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Research paper

Sensitivity of envelope following responses to vowel polarity

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ABSTRACT

Envelope following responses (EFRs) elicited by stimuli of opposite polarities are often averaged due to their insensitivity to polarity when elicited by amplitude modulated tones. A recent report illustrates that individuals exhibit varying degrees of polarity-sensitive differences in EFR amplitude when elicited by vowel stimuli (Aiken and Purcell, 2013). The aims of the current study were to evaluate the incidence and degree of polarity-sensitive differences in EFRs recorded in a large group of individuals, and to examine potential factors influencing the polarity-sensitive nature of EFRs. In Experiment I of the present study, we evaluated the incidence and degree of polarity-sensitive differences in EFR amplitude in a group of 39 participants. EFRs were elicited by opposite polarities of the vowel /ε/ in a natural /hVd/ context presented at 80 dB SPL. Nearly 30% of the participants with detectable responses ($n = 24$) showed a difference of greater than ~39 nV in EFR response amplitude between the two polarities, that was unexplained by variations in noise estimates. In Experiment II, we evaluated the effect of vowel, frequency of harmonics and presence of the first harmonic (h1) on the polarity sensitivity of EFRs in 20 participants with normal hearing. For vowels /u/, /a/ and /i/, EFRs were elicited by two simultaneously presented carriers representing the first formant (resolved harmonics), and the second and higher formants (unresolved harmonics). Individual but simultaneous EFRs were elicited by the formant carriers by separating the fundamental frequency in the two carriers by 8 Hz. Vowels were presented as part of a naturally produced, but modified sequence /susaʃi/, at an overall level of 65 dB SPL. To evaluate the effect of h1 on polarity sensitivity of EFRs, EFRs were elicited by the same vowels without h1 in an identical sequence. A repeated measures analysis of variance indicated a significant effect of polarity on EFR amplitudes for the vowel /u/ and a near-significant effect for /i/, when h1 was present. EFRs elicited by unresolved harmonics and resolved harmonics without h1 demonstrated no significant differences in amplitude due to polarity. The results suggest that h1 contributes to the polarity sensitivity of EFRs elicited by low frequency F1 carriers. However, it is unlikely that this is only due to the influence of a polarity-sensitive frequency-following response to the fine structure at h1. Removing h1 by filtering also decreased the asymmetry of the vowel envelope, especially for those with low first formant frequencies. A measure called the envelope asymmetry index was computed to evaluate the relationship between stimulus envelope asymmetry above and below the baseline, and polarity-sensitive differences in EFR amplitude. A significant positive correlation between envelope asymmetry index and absolute amplitude differences in EFR due to polarity suggests that one of the causes contributing to the polarity sensitivity of EFRs could be the asymmetry in stimulus envelope. This stimulus characteristic, however, explains only a fraction of the variability observed and there may be other factors that contribute to individual differences in polarity sensitivity of the EFR to naturally produced vowel stimuli.

1. Introduction

In electrophysiological measurements, averaging responses to opposite polarities of the stimulus has been recommended for reducing or eliminating stimulus artifact (Akhoun et al., 2008;

Abbreviations: EFR, envelope following response; FFR, frequency following response; FA, fourier analyzer; RM-ANOVA, Repeated measures analysis of variance

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Campbell et al., 2012; Arnold, 2007; Small and Stapells, 2004). Averaging responses to opposite polarities has also been used to enhance Envelope Following Responses (EFR) by reducing contamination by the Frequency Following Response (FFR) and cochlear microphonic (Aiken and Picton, 2008). The EFR is a response phase-locked to the stimulus envelope which is minimally affected by an inversion of stimulus polarity and hence preserved when responses to opposite polarities are added (Aiken and Picton, 2008; Gockel et al., 2011; Greenberg et al., 1987; Small and Stapells, 2005). The FFR is a neural response phase-locked to the stimulus fine structure/spectral characteristics. The FFR is sensitive to inversion of the stimulus and doubles in frequency when averaged across opposite stimulus polarities (Aiken and Picton, 2008; Chimento and Schreiner, 1990; Huis in't Veld et al., 1977; Krishnan, 2002). Likewise, the cochlear microphonic is a presynaptic response generated from the outer hair cells that also closely follows the polarity of the stimulus (Chimento and Schreiner, 1990; Huis in't Veld et al., 1977). Therefore, averaging responses to alternate polarities to enhance EFRs is based on evidence that demonstrates sensitivity of the FFR and cochlear microphonic to stimulus polarity as well as general insensitivity of the EFR to stimulus polarity, preserving it in the averaged alternate polarity response.

Only a few studies report and evaluate differences in EFRs due to stimulus polarity. The stimuli used in these studies are either amplitude-modulated (AM) tones or vowels. In a study that used AM tones, a small but statistically significant difference was noted in the response amplitude (mean difference of ~6 nV) and phase (mean difference of ~13°; Small and Stapells, 2005). In an earlier study that used synthetic vowel stimuli (Greenberg, 1980; pp. 122–125), polarity-sensitive amplitude differences were observed but not quantified. In a more recent study that used natural vowel stimuli (/a/ and /i/), significant and marginally larger differences (mean of absolute differences was ~17 nV) were observed in EFR response amplitudes to opposite stimulus polarities (Aiken and Purcell, 2013). Although EFR amplitudes to opposite polarities were significantly different in both these studies, response amplitudes in conditions where opposite polarities were averaged did not vary significantly from the responses where only the same polarity was averaged (Aiken and Purcell, 2013). This is further supported by a more recent study that illustrated no significant differences in response amplitudes at the fundamental frequency (for the stimulus /da/) between condensation, rarefaction and alternating polarity stimulus conditions (Kumar et al., 2013), although their 40 ms stimulus contained only the consonant-vowel transition and not the steady-state vowel. These results show that EFRs elicited by AM tones and certain vowels may be sensitive to polarity but only to a degree that does not significantly affect response amplitude estimates at the group level when responses to opposite polarities are averaged.

However, it is important to note that individual variations exist in the degree of polarity sensitivity. In Aiken and Purcell (2013), describing data from nine participants, differences in response amplitudes observed due to polarity in any individual ranged from a minimum of 0.4 to a maximum of 72 nV. The differences varied across individuals and across stimuli within individuals. At the group level, averaging responses to opposite polarities did not affect the EFR amplitudes. However, it is likely that averaging responses to opposite polarities may under-estimate the maximum response amplitude possible in those individuals exhibiting large amplitude differences due to polarity. The extent of polarity-sensitive amplitude differences may also affect response detection, as statistical detection tests (for example, the *F*-test) are typically based on the individual's response averaged across polarity. Since individual variations are of significance for clinical measures, our first aim was to study the incidence and degree of polarity-sensitive amplitude differences in EFRs recorded on a large number of individuals in Experiment I.

Greenberg (1980, chapter 7) was the first to report polarity sensitivity for vowel stimuli. Figures 7.13 and 7.14 (Greenberg, 1980, chapter 7) illustrate that the EFR at the modulation frequency (the fundamental frequency of the voice, f_0) was not completely canceled when responses to opposite polarities of synthetic vowels were subtracted from each other. This provides evidence for differences in EFR characteristics in response to opposite stimulus polarities that, if otherwise equal, would have completely canceled in the subtracted average or the − − average shown in Aiken and Picton (2008; Panel L, Fig. 2; the − − average is obtained by subtracting responses to opposite stimulus polarities). The residual EFR varied across different vowels and Greenberg's three participants. A suspected reason for the residual EFR activity in the subtracted response was the acoustic envelope asymmetry in the eliciting stimulus (Greenberg, 1980; Skoe and Kraus, 2010). Another reason that could contribute to the polarity sensitivity of EFRs to vowel stimuli is the influence of the FFR. Unlike AM tones, the frequency at which the EFR is elicited is also the frequency of the first voice harmonic (h1). Since we know from previous studies that the FFR is sensitive to stimulus polarity, it is possible that polarity sensitivity of the EFR is a compound effect of both the FFR and EFR elicited at the same frequency. The FFR may add constructively or destructively with the EFR depending on the stimulus polarity. Hence, this study evaluated the influence of h1 (possibly eliciting an h1 FFR) by comparing polarity-sensitive differences in EFR amplitude elicited by vowels with and without h1.

The above discussion pertains to vowels elicited by the full bandwidth of a vowel, natural or synthetic. EFRs elicited by vowels are thought to be dominated by harmonics in the region of the first formant (F1), relative to the second (F2) and higher formants (F2+; Choi et al., 2013; Laroche et al., 2013). The first seven to eight harmonics are spectrally resolved, meaning, the auditory filters respond to a single harmonic of the complex signal and hence the output of these filters is a sinusoid (Oxenham, 2008; Oxenham et al., 2009). But the higher order harmonics are unresolved, meaning, the auditory filters process more than one harmonic of the complex signal and hence the output is an interaction between individual harmonics (Oxenham, 2008). The F1 of English vowels are mostly below 1 kHz and the F2 are above 1 kHz (Hillenbrand et al., 1995). Therefore, for f_0 ranging between 100 and 140 Hz, it is likely that the EFRs from the region of F1 are generated from harmonics that are spectrally resolved (the corresponding harmonic would be 700–980 Hz respectively) whereas EFRs generated from the region of F2 or F2+ are generated from harmonics that are spectrally unresolved (Laroche et al., 2013). In the literature, there is evidence to suggest that characteristics of EFRs elicited by lower frequency carriers or resolved harmonics vary from EFRs elicited by higher frequency carriers or unresolved harmonics. Data from Greenberg et al. (1987) illustrates that at low intensities, the modulation depth, systematically varied by altering the onset phase of individual harmonics, had no effect on the EFRs generated by a low frequency harmonic complex. However, the EFRs generated by a high frequency harmonic complex systematically reduced in amplitude with a reduction in modulation depth. This is similar to findings from Krishnan and Plack (2011), where the onset phase only affected EFRs generated from the region of unresolved harmonics. As well, the effects of noise on EFRs generated from the F1 region varies from those generated from regions of higher formants (Laroche et al., 2013). EFRs generated from the region of unresolved harmonics were more susceptible to noise compared to EFRs generated from resolved harmonics at equal stimulus levels and signal-to-noise