazard et al., 2010a; Summerfield and Marshall, 1995; Tyler et al., 1997). Specifically, both the rate and trajectory of auditory performance over time is seen to vary across individuals (Holden et al., 2013; Tyler et al., 1997), and word identification across a cohort of CI users can span the entire possible range of test scores (0–100% correct, Lazard et al., 2010a).

In some ways, the variation in speech perception is unsurprising. Firstly, the CI provides an artificial sensation of hearing that is markedly different from that of normal hearing. Therefore, CI users have to acclimatize to and learn to process this novel and degraded sound signal. Ability to do so is seen to vary between individuals and as a function of time (Tyler and Summerfield., 1996). Secondly, CI recipients are commonly heterogeneous in many clinical characteristics that are known to influence auditory performance with a CI. These factors include, but are not limited to, the duration of deafness prior to cochlear implantation (Blamey et al., 2013; Green et al., 2007; Holden et al., 2013; Summerfield and Marshall, 1995), level of preoperative usable residual hearing (Gomaa et al., 2003; Lazard et al., 2012a), and history of hearing aid use (Lazard et al., 2012a). Device-related factors including the device brand (Lazard et al., 2012a) and the number of active electrodes (Blamey et al., 1992; Lazard et al., 2012a) have also been shown to influence CI outcome, as well as surgical factors including the positioning of the electrode array within the cochlea (Aschendorff et al., 2007; Holden et al., 2013; Skinner et al., 2007) and the depth of electrode insertion (Blamey et al., 1992; Finley and Skinner, 2008; Skinner et al., 2002; Yukawa et al., 2003). Multi-factor models of CI outcome have proved invaluable in establishing the relative importance of these factors in CI success, and thus in providing information that can help to guide the assessment process within the clinic and to inform patients' expectations (Blamey et al., 1992, 2013; Gantz et al., 1993; Green et al., 2007; Lazard et al., 2012a; Summerfield and Marshall, 1995). However, a large portion of variance in CI outcome remains unexplained by these models (up to 80%; Lazard et al., 2012a). Therefore, examining factors beyond these peripheral and routine clinical characteristics may help to provide a more comprehensive understanding of individual variability in CI outcome. In this review we outline the importance of examining central factors, namely cortical function and plasticity, as determinants of CI outcome. Specifically, we evaluate the current evidence of deafness-related changes within the bilateral superior temporal cortex (STC).

1.2. A contributing role of cortical factors

Neuroimaging studies have indicated that the ability to recruit bilateral auditory association cortices, located within the STC, in response to auditory speech stimulation may be crucial for achieving proficient levels of auditory performance with a CI (Fujiki et al., 1999; Green et al., 2005; Mortensen et al., 2006). However, evidence of 'cross-modal' cortical plasticity has been observed in cases of profound pre-lingual deafness, whereby auditory brain regions can become more responsive to the intact senses, such as vision (Finney et al., 2001) or touch (Auer et al., 2007). Such evidence has generated much interest in how this cross-modal recruitment of auditory brain regions may also occur in cases of post-lingual deafness: in particular, how it may limit an individual's ability to recruit temporal brain regions in response to speech and thus understand auditory speech information with a CI (Buckley and Tobey, 2011; Doucet et al., 2006; Lee et al., 2001, 2007a; Sandmann et al., 2012).

Establishing cortical factors important to CI success could help to more reliably inform prognosis. Whether the direct measurement of pre-implant cortical function and plasticity, which is not currently conducted in CI clinics, could offer additional prognostic value above that of routinely available clinical information remains unknown. Furthermore, how the cortex subsequently adapts to the restoration of auditory inputs following cochlear implantation and its relation to individual variability in CI outcome is also unclear. Indeed, cochlear implantation offers a unique opportunity to study the effects of auditory deprivation, and its subsequent amelioration, on cortical function and plasticity. However, longitudinal examinations of this remain lacking largely due to methodological challenges.

1.3. Aim of the review

Here we review evidence concerning the impact of cortical plasticity within STC on CI outcome. We first outline the role of the STC in auditory speech perception with a CI and the impact that cross-modal plasticity may have on CI outcome (section 2). Given the involvement of the STC in the processing of both auditory and visual speech cues (speechreading), as well as the importance of speechreading during deafness and cochlear implantation, we consider plasticity effects related to speechreading within these regions (section 3). The potential benefits of speechreading and associated plasticity for maintaining the functional integrity of the left STC, and enabling successful auditory rehabilitation in post-lingually deafened adults, are discussed (section 4). Furthermore,