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Source analysis of auditory steady-state responses in acoustic and electric hearing

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ABSTRACT

Speech is a complex signal containing a broad variety of acoustic information. For accurate speech reception, the listener must perceive modulations over a range of envelope frequencies. Perception of these modulations is particularly important for cochlear implant (CI) users, as all commercial devices use envelope coding strategies. Prolonged deafness affects the auditory pathway. However, little is known of how cochlear implantation affects the neural processing of modulated stimuli. This study investigates and contrasts the neural processing of envelope rate modulated signals in acoustic and CI listeners.

Auditory steady-state responses (ASSRs) are used to study the neural processing of amplitude modulated (AM) signals. A beamforming technique is applied to determine the increase in neural activity relative to a control condition, with particular attention paid to defining the accuracy and precision of this technique relative to other tomographies. In a cohort of 44 acoustic listeners, the location, activity and hemispheric lateralisation of ASSRs is characterised while systematically varying the modulation rate (4, 10, 20, 40 and 80 Hz) and stimulation ear (right, left and bilateral). We demonstrate a complex pattern of laterality depending on both modulation rate and stimulation ear that is consistent with, and extends, existing literature.

We present a novel extension to the beamforming method which facilitates source analysis of electrically evoked auditory steady-state responses (EASSRs). In a cohort of 5 right implanted unilateral CI users, the neural activity is determined for the 40 Hz rate and compared to the acoustic cohort. Results indicate that CI users activate typical thalamic locations for 40 Hz stimuli. However, complementary to studies of transient stimuli, the CI population has atypical hemispheric laterality, preferentially activating the contralateral hemisphere.

1. Introduction

Speech is a complex signal containing a broad variety of acoustic information. For accurate speech perception, the temporal envelope of speech is particularly important (Shannon et al., 1995). The temporal envelope consists of variations in the overall amplitude of the sound pressure wave, characterised by rates of modulation between 2 and 50 Hz (Rosen, 1992). More specifically, modulation rates around 4 and 20 Hz are considered fundamental for speech perception due to their relation with the rate of syllables and phonemes, important phonological segments in speech (Edwards and Chang, 2013). Envelope coding is used to convey information to CIs users, further accentuating the importance of modulation sensitivity for this population (Fu, 2002; Wouters et al., 2015).

Given the importance of envelope rate modulations in speech, it is of particular interest to understand where and how these modulations are represented and processed within the human auditory pathway. The capability of the auditory system to process temporal modulations can be investigated by means of ASSRs. ASSRs are neural responses evoked during auditory stimulation with a temporally modulated stimulus, and reflect how well the auditory system phase locks to the stimulus rhythm (Picton et al., 2003). These evoked potentials have been linked to several perceptual outcomes, ASSRs are used clinically to objectively determine frequency specific hearing thresholds (Rance et al., 1995), and have also been related to speech perception (Dimitrijevic et al., 2004; Poelmans et al., 2012a). In CI users, EASSRs have been used to predict hearing thresholds (Hofmann and Wouters, 2012) and related to modulation sensitivity (Luke et al., 2015).

A variety of imaging methods have shown ASSRs activate the entire auditory pathway, with different modulation rates preferentially activating different pathway segments (Rance, 2008). Higher modulation

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rates (≳80 Hz) predominantly activate the brainstem, with lower rates (≲40 Hz) activating the thalamus and auditory cortices (Reyes et al., 2004; Roß et al., 2000; Herdman et al., 2002; Giraud et al., 2000; Langers et al., 2005). Less is known about the hemispheric lateralisation of modulated auditory stimuli, where changes may represent variation in underlying functional relationships between different processing centres (Langers et al., 2005). A right hemispheric preference has been observed for 40 Hz ASSRs regardless of stimulation ear (Roß et al., 2000). 4 Hz modulated signals exhibit contralateral auditory cortex (AC) activation for monaural stimulation (Langers et al., 2005), and right activation during bilateral stimulation (Hymers et al., 2010; Prendergast et al., 2010). However, scalp level analysis indicates there may be additional richness to this variation that is yet to be quantified on a source level (Poelmans et al., 2012a; Gransier et al., 2016). We hypothesise that source analysis of ASSRs will reveal hemispheric lateralisation that is dependant on modulation rate and stimulation modality.

Typical development of the auditory pathway is presumably beneficial for speech perception, and is facilitated by providing auditory stimulation within developmental sensitive periods (Kral and Sharma, 2012). Unfortunately, deprivation of auditory stimulation is accompanied by modifications to the auditory system (Lazard et al., 2011) and reduced performance (Lazard et al., 2012; Kral and Sharma, 2012). The effect of reintroducing auditory stimulation is less well known, investigation has been hindered by incompatibilities between CIs and magnetic resonance imaging (MRI) (Majdani et al., 2009), and has required the development of alternative source analysis methods. Gilley et al. (2008) demonstrated reorganised cortical pathways using a electroencephalography (EEG) sLORETA source reconstruction of cortical evoked potentials. Wong and Gordon (2009) introduced an EEG beamforming method (Van Veen and Buckley, 1988) for analysing the sources of transient responses, this method was used to demonstrate unilateral implantation results in contralateral dominance that can be mitigated with timely bilateral implantation (Gordon et al., 2013). However, CI recipients primarily rely on envelope cues transmitted via sustained modulations (Friesen et al., 2001). We hypothesise that similar to transient stimuli, enhanced contralateral activation will be seen for modulated stimuli.

To summarise, we hypothesise that EEG beamforming will provide a measure with adequate sensitivity to reveal hemispheric lateralisation of ASSRs. This methodology will reveal hemispheric lateralisation that is modulation rate and stimulation modality dependent. Further, in the CI population we hypothesise that enhanced contralateral activation will be seen for modulated stimuli. Below we introduce the EEG beamforming method and quantify the accuracy and precision with reference to other tomographies. In the acoustically stimulated population, the location, strength and lateralisation is characterised for modulation rates 4, 10, 20, 40 and 80 Hz with stimuli presented monaurally to the left ear, monaurally to the right ear and bilaterally. This result is used as a baseline for which to compare the CI cohort. With extensions to remove the CI artifacts, the beamforming method is applied to five right ear implanted CI participants for the 40 Hz rate, and the two cohorts are compared.

2. Materials and methods

2.1. Participants

Two groups of listeners participated in this study. The first cohort comprised of 44 acoustic hearing participants (5 males, mean age 22). All acoustic hearing participants had audiometric thresholds below 25 dB HL on all octave frequencies between 0.25 and 8 kHz and reported no history of language or learning disabilities, brain injury or neurological disorders. The second cohort comprised of five CI, i.e. electrical, hearing participants (3 males, mean age 61). All electrical hearing participants were Cochlear Nucleus CI users with devices implanted in the right ear. Testing was approved by the Medical Ethics Committee of the UZ Leuven (approval number B322201316755 for acoustic hearing participants and B32220072126 for CI participants) and informed consent was obtained from all participants.

2.2. Stimuli

2.2.1. Acoustical stimulation

Acoustic stimuli consisted of amplitude modulated speech-weighted noise with 100% modulation depth, presented to the participants at 70 dB SPL through ER-3A insert phones. The carrier noise was adopted from the 'Leuven Intelligibility Sentence Test' and represents the long-term average speech spectrum of 730 sentences of a female speaker (Van Wieringen and Wouters, 2008). Five modulation rates (4, 10, 20, 40 and 80 Hz) were presented in three modalities (monaurally to the left ear, monaurally to the right ear and bilaterally to both ears). The broad range of modulation rates was chosen to investigate ASSRs generated along the entire auditory pathway from brainstem to AC. Additionally, 4, 10 and 20 Hz rates were chosen to represent typical syllable and phoneme rates in speech (Greenberg et al., 1996; Greenberg and Takayuki, 2004). The 40 and 80 Hz rates were selected as they produce the largest scalp signal-to-noise ratios (SNRs) and are the most commonly studied rates (Picton et al., 2003). Both uni- and bilateral stimulation modalities were included, for it has been shown to significantly affect lateralisation on source (Langers et al., 2005) and scalp level (Poelmans et al., 2012a). A silence condition was also measured as a reference for the beamforming procedure. Each of the sixteen conditions was presented for 5 min in a randomised order.

2.2.2. Electrical stimulation

Electrical stimulation consisted of amplitude modulated biphasic pulse trains presented via the NIC research platform (Hofmann and Wouters, 2010, 2012). All stimuli were presented in bipolar mode, both the active and return CI electrodes were located within the cochlea. Bipolar mode was used as it induces shorter EEG artifacts than in monopolar mode, and which can be removed on the ipsilateral side. In each participant three CI electrode pairs were stimulated, a basal, middle and apical electrode pair. Ten minutes of EEG were recorded per CI electrode pair. A pulse rate of 900 pulses per second (pps) was used, to match the users daily clinical processor. Stimuli were modulated between the threshold and comfort level as described in Luke et al. (2015). Psychophysical experiments were conducted to determine the threshold and comfort levels, this reduced the time available to measure EEG. Due to the reduced time, only a single modulation rate was investigated in the electrical hearing population. A 40 Hz modulation rate was used as it yields the highest SNR and can be consistently detected in the CI population (Gransier et al., 2016; Luke et al., 2015; Deprez et al., 2017), and laterality results have been established in the acoustically stimulated population (Roß et al., 2003).

2.3. EEG acquisition

EEGs were recorded with a Biosemi ActiveTwo system using sixty-four active Ag/AgCl electrodes mounted in head caps according to the 10–20 electrode system. The use of electrode caps ensures consistent electrode spacing and positioning. All recordings were administered in a double-walled soundproof booth with a Faraday cage. Participants were asked to relax while watching a soundless movie. Watching a movie prevents the participants from falling asleep and ensures non-attentive listening to the auditory stimuli, thereby controlling for possible effects of sleep and attention (Roß et al., 2003). To avoid excessive movement or muscle tensions, participants were encouraged to lie quietly and relax during auditory stimulation. The data was sampled at a rate of 8192 Hz and saved for offline processing.