# Impact of Effortful Word Recognition on Supportive Neural Systems Measured by Alpha and Theta Power

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**Objectives:** The goal of this study was to use theta and alpha electroencephalography (EEG) frequency power and self-report measures to examine performance monitoring, cognitive inhibition, and perceived effort required for speech understanding in noise. It was hypothesized that with a linear increase in word recognition task difficulty, there would be a linear increase in listening effort and word recognition performance would decrease in the challenging conditions. In addition, theta and alpha power would have an inverted U-shape across easy to challenging listening conditions. The inverted U-shape would reflect the neural underpinnings of listening effort that cannot be measured by task performance alone.

**Design:** EEG data were collected in 34 normal-hearing adults (18 to 33 years old) during the Words-In-Noise (WIN) test, which was presented in sound field. EEG frequency data were averaged and analyzed at three frontal channels for theta power (4 to 8 Hz), which is thought to reflect performance monitoring, and three parietal channels for alpha power (8 to 12 Hz), which is thought to reflect cognitive inhibition. A ten-point visual analog scale was administered after each WIN signal-to-noise ratio (SNR) condition to capture self-reported required and invested listening effort (RLE and ILE, respectively). The WIN SNR conditions were presented in descending and random order.

**Results:** The SNR presentation (descending or random SNR) had a null effect on word recognition performance; however, presentation did have an effect on theta power, alpha power, and ILE. When controlling for presentation, there were significant effects of SNR and presentation on both theta and alpha frequency power. Theta and alpha power had an inverted U-shape as a function of SNR from easy to challenging, with peak power in the moderate SNR conditions. RLE and ILE both significantly increased as task difficulty increased as expected; however, RLE showed a stronger relation to task performance than ILE. Alpha power was a significant predictor of RLE, ILE, and WIN performance when controlling for SNR.

**Conclusions:** The elevated theta and alpha power in the easy to moderate SNRs and alpha power predicting self-reported listening effort suggest the activation of supportive neural systems during word recognition that could be considered a marker of listening effort. Moreover, the measures of neural support systems and listening effort were independent from task performance, which is a key element to further understanding the neural bases for listening effort. In the context of the broader literature, these results are consistent with (1) a parietal alpha role in supporting inhibitory control to suppress irrelevant information and (2) a frontal theta role in supporting performance monitoring in difficult listening conditions where speech recognition is feasible.

**Key words:** Alpha power, EEG, Effortful listening, Theta power, Word recognition.

**Abbreviations:** EEG = electroencephalogram; ELU = ease of language understanding; EMG = Electromyography; ERP = event-related potential; FUEL = Framework for Understanding Effortful Listening; GLMM = generalized linear mixed models; ICA = Independent Component Analysis; ILE = invested listening effort; NU-6 = Northwestern Auditory Test Number 6; PSD = power spectrum density; RLE = required listening effort; SNR = signal to noise ratio; SPL = sound pressure level; WIN = words-in-noise.

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## INTRODUCTION

Difficulty understanding speech in noise is a common complaint by those with hearing loss. Clinicians have limited ability to predict speech-in-noise performance, as patients with similar degrees of hearing loss and audiogram configurations perform differently on speech-in-noise tasks (Plomp 1986). Listeners with and without hearing aids report that focused mental effort is required to understand speech, particularly in adverse listening conditions. This additional mental effort is described as listening effort (Pichora-Fuller 2007; Pichora-Fuller et al. 2016). Over time, or in difficult listening conditions, listening effort can cause stress and mental fatigue, contributing to negative psychosocial consequences (e.g., social withdrawal) or limited/discontinued hearing aid use (Mackersie & Cones 2011; Eckert et al. 2016; Pichora-Fuller 2007; Alhanbali et al. 2017). The amount of listening effort required to recognize speech varies by individual and by listening condition (Pichora-Fuller et al. 2016). Therefore, having a way to measure and account for listening effort in individual hearing aid fittings and auditory rehabilitation plans may improve adoption of an intervention and/or hearing-related outcomes in those with hearing loss. These advances require clear definitions of effort, guided at least in part by an understanding of the neural bases for listening effort.

### The Construct of Listening Effort

There is clinical and basic science interest in the construct and measurement of listening effort, particularly with regard to improving hearing aid outcomes, as evidenced by

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two international workshops devoted to the topic (Kiessling et al. 2003; Pichora-Fuller et al. 2016). Two of the more common models of listening effort include the Ease of Language Understanding (ELU) model (Rönnberg 2003; Rönnberg et al. 2013) and the Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al. 2016). In the ELU model, multimodal input (e.g., speech) is compared with a mental lexicon, and if there is a mismatch, a processing loop facilitated by working memory is engaged. The FUEL model takes a more global perspective that considers the influence of task demands, motivation, and time on effort in a difficult listening environment.

All listeners experience some degree of listening effort, and evidence suggests that it increases with hearing loss and age, even with use of amplification (Pichora-Fuller 2007). This is to be expected, especially for new hearing aid users adapting to their devices, as aging has a well-documented link with hearing loss and decline in speech perception (Committee on Hearing, Bioacoustics, and Biomechanics 1988; Jerger et al. 1989).

Some attempts to measure listening effort have revealed important information about subjective experience through self-report surveys [e.g., Speech Spatial and Qualities of Hearing Scale by Gatehouse & Noble (2004); and the NASA Task Load Index by Hart & Staveland 1988] and behavioral performance through working memory tasks [e.g., digit span test in the Woodcock-Johnson intelligence test by Woodcock et al. (2001); Auditory Inference Span test by Rönnberg et al. (2011); Sentence-final Word Identification and Recall test by Ng et al. (2013); Word Auditory Recognition and Recall Measure by Smith et al. 2016] and dual tasks [for a review of listening effort dual-tasks, see Gagné et al. (2017)]. Nonetheless, these approaches do not provide direct measurement of neural processing demands of a challenging listening task.

Objective metrics of listening effort have included pupillometry, heart rate, skin conductance, functional magnetic resonance imaging, and functional near-infrared spectroscopy (Koelewijn et al. 2012; Zekveld et al. 2010; Mackersie et al. 2015; Mackersie & Calderon-Moultrie, 2016; Eckert et al. 2016; Rovetti et al. 2019). The electroencephalogram (EEG) is another objective approach to measuring the neural processes contributing to listening effort (Obleser & Kotz 2011; Obleser & Weisz 2012; Bernarding et al. 2013; Weisz & Obleser 2014; Billings et al. 2015; McMahon et al. 2016; Dimitrijevic et al. 2019).

## EEG Frequency and Cognition

EEG is the surface (i.e., scalp) electrical recording summed from neuronal generators through volume conduction of the brain and surrounding tissue. EEG waveforms, either continuously recorded or time-locked to a stimulus, are often analyzed by breaking them down into frequency bands such as alpha (Berger 1929) and theta (Klimesch 1999). EEG has been utilized in several clinical measures of brain function and cognitive processes (Schomer & da Silva 2012).

EEG has temporal resolution on a millisecond scale and frequency properties associated with different cognitive functions, but limited source localization in comparison to metabolic based measures (e.g., positron emission tomography and functional magnetic resonance imaging). Nonetheless, EEG is relatively low cost, noninvasive, and the recording equipment is silent compared with other brain imaging techniques allowing for continuous recording in an auditory paradigm. EEG can be used to measure underlying neural mechanisms that may be associated with effortful listening thus, providing complementary information in the development of an objective measure of listening effort. The current study will focus on the EEG measure of frequency power. Frequency power is a measure of the amplitude in a given frequency range that reflects the number of neurons firing at a given rate or frequency.

**Theta** • The focus of this work was to examine the role of active performance monitoring, as measured by frontal midline theta (4 to 8 Hz). Frontal midline theta has been associated with the processing of novel information, stimuli and response conflict, negative feedback, and realization of errors (Cavanagh & Frank 2014). In addition, frontal midline theta is enhanced following events that generate uncertainty and indicate the need for adaptive control [for a review, see Cavanagh et al. (2012)]. It is theorized that frontal midline theta provides a temporal template (i.e., theta wave peaks decrease activity and troughs increase activity) to organize the processing and the transfer of information for task relevant areas (Fries 2005). Cavanagh et al. (2009) showed that trials subsequent to an error showed increased theta and slower reaction times, suggesting a link between increased theta and the recruitment of performance monitoring. Theta power seems to relate to at least the opercular component of this cingulo-opercular activity and more strongly to the suppression of the default mode network (Scheeringa et al. 2009), which is often negatively correlated with cingulo-opercular regions (Wen et al. 2013).

Specific to auditory processing, Wisniewski et al. (2015) and Wisniewski (2017) have shown increased frontal midline theta activity during a speech-in-noise recognition task and an auditory discrimination task. Frontal theta varied over different signal to noise ratios (SNRs), suggesting that decreasing SNR produced increased effort because performance remained relatively stable. These findings suggest that the challenging listening conditions generate uncertainty and increased performance monitoring demand to track and optimize performance, as reflected by the increased frontal midline theta.

**Alpha** • The alpha frequency was discovered by Berger (1929), as a predominate signal in the EEG and is typically specified with a range of 8 to 12 Hz. Alpha power recorded over parietal and occipital cortex has been associated with working memory (Gevins et al. 1996; Scharinger et al. 2015, 2017). Working memory, or the ability to hold and process information regarding a task (Baddeley & Hitch 1974), is a central component in both the ELU and FUEL listening effort models (Rönnberg 2003; Rönnberg et al. 2013; Pichora-Fuller et al. 2016). Previous research has shown when listeners attend to speech in background noise, or speech that has been spectrally degraded, changes in attention and memory load are reflected in alpha power (Dimitrijevic et al. 2017; Obleser et al. 2012; Paul et al. 2021; Wöstmann et al. 2015). Relative changes in alpha power could represent three mechanisms: (1) an increase in alpha power could represent the suppression of neural activity that is not task relevant [e.g., suppression in the visual cortex for an auditory task; Jensen & Mazaheri (2010)], (2) an increase could reflect the suppression of background noise processing (Strauß et al. 2014), and (3) a decrease in alpha power could reflect less inhibition (i.e., more excitation) in sensory-related areas for target signal processing (Osipova et al. 2008).

In addition, parietal alpha is characteristic of the fronto-parietal network (Fellrath et al. 2016; Sadaghiani & Kleinschmidt 2016), representing the increased working memory demands and the need to suppress attention to irrelevant or distracting stimuli. These observations are consistent with evidence that alpha reflects a top-down attentional control mechanism to be utilized in challenging listening conditions.

### EEG and Listening Effort

Studies utilizing EEG as a measure of listening effort and speech perception in listeners with and without hearing loss typically focus on event-related potential (ERP) components P1, N1, and P2 [e.g., Billings et al. (2015)] or EEG frequency oscillations of alpha, theta, and gamma (Obleser & Kotz 2011; Obleser & Weisz 2012; Bernarding et al. 2013; Weisz & Obleser 2014; Dimitrijevic et al. 2019; Seifi Ala et al. 2020). Described below are previous studies that have shown an impact of listening condition or hearing loss on EEG frequencies, with effects on alpha and theta frequency varying across different listening conditions. Theta power has been observed to increase in a left frontotemporal region with more spectral detail in speech stimuli (Obleser & Weisz 2012) and increase in the frontal midline with self-reported listening effort and decreasing SNR (Wisniewski et al. 2015). Alpha power has been observed to (1) increase with memory load and acoustic degradation (Obleser et al. 2012); (2) increase for low and intermediate memory load with normal to mild hearing loss and decrease for high memory load with moderate hearing loss (Petersen et al. 2015); and (3) modulate noise suppression in speech (Strauß et al. 2014). Previous studies have used an increase of numbers (digit span) or words to recall as a manipulation of working memory in varying SNRs. The novel aspects of the current study include the examination of EEG frequencies during a single word-recognition task with parametrically varied easy to challenging SNR conditions to examine neural functions that were hypothesized to change within listeners with increasing listening difficulty and increased subjective listening effort.

### Study Goals and Hypotheses

The current study examined frontal theta and parietal alpha frequency changes during word recognition in background noise. The hypotheses of this study are summarized in Figure 1. Word recognition performance (Fig. 1, solid black line) was expected to be at ceiling for the young listeners with normal hearing until the challenging SNRs in which performance was expected to steadily decline with decreasing SNR. Theta frequency power (Fig. 1, long dash blue line) was hypothesized to increase linearly with a peak in a more challenging SNR than the SNR at which word recognition declines, and decrease in power in more challenging SNRs, fitting a positive linear and negative quadratic polynomial model. This linear increase and peak of theta power in more challenging SNRs would reflect the growing uncertainty and need for adaptive control, with an eventual disengagement in the most challenging SNRs. The alpha frequency power (Fig. 1, dotted red line) was hypothesized to increase for easier SNRs while task performance was maintained at ceiling and decline with word recognition performance in challenging SNRs, fitting a negative quadratic polynomial model. The SNR that evokes the highest alpha and theta power was hypothesized to reflect the peak cognitive inhibition and performance monitoring, respectively. An additional self-report measure was hypothesized to increase linearly with decreasing SNRs (Fig. 1, dash dotted green line) fitting a positive linear polynomial model. Detailed model predictions for each measure are described in the Statistical Analysis section.

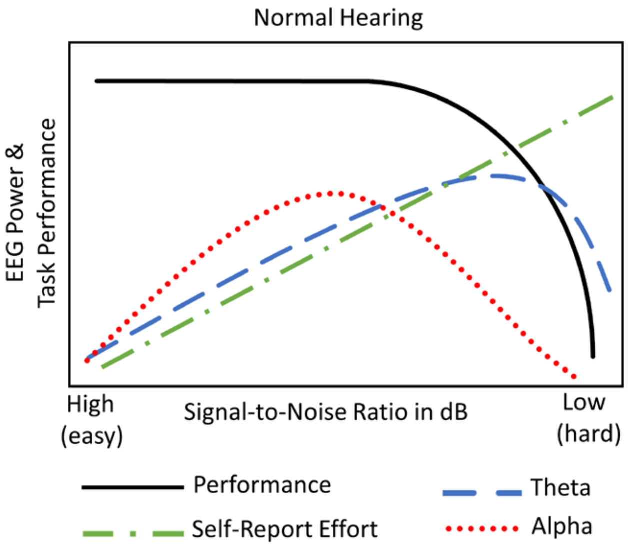

Fig. 1. Hypothesized word recognition performance and electroencephalography (EEG) frequency power across signal-to-noise ratios (SNRs) of a words-in-noise recognition task. Word recognition performance (solid black line) was expected to decline in challenging SNRs and self-reported effort (dash dotted green line) was expected to linearly increase with decreasing SNR. Alpha power (8–12 Hz, dotted red line), and theta power (4–8 Hz, long dash blue line) were expected to each have an inverted U-shape reflecting different cognitive states with decreasing SNR.

## MATERIALS AND METHODS

### Participants

Thirty-four participants were enrolled for this study. The mean age of the participants was 22.68 years (SD = 4.5, range = 18 to 33) and 20 were female. The study was approved by the East Tennessee State University/Veterans Affairs (VA) Institutional Review Board and VA Research and Development Committee. Participants were recruited from East Tennessee State University undergraduate and graduate programs. All participants completed an Institutional Review Board-approved consent form indicating their understanding of the procedures and their willingness to participate in the study prior to study commencement. After consenting, otoscopy was performed, and a pure-tone air conduction audiogram was obtained for each ear. The mean pure-tone threshold across ears was 6.0 dB hearing level (HL, SD = 3.18, range = −0.9 to 12.2). Participants had to have pure-tone thresholds ≤25 dB HL for octave frequencies of 250 to 8000 Hz and inter-octave frequencies of 3000 and 6000 Hz (American National Standards Institute, 2010) in each ear; be native American English speakers; and pass a cognitive screening measure, the Montreal Cognitive Assessment with a score of ≥26 (Nasreddine et al. 2005). The highest level of education was recorded in years as part of the Montreal Cognitive Assessment. A case history interview was conducted to rule-out comorbid conditions. Participants who were deemed eligible for the study proceeded with the experimental portion of the study which required preparation for EEG measures and fitting of the EEG cap (Neuroscan 64 channel, Charlotte, NC).

## Materials

**Word Recognition** • The Words-In-Noise (WIN) test (Wilson 2003; Wilson et al. 2003) was used to measure word recognition performance in noise. The WIN consists of two lists of 35 (total of 70) Northwestern University Auditory Test Number 6 (NU-6; Tillman & Carhart 1966) words with a six-talker babble. Each list has five unique words at seven SNRs from 24 to 0 dB, in 4 dB decrements. The noise level remains constant and the level of the words varies to determine the SNRs. The task of the listener was to repeat the word following the carrier phrase "say the word__". Responses were recorded as correct, incorrect, or no response for each item. The percent correct performance was calculated at each SNR. A unique practice list (WIN list 3, Wilson & Watts 2012) was presented prior to the administration of the WIN to help control for practice effects and was not included in the task performance or EEG analysis.

**Listening Effort** • Two listening effort surveys were administered. The 'required' listening effort (RLE) survey characterized how much effort was required to perform each SNR condition of the WIN test, while the 'invested' listening effort (ILE) survey characterized how much effort the participant actually invested when performing each SNR condition of the WIN test. These two self-reported effort measures provided more specific estimates of subjective listening effort and limited the possibility that participants would inconsistently consider task difficulty versus the amount of effort they experienced. A 10-point (0 to 9) Likert scale was used to measure subjective effort for both surveys, as in Rönnberg et al. (2011). The RLE asked the participant to "Rate on the scale from 0-9 below the amount of effort *required* to listen to the passage (how hard was it)". The ILE asked the participants to "Rate on the scale from 0 to 9 below the amount of effort *invested* in listening to the passage (how hard did you try)". For both surveys, 'No effort' 'and 'Greatest possible effort' language was used as endpoints for the possible range of effort to guide participant responses.

## Procedure

For the experimental portion of the study, the WIN auditory stimuli were presented by STIM2 (Neuroscan systems) routed to a sound field speaker (Grason-Stadler, Eden Prairie, MN) while the participant was seated 1 m, 0º azimuth in a sound-treated booth (IAC Acoustics, Naperville, IL). The presentation level of the WIN was at 70 dB sound pressure level (SPL) to ensure audibility of the materials. First, the practice WIN list was presented in the descending SNR presentation. Next, List 1 of the WIN was presented followed by List 2. In order to control and examine possible SNR presentation order effects, the WIN test (lists 1 and 2, totaling 70 trials) was administered twice (for a total of 140 trials), once with the SNRs presented in descending order so that results could be interpreted in the context of a typical clinical administration of the test and once with the SNRs presented in a semi-randomized order. The semi-randomized order was organized to control for easier SNRs presented before or after challenging SNRs (e.g., 24 dB SNR followed by 0 dB SNR or 0 dB SNR followed by 24 dB SNR). The descending presentation and semi-randomized presentation were counterbalanced such that the even-numbered participants received the descending presentation first followed by the random presentation and were in the reverse order for the odd-numbered participants. Following each SNR condition, the RLE and ILE survey ratings were obtained by asking the participant to provide a verbal response on a 0 to 9 scale. For reference, each participant was provided a copy of the rating scales in a written format. The entire single session was 2.5 hours in duration, and participants were provided breaks every 30 minutes to help control for fatigue.

## EEG Methods

EEG frequencies were recorded at 64 channel locations (Fig. 2) using the modified International 10-20 system. Data were collected by CURRY 8 software at a 500 Hz sampling rate with a ground electrode at AFz and reference electrode between Cz and CPz. Impedances were lowered below 10K ohms on each channel prior to the WIN test.

Data analysis was performed using the MATLAB plugin EEGLAB (Delorme & Makeig 2004). Recordings were downsampled from 500 Hz to 250 Hz (to facilitate computation), band-pass filtered (0.5 to 100 Hz), and re-referenced to a common average across all electrodes to facilitate comparisons to other studies. For artifact correction, an independent component analysis (ICA) was performed using the EEGLAB function run_ica, then the ICLabel function computed a probability for the source of each component across seven categories (Pion-Tonachini et al. 2019). These seven source categories included (1) brain, (2) eye blink/movement, (3) muscle, (4) heart, (5) line noise, (6) channel noise, and (7) other. Any component that had a probability >90% in categories 2-6 was rejected (similar to Lin et al. 2021). The mean number of components removed was 7.5 with a range of 2 to 17 across participants.

A design of two epoch windows for analysis was initially executed; however, after initial analysis a third epoch window was added to best capture theta frequency power as described by Wisniewski (2017). Figure 3 shows the time periods of each WIN test trial that were examined and included: (1) *Carrier Phrase*, an 800 ms window (3200 samples) during the carrier

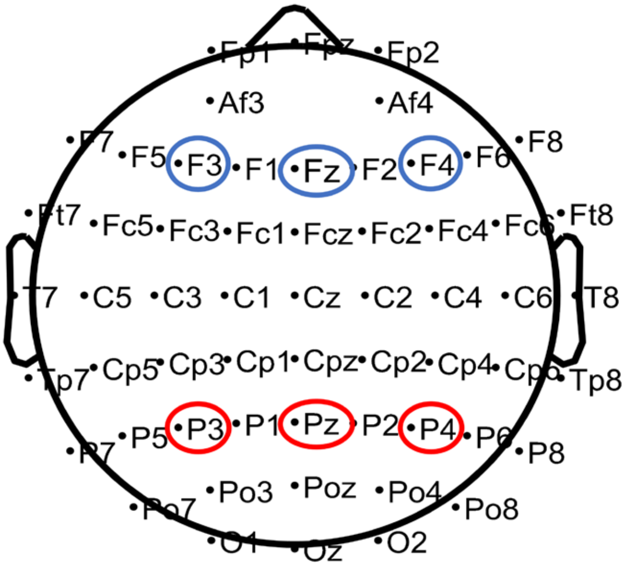

Fig. 2. The 64-channel montage used to collect electroencephalogram (EEG) data. Channel F3, Fz, and F4 (blue circle) were the sources for frontal theta and P3, Pz, and P4 (red circle) were the sources for parietal alpha frequency power analysis.

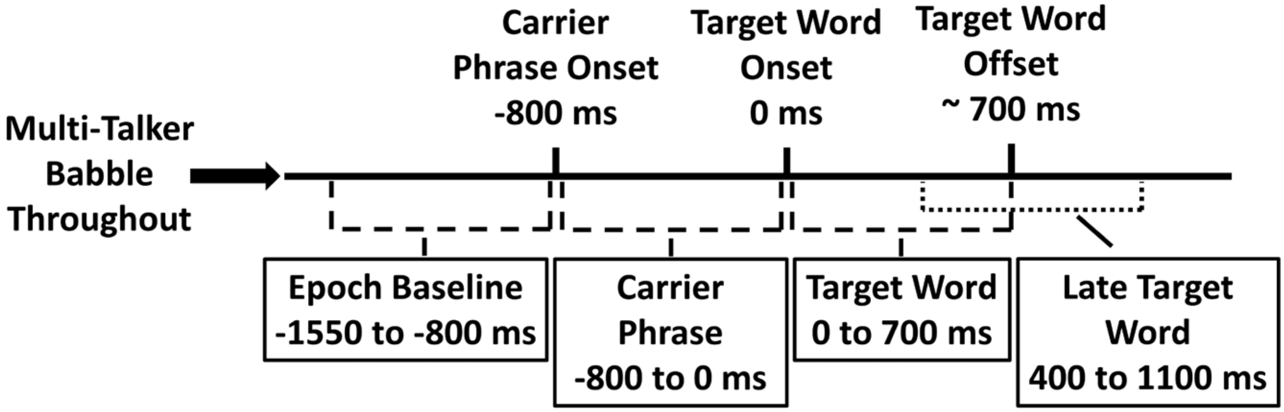

Fig. 3. Timeline for a single trial with stimulus time markers above the solid line and extraction of epoch windows below solid line. All time points are referenced to the onset of the target word (0 ms). Multi-talker babble was presented continuously across a signal-to-noise ratio block of five trials.

phrase "Say the word__" to examine activity during speech or cue processing prior to the target word; (2) *Target Word*, a 700 ms window (2800 samples) during the target word to examine activity during word recognition in multi-talker babble; and (3) *Late Target Word*, a 700 ms window (2800 samples), occurring 400 ms post target word onset, designed to capture the highest amounts of theta frequency power.

The WIN paradigm has three epoch windows of interest (carrier phrase, target word, late target word) with no time between them. Therefore, the application of the traditional frequency baseline correction prior to each epoch would contain the EEG activity of the previous epoch (e.g., the baseline correction of the target word epoch would occur during the presentation of the carrier phrase). To address this issue, a larger epoch (2650 ms) containing the carrier phrase, target word, and late word included a baseline of 750 ms taken prior to the carrier phrase (Fig. 3). During this baseline, only background babble was presented. The carrier phrase, target word, and late target word epochs were taken from the baseline corrected larger epoch. This resulted in the carrier phrase, target word, and late word epochs to use the same 750 ms baseline correction window prior to the carrier phase. A larger baseline could have been contaminated by the response of the participant from the previous trial. If the ERP amplitude of the epoch was higher than 50 μV, the trial was rejected. Prior to epoch rejection, there were 140 epochs per participant. The epoch rejection criteria resulted in the rejection of 12% of total trials.

EEG frequency power data were extracted and averaged from electrodes F3, Fz, and F4 for theta frequency power and P3, Pz, and P4 for alpha frequency power analysis (circled, Fig. 2). The mean absolute spectral density across epochs was calculated for each frequency band (4 to 12 Hz, 1 Hz resolution). There was no window-overlap of the carrier phrase and target word epochs; however, there was a window-overlap of 300 ms (1200 samples) of the target word and late target word epochs. This approach provides the theta and alpha activity during three different phases of the task that could be influenced by SNR. Alpha and theta frequency values were skewed, thus, a log transform was performed to obtain a standard distribution. The electrodes used and rejection threshold are similar to previous EEG listening effort studies (Obleser & Kotz 2011; Bernarding et al. 2013; Billings et al. 2015). The EEGLAB function spectopo was utilized to compute the power spectrum density (PSD).

$$\mathrm{PSD} = 10 * \log_{10}\left(\mu \mathrm{V}^2 / \mathrm{Hz}\right)$$

Each EEG epoch was organized by the response type of correct word recognition, incorrect word recognition, or no response. Given that the sample was composed of young adults with normal hearing, there were few no responses; thus, no response epochs were excluded.

### Statistical Analysis

Data analysis was performed by fitting generalized linear mixed models (GLMM) as implemented by the R package *lme4* (Bates et al. 2015). Mixed models are a flexible and powerful alternative to repeated-measures analysis of variance, which impose more restrictions (or assumptions). The linear mixed models provided increased sensitivity to effects, particularly for the poorer SNR conditions in which fewer participants provided correct responses.

The GLMMs were designed to examine SNR effects, while also examining potential effects of presentation (i.e., descending and random SNR conditions) and response type (correct and incorrect). The SNR condition was centered (on 12 dB SNR), and SNR was treated as a continuous variable. The general strategy for each measure was to fit a sequence of nested mixed models of increasing complexity beginning with an empty model (model 1) that only had the dependent variable (e.g., either alpha power, theta power, or self-reported listening effort) and introducing main effects (model 2) and the main effects plus the interaction terms (model 3). This resulted in a sequential comparison of an empty model versus a main effects model (model 1 versus model 2) and then a main effects model versus a presentation effect with interaction of presentation and main effect model (model 2 versus model 3). A chi-squared difference test was used to compare the fit of these nested models, and the *p* value reflected the significance of the additional terms in the more complex model for each comparison. Response type did not have a significant effect on theta or alpha frequency power (see Supplemental Digital Content 1, http://links.lww.com/EANDH/B12 for details about these analyses) and will not be discussed further.

Instead of describing the effects of SNR through traditional post-hoc tests among SNR levels, polynomial tests were carried out to describe the effects of SNR. The hypotheses for each measure were examined using polynomial functions across

SNR, which optimized sensitivity to non-linear effects from this parametrically designed WIN experiment (Fig. 1). The self-report measures ILE and RLE were hypothesized to have a significant positive linear polynomial test and non-significant quadratic and cubic test. Theta frequency power was hypothesized to have a significant positive linear and negative quadratic polynomial test with non-significant a cubic test for the target word epoch. Alpha frequency was hypothesized to have a significant negative quadratic test for the target word epoch with a non-significant linear (i.e., centered variable) and cubic test. A sequential-Bonferroni, or Holms correction, was carried out to control for multiple comparisons (Holm 1979).

Correlations among theta, alpha, ILE, RLE, and WIN performance, were conducted with adjusted Benjamini-Hochberg *p* values. Significant correlations of $r < 0.3$ were not considered meaningful.

## RESULTS

### WIN Performance

The mean percent-correct recognition scores (collapsed across word list and presentation) are presented as a function of each SNR in Figure 4. As seen in the figure, the recognition performance decreased with descending SNR, specifically lower than 12 dB SNR. This was consistent with the hypothesis for word recognition in Figure 1. A chi-squared difference test was used to compare the fit of these nested models (GLMM) and the results showed that SNRs of the WIN had a significant effect on WIN performance [$\Delta X^2$ (6) = 1645.3, $p < 0.001$], which was consistent with our hypothesis.

### EEG Frequency Results

**Carrier Phrase** • The carrier phrase epoch window was from −800 to 0 ms from target word onset (Fig. 3). This epoch window was assessed to examine the effect of the carrier phrase or cue in multi-talker babble. An ERP analysis was carried out for each epoch window to examine the effect of an N1/P2 component. N1/P2 ERP components are evoked by stimulus onset and in the theta band (e.g., 2 to 5 Hz, Lightfoot 2016). Specifically, the carrier phrase window would be the expected epoch window to show N1/P2 effects as it is the onset of the attended stimulus; however, the carrier phrase did not show any significant SNR effects of N1/P2 in the ERP or the frequency analyses (see Figure 1 and target word Figure 2 in Supplemental Digital Content 1, http://links.lww.com/EANDH/B12). The lack of an N1/P2 in the carrier phrase onset could be explained by the ongoing background babble, thus, there was no break in the auditory stimuli within an SNR block and no onset of auditory stimuli to evoke an N1/P2. Figures 5A, B show the only significant effect of SNR for the theta and alpha band (respectively) is at isolated electrodes. Effects that are limited to a single electrode are most likely recording artifacts given the lack of volume conduction, the smearing of an EEG signal across electrodes as a result of recording an electrical signal in a salt-water medium. Figures 5C, D show the mean frequency power spectrum of each SNR for the selected frontal and parietal electrodes, circled in Figures 5A, B. Figure 6 shows theta frequency power (triangle) was similar across SNRs and alpha frequency power (square) showed an inverted U-shape change across SNRs. The GLMM results, as shown in Table 1, confirmed that SNR did not have an effect on theta power; however, SNR did have significant negative linear and positive cubic effects for alpha power. The significant effect of SNR on alpha power was not hypothesized for the carrier phrase. Presentation (random SNR versus descending SNR) did not have a significant effect on the model; however, controlling for presentation did remove the significant linear and cubic effects of SNR on alpha power (Table 2). These two points suggest the effect of SNR on alpha power is not robust during the carrier phrase.

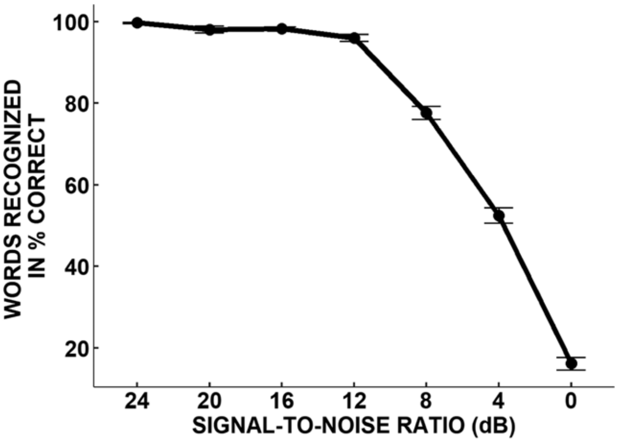

Fig. 4. Percent correct word recognition scores across signal-to-noise ratio (SNR) conditions of the Words-in-Noise (WIN) test. Error bars represent +/− 1 SD.

**Target Word** • The target word epoch window was 0 to 700 ms from target word onset (Fig. 3). This epoch window was assessed to examine the effect of word recognition in multi-talker babble. Figures 7A, B show a significant effect of SNR on theta and alpha power, respectively. The pattern of significant activity found over the lateral/frontal electrodes for theta and alpha were not hypothesized and the study was not designed to analyze lateral prefrontal cortex activity. Nonetheless, the EEG data from a group of left (F7, F5, and FC5) and right (F8, FC6, FC4, and F4) frontal electrodes were averaged together and used for further analysis. This analysis resulted in over 40% of epochs not meeting the <50 μV threshold after ICA and ICLabel artifact rejection, suggesting a large presence of artifact activity in the lateral prefrontal cortex EEG data. No further analysis was carried out for the lateral prefrontal cortex. Figure 7A also shows an SNR effect on theta power over the right occipital/parietal lobe; however, this activity seems to have borderline significance and was not examined further. Figure 7B shows the significant effect of SNR on alpha power over the parietal electrodes. Figures 7C, D show the mean frequency power spectrum of each SNR for the selected frontal and parietal electrodes, circled in Figures 7A, B. Figure 8 shows theta frequency power (triangle) was similar across SNRs and alpha frequency power (square) had an inverted U-shape change across SNRs. The GLMM results, see Table 1, confirmed that SNR did not have an effect on theta power; however, SNR did have a significant negative quadratic effect on alpha power. Theta power had a significant effect of presentation, with the random SNR reducing theta power (see Figure 3 in Supplemental Digital Content 1, http://links.lww.com/EANDH/B12). Controlling for the presentation effect resulted in a significant negative quadratic SNR effect on theta (Table 2). Alpha power had a significant effect of presentation that reduced alpha power in the random presentation (see Figure 4 in Supplemental Digital Content 1,

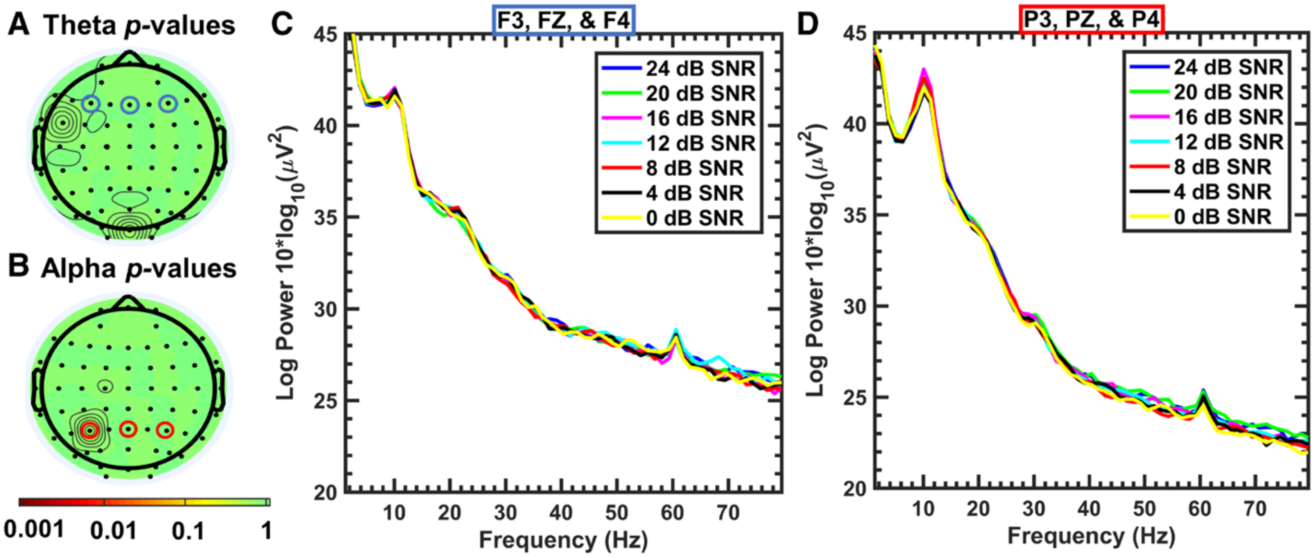

Fig. 5. Carrier phrase epoch (A and B) topography of *p* values, Holms correction for multiple comparisons, for the effect of signal-to-noise ratio (SNR) for theta (A) and alpha (B). Each topography has the frontal (blue circle) and parietal (red circle) electrodes selected. C, Frequency power spectrum for F3, Fz, and F4. D, Frequency power spectrum for P3, Pz, and P4.

http://links.lww.com/EANDH/B12). Controlling for the effect of presentation still resulted in a significant negative quadratic effect of SNR on alpha power.

The negative quadratic result for alpha power was consistent with the hypothesis and was further supported by the non-significant linear and cubic results. The significant effect of presentation on theta power was unexpected; however, it did reveal a significant negative quadratic effect consistent with the hypothesis.

**Late Target Word** • Wisniewski (2017) found the strongest effect on theta in a later time window of 400 to 1400 ms post stimulus onset. To examine this later time window and to keep an epoch window size consistent within the study (700 ms), a time window of 400 to 1100 ms was analyzed (Fig. 3). Figures 9A, B show the significant effect of SNR for the theta and alpha band (respectively) across several electrodes. The pattern of SNR effect on theta in Figure 9A does not show a midline frontal change in power; however, it seems to show a pattern of change over the right frontal lobe. The pattern of SNR effect on alpha power in Figure 9B shows frontal, parietal, and occipital patterns of change. These unexpected patterns in Figures 9A, B suggest the results for the late target word could be contaminated with electromyography (EMG) or other motor-related artifacts and should be interpreted with caution. Figures 9C, D show the mean frequency power spectrum of each SNR for the selected frontal and parietal electrodes, circled in Figures 9A, B. Figure 10 shows theta frequency power (triangle) was significantly reduced in the highest and the lowest SNR conditions compared with the other SNR conditions. Specifically, the significant negative quadratic results reflect the theta power reduction at higher and lower SNR levels (Table 1). Interestingly, presentation did not have a significant effect on theta power; however, adding presentation to the model nullified the negative quadratic effect of SNR on theta power (Table 2). The hypotheses did not consider late target word effects for alpha. Nonetheless, the results show possible SNR effects on alpha power beyond the presentation of the target word. Alpha frequency power (square, Fig. 10) showed an inverted U-shape (Table 1). Moreover, polynomial tests showed a significant negative linear, negative quadratic, and positive cubic results. Presentation did not have a significant effect on alpha power and resulted in a significant negative quadratic effect of SNR (Table 2).

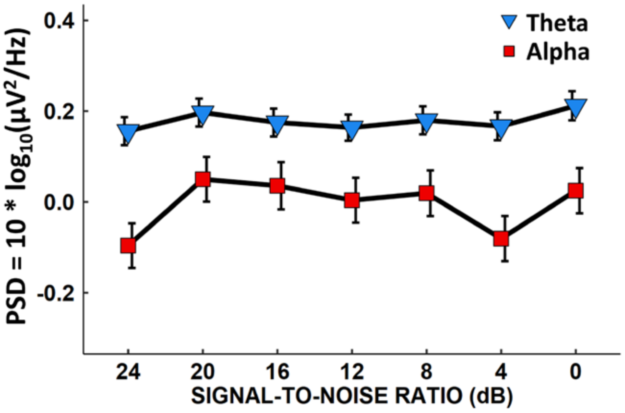

Fig. 6. Mean theta frequency power (blue downward-triangle) and alpha frequency power (red square) plotted across signal-to-noise ratio (SNR) conditions for the carrier phrase window of −800 to 0 ms prior to target word onset. Error bars represent 1 SD. Note the alpha power negative values are a result of the log transform, as these values were positive prior to the log transform and do not reflect a suppression of alpha frequency power.

**Interindividual Variability** • The interindividual variability of theta and alpha power for the carrier phrase, target word, and late target word have been plotted in Figures 8, 9, and 10 in Supplemental Digital Content 1, http://links.lww.com/EANDH/B12. The interindividual variability plots show very similar patterns to the plots that pooled all trials (Figs. 6, 8, and 10); however, the error bars are much larger in the interindividual variability plots. This suggests that there is a large amount of variability between participants, particularly in alpha power. Moreover, the between participant variability could be evidence of individual patterns of frequency power when listening conditions are consistent across participants.

**TABLE 1. Effect of SNR on frequency power and fit of linear, quadratic, and cubic models**

| | | SNR | SNR Polynomial *t* Values | | | | |
|---|---|---|---|---|---|---|---|
| Epoch | Measure | $\Delta X^2$ (df) | df | Linear | Quadratic | Cubic | Fig. |
| Carrier phrase | Theta | 1.23 (3) | 4112 | −0.83 | 0.27 | 1.03 | Fig. 6 |
| | Alpha | 11.89 (3)* | 4112 | −2.50† | −1.93 | 2.73† | Fig. 6 |
| Target word | Theta | 4.52 (3) | 4112 | −0.37 | −2.07 | 0.36 | Fig. 8 |
| | Alpha | 41.41 (3)‡ | 4112 | −0.26 | −6.36‡ | 0.42 | Fig. 8 |
| Late target word | Theta | 17.54 (3)‡ | 4112 | −1.55 | −3.82‡ | 1.27 | Fig. 10 |
| | Alpha | 38.71 (3)‡ | 4112 | −3.61‡ | −4.85‡ | 2.94* | Fig. 10 |

*Epoch window times are relative to the onset of the target word (0ms). Carrier phrase window of −800 to 0ms, target word window of 0 to 700ms, and late target word 400 to 1100ms.*
*Significance levels*
**p ≤ 0.05.*
*†p ≤ 0.01.*
*‡p ≤ 0.001.*
*SNR, signal-to-noise ratio.*

**TABLE 2. Effect of SNR and presentation on frequency power and fit of linear, quadratic, and cubic models**

| | | SNR and Present. | | Present. | SNR Polynomial *t* Values | | | SDC |
|---|---|---|---|---|---|---|---|---|
| Epoch | Measure | $\Delta X^2$ (df) | df | Random | Linear | Quadratic | Cubic | Figure |
| Carrier phrase | Theta | 5.23 (4) | 4108 | 0.45 | −1.11 | 0.40 | 1.47 | — |
| | Alpha | 4.54 (4) | 4108 | −1.73 | −1.36 | −2.70 | 1.71 | — |
| Target word | Theta | 14.93 (4)* | 4108 | −3.32 * | 1.00 | −3.04† | −0.72 | Fig. 3 |
| | Alpha | 11.22 (4)† | 4108 | −3.04† | −0.23 | −5.69‡ | 0.57 | Fig. 4 |
| Late target word | Theta | 0.25 (4) | 4108 | 0.41 | −1.28 | −2.56 | 1.10 | — |
| | Alpha | 13.20 (4)† | 4108 | −2.59 | −2.39 | −5.09‡ | 2.54 | — |

*Epoch window times are relative to the onset of the target word (0ms). Carrier phrase window of −800 to 0ms, target word window of 0ms to 700ms, and late target word 400 to 1100ms. The interaction of presentation (present.) and SNR was not significant across models, and not reported here. All figures cited are in the Supplemental Digital Content (SDC) 1 (http://links.lww.com/EANDH/B12).*
*Significance levels*
**p ≤ 0.05.*
*†p ≤ 0.01.*
*‡p ≤ 0.001.*

## Self-Reported Listening Effort

The self-reported ILE and RLE (collapsed across word list and presentation) are shown in Figure 11 to demonstrate the significant effects of SNR on self-reported listening effort (see Table 3). For ILE and RLE, polynomial parameters in the models demonstrated a significant positive linear, positive quadratic, and negative cubic effects (see Table 3). There was mostly likely an interaction of three polynomial terms for each result to be significant, with each term fitting a portion of the shape across SNRs. The positive linear model was consistent

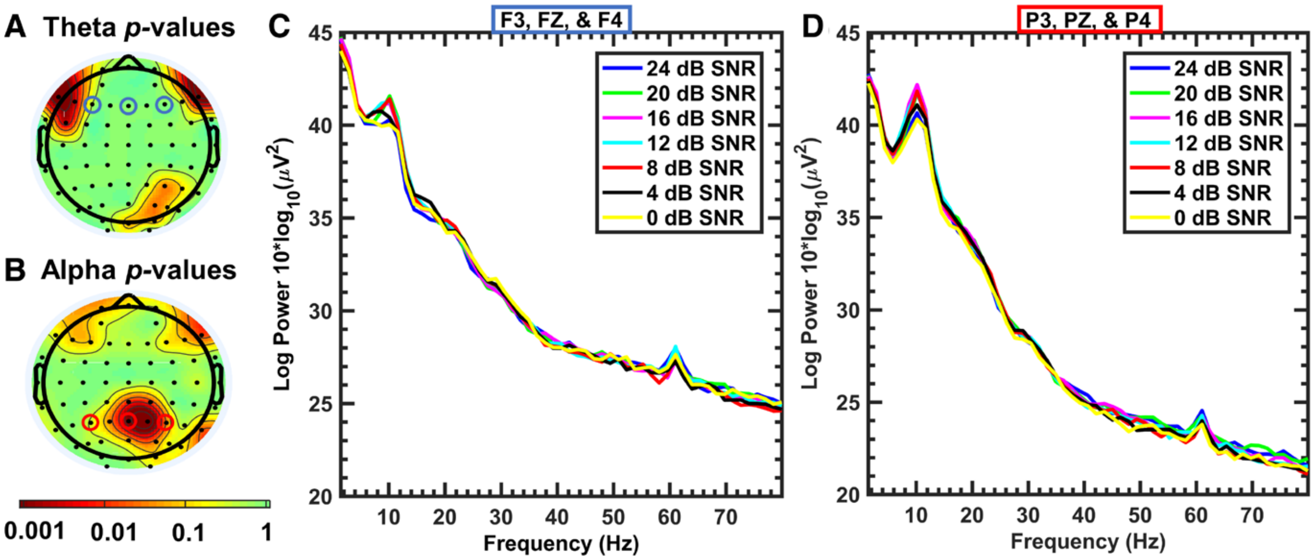

Fig. 7. Target word epoch (A and B) topography of *p* values, Holms correction for multiple comparisons, for the effect of signal-to-noise ratio (SNR) for theta (A) and alpha (B). Each topography has the frontal (blue circle) and parietal (red circle) electrodes selected. C, Frequency power spectrum for F3, Fz, and F4. D, Frequency power spectrum for P3, Pz, and P4.

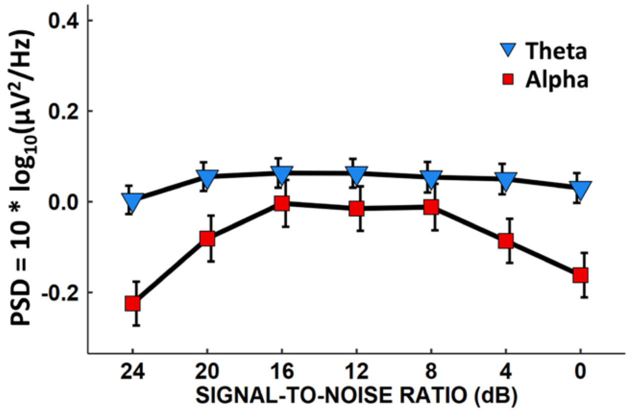

Fig. 8. Mean theta frequency power (blue downward-triangle) and alpha frequency power (red square) plotted across signal-to-noise ratio (SNR) conditions for the target word window of 0 to 700 ms post target word onset. Error bars represent one standard deviation. Note the alpha power negative values are a result of the log transform, as these values were positive prior to the log transform and do not reflect a suppression of alpha frequency power.

with the hypothesis for ILE and RLE (Fig. 1) and was driven by the positive linear direction in the moderate SNRs. The positive quadratic result suggests it was driven by the upward curve from the easy to moderate SNRs and the negative cubic result suggests that it was driven by the downward change in the most challenging SNRs.

## Correlations Among WIN and Demographic Measures

Correlations of 5 measures for the target word epoch and late target word epoch were similar and are presented in Tables 4 and 5, respectively. The target word epoch had a strong positive correlation and was found between the self-report measures (ILE and RLE, $r = 0.71$), ILE and RLE with WIN performance (−0.60 and −0.86, respectively), and a moderate positive correlation was found between theta and alpha frequency power ($r = 0.64$). As a point of interest, the EEG frequency measures (theta and alpha) and self-report (ILE and RLE) had some similarities in their distributions across SNRs; however, individual differences in EEG frequency and self-report measures were not significantly related.

## Regression of EEG Frequency Power on WIN and Self-Reported Listening Effort

The correlations between EEG frequency power and self-reported listening effort were not significant; however, the correlations were collapsed across SNR and presentation, and therefore, did not control for the significant effects of SNR and presentation. To account for the effect of SNR and presentation, theta and alpha power were both entered into linear regression models that controlled for SNR and presentation to predict WIN, ILE, and RLE for each epoch (see Table 6). Theta power had no significant relations to WIN, ILE, or RLE. In contrast, alpha power was significantly related to ILE and RLE for the carrier phrase, all three measures (WIN, ILE, and RLE) for the target word, and RLE for the late target word. Alpha power and SNR had a significant interaction on ILE for the carrier phrase, target word, and late target word. These results suggest a consistent effect of alpha power on ILE, and to a lesser degree on RLE and WIN performance. Presentation was significant for ILE in the carrier phrase, target word, and late target word. There was a significant interaction of presentation and SNR for RLE for all three epochs. The effect of presentation on ILE suggests that there was higher invested effort in the descending presentation, and the interaction of presentation and SNR on RLE suggests that the descending presentation at more difficult SNRs had higher required effort.

# DISCUSSION

The purpose of the current study was to examine the effect of a words-in-noise recognition task on EEG and self-report measures in a listening effort framework. We hypothesized different

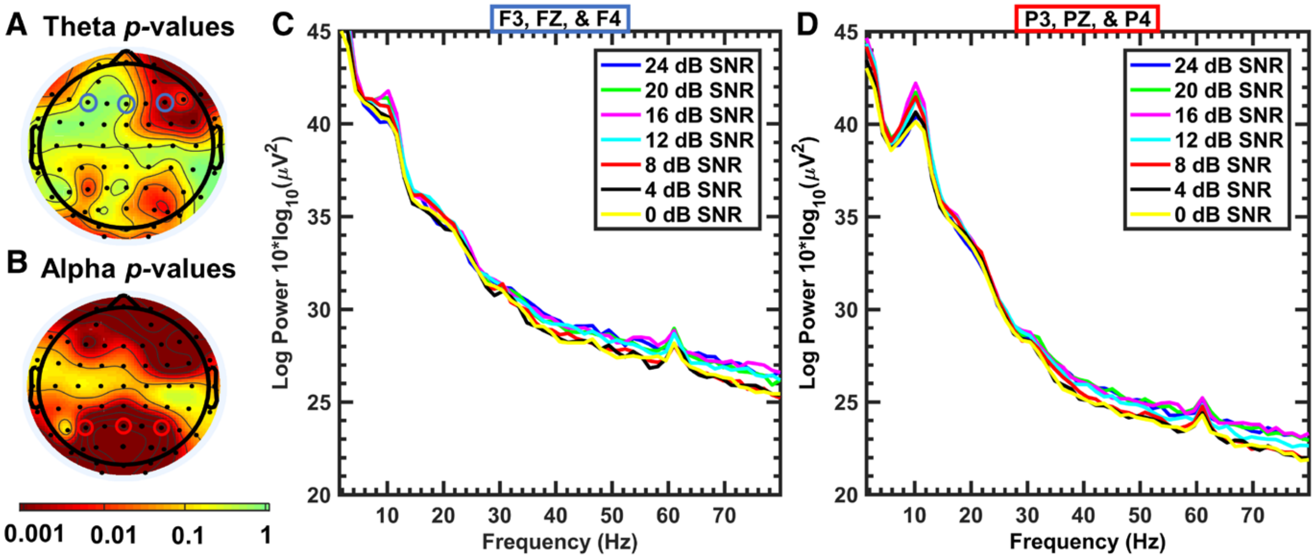

Fig. 9. Late target word (A and B) topography of $p$ values, Holms correction for multiple comparisons, for the effect of signal-to-noise ratio (SNR) for theta (A) and alpha (B). Each topography has the frontal (blue highlight) and parietal (red highlight) electrodes selected. C, Frequency power spectrum for F3, Fz, and F4. D, Frequency power spectrum for P3, Pz, and P4.

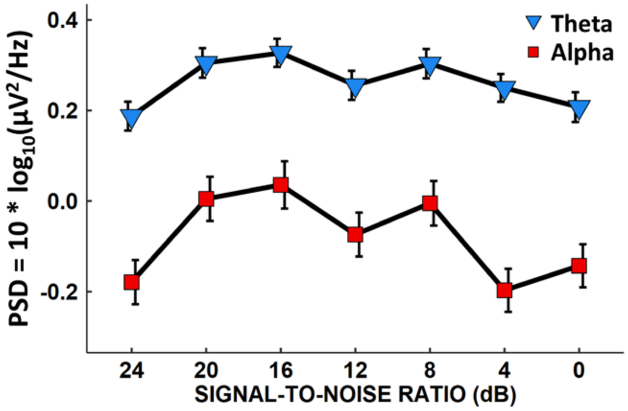

Fig. 10. Theta frequency power (blue downward triangle) and alpha frequency power (red square) of signal-to-noise ratios (SNRs) for the late target word 400 to 1100 ms post target word onset. Note the alpha power negative values are a result of the log transform, as these values were positive prior to the log transform and do not reflect a suppression of alpha frequency power.

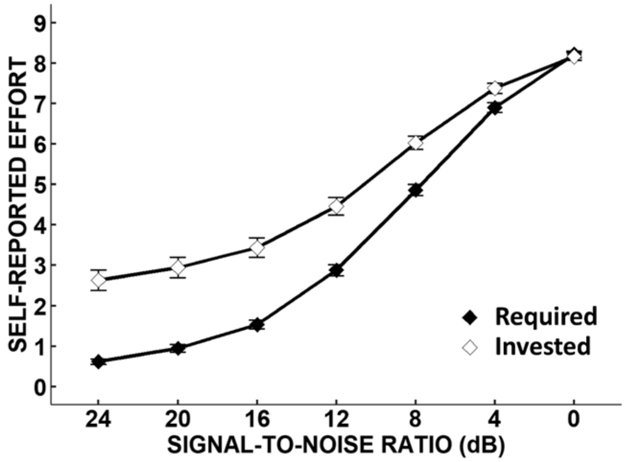

Fig. 11. The mean required listening effort (RLE) ratings (black diamonds) and invested listening effort (ILE) ratings (white diamonds) are plotted across signal-to-noise ratio (SNR) conditions. The error bars represent 1 SD.

polynomial shapes for each measure (Fig. 1) across the easy-to-challenging SNRs: (1) word recognition would be at ceiling until the challenging SNRs, then it would decline with SNR for the young listeners with normal pure-tone hearing, (2) theta power would fit a positive linear model and negative quadratic model, reflecting the increase in performance monitoring for easy to moderate SNRs and decline for challenging SNRs, (3) alpha power would fit a negative quadratic model, reflecting the increase and decline of cognitive inhibition across SNRs, and (4) RLE and ILE would fit a positive linear model of SNRs, showing the linear increase in task difficulty. We discuss the results, as well as limitations of the study, in the context of a cognitive conceptual framework.

Theta power results were more complex than hypothesized. Relative to challenging SNR levels, theta power was elevated in moderate conditions demonstrated by the negative quadratic results. Nonetheless, this does not seem to be a robust effect as target word theta power was only significant when controlling for presentation effects (Table 2) and was not significant in correct only trials (see Table 2 in Supplemental Digital Content 1, http://links.lww.com/EANDH/B12). In addition, late target word theta power showed a significant negative quadratic effect of SNR; however, when controlling for presentation this was a null effect (Table 2). The properties of the WIN task could explain the limited effects for theta. Specifically, the WIN uses single word recognition, which is limited novel information, and the WIN provides no feedback, which limits the realization of errors and omits negative feedback. Nonetheless, the effects of presentation could provide more insight to listening effort and are discussed below.

Previous studies have demonstrated that a left inferior frontal sulcus region that exhibits increased activity during working memory (Gruber 2001; Crottaz-Herbette et al. 2004) also exhibits increased activity with cingulo-opercular regions during speech recognition in noise (Vaden et al. 2013; 2015). The effects of theta are interpreted with caution, as they are not present in the correct only trials.

Alpha power, a marker of inhibitory control, showed an inverted U-shape for the target word across SNRs, consistent with the hypothesis and previous research (Fig. 1, dotted line and Fig. 8, square; Paul et al. 2021). The inverted U-shape for alpha power during the target word was significant when controlling for presentation and driven by the correct only trials (Table 3 and Figure 5 in Supplemental Digital Content 1, http://links.lww.com/EANDH/B12). The inverted U-shape suggests an increase of cognitive inhibition with moderately increasing task difficulty (Jensen & Mazaheri 2010; Klimesch 1999). Increased alpha power has been associated with increased performance in working memory tasks (Klimesch 1999; Krause et al. 1996). In the current paradigm inhibition, specifically, auditory selective inhibition (Strauß et al. 2014; Wöstmann et al. 2016) may be required for the encoding of information when acoustic stimuli are degraded or the salience of distractor speech increases (Obleser et al. 2012; Wöstmann et al. 2017), perhaps through activation of the fronto-parietal network (Sadaghiani & Kleinschmidt 2016).

These results show a common finding of decreased frequency power in moderate to challenging SNR conditions for

**TABLE 3. Effect of SNR on self-reported measures of ILE and RLE and fit of linear, quadratic, and cubic models**

| | $\Delta X^2$ (df) | SNR Polynomial *t* Values | | | | |
|---|---|---|---|---|---|---|
| | SNR | df | Linear | Quadratic | Cubic | Figure |
| ILE | 1038.64 (4)* | 915 | 20.52* | 6.78* | –5.02* | Fig. 11 |
| RLE | 1972.69 (4)* | 915 | 37.23* | 16.50* | –7.83* | Fig. 11 |

**p ≤ 0.05.*
*†p ≤ 0.01.*
*‡p ≤ 0.001.*
*ILE, invested listening effort; RLE, required listening effort.*

**TABLE 4. Target word epoch Pearson *r* correlations among dependent variables**

| Measure | Theta | Alpha | ILE | RLE | WIN |
|---|---|---|---|---|---|
| Theta | 1 | | | | |
| Alpha | 0.64* | 1 | | | |
| ILE | –0.01 | –0.01 | 1 | | |
| RLE | –0.01 | –0.05 | 0.71* | 1 | |
| WIN | 0.02 | 0.05 | –0.60* | –0.86* | 1 |

*Strong correlations ($r \geq 0.7$), moderate correlations ($r \leq 0.7$ and $\geq 0.5$), and weak correlations ($r \leq 0.5$ and $\geq 0.3$). Correlations with $r < 0.3$ and $p < 0.05$ are not considered significant.*
**Significant correlations ($p \leq 0.001$).*
*ILE, invested listening effort; RLE, required listening effort; and WIN, word recognition % correct.*

**TABLE 5. Late target word epoch Pearson *r* correlations among dependent variables**

| Measure | Theta | Alpha | ILE | RLE | WIN |
|---|---|---|---|---|---|
| Theta | 1 | | | | |
| Alpha | 0.57* | 1 | | | |
| ILE | –0.01 | –0.12 | 1 | | |
| RLE | –0.02 | –0.07 | 0.71* | 1 | |
| WIN | 0.05 | 0.08 | –0.60* | –0.86* | 1 |

*Strong correlations ($r \geq 0.7$), moderate correlations ($r \leq 0.7$ and $\geq 0.5$), and weak correlations ($r \leq 0.5$ and $\geq 0.3$). Correlations with $r < 0.3$ and $p < 0.05$ are not considered significant. Correlations with $r < 0.3$ and $p < 0.05$ are not considered significant.*
**Significant correlations ($p \leq 0.001$).*
*ILE, invested listening effort; RLE, required listening effort; WIN, word recognition % correct.*

alpha power and to a lesser degree theta power. This decrease of power was also found in correct only responses for alpha power, suggesting that the decrease in power did not reflect the participant "giving up" (similar results in Paul et al. 2021). This reduction coincided with a decrease in word recognition performance and may indicate reduced use of supporting neural systems when listeners recognize limited benefit from the use of these systems. We predict that a decision to reduce use of the related systems occurs when the amount of perceived effort is greater than the extent of word recognition. That is, listeners may be engaging in neuroeconomic or opportunity cost decision-making when working hard to recognize speech has limited utility (Eckert et al. 2016). The significant effect of alpha power predicting ILE shows some support for our prediction; however, the expected value from speech recognition was not measured in the current study.

The self-report measures of ILE and RLE were designed to capture the difference in invested effort and required effort in varying SNRs. ILE and RLE had a strong positive correlation, with a shared variance of 50% ($r = 0.71$). Importantly, the two measures did show some differences. ILE shared less variance (36%, $r = -0.60$) with WIN performance than RLE (74%, $r = -0.86$) with WIN performance. The difference in shared variance shows that RLE ratings had a closer link to task difficulty and possibly word recognition performance than ILE ratings. Moreover, alpha power was a significant predictor of ILE, and ILE was elevated relative to RLE in easier SNRs with few word recognition errors. This suggests that ILE was driven more by cognitive inhibition than task performance and RLE was driven by performance, similar to previous studies showing a close relation of objective task difficulty with "required effort" measures and lack of relation between "invested effort" and task difficulty (Hsu et al. 2017; Mulert et al. 2007). In addition, ILE and RLE showed little variation in challenging SNRs. This could be a result of the low sensitivity of the measures, or the low sensitivity of the perception of effort.

The current study showed variation in SNR contributed to changes in alpha power that occurred with changes in ILE and RLE across participants. Theta power did not have an effect on ILE, suggesting a disconnect between performance monitoring and perceived invested effort in the current paradigm. The discrepancy between theta power and self-report measures could be a result of the time-limited application of performance monitoring evoked by a single word recognition paradigm. Wöstmann et al. (2017) suggested that theta power may reflect the serial rehearsal of items in memory. Increasing the number of items to recognize or adding a recall task with items presented in background noise could prolong and deepen the level of engagement for performance monitoring resulting in more perceptive changes to listening effort.

**TABLE 6. Linear regression of frequency power on self-report, presentation, and word in noise (WIN) performance while controlling for signal-to-noise ratio (SNR)**

| | | Theta | Alpha | Theta* SNR | Alpha* SNR | Present. | Present.* SNR |
|---|---|---|---|---|---|---|---|
| Epoch | Measure | *t* | *t* | *t* | *t* | *t* | *t* |
| Carrier phrase | WIN | 0.75 | 1.71 | –2.49 | 1.08 | –0.73 | –1.51 |
| | ILE | 1.84 | –3.52† | 1.78 | 4.03‡ | 3.58† | 0.58 |
| | RLE | 0.78 | –2.86* | 0.78 | 1.60 | 1.80 | 3.46† |
| Target word | WIN | 1.32 | 3.12* | –1.65 | 1.28 | –0.69 | –1.54 |
| | ILE | 0.99 | –3.20† | –0.74 | 6.05‡ | 3.23† | 0.75 |
| | RLE | –0.87 | –4.47‡ | 0.62 | 2.22 | 1.78 | 3.49† |
| Late target word | WIN | 1.52 | 2.52 | –1.42 | 1.93 | –0.48 | –1.46 |
| | ILE | –0.43 | –2.34 | –1.49 | 6.20‡ | 3.40† | 0.50 |
| | RLE | –1.05 | –3.63† | 1.05 | 2.11 | 1.78 | 3.44 † |

*Degrees of freedom were 4166 for all models. Epoch window times are relative to the onset of the target word (0ms). Carrier phrase window of –800ms to 0ms, target word window of 0 to 700ms, and late target word 400 to 1100ms. SNR was significant in all analyses ($p \leq 0.0001$) and was not included here. Interactions of presentation (present.) with theta and alpha were non-significant and not included here.*
*Significance levels*
**$p \leq 0.05$.*
*†$p \leq 0.01$.*
*‡$p \leq 0.001$.*
*ILE, invested listening effort; RLE, required listening effort; SNR, signal-to-noise ratio; WIN, word in noise.*

Two different presentations were included as a control for the effects of SNR order, but significant effects of presentation were not hypothesized to affect the theta, alpha, or self-report results. The randomization of the SNRs reduced theta and alpha power in the target word epoch compared with descending SNRs. In addition, the effect of presentation was also present in self-reported effort measures when controlling for the effects of theta and alpha. The descending presentation was a predictor of higher ILE, and the descending presentation interacted with SNR to predict higher RLE compared with the randomized presentation. These results show evidence of a link between theta and alpha power with self-reported effort. It is possible that stimulus presentation and alpha power modulate self-reported effort. For example, when listening conditions deteriorate in a predictable fashion, there is a hypothetical chain of events: (1) anticipation of increasingly challenging listening conditions, (2) recruitment of additional neural support systems to meet anticipated challenge or adaptive control, and (3) a subsequent increase in self-reported listening effort. When listening conditions are unpredictable, anticipation is limited and this chain of events is halted. It is important to note that the descending presentation did not alter task performance from the randomized presentation here and in a previous study (Wilson et al. 2003). The independence of neural support systems and listening effort measures from task performance measures is a key element to further understand the neural bases for listening effort. Further studies should focus on the listening conditions that have consistent task performance and reveal fluctuations in self-report and objective listening effort measures (e.g., Lunner et al. 2020) to better capture the subtle changes in neural support systems that influence perceived listening effort.

**Limitations** • There were limitations in the current study. First, the paradigm of single-word recognition may have limiting effects compared with sentence recognition. Sentence recognition would have a higher working memory load, resulting in stronger effects on the effortful listening measures. Future studies should examine the varying effects of sentence recognition on EEG measures of effortful listening. Second, a possible confound to the alpha frequency power inverted U-shape was the possibility of eye/gaze movement across SNRs. While participants were instructed to maintain a forward gaze the lower SNRs and increased difficulty in word recognition could have resulted in a shift in eye gaze and possibly altered parietal frequency power results. This behavior would have been consistent with the hypothesis that lower alpha and theta in the lower SNR conditions reflected reduced use of supporting neural systems. Nonetheless, there was no visual target to fixate and no eye-tracking to record eye gaze. Future studies will incorporate a fixation target and eye-tracking. Third, the EEG collected during the late target word could have contributions from premotor neural activity associated with the participant preparing to verbally respond with the word recognized. Future studies will consider alternative methods to separate these neural processes in this epoch window.

## CONCLUSION

The results of this study add to the growing body of literature showing the effect of listening conditions on alpha and theta power. The elevated theta and alpha power in the easy to moderate SNRs and alpha power predicting invested listening effort suggest the application of supportive neural systems in word recognition and could be considered a marker of listening effort within the FUEL model (Pichora-Fuller et al. 2016). The moderately difficult listening conditions appeared to be where there were inflection points, or a steep rise in subjective listening effort ratings and decrease in alpha power. These observations have practical significance for studies on listening effort where there is interest in the SNR condition that contributes to listening effort despite accurate performance, perhaps, for example, in intervention studies designed to examine changes in listening effort over time.

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