FREQUENCY, ATTENTION, AND PHONETIC CHARACTERISTICS THAT INFLUENCE THE RIGHT-EAR ADVANTAGE FOR SPEECH PERCEPTION

A Thesis
Presented to
The Faculty of the Department
of Psychology
University of Houston

In Partial Fulfillment
of the Requirements for the Degree of
Master of Arts

Katie McCulloch
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The right-ear advantage (REA) for linguistic stimuli (Kimura, 1961, 1967) is thought to represent an asymmetry of speech perception favoring the left hemisphere. This study seeks to clarify how the REA is altered by: attention instructions, filtering of stimuli, background noise, and phonetic properties of stimuli, viz., voice onset time (VOT) and place of articulation (POA). Participants heard monosyllabic rhyming words from the Halwes (1990) Fused Dichotic Word Test and were instructed to attend to the left or right ear, or to divide attention equally. Stimuli in Experiment 1 were unfiltered, high-pass filtered, or low-pass filtered, and stimuli in Experiment 2 were presented with no noise, white noise, high-pass filtered noise, or low-pass filtered noise. The initial consonants of each dichotic pair were categorized according to POA (bilabial, alveolar, or velar) and VOT (voiced or unvoiced). Repeated-measures ANOVAs performed on laterality ratios showed statistically significant main effects for attention, background noise, VOT, and POA. Right-ear attention, the absence of background noise, and bilateral bilabial presentation enhanced the right-ear advantage. Furthermore, attention interacted with background noise, POA, and VOT.

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Frequency, Attention, and Phonetic Characteristics That Influence the Right-Ear Advantage for Speech Perception

Much of what is understood about speech perception involves the transmission of the auditory signal within the ear and auditory nerve. Much less is known about what happens when the auditory signal reaches the cortex and undergoes further processing. Early neuropsychological work has demonstrated the presence of asymmetries in auditory perception. Handedness is generally correlated with contralateral language representation, but this is not a perfect correlation. It is estimated that at least 95% of right-handed individuals have language represented in the left hemisphere, but the other 5% may have right hemisphere or bilateral representation (Carter, Hohenegger, & Satz, 1980; Loring et al, 1990).

One of the major experimental tasks used by researchers to study language lateralization is dichotic listening. In this task two different auditory stimuli are simultaneously presented to each ear. The participant is then instructed to report the stimulus that was heard most clearly. Researchers have shown how auditory perception is altered under various conditions and manipulations of the basic dichotic listening paradigm. The task was originally used with strings of digit names and has evolved to utilize primarily consonant-vowel (CV) syllables (Studdert-Kennedy & Shankweiler, 1970) and consonant-vowel-consonant (CVC) words (Wexler & Halwes, 1983, 1985). Halwes (1990) developed the Fused Dichotic Word Test (FDWT), which utilizes monosyllabic rhyming CVC words that differ only in their first phoneme (e.g., car/bar).

The right-ear advantage (REA) for linguistic information was discovered by Kimura (1961, 1967), who demonstrated that when sounds are presented in dichotic competition people tend to perceive the stimuli presented to their right ear more often than the stimuli presented to the left ear. The observed asymmetry of speech perception is theorized to be the result of structural components of the brain. Kimura argued that the right ear is preferred because of its crossed, direct connection to the left hemisphere, where language is represented in most persons. Kimura's "structural model" also postulates a central component that suppresses the competing ipsilateral pathway in favor of the contralateral pathway, from right ear to left hemisphere. There has been continuing evidence for this theory since its inception, especially with the development of more advanced imaging techniques. Davidson and Hughahl (1990) showed that a larger REA is correlated with greater evoked potential activation in the left temporo-parietal region of the brain. However, DeLeon, Hiscock, and Jansen (2011) showed that the difference between individuals who show an REA and those who do not is related to the speed of conduction, rather than the amplitude of the left hemisphere response.

Since the discovery of the REA, other researchers have disputed Kimura's explanation, arguing that asymmetries of speech perception depend on lateral shifts of attention (Kinsbourne, 1970, 1973). Before Kimura had noted the REA, Broadbent (1954) had shown that attention is an integral component to the perception of speech when there are competing signals. Kinsbourne (1970) applied such early cognitive discoveries in his explanation of the REA, arguing that it is a function of attentional tendencies, rather than a phenomenon arising solely from structural elements of the brain. He explained that the tendency to attend to the right ear, or more generally the right side of space, is the result of an expectation of linguistic stimuli. Because the left hemisphere typically represents language, an expectation for linguistic stimuli primes the left hemisphere and subsequently focuses attention to the contralateral, right side of space.

During experiments that utilize dichotic listening, an REA is normally obtained when attention is divided between both ears. However, it is possible to alter the degree of the REA by manipulating attention via instrustions to focus on one ear or the other, or to divide attention equally between the ears (Hiscock, Inch, & Kinsbourne, 1999). When attention is focused on the right ear and the participant is asked to disregard stimuli presented to the left ear, the REA is enhanced. When attention is focused to the left ear and the participant is instructed to report what is heard only from that ear, the REA is diminished and in some instances a marginal left-ear advantage may actually be noted (Asbjørnsen & Hugdahl, 1995). Hiscock and Bergstrom (1982) noted that a significant REA was found in normal children only when attention was primed to the right ear. The bias favoring the right ear persisted over an interval of one week. This implies that an attentional bias to the right side of space and the right ear may have strong effects that are resistant to change. There was previously speculation that the FDWT task was not susceptible to attentional biases, but Voyer and Ingram (2005) demonstrated that in fact there are consistent attentional biases when using the FDWT task. This suggests that attentional biases are capable of influencing the REA for even the most carefully matched dichotic stimuli.

Another proposed element involved in the perception of speech is the sound frequency of auditory stimuli. Ivry and Robertson (1998) have proposed the Double Filtering by Frequency (DFF) theory to explain how perceptual asymmetry at the central level of processing is influenced by stimulus frequency. The DFF theory explains that each of the cerebral hemispheres is tuned to a limited spectrum of frequencies and is designed to process sensory input accordingly. The left hemisphere is primarily responsible for processing relatively high frequencies, whereas the right hemisphere is specifically tuned for lower frequencies. The DFF theory is largely based on the findings of visual asymmetry but has been extended by the authors to apply to auditory perception. High frequency sounds are considered to be analogous to higher spatial frequencies, whereas low frequency sounds are considered to be analogous to lower spatial frequencies.

White noise is not associated with a discriminable pitch because energy is distributed equally over the entire range of frequencies. Nonetheless, the addition of white noise to speech has been shown to affect the cerebral hemispheres differentially. Shtyrov et al. (1998, 1999) utilized magnetoencephalography (MEG) to measure the magnetic mismatch negativity (MMNm) response, a cortical response to deviations in elements of speech, such as pitch, duration, or intensity. The researchers showed that, when CV or CVC stimuli are embedded in white noise, the left hemisphere’s normally strong MMNm response is decreased and the right hemisphere’s MMNm is enhanced. Davis (2008) additionally showed that left hemisphere activation is smallest for speech presented in white noise, but increased when the noise was band-filtered by frequency. It is expected that white noise will have a similar effect on the dichotic listening task of the current study. Thus, we expect greater disruption of the REA when speech is presented within white noise than when the high or low frequency bands are selectively attenuated.

Speech perception and the REA may also be influenced by linguistic properties of individual words. Specifically, voice onset time (VOT) has been shown to group consonants as voiced or unvoiced and influence their perception (Molfese, 1978; Lisker, 1975). Voiced consonants include the letters ‘b’, ‘d’, and ‘g’. These sounds cause the vocal folds to rapidly vibrate as air is passed between them and the sound is produced quickly, with a VOT ranging from approximately 11ms to 27ms (International Phonetic Association [IPA], 2005; Voyer & Techentin, 2009). Unvoiced consonants such as ‘p’, ‘t’, and ‘k’, cause the vocal cords to vibrate at a slower frequency or speed than voiced sounds and the sound is produced later than for voiced sounds, with a VOT of approximately 71ms to 83ms. Most evidence shows that VOT of the initial consonant sound affects the REA to a degree that depends on the interaction of ear of presentation and voicing category (Segalowitz & Cohen, 1989; Repp, 1977; Rimol, Eichele, & Hugdahl, 2006; Sandmann, Eichele, Specht et al, 2007). When an unvoiced word is presented to the right ear and a voiced word is presented to the left ear, the REA is enhanced. When this is reversed, such that an unvoiced word is presented to the left ear and a voiced word to the right ear, the REA is reduced. When voicing is similar in both ears, the magnitude of the REA falls between these two extremes.

There is evidence that the magnitude of the REA varies according to other phonemic classes as well. For example, manner of articulation describes how the vocal tract is closed and to what degree. Manner of articulation has been shown to influence the REA, such that stop consonants (‘p’, ‘b’, ‘t’, ‘d’, ‘k’, and ‘g’) produce a greater REA than other classifications (Cutting, 1974). Based on this literature, place of articulation is another phonemic property of words that has been investigated for its effects on the REA. Place of articulation refers to the location at which the sound is articulated within the vocal tract (IPA, 2005). In the English language, bilabials (‘p’ and ‘b’) are articulated at the lips, whereas alveolars (‘t’ and ‘d’) are articulated on the tip of the tongue and velars (‘k’ and ‘g’) on the back of the tongue. The peak energy of bilabials is the lowest in frequency, varying from 600-800Hz typically. Velars normally range from 1800-2000Hz and alveolars have their greatest peak energy at approximately 4000Hz (Fry, 1979). Based on the DFF theory the frequency of consonants may influence the REA, such that consonants with higher peak energies would be processed preferentially by the left hemisphere and consonants with lower peak energies would tend to be processed by the right hemisphere. Across voicing categories bilabials have the shortest VOT, alveolars have a moderate VOT, and velars have the longest VOT (Olive, Greenwood, & Coleman, 1993). Berlin et al. (1973) showed that velars to tend to be perceived most accurately, with bilabials following, and alveolars being perceived least accurately. Voyer and Techentin (2009) showed that velar consonants presented to the right ear produced the greatest REA and, when velars are presented to the left ear, an LEA is observed. In light of the results for velars, the authors investigated stimulus dominance, the situation in which a particular stimulus is detected more accurately or reported more frequently regardless of the ear of presentation. Voyer and Techentin (2009) observed stimulus dominance for both of the velar phonemes, ‘k’ and ‘g’, as well as the unvoiced bilabial phoneme, ‘p’. The reason that these phonemes are perceived more readily than other phonemes is unexplained, but the preferences may be influenced by other factors such as VOT.

In addition, a lag effect has been observed in dichotic listening tasks (Berlin et al., 1973). A stimulus is preferentially perceived if its onset is delayed 60-90ms relative to the stimulus with which it is paired (Wood, Hiscock, & Widrig, 2000). This lag effect does not interact with focused attention to either ear and is thought to be pre-attentional. As mentioned earlier, unvoiced phonemes have a VOT ranging from 71ms to 83ms, which is within the range of the lag effect (Voyer & Techentin, 2009). This provides an explanation for findings that unvoiced consonants are perceived more accurately than voiced consonants

(Berlin, et al., 1973). Accordingly, we predict that unvoiced consonants will be perceived preferentially over voiced consonants, regardless of the ear of presentation or attentional instruction. As stimulus onset asynchrony increases between the signals, accuracy has been shown to increase (Berlin et al., 1973; Wood et al., 2000). Thus, we would also predict that unvoiced-voiced pairings will show fewer errors than voiced-voiced or unvoiced-unvoiced pairs in the present experiment.

The present study is intended to determine how the REA is influenced by two bottom-up factors – frequency and phonemic characteristic—and a top-down factor - endogenous allocation of attention. Hugdahl (2000) distinguished between bottom-up factors, which are specialized features of the hemispheres for processing stimulus-driven information, and top-down factors, which are variables influenced by the dynamic modulation of cognitions or task instructions of the task. He proposed that speech perception is the resulting sum of bottom-up effects and top-down effects, suggesting that there are additive effects of each factor. Westerhausen, et al. (2008) demonstrated interactive effects among inter-aural intensity variation, attention, and ear of presentation on the REA for linguistic stimuli. However, they noted that the interactions of attention or intensity with ear accounted for most of the variability (35-43%), whereas the 3-way interaction explained very little of the variance (2%). This indicates that the main effects in the present study, which account for ear asymmetry, are likely more influential in the overall perception of speech than their interactions. Addition of these strong main effects by each factor may be an important contribution to the REA. There appears to be some evidence for interaction among the top-down and bottom-up factors, as well as reason to expect additive effects among the factors to explain the overall of processing of speech.

This experiment will supplement the existing body of research regarding how the two cerebral hemispheres differ in their contributions to speech processing. It is hypothesized that the REA for perceiving words when presented simultaneously to both ears will be altered by the distribution of attention, the presentation of binaural noise of different acoustic properties, and phonemic classification of the words presented. We hope to replicate previously established effects of attention and phonemic characteristics as well as evaluate effects of filtered and unfiltered noise. We will investigate the effects of these variables by analyzing two separate archival dichotic listening datasets. Experiment 1 utilizes high-pass and low-pass filtering of stimuli, and Experiment 2 utilizes unaltered white noise, as well as white noise that has been high-pass or low-pass filtered.

It is predicted that each of the factors selected for study will influence the degree of REA and accuracy of perception. There may be interactive effects among the three factors in producing the REA as well as main effects. Specific predictions are listed below:

(1) It follows from DFF theory that low-pass filtering of the stimuli will reduce the REA and high-pass filtering of the stimuli will enhance the REA.

(2) It also follows from DFF theory that low-pass filtered noise will enhance the REA and high-pass filtered noise will reduce the REA. It is also predicted that white noise will reduce the REA to a greater extent than filtered noise because white noise will minimize all of the bottom-up factors that produce an REA.

(3) All attention conditions will demonstrate a REA, but focused attention to the right ear will produce the greatest REA, divided attention will produce a moderate REA, and focused attention to the left ear will produce the smallest REA.

(4) Voice onset time and POA of the initial consonant will alter the REA, such that long VOT consonants (unvoiced and velars) in the right ear will enhance the REA and short VOT consonants (voiced and bilabials) in the right ear will diminish the REA.

(5) The conjoint effect of these variables (filtering or noise, attention, and POA or VOT) on the REA will show additive effect with one another. For example, focused attention to the right ear with low-pass filtered noise and a long VOT consonant will produce the greatest REA of all possible combinations, whereas focused attention to the left ear with white noise and a short VOT consonant in the right ear will produce the smallest REA.

Experiment 1

Method

Participants

Data were obtained from an undergraduate psychology honors thesis conducted by Heather Dial, under the supervision of Dr. Merrill Hiscock. Forty-eight right-handed University of Houston undergraduate students (24 males and 24 females) volunteered to participate and are included in the dataset. The mean age of participants was 20.2 years (*SD*=3.3) and ranged from 18 to 33 years. Participants were excluded if they reported abnormal hearing. The degree of right-handedness for each participant was assessed using a modified form of the Edinburgh Handedness Inventory (Oldfield, 1971).

Materials

The FDWT dichotic listening stimuli (Wexler & Halwes, 1985) were presented via Koss (Milwaukee) UR-20 headphones and amplified by Pyle (Brooklyn) Pro PTA1 15 watt stereo power amplifier. The headphone sound intensities were calibrated using a Bruel & Kjaer (Copenhagen) Artificial Ear Type 4152 and Precision Sound Level Meter Type 2203. The average sound intensity was 80.7 dB (A-scale) at the right headphone and 81.4 dB (A-scale) at the left headphone. The auditory stimuli were generated and frequency-filtered using Power Sound Editor Free (Carson City) Version 6.3.1 software. Filter type was found to be consistent with Chebyshev Type 1 filters with zero-phase. The effect of low-pass filtering appeared consistent with expectation, although the high-pass filtering cut-off appeared to be lower than expected, allowing more low frequency components than specified. Software for the experiment was provided by Dr. Daniel Voyer of the University of New Brunswick and run using E-Prime software (version 1.1; Psychology Software Tools Inc.).

Degree of right-handedness was calculated using a laterality ratio:

$$\text{Handedness} = 100 * \left(\frac{\text{RH-LH}}{\text{RH+LH}}\right).$$

Negative numbers indicate the degree of left-handedness and positive values indicate right-handedness. The mean handedness laterality ratio among all participants was +81.3 (*SD*=16.9) and ranged from +29.4 to +100.

Procedure

Participants were tested at the University of Houston in a sound-attenuated room with an ambient sound level of 34 dB (A-scale). Participants then completed the dichotic listening task using Koss UR-20 headphones and a desktop computer with a Windows operating system. The experiment consisted of three filtering conditions with 90 word pairs in each: the standard FDWT task, stimuli high-pass filtered at 2500 Hz, and stimuli low-pass filtered at 625 Hz. The word pairs in conditions 2 and 3 were filtered using Power Sound Editor Free version 6.3.1. Each filtering condition was further separated into three attention blocks of 30 word pairs. The word pairs rhymed and varied in their initial consonant: 15 bilabial, 6 alveolar, and 9 velar; 8 voiced and 22 unvoiced. The first attention block required participants to choose the word that was best heard. In the second attention block participants were instructed to attend to the left ear only and in the third attention block the instructions were to attend to the right ear only. Filtering conditions and word pairs were randomly ordered and placement of the headphones (right headphone to the right or left ear) was counterbalanced among all participants. Participants selected one word out of four word choices presented horizontally across the computer screen in front of them and the task progressed to the next trial upon selecting a word.

Statistical Analysis

Independent variables included filtering (no filter, high-pass, or low-pass), attention instructions (free recall, left ear, or right ear), POA phonemic category for stop consonants (bilabial/bilabial, bilabial/alveolar, bilabial/velar, alveolar/bilabial, velar/bilabial, or velar/velar), and VOT phonemic category (voiced/voiced, unvoiced/voiced, voiced/unvoiced, or unvoiced/unvoiced). The dependent variable was the number of correct responses. The REA was be determined by a laterality ratio in which positive values denote the degree of REA (+100 being the strongest) and negative values indicate the degree of LEA (-100 being the strongest):

$$\text{Laterality Ratio} = 100 * \left(\frac{\text{Correct RE-Correct LE}}{\text{Correct RE+Correct LE}}\right).$$

Data were analyzed using Microsoft Office Excel and IBM SPSS Statistics 19.0. Data were first analyzed in a 3x3x6 repeated-measures analysis of variance (ANOVA) with factors being filtering, attention, and POA of the initial consonant as the respective factors and laterality ratio as the dependent variable. Another 3x3x4 repeated-measures ANOVA was computed with filtering, attention, and VOT of the initial consonant as factors. The Bonferroni correction was used in tests of follow-up pairwise comparisons. Cell sizes were originally balanced among filtering and attention conditions, but became unbalanced when introducing phonetic characteristics. There was not equal sampling within the classifications of POA: bilabial/bilabial (*n*=2), alveolar/bilabial (*n*=6), velar/bilabial (*n*=7), bilabial/alveolar (*n*=6), bilabial/velar (*n*=7), velar/velar (*n*=2), or within VOT categories: voice/voice (*n*=2), unvoiced/voiced (*n*=6), voiced/unvoiced (*n*=6), and unvoiced/unvoiced (*n*=16). The Huynh-Feldt correction was applied to the results for cases that violated the assumption of sphericity (see Appendix A). T-tests were conducted to determine if mean performance in each condition was greater than chance.

Results

Place of Articulation

Table 1 shows the marginal means. The Filtering x Attention x POA ANOVA yielded a significant main effect only for POA, $F(2.5, 120.7)=5.17$, $p=.004$. Pairwise comparisons using the Bonferroni correction indicated that competition between two velars significantly reduced the REA in comparison with stimulus pairs that included bilabials, except when a velar was present in the right ear, $p\leq.05$. Nevertheless, the presence of a velar consonant in the right ear, with a bilabial in the left, yielded a reduced mean REA in comparison to the inclusion of two bilabials, $p=.03$. Statistically significant main effects were not found for filtering or attention.

The ANOVA yielded a significant Attention x POA interaction, *F(*8, 382.4)=4.63, *p*<.001. Figure 1 shows mean REAs for each POA combination as a function of attention condition. There was little additive effect of attention when a bilabial was presented to the right ear only, i.e., in the pairing of alveolar/bilabial and velar/bilabial. The pattern for dual velar pairs was opposite to what would be expected, i.e., left-ear attention produced the greatest REA and right-ear attention showed the smallest REA. However, in the other three word pairings, bilabial/bilabial, bilabial/alveolar, and bilabial/velar, the expected additive effects of attention condition were observed. ANOVA showed a significant 3-way interaction among all of the variables: filtering, attention, and POA, *F*(16.1, 772.7)=2.03, *p*=.009. Figures 2, 3, and 4 illustrate the effect of attention condition on the REA for each category of POA pairs under conditions of no filtering, high-pass filtering, and low-pass filtering, respectively. Statistically significant two-way interactions for filtering with attention or POA were not observed.

Voice Onset Time

Table 2 shows the marginal means. The Filtering x Attention x VOT ANOVA yielded a significant main effect for attention, *F*(2, 96)=10.62, *p*<.001. Focused attention to the right ear (*M*=19.86, *SE*=2.31) resulted in the greatest REA, whereas focused attention to the left ear (*M*=7.99, *SE*=2.17) was associated with the smallest observed REA. A significant main effect was also obtained for VOT, *F*(1.8, 85.9)=3.24, *p*=.049. Pairwise comparisons showed that unvoiced/voiced pairings had a greater REA than dual unvoiced pairs, *p*=.008. A statistically significant main effect was not found for filtering.

ANOVA yielded a significant interaction between attention and VOT, *F*(4.7, 225.3)=2.42, *p*=.04. The REA for pairs containing a voiced consonant increased as the attentional condition increasingly involved the RE. However, the REA for pairs of unvoiced consonants remained relatively constant across attentional conditions. These patterns are shown in Figure 5. Two-way interactions of filtering with attention or VOT were not obtained, nor was there a statistically significant 3-way interaction.

Accuracy

Table 3 displays the mean error rate for each level of filtering, attention, POA, and VOT. The overall error rate was 10.33% (*SD*=6.53). Mean performance was determined to greater than chance across all levels of filtering and attention. Dual bilabial word pairs had the lowest error rate (*M*=1.02%, *SD*=7.08), whereas dual velar pairs had the greatest rate of errors (*M*=57.14%, *SD*=41.56), which was more than 50%, *t*(440)=7.14, *p*<.001. Each dual velar item, coat/goat, *t*(440) = -5.11, p<.001, and goat/coat, *t*(440) = -2.70, *p*=.007, were determined to have mean error rates greater than 50%. Dual voiced and dual unvoiced pairs had lower error rates than pairs including both voiced and unvoiced consonants.

Discussion

The first experiment was aimed at defining the effects of filtered stimuli, attention, POA, and VOT on the REA. The objectives were to determine which factors were important in determining laterality and whether those factors would interact additively.

It was predicted that low frequencies (low-pass filtering) would reduce the REA, while high frequencies (high-pass filtering) would enhance the normal REA. However, differential filtering effects were obtained only in conjunction with the manipulation of both place of articulation and attention. Under low-pass filtering and left attention, conditions that are expected to reduce the REA, there is little differentiation among POA categories in predicting the REA. There was no observed main effect of filtering on the REA though.

These results do not provide evidence for the DFF theory and the importance that the theory places on frequency for the processing of speech. It is possible that the cut-off frequencies specified for filtering caused the filters to be too weak to demonstrate the expected effects. Alternatively, it might be necessary to filter the left- and right-ear signals differentially, e.g., with high-pass filtering of one channel and simultaneous low-pass filtering of the other channel, in order to alter the REA. Differential filtering would assess the possibility that relative disparity in sound frequency, rather than the absolute frequency, determines the hemisphere that preferentially processes a signal (Ivry & Robertson, 1999).

It was also predicted that focused attention to the right ear would produce a strong REA, whereas focused attention to the left ear would result in the smallest REA. The results supported this hypothesis but also indicated that attention interacted with both phonetic categories. Across VOT and POA, some phonetic combinations showed additive effects by attention, but other phonetic pairings did not. The effects of attention had the opposite directionality when velars were presented, and dual velars generally showed a LEA across all attentional levels. Based on Voyer and Techentin (2009) it was expected that velars would show the greatest REA. However, these researchers demonstrated that participants most often selected the bilabial ‘p’, as well as velar consonants, well above other consonants.

Differences in VOT had unexpected results. It was initially predicted that unvoiced consonants in the RE would produce the greatest REA, but the data indicate that when one unvoiced and one voiced consonant were presented together, the REA was larger than that obtained with either dual unvoiced or voiced pairs. Unvoiced consonants did not show the large, persistent REA that was expected. Interaction between VOT and attention was demonstrated as well, indicating that voiced consonants in the RE showed large additive effects of attention, whereas unvoiced consonants in the RE produced an REA that was stable across attentional conditions.

Overall, there were strong effects of attention and phonetic characteristics on the REA. There were some unexpected effects of phonetic characteristics, although the body of research for this specific topic is minimal at this time. The results failed to show main effects of filtering, which is inconsistent with the DFF theory. This theory may not be accounting for the primary methods of speech processing. Frequency-filtering may not be as influential as other factors, such as attention and phonetics, on the REA at the cortical level of processing.

Experiment 2

Method

Participants

Data were obtained from an undergraduate psychology honors thesis conducted by Natasha Lachner, under the supervision of Dr. Merrill Hiscock. Fifty-one right-handed University of Houston undergraduate students (13 males and 38 females) volunteered to participate and are included in the dataset. The mean age of participants was 21.7 years (*SD*=2.6) and ranged from 18 to 33 years. Participants were excluded if they reported abnormal hearing. The degree of right-handedness for each participant was assessed using a modified form of the Edinburgh Handedness Inventory.

Materials

The materials used were identical to those used in Experiment 1. The signals and noise were amplified to a sound intensity of 80 dB (A-scale). The degree of right-handedness was again calculated using the laterality ratio. The mean handedness laterality among all participants was +73.0 (*SD*=20.8) and ranged from +33.3 to +100.

Procedure

The procedure was similar to that used in Experiment 1. However, this experiment consisted of four noise conditions: the standard FDWT task without noise; stimuli presented in background white noise stimuli presented in background noise that was high-pass filtered at 1250Hz; and stimuli presented in background noise that was low-pass filtered at 1250Hz. The word pairs in conditions 2, 3, and 4 were modified using Power Sound Editor Free version 6.3.1. Characteristics of the applied filters are discussed in Experiment 1.

Statistical Analysis

Independent variables included background noise condition (no noise, white noise, high-pass filtered noise, or low-pass filtered noise), attention instructions (free recall, left-ear attention, or right-ear attention), POA category for stop consonants (bilabial/bilabial, bilabial/alveolar, bilabial/velar, alveolar/bilabial, velar/bilabial, or velar/velar), and VOT category (voiced/voiced, unvoiced/voiced, voiced/unvoiced, or unvoiced/unvoiced). The dependent variable was the number of correct responses. The laterality ratio was calculated based on the equation used in Experiment 1.

Data were analyzed using Microsoft Office Excel and IBM SPSS Statistics 19.0. POA data were analyzed in a 4x3x6 repeated-measures ANOVA with noise condition, attention, and POA of the initial consonant as the respective factors and laterality ratio as the dependent variable. Another 4x3x4 repeated-measures ANOVA was computed with noise condition, attention, and VOT of the initial consonant as factors. The Bonferroni correction was used in tests of follow-up pairwise comparisons. Cell sizes were originally balanced among noise and attention conditions, but became unbalanced when introducing phonetic characteristics; phonetic characteristics of the stimuli words are described in Experiment 1. The Huynh-Feldt correction was applied to the results for cases that violated the assumption of sphericity (see Appendix A for further information). T-tests were conducted to determine if mean performance in each condition was greater than chance.

Results

Place of Articulation

A Noise x Attention x POA ANOVA with laterality as the dependent variable yielded significant main effects for each of the factors (Table 4). A significant main effect for noise, $F(2.2, 108.9)=3.82$, $p=.022$, indicates that the addition of unfiltered white noise reduced the REA as compared with the presence of high-pass filtered white noise, $p=.003$. There was also a significant main effect for the attentional instructions, $F(2, 100)=6.05$, $p=.003$. Attention directed to the left ear ($M=4.02$, $SE=2.66$) produced a smaller REA than attention to the right ear ($M=10.37$, $SE=2.78$), $p=.005$. Place of articulation also had a significant main effect on ear laterality, $F(2.8, 137.6)=3.86$, $p=.013$. Dual bilabials produced the greatest REA ($M=19.12$, $SE=4.20$) and a pair of velars produced the smallest mean REA ($M=-7.35$, $SE=2.85$).

There was a significant interaction of noise and attention on the REA, $F(6, 300)=3.85$, $p=.001$. As shown in Figure 6, the addition of noise, with or without filtering, reduced the differences among attention conditions. A significant interaction of attention and POA was also obtained, $F(6.4, 319.7)=2.53$, $p=.019$. Figure 7 shows that the normally strong REA of bilabial consonants was further enhanced by the addition of attention focused on the right ear (*M*=28.92, *SD*=4.87). There was not a significant interaction of noise with POA or among all factors.

Voice Onset Time

Table 5 shows the means associated with main effects. A significant main effect was obtained for attention, *F*(2, 100)=9.43, *p*<.001. Pairwise comparisons showed that focused attention to the right ear produced a larger REA (*M*=14.04, *SE*=3.46) than either attention to the left ear, *p*=.034, or divided attention, *p*=.001. There were no statistically significant main effects for noise or VOT.

A significant interaction of noise and attention, *F*(5.3, 262.8)=5.12, *p*<.001, again indicated that the addition of noise reduced the differences among attention conditions. Statistically significant interactions were not obtained between noise and VOT or between attention and VOT, and the 3-way interaction was not significant.

Accuracy

Table 6 depicts mean percent error score for each factor and level. The overall error rate was 14.44% (*SD*=11.30). Mean performance was greater than chance across all levels of noise and attention. Dual velar pairs had the largest error rate (*M*=54.66%, *SD*=42.80) of the other POA combinations and were performed at an error rate greater than 50%, *t*(611)=2.69, *p*=.007. The goat/coat pair yielded performance at the level of chance, *t*(611)=0.49, *p*>.05, and the coat/goat pair yielded an error rate greater than 50%, *t*(611)=-5.20, *p*<.001. All other phonemic categories and word pairs were endorsed over the distractor words with greater accuracy than chance.

Discussion

The second experiment was designed to determine the influence of background noise, attention, POA, and VOT on the REA. Unfiltered white noise was predicted to show the greatest reduction in the REA because it would minimize bottom-up factors that produce the REA. The results indicated that white noise reduced the REA in comparison with the high-pass condition. The baseline condition in which stimuli were presented in the absence of noise had a greater REA than this high-pass condition but was not significant because of the greater variance noted. It was also hypothesized that white noise would diminish the REA to a greater extent than filtered noise. High-pass filtered noise demonstrated a larger REA than white noise, although low-pass filtered noise did not. Low-pass filtered noise was predicted to enhance REA magnitude, while high-pass filtered noise was predicted to reduce the REA. However, the results showed that high- and low-pass filtered noise did not alter the REA obtained in the baseline condition. This lack of an effect for the filtering of noise does not provide support for the DFF theory. However, the processing of linguistic stimuli within noise is not specifically discussed and may have different implications than directly manipulating the relative sound frequency of the linguistic stimuli.

It was hypothesized that attention would affect the REA, such that focused attention to the right ear would produce the greatest REA, divided attention would produce a moderate REA, and focused attention to the left ear would show the smallest REA. This hypothesis was supported by a main effect of attention that reflected this pattern. Attention also interacted with noise and POA. The typical effects of attention were diminished by noise. Furthermore, attention to the right ear was shown to enhance disproportionately the already large REA of bilabial consonants but these additive effects of attention were not note for other consonants.

There were significant effects of POA, such that bilabials produced a strong REA and velar presentation produced an overall LEA. This was somewhat unexpected based on previous findings (Voyer & Techentin, 2009), but consistent with the results of Experiment 1. However, Experiment 2 yielded no significant results of VOT to report. As there were significant VOT effects in Experiment 1, there may be a selective influence of the background noise on the phonemic category of VOT. Noise may suppress the processing of characteristics of VOT that are important to determining laterality.

The strong effects of attention and POA on the REA were reproduced in Experiment 2. Although high- and low-pass filtering of the dichotic stimuli in Experiment 1 did not have a significant effect on the REA, the introduction of background noise in Experiment 2 had a strong effect on selective attention.

General Discussion

A large research literature addresses auditory laterality and particularly the prevalence and magnitude of the REA under varying conditions (Hugdahl, 1998, 2011). The influence of attention on ear asymmetries has been studied extensively (Hiscock & Kinsbourne, 2011), but less information is available regarding the influence of other variables such as the frequency components of stimuli, background noise, place of articulation, and voice onset time. The present study was designed to evaluate whether these other factors have effects on the laterality of speech perception, and whether they interact with attention instructions or have only additive effects on the REA.

The addition of background noise, as well as the high-pass and low-pass filtering of the noise, appears to have a considerable effect on auditory perception, whereas the filtering of speech stimuli themselves has a weaker effect that depends on other factors such as phonetics and attention. Attention interacted repeatedly with noise and phonetic characteristics of the stimuli, and appeared to have the expected effects on selected phonetic pairings but not others.

It was hypothesized that unvoiced and velar consonants in the right ear would enhance the REA, and that voiced and bilabial consonants in the right ear would diminish the REA. POA and VOT effects on the REA were found, with the exception of VOT effects in the presence of background noise, but the direction of these effects was not consistent with the hypotheses. There was a strong REA when bilabial consonants were presented to either ear and a greatly reduced REA with velar consonants. The results support the conclusion that, regardless of ear of presentation, voiced and bilabial consonants produce a strong REA whereas unvoiced and velar consonants produce the smallest REA. These results are unexpected based on the extant literature, although there very few existing studies describing the effects of POA. VOT effects were not observed in the presence of background noise, but significant effects materialized when the stimuli were filtered. It was shown that an unvoiced/voiced pairing enhanced the REA in comparison with a dual unvoiced pair. This was unexpected. Based on previous studies regarding stimulus onset asynchrony and the lag effect, pairs with voiced and unvoiced consonants were expected to be more accurately perceived than dual voiced or unvoiced pairs. However, unvoiced/voiced pairings in fact had stronger REAs than pairs with an unvoiced consonant in the RE or both ears. Additionally, pairs that included an unvoiced and voiced consonant were associated with greater mean percentages of errors than only voiced or only unvoiced pairs.

It is important to note that instructed focus of attention, which is considered to be a controlled, top-down (endogenous) variable (Hiscock & Kinsbourne, 2011), interacts significantly with phonetic and frequency characteristics of the stimuli, which are considered bottom-up (exogenous) variables. Across each experiment attention was shown to interact with phonetic characteristics and background noise in determining the degree of laterality. Based on Hugdahl (2000), it was proposed that there would be additive effects among top-down and bottom-up effects on the asymmetry of speech perception. The present results provide some evidence for additive effects of attention and selected phonetic characteristics, but not for additive effects across all factors. The magnitude of the REA was determined not only by bottom-up factors but also by the interaction of bottom-up factors with the top-down variable of volitional attention. There was a significant interaction between the bottom-up factors of stimulus filtering and POA, but this interaction was modulated by the top-down factor of attention, as indicated by a significant three-way interaction. This constitutes further evidence that each factor contributes to the overall REA in the perception of speech, and it supports the interpretation of speech processing as a composite of many factors, including speech-sound frequency, attention, and certain phonetic attributes of the initial stop consonant.

One of the limitations of this study is that it was archival. Therefore, although noise, stimulus filtering, and attention were balanced for the purpose of their initial investigation, the Halwes Fused Dichotic Words Test (FDWT) is not balanced by phonetic classifications so as to include all possible POA combinations. The unbalanced design may have resulted in low sensitivity for detecting differences within phonetic categories as well as possible interactions between phonetic categories and the other factors. Furthermore, the datasets were dependent on the choice of filtering previously specified. The filters in Experiment 1 may have been too loose to elicit the predicted effects of filtering. Consequently, the cut-off selected for filtering noise at in Experiment 2 was adjusted, but the resultant filtering may not have been optimal for disrupting only the high- or low-frequency component of the superimposed speech signal. The discrepancy in filter parameters makes it difficult to compare results of filtering between the two experiments. On the other hand, the filtering of the speech signal and the filtering of background noise may require different filter parameters if they are to cause comparable disruption of perception. Future research will be necessary to determine if there is a point at which high- and low-pass filtering is effective in producing results consistent with the DFF theory and, as noted previously, it may be necessary to filter the two simultaneous speech sounds differently.

Effects of POA were inconsistent with previous studies with respect to the ear advantage obtained for bilabial and velar consonants. Why dual velar pairs were selected less often than the distractor words in both experiments is not understood. Furthermore, there is no obvious explanation for the finding that participants consistently selected the word presented to the left ear when they did correctly select one of the velar words. The literature base is minimal for studies attempting to demonstrate POA effects on the REA. Future research should be undertaken to confirm the directionality of ear advantages for bilabials and velars. Furthermore, additional research is necessary to explain why velars are preferentially reported from the left ear and why they show such high error rates.

In the present study only one top-down factor was investigated, viz., attention, which has shown historically strong and reliable effects. Therefore, determining if additional top-down have effects on the asymmetry of speech perception may be of interest for future research. Top-down factors of interest might include word frequency in the English language, participant familiarity with stimulus words, and regional accents. There are likely to be many factors, besides those chosen for this study, that have the potential to influence the overall laterality of speech processing.

Hugdahl (2000) proposed a compromise solution to the apparent conflict between Kimura's structural model and Kinsbourne's attentional model of speech perception by suggesting that speech perception is the additive result of all factors, top-down and bottom-up. Top-down factors are exemplified by volitional shifts of attention, which can either enhance or diminish the REA, which is attributable in Hugdahl's model to bottom-up (i.e., stimulus) factors. According to Hugdahl, the inherent REA for speech sounds depends fundamentally on the asymmetrical structure of the brain and its input pathways. Hugdahl postulates that this REA is determined by stimulus characteristics but can be modified somewhat by volitional shifts of attention. Hiscock, Kinsbourne, and Inch (1999) proposed a similar model in which ear asymmetry in an initial stage of signal processing is determined by stimulus characteristics but may be altered in a second stage of processing by top-down variables. One of the major differences between models is that Hiscock et al. (1999) proposed that asymmetry at the first stage is attributable either to fixed, structural factors or to a pervasive rightward attention bias that is generated by exogenous factors. Thus, whereas the Hugdahl model construed the REA as the resultant of various top-down and bottom-up factors, the Hiscock et al. model implies that the top-down factors reflect decision processes that are distinct from the bottom-up processes--whether structural or attentional--that produce the characteristic REA for a particular category of dichotic stimuli. Hiscock et al. supported their model with evidence that volitional attention shifts alter the REA for localization of dichotic stimuli in a signal-detection paradigm but they do not alter the REA for detection.

The present study did not show additive effects, but rather, the results yielded consistent interactions among top-down and bottom-up processing components. The present study thus supports a compromise between the structural and attentional models, but not the specific compromises that either Hugdahl (2000) or Hiscock et al. (1999) had proposed. In demonstrating interactive rather than additive effects among top-down and bottom-up factors, it highlights the importance of considering simultaneously the stimulus factors and the attentional factors that underlie asymmetries of speech perception. The results of this study were not consistent with the predominance of one set of variables over the other, but rather showed that both are involved. Researchers often attempt to investigate either top-down or bottom-up factors, but rarely both in the same study. This study should encourage researchers to design experiments that consider both categories of variable that influence speech perception and the REA. Further investigation is necessary to understand the degree of importance of interactions between top-down and bottom-up variables for the perception and processing of speech.

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Table 1. Marginal means of ear laterality for Experiment 1, including POA. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SE***
Filtering	No Filter	10.73	2.03
	High-Pass Filtered	8.64	1.90
	Low-Pass Filtered	10.19	1.69
Attention	Left-Ear	8.27	1.78
	Divided	9.19	1.79
	Right-Ear	12.10	1.59
Place of Articulation	Bilabial/Bilabial	27.21	4.71
	Alveolar/Bilabial	12.22	6.58
	Velar/Bilabial	12.23	5.40
	Bilabial/Alveolar	12.85	6.04
	Bilabial/Velar	6.87	5.25
	Velar/Velar	-12.25	3.31

Table 2. Marginal means of ear laterality for Experiment 1, including VOT. The first VOT category applies to the LE stimulus and the second VOT category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SE***
Filtering	No Filter	15.41	2.57
	High-Pass Filtered	12.87	2.28
	Low-Pass Filtered	13.52	2.13
Attention	Left-Ear	7.99	2.17
	Divided	13.95	2.31
	Right-Ear	19.86	2.31
Voice Onset Time	Voiced/Voiced	8.77	3.22
	Unvoiced/Voiced	22.39	4.90
	Voiced/Unvoiced	18.31	5.52
	Unvoiced/Unvoiced	6.26	1.16

Table 3. Mean percent errors committed in Experiment 1 among each of the levels of filtering, attention, and phonetics. Performance accuracy (left- or right-ear hit) compared to chance selection at 50%. The first POA or VOT category applies to the LE stimulus and the second POA or VOT category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SD***	***df***	***t***	***p***
Filtering	No Filter	10.57	6.11	146	-78.23	<.001
	High-Pass Filtered	8.75	6.31	146	-79.31	<.001
	Low-Pass Filtered	11.68	6.85	146	-67.82	<.001
Attention	Left-Ear	11.84	7.36	146	-62.84	<.001
	Divided	9.48	6.07	146	-81.00	<.001
	Right-Ear	9.68	5.83	146	-83.84	<.001
POA	Bilabial/Bilabial	1.02	7.08	440	-48.98	<.001
	Alveolar/Bilabial	9.11	11.87	440	-40.89	<.001
	Velar/Bilabial	6.54	9.57	440	-43.46	<.001
	Bilabial/Alveolar	9.03	11.33	440	-40.97	<.001
	Bilabial/Velar	5.57	9.80	440	-44.43	<.001
	Velar/Velar	57.14	41.56	440	7.14	<.001
VOT	Voiced/Voiced	3.40	13.48	440	-46.60	<.001
	Unvoiced/Voiced	17.35	14.02	440	-32.65	<.001
	Voiced/Unvoiced	14.93	13.70	440	-35.07	<.001
	Unvoiced/Unvoiced	6.85	7.09	440	-43.15	<.001
Overall		10.33	6.53	440	-127.60	<.001

Table 4. Marginal means of ear laterality for Experiment 2, including POA. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SE***
Noise	No Noise	11.02	2.23
	White Noise	1.97	3.85
	Low-Pass White Noise	6.82	3.09
	High-Pass White Noise	10.48	3.31
Attention	Left-Ear	4.02	2.66
	Divided	8.32	2.93
	Right-Ear	10.37	2.78
Place of Articulation	Bilabial/Bilabial	19.12	4.20
	Alveolar/Bilabial	11.96	7.29
	Velar/Bilabial	10.42	4.54
	Bilabial/Alveolar	5.82	4.04
	Bilabial/Velar	5.47	5.04
	Velar/Velar	-7.35	2.85

Table 5. Marginal means of ear laterality for Experiment 2, including VOT. The first VOT category applies to the LE stimulus and the second VOT category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SE***
Noise	No Noise	13.49	2.67
	White Noise	3.53	4.50
	Low-Pass White Noise	9.03	3.57
	High-Pass White Noise	10.42	4.08
Attention	Left-Ear	4.26	3.14
	Divided	9.06	3.46
	Right-Ear	14.04	3.46
Voice Onset Time	Voiced/Voiced	3.11	3.57
	Unvoiced/Voiced	11.36	6.58
	Voiced/Unvoiced	15.41	4.50
	Unvoiced/Unvoiced	6.60	3.32

Table 6. Mean percent errors committed in Experiment 2 among each of the levels of noise, attention, and phonetics. Performance accuracy (LE or RE hit) compared to chance (50%). The first POA or VOT category applies to the LE stimulus and the second POA or VOT category applies to the RE stimulus.

Variable	**Level**	**Mean**	***SD***	***df***	***t***	***p***
Noise	No Noise	8.61	6.63	152	-77.23	<.001
	White Noise	21.76	14.42	152	-24.22	<.001
	Low-Pass White Noise	14.68	10.56	152	-41.35	<.001
	High-Pass White Noise	12.72	7.66	152	-60.19	<.001
Attention	Left-Ear	16.11	12.07	203	-40.10	<.001
	Divided	13.73	11.51	203	-45.03	<.001
	Right-Ear	13.50	10.11	203	-51.60	<.001
Place of Articulation	Bilabial/Bilabial	13.73	28.02	611	-32.03	<.001
	Alveolar/Bilabial	11.87	15.45	611	-61.03	<.001
	Velar/Bilabial	10.32	14.47	611	-67.85	<.001
	Bilabial/Alveolar	13.67	16.98	611	-52.93	<.001
	Bilabial/Velar	7.98	12.05	611	-86.25	<.001
	Velar/Velar	54.66	42.80	611	2.69	.007
VOT	Voiced/Voiced	8.33	22.62	611	-45.58	<.001
	Unvoiced/Voiced	19.23	15.31	611	-49.73	<.001
	Voiced/Unvoiced	18.71	16.87	611	-45.89	<.001
	Unvoiced/Unvoiced	11.82	13.21	611	-71.51	<.001
Overall		14.44	11.30	611	-77.83	<.001

Figure 1. Effects of attention and POA on the REA in Experiment 1. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

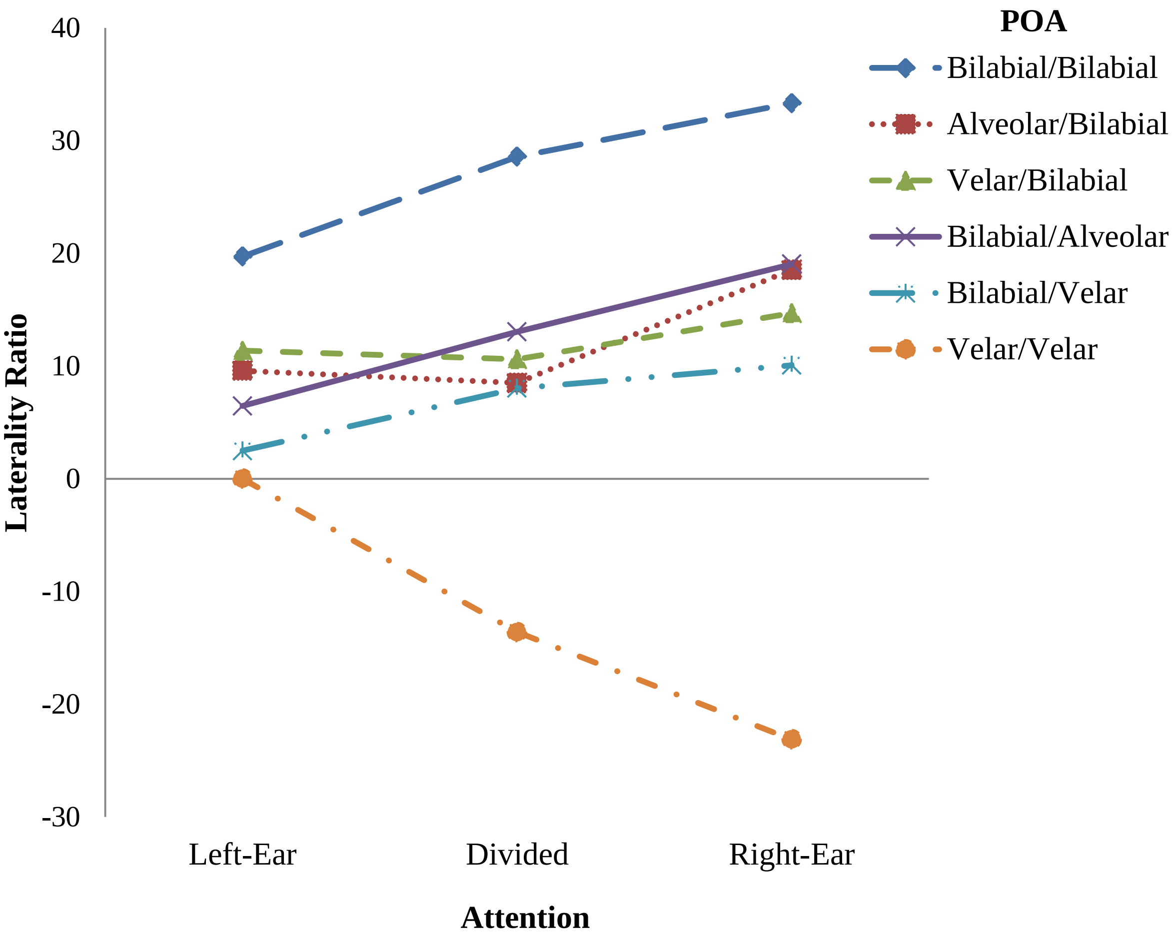


Figure 2. Effects of filtering, attention, and POA on the REA in Experiment 1. The effect of attention and POA when there is no filtering. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

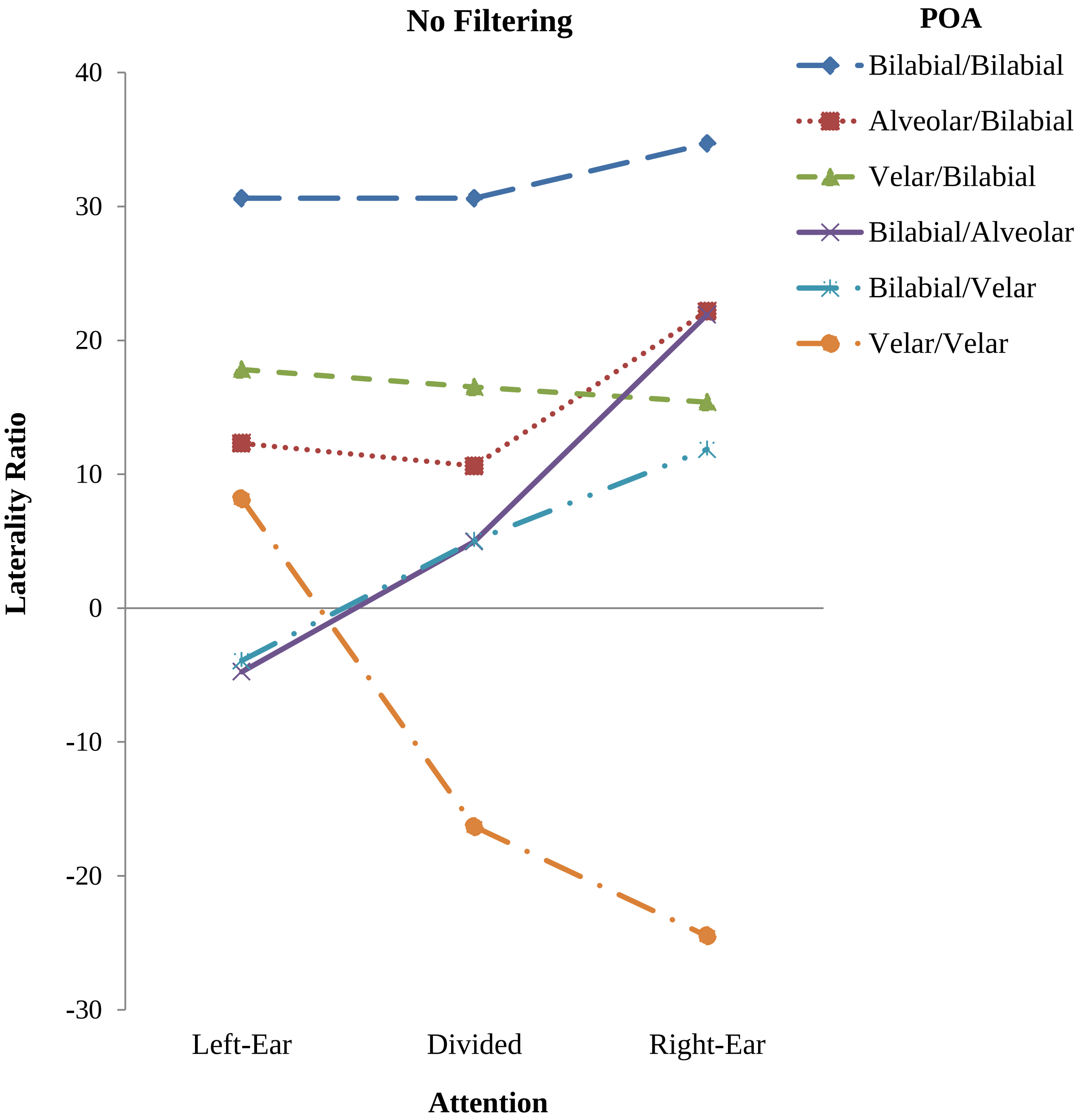


Figure 3. Effects of filtering, attention, and POA on the REA in Experiment 1. The effect of attention and POA on the REA within the context of high-pass filtering. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

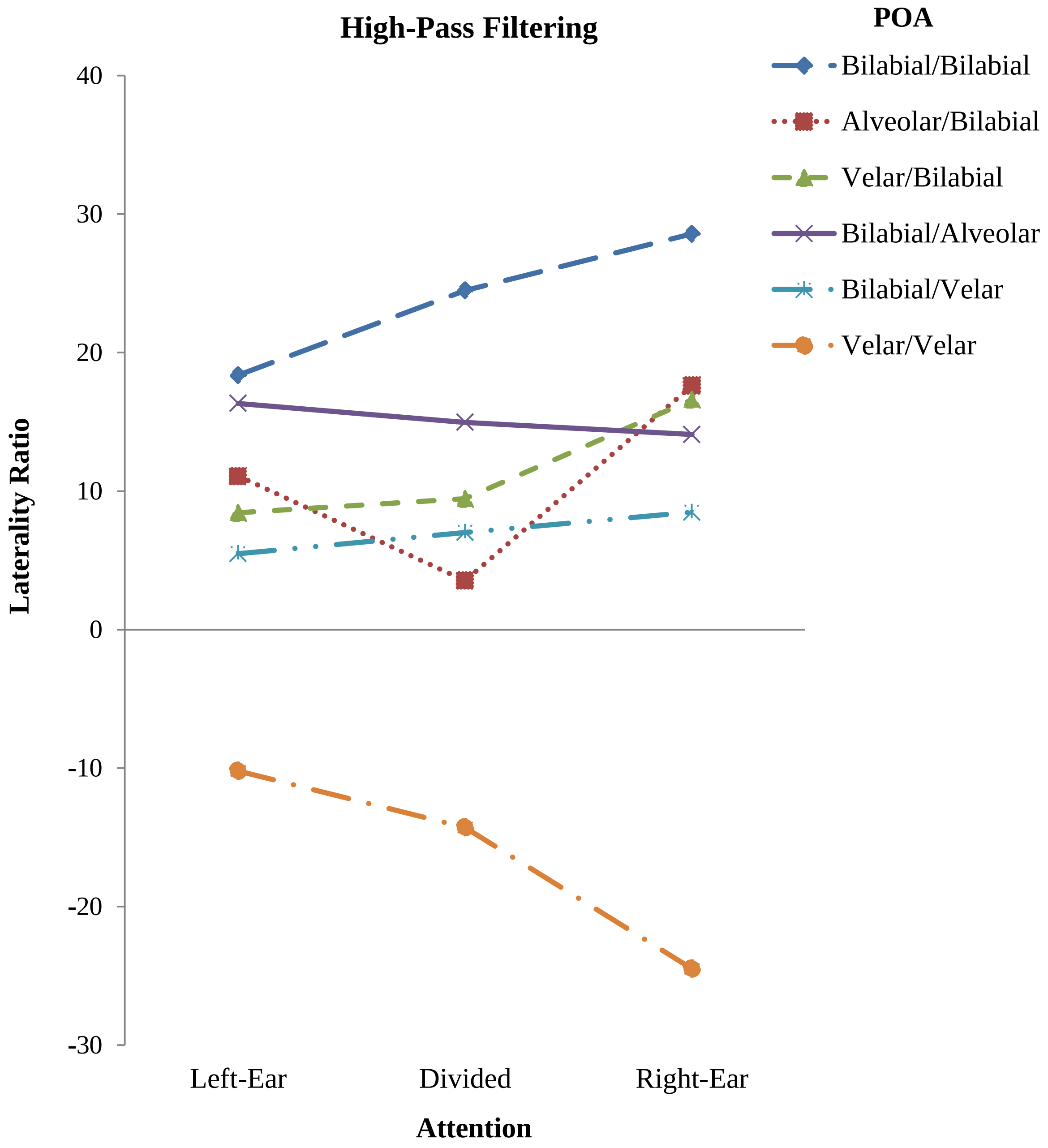


Figure 4. Effects of filtering, attention, and POA on the REA in Experiment 1. The effect of attention and POA on the REA within the context of low-pass filtering. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.

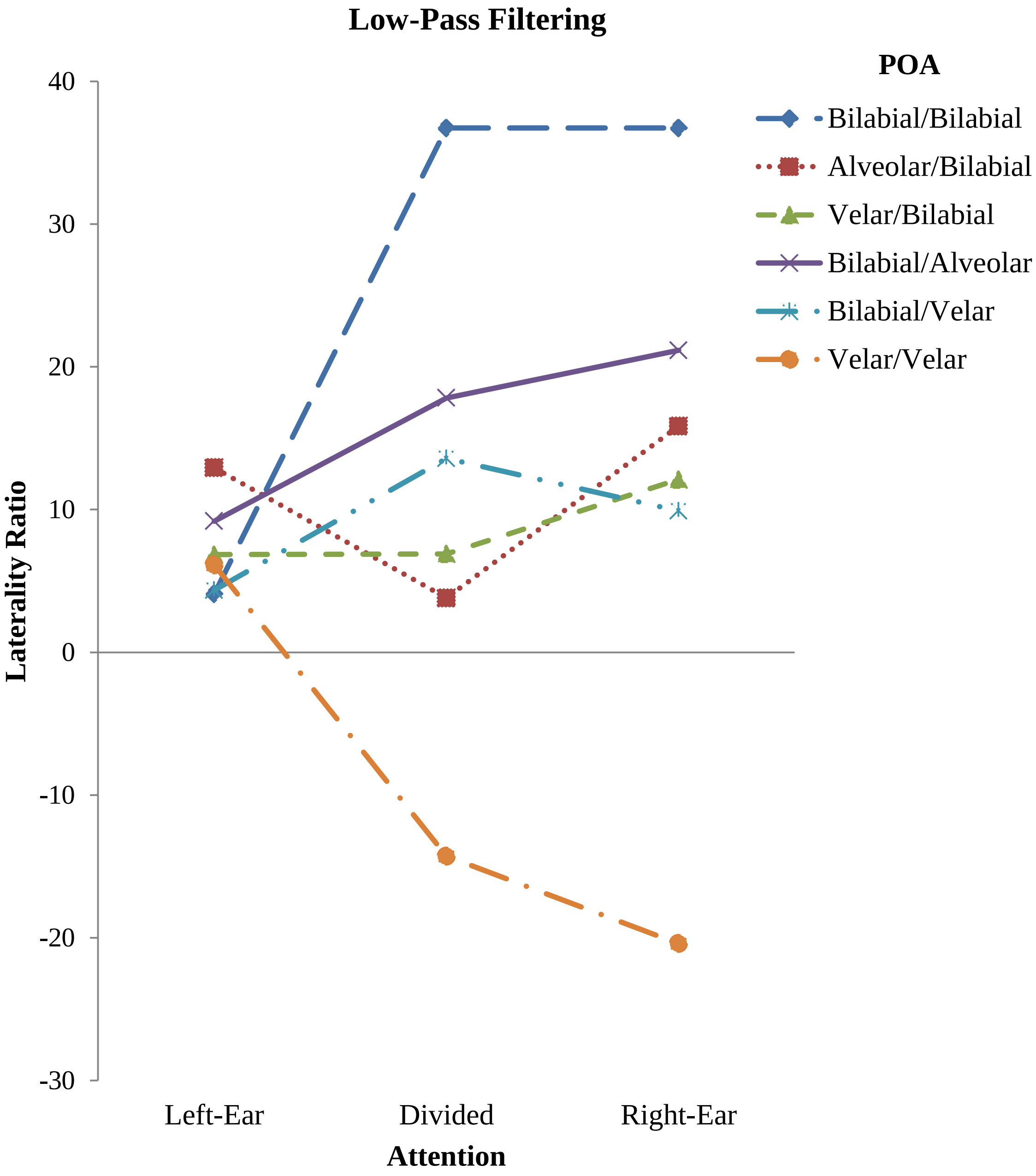


Figure 5. Effects of attention and VOT on the REA in Experiment 1. The first VOT category applies to the LE stimulus and the second VOT category applies to the RE stimulus.

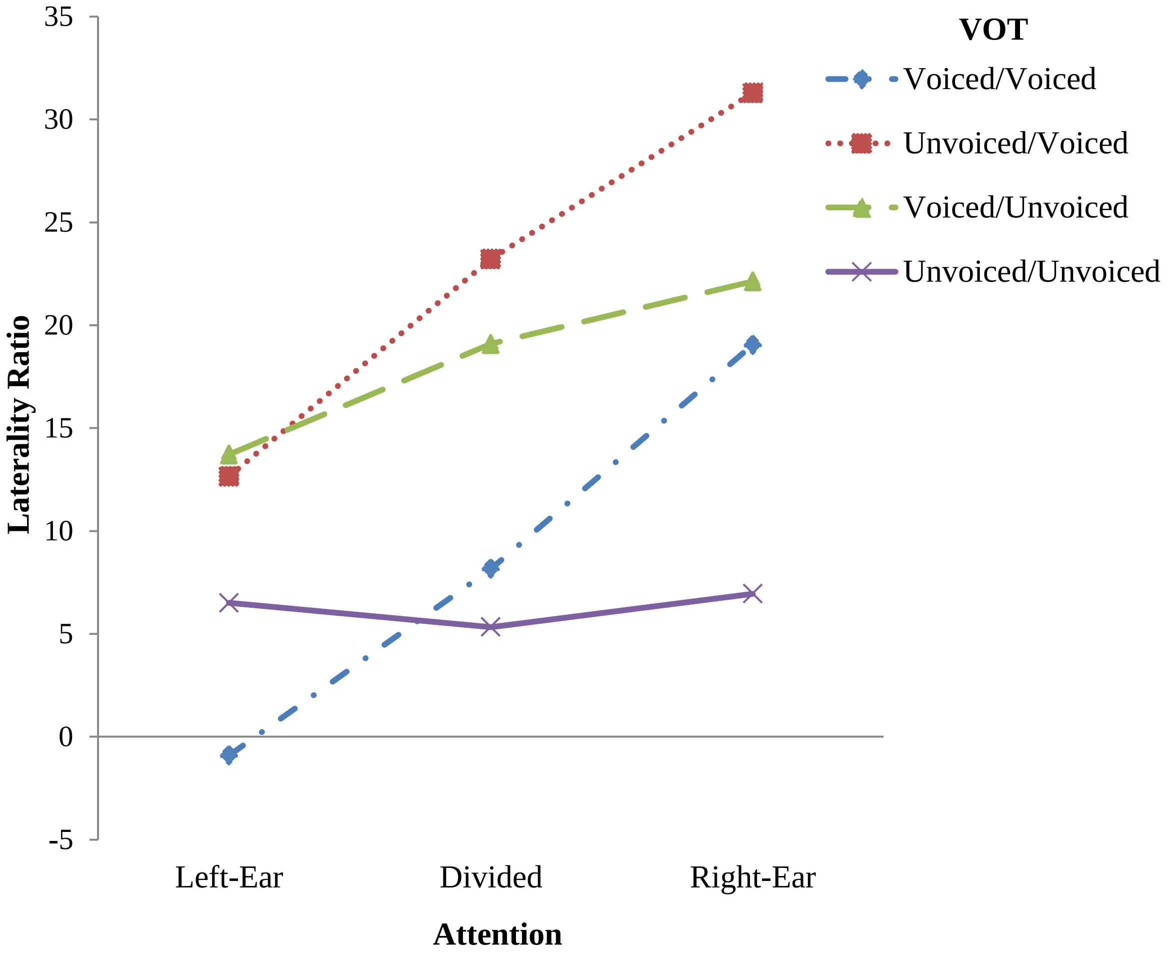


Figure 6. Effects of noise and attention on the REA in Experiment 2.

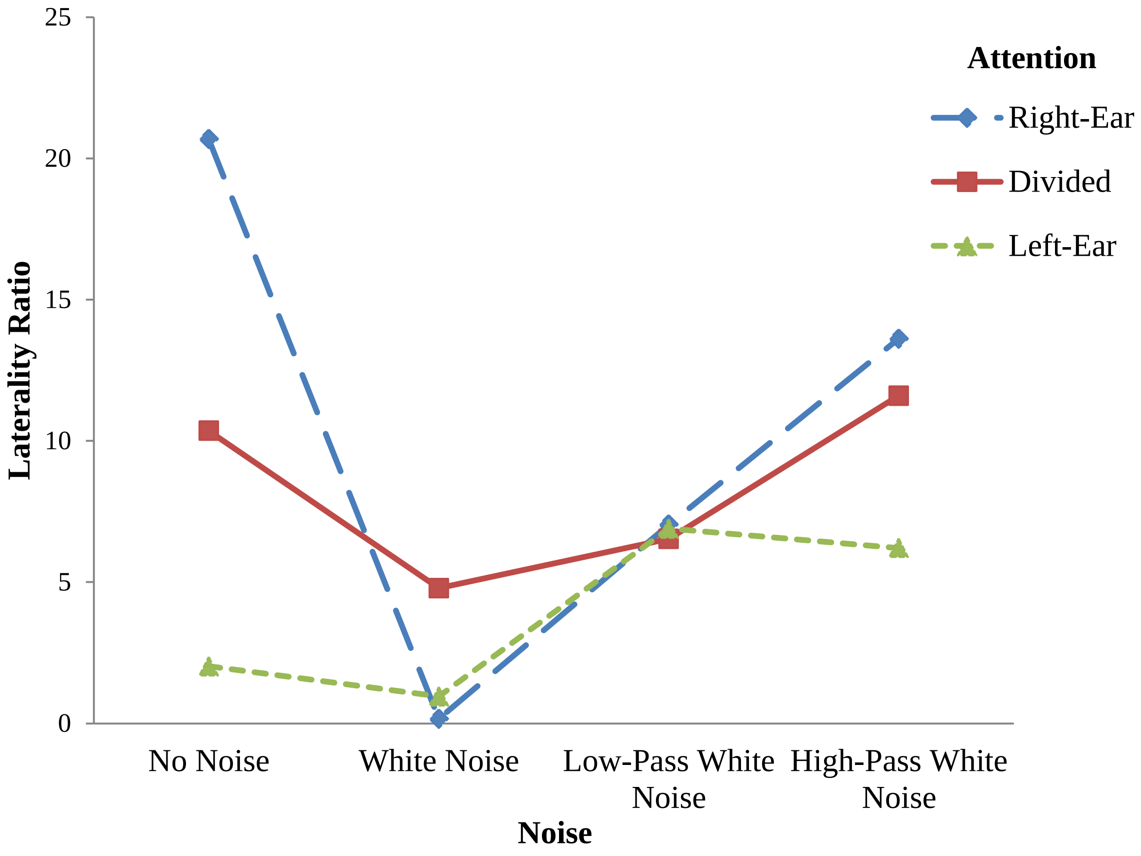
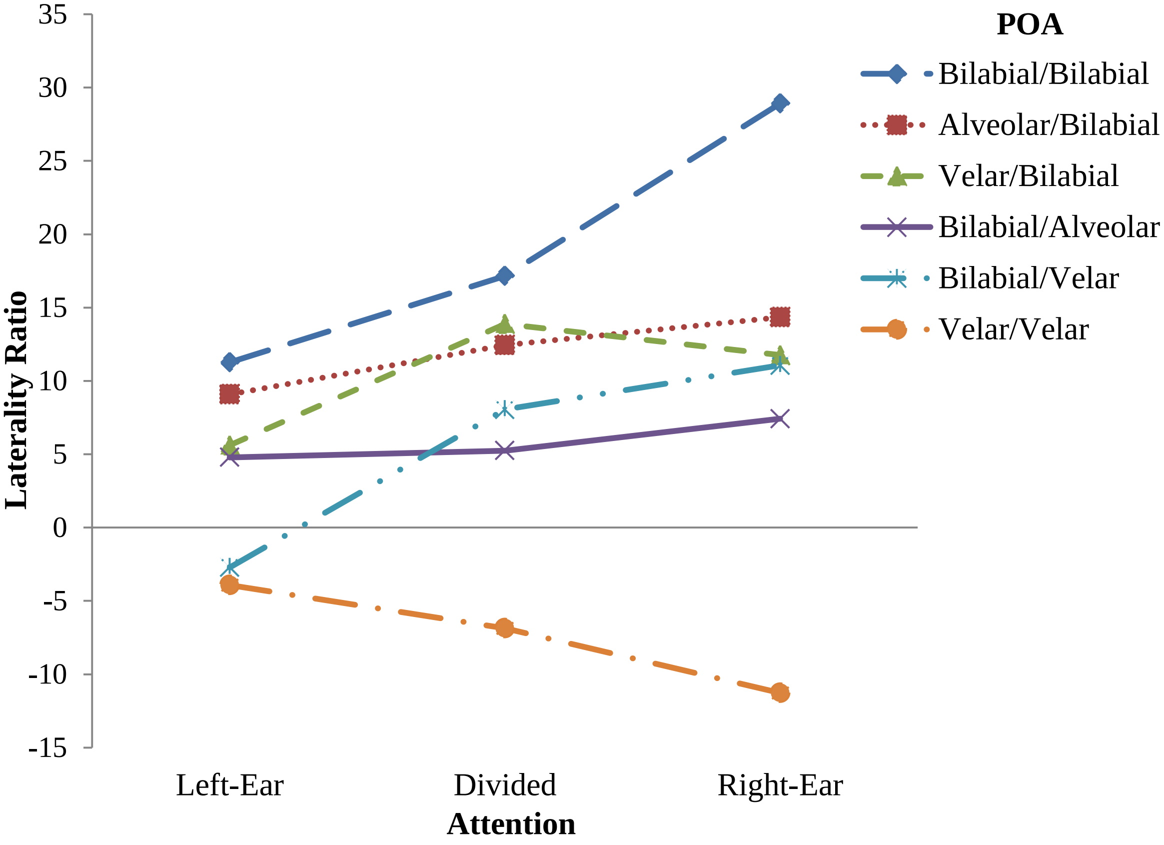


Figure 7. Effects of attention and POA on the REA in Experiment 2. The first POA category applies to the LE stimulus and the second POA category applies to the RE stimulus.



Appendix A. Results of sphericity testing by each experiment and analysis of variance.

Experiment 1 – Place of Articulation:

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of POA, $\chi^2(14)=143.94$, $p<.001$, as well as the interactions of filtering and POA, $\chi^2(54)=201.36$, $p<.001$, attention and POA, $\chi^2(54)=118.88$, $p<.001$, and the 3-way interaction, $\chi^2(209)=319.03$, $p<.001$. Therefore degrees of freedom were corrected using the Huynh-Feldt estimates of sphericity where appropriate: $e=.50$ for the main effect of VOT, $e=.50$ for the interaction of filtering and VOT, $e=.80$ for the interaction of attention and VOT, and $e=.81$ for the 3-way interaction of all variables.

Experiment 1 – Voice Onset Time:

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of VOT, $\chi^2(5)=66.81$, $p<.001$, as well as the interactions of filtering and VOT, $\chi^2(20)=72.65$, $p<.001$, attention and VOT, $\chi^2(20)=71.42$, $p<.001$, and the 3-way interaction, $\chi^2(77)=176.98$, $p<.001$. Therefore degrees of freedom were corrected using the Huynh-Feldt estimates of sphericity where appropriate: $e=.60$ for the main effect of VOT, $e=.84$ for the interaction of filtering and VOT, $e=.78$ for the interaction of attention and VOT, and $e=.80$ for the 3-way interaction of all variables.

Experiment 2 – Place of Articulation:

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of noise, $\chi^2(5)=29.59$, $p<.001$, and POA, $\chi^2(14)=127.02$, $p<.001$, as well as the interactions of noise and POA, $\chi^2(119)=203.97$, $p<.001$, attention and POA, $\chi^2(54)=151.84$, $p<.001$, and the 3-way interaction, $\chi^2(464)=646.89$, $p<.001$. Therefore degrees of freedom were corrected using the Huynh-Feldt estimates of sphericity where appropriate: $e=.73$ for the main effect of noise, e=.55 for the main effect of POA, e=.83 for the interaction of noise and POA, e=.64 for the interaction of attention and POA, and e=.76 for the 3-way interaction of all variables.

Experiment 2 – Voice Onset Time:

Mauchly’s test indicated that the assumption of sphericity had been violated for the main effects of noise, $\chi^2(5)=32.33$, $p<.001$, and VOT, $\chi^2(5)=101.62$, $p<.001$, as well as the interactions of noise and attention, $\chi^2(20)=38.56$, $p=.008$, noise and VOT, $\chi^2(44)=105.81$, $p<.001$, attention and VOT, χ^2(20)=33.92, $p=.027$, and the 3-way interaction, $\chi^2(170)=268.56$, $p<.001$. Therefore, degrees of freedom were corrected using the Huynh-Feldt estimates of sphericity where appropriate: e=.72 for the main effect of noise, e=.48 for the main effect of VOT, e=.88 for the interaction of noise and attention, e=79 for the interaction of noise and VOT, e=.91 for the interaction of attention and VOT, and e=.88 for the 3-way interaction of all variables.