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Theta- and alpha-power enhancements in the electroencephalogram as an auditory delayed match-to-sample task becomes impossibly difficult

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Abstract

Recent studies have related enhancements of theta- (∼4–8 Hz) and alpha-power (∼8–13 Hz) to listening effort based on parallels between enhancement and task difficulty. In contrast, nonauditory works demonstrate that, although increases in difficulty are initially accompanied by increases in effort, effort decreases when a task becomes so difficult as to exceed one's ability. Given the latter, we examined whether theta- and alpha-power enhancements thought to reflect effortful listening show a quadratic trend across levels of listening difficulty from impossible to easy. Listeners ($n = 14$) performed an auditory delayed match-to-sample task with frequency-modulated tonal sweeps under impossible, difficult (at ∼70.7% correct threshold), and easy (well above threshold) conditions. Frontal midline theta-power and posterior alpha-power enhancements were observed during the retention interval, with greatest enhancement in the difficult condition. Independent component-based analyses of data suggest that theta-power enhancements stemmed from medial frontal sources at or near the anterior cingulate cortex, whereas alpha-power effects stemmed from occipital cortices. Results support the notion that theta- and alpha-power enhancements reflect effortful cognitive processes during listening, related to auditory working memory and the inhibition of task-irrelevant cortical processing regions, respectively. Theta- and alpha-power dynamics can be used to characterize the cognitive processes that make up effortful listening, including qualitatively different types of listening effort.

KEYWORDS

auditory processes, event-related synchronization, hearing, independent component analysis, working memory

1 | INTRODUCTION

An increasing number of studies are exploring how oscillatory dynamics of the electro- and magnetoencephalograms (EEG and MEG, respectively) reflect the use of cognitive resources in effortful listening (for review, see Krause, Lang, Laine, Kuusisto, & Pörn, 1996; Weisz, Hartmann, Müller, Lorenz, & Obleser, 2011; Wisniewski, 2017). Much of this work has demonstrated sustained enhancements to within-band power during auditory selective attention and working memory tasks that vary in difficulty. For instance, frontal-midline theta power in the EEG has been found to increase as signal-to-noise ratio (SNR) decreases during sentence recognition (Wisniewski et al., 2015). The same is not observed when listeners passively hear speech in noise while watching a silent movie (Dimitrijevic, Smith, Kadis, & Moore, 2017; Wisniewski et al., 2015). Obleser, Wöstmann, Hellbernd, Wilsch, and Maess (2012) observed alpha-power enhancements in a speech listening task that increased with increasing degradation of acoustic input and increasing memory load. Similar alpha-band enhancements have been observed in a variety of different listening tasks (Dimitrijevic et al., 2017; Krause et al., 1996; McMahon et al., 2016; Pesonen, Björnberg, Hämäläinen, & Krause, 2006; Peterson, Wöstmann, Obleser, Stenfelt, & Lunner, 2015). Though commonly observed during speech listening, these theta- and alpha-power enhancements also occur during simple nonspeech listening tasks such as frequency discrimination (e.g., van Dijk, Nieuwenhuis, & Jensen, 2010; Wisniewski, 2017), demonstrating that they are not speech specific.

Several have proposed that enhancements of theta and alpha power (Eckert, Teubner-Rhodes, & Vaden, 2016; McMahon et al., 2016; Obleser et al., 2012; Wisniewski et al., 2015; Wisniewski, 2017) can be used as indices of listening effort—"the mental exertion required to attend to, and understand, an auditory message" (McGarrigle et al., 2014). Frontal-midline theta dynamics have been repeatedly associated with working memory and cognitive control processes (Gevins, Smith, McEvoy, & Yu, 1997; Jensen & Tesche, 2002; Klimesch, Schack, & Sauseng, 2005; Onton, Delorme, & Makeig, 2005; for intracranial EEG recordings, also see Raghavachari et al., 2001), while current theoretical work in cognitive neuroscience suggests that alpha-power enhancements reflect functional inhibition of unattended inputs (for review, see Klimesch, 2012) or task-irrelevant brain regions (for review, see Jensen & Mazaheri, 2010). Interestingly, models from cognitive hearing science developed in parallel posit that working memory and top-down attentional resources become increasingly used as listening increases in difficulty (e.g., the Ease of Language Understanding Model; Rönnberg, Rudner, Foo, & Lunner, 2008; Rönnberg et al., 2013). For instance, when speech is masked by background noise (e.g., multiple talkers in a crowded room), attention and memory resources become increasingly important for understanding the target speech stream. In silence, the same speech stream would be understood effortlessly (for review, see Rönnberg et al., 2013).

The relationship between task difficulty and effort, however, is well demonstrated to be nonmonotonic (Brehm & Self, 1989; Kukla, 1972; for review, see Richter, 2016). In general, the effort one invests into a given task is low if the amount of effort needed to successfully accomplish that task exceeds ability (e.g., if the task is impossible; Kukla, 1972). This notion is consistent with repeated reports from clinicians that individuals suffering from hearing impairments avoid conversation, or give up on listening, to reduce the costs associated with increased effort (e.g., Weinstein & Ventry, 1982). Few studies have investigated potential nonmonotonic relationships between theta- or alpha-power enhancements and task difficulty during listening. Peterson et al. (2015) found that individuals suffering from moderate hearing loss showed an increasing enhancement of alpha power as SNR decreased and memory load increased. This was only up to a point. When the task was sufficiently difficult (e.g., 6-digit load at −4 dB relative to ~80% threshold), alpha power enhancement was reduced relative to easier conditions (e.g., 4-digit load at 0 dB relative to ~80% threshold). A nonmonotonic trend over a continuum of task difficulty, though demonstrated with hearing impaired listeners (Peterson et al., 2015), has not been observed using normal hearing listeners to our knowledge. Nor has any related study used a nonspeech auditory task (although, for peripheral psychophysiological measures, see Richter, 2016). A focused examination of nonmonotonic trends across task difficulty in the frontal midline theta rhythm has also not been conducted.

Here, we asked how theta- and alpha-power enhancements change as a nonspeech auditory delayed match-to-sample task (i.e., ABX task) becomes impossibly difficult. Frequency-modulated tonal sweeps of varying rates were presented in A, B, and X order with a 2.5-s delay between the offset of B and the onset of X. X was always a match to either A or B. A participant's task was to indicate whether X matched A or B. Three levels of difficulty were compared: impossible, difficult, and easy. In the impossible condition, an individual could not feasibly accomplish the task. Stimulus A, B, and X were identical. In the difficult condition, A and B differed at an individual's predetermined ~70.7% correct threshold. In the easy condition, A and B differed well above the predetermined threshold. High-density (135 channels) EEG recordings were made throughout the experiment. It was hypothesized that both frontal midline theta-power and alpha-power enhancements during the retention interval would be greatest in the difficult condition. The easy condition would show low enhancement since the task could be accomplished successfully without extensive use of cognitive processes indexed by theta- and alpha-power enhancements. The impossible condition would be so difficult as to not justify the cost of utilizing such resources, and would thus also show very little enhancement of theta and alpha power.

We performed both planned analyses of theta- and alpha-power enhancements on data obtained at electrodes, and exploratory analyses of independent component processes extracted from the high-density EEG data. The former served as a way to assess our hypotheses with a restricted analysis clearly derived from previous work. The latter served to examine the roles of potentially multiple brain processes in theta- and alpha-power enhancements seen in the channel data. EEG reflects a mixture of brain and nonbrain processes (e.g., several different cortical processes and eye movement artifacts). Independent component analysis (ICA) is a blind

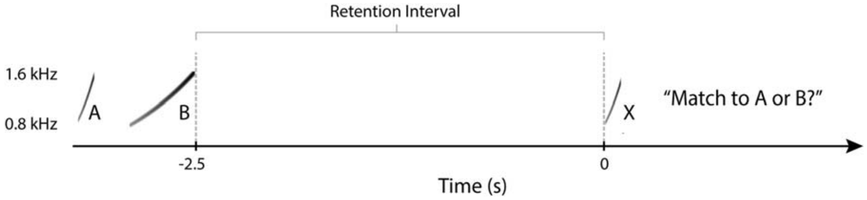

FIGURE 1 Depiction of a typical easy trial in the employed delayed match-to-sample task. Single FM sweeps are shown. All combinations of sweep rate assignments to A, B, and X were used in the actual experiment

source separation algorithm that can decompose linearly mixed processes contributing to the EEG recorded at scalp channels (Delorme & Makeig, 2004; Delorme, Palmer, Onton, Oostenveld, & Makeig, 2012). An ICA decomposition of EEG data returns a spatially fixed and maximally temporally independent set of component processes without relying on a priori assumptions about the spatial distributions and temporal dynamics of those processes. As with channel activities, activities of independent components (ICs) can be examined in the time-frequency domain for theta- and alpha-power enhancements. ICs identified by ICA are often found to account for a significant amount of variability in both frontal midline theta (e.g., Onton et al., 2005; Scheeringa et al., 2008; Wisniewski et al., 2015) and alpha rhythms (e.g., Gramann et al., 2010; Makieg & Onton, 2009; Wisniewski, Mercado, Church, Gramann, & Makeig, 2014; Wisniewski, Mercado, Gramann, & Makeig, 2012). The ICA approach is especially useful for the current research because analyses of ICs have the potential to disentangle the contributions of multiple brain sources to theta- and alpha-power effects seen at channels.

2 | METHOD

2.1 | Participants

Fifteen individuals (6 females; ages 19–30) from the area surrounding Wright-Patterson Air Force Base, OH, were paid to participate or participated on a volunteer basis. All reported normal hearing, had prior experience with psychoacoustic tasks, and signed a U.S. Air Force Institutional Review Board informed consent document. One individual was dropped from analysis because of an excessively noisy EEG. The final sample contained 14 participants.

2.2 | Stimuli, task, and apparatus

Frequency-modulated (FM) tonal sweeps, sweeping from low to high in frequency from 800 to 1600 Hz, were used as stimuli. FM sweeps are acoustically complex, like many real-world sounds (e.g., speech), yet are unfamiliar to participants and are unlikely to be associated with any preexisting biases or labels (see deCharms, Blake, & Merzenich, 1998; Wisniewski, Church, & Mercado, 2010).

An auditory delayed match-to-sample task was used (see Figure 1). On each trial, two FM sweep stimuli (A, then B) were presented back to back with 200 ms of silence in between. One of these stimuli was always a standard rate. The other was a nonstandard rate selected to make the task "impossible," "difficult," or "easy" (see below). After a 2.5-s retention interval, a comparison sound (X) was presented that matched either A or B. Participants' task was to indicate whether X matched A or B using marked keys on a computer keyboard. There was no feedback of correctness. Participants were instructed to withhold responding until after the offset of X. There were no response deadlines. Whether or not X was a match to A or B and the assignment of standard and nonstandard stimuli to the A and B intervals was completely counterbalanced.

A rate of 8 octaves per second was used as the standard rate of FM. Two other rates of FM were assigned individually based on ~70.7% correct thresholds for telling the standard rate from slower rates. These thresholds were measured in a preexperimental session on a separate day prior to the experiment. Thresholds were determined for each individual using two-up, one-down adaptive tracks (Levitt, 1971), adapting the rate of the nonstandard FM stimulus (initially 3 octaves per second) up 0.15 octaves per second after every two consecutive correct responses, and down 0.15 octaves per second after every incorrect response. In the preexperimental session, there were two of these adaptive tracks run per participant. Tracks were ended after eight reversals, and the threshold for a track was considered to be the mean of the last four reversals. The mean of thresholds for the two tracks was taken as that participant's threshold. Two individualized rates were then selected. One rate was selected to be the comparison rate at an individual's threshold ($M = 6.05$ octaves per second, $SD = .59$). The other was half the rate of that threshold rate ($M = 3.03$ octaves per second, $SD = .29$). For the experiment, on impossible trials, A and B FM rates were identical at the standard 8 octaves per second rate. Trials in which A and B rates differed at threshold were considered difficult, and trials using rates half the rate of the threshold rate were considered easy. There were 36 trials in each of six blocks (216 trials total; 72 per condition). Conditions were randomized across trials within a block.

Experimental procedures and data acquisition were performed using MATLAB R2013a (Natick, MA) and BioSemi Acquisition software (BioSemi, Amsterdam, Netherlands). Sounds were presented over Etymotic ER-2 earphones (Etymotic Research, Elk Grove Village, IL) in a sound-attenuating booth.

2.3 | Electrophysiological data collection and processing

A 135-channel array of electrodes was used. A BioSemi Active II system, recording at a 2048 Hz sampling rate and 24-bit A/D resolution, was used to collect data. One hundred and twenty-eight electrodes were fixed within a cap and arranged according to a BioSemi equiradial layout. The remaining seven electrodes were placed at the mastoids, on lateral sides and below each eye, and on the tip of the nose. Data were referenced online to the common-mode-sense/driven-right-leg (CMS/DRL) reference of the BioSemi system (see www.biosemi.com). Electrode offsets relative to CMS/DRL were brought within 25 μV or else were rejected from analysis.

All offline analyses were performed using EEGLAB (Delorme & Makeig, 2004; http://sccn.ucsd.edu/eeglab) and custom MATLAB scripts/functions. The data were referenced offline using an average reference, resampled at 256 Hz, and digitally band-pass filtered between 0.5 and 100 Hz. Channels contaminated by excessive noise or movement artifacts by visual inspection were then removed.

Full-rank extended infomax ICA was applied to each individual's data using the binica() function in EEGLAB. ICA finds a set of weights (W) that linearly unmixes the channel data (x) into a sum of maximally temporally independent and spatially fixed components (u) such that $u = Wx$. The rows of u are IC activities that can be analyzed in a manner identical to scalp channels. Columns of the inverse weight matrix, W^{-1}, give projection weights from each IC to the scalp. Projections can then be used to estimate the locations of equivalent current dipoles for individual ICs in a head model. For each dataset, an ICA model was trained for 512 iterations or until weight change fell below 1e-7. Here, ICs were selected for rejection based on visual inspection of their activities and spectra (for review and guidelines on IC selection, see Jung et al., 2009; Makeig & Onton, 2009). These IC processes were subsequently removed from channel data (i.e., artifact correction was conducted) in order to examine theta- and alpha-power dynamics in their absence. For further information on the application of ICA in EEG research, see Makeig, Debener, Onton, and Delorme (2004) and Makeig, Jung, Bell, Ghahremani, and Sejnowski (1997).

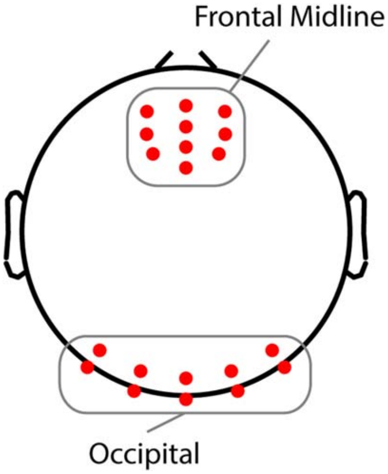

FIGURE 2 Locations of electrodes within the frontal midline and occipital electrode groups used in the analysis of channel data

2.4 | Channel groups

Based on previous work (e.g., Krause et al., 1996; Pesonen et al., 2006; Wisniewski et al., 2015; Wisniewski, 2017), two different groups of channels were selected for the analysis of theta- and alpha-band power modulations. A frontal midline group of channels and a group of channels over the occipital lobes were expected to show enhancements in theta- and alpha-power, respectively (see Figure 2).[1]

2.5 | IC process selection and clustering

IC processes not already identified as artifacts were selected for further analysis based on the proportion of variance in channel data they accounted for, their scalp projections, and the location of their equivalent current dipole models. IC processes that ranked in the top 60 of IC processes in regard to their contribution to variability in channel data were retained. Next, scalp maps judged as dipolar were selected (see Delorme et al., 2012). These IC processes were then fit with single equivalent current dipole models. In this process, electrode locations were fit to a template boundary element head model and then localized in the template brain using the dipfit() function in EEGLAB (Oostenveld & Oostendorp, 2002). ICs retained for later clustering were those for which the estimated equivalent current dipole was in the brain volume and for which the scalp projection of the equivalent

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[1] An alternative group of electrodes containing parietal channel locations was also examined. Analyses on this group of channels produced the same trends over conditions as the occipital group of channels. In general, there was less enhancement observed for this channel grouping (see scalp maps of alpha power in Figure 3).

dipole accounted for at least 85% of the variance in the IC scalp projection. An average of 9.92 ICs (*SD* = 3.45) were retained per participant.

Retained IC processes were clustered into groups based on the location of equivalent current dipoles and PCA reduced representations of their spectra. A k-means procedure was used to group each IC process into one of 10 different clusters. The number of clusters for clustering was determined objectively based on the average number of ICs per individual meeting the selection criteria.

2.6 | Event-related spectral dynamics

Channel data and ICs were analyzed similarly. Epochs of 5.5 s (from 4.5 s before to 1 s after the onset of X) were extracted from continuous data. The newtimef() function of the EEGLAB toolbox was used to compute each channel's and IC's event-related spectrum using complex Morlet wavelets in a frequency range between 3 and 50 Hz (3 cycles at the lowest frequency to 25 cycles at the highest) centered at 200 time points within an epoch (~22-ms time steps). The mean power spectrum from −4,500 ms to −3,300 ms (across all epochs within a condition) was used as a baseline for computing relative power. Percentage of baseline power (see Cohen, 2014; Mazaheri & Picton, 2005) was used as a relative power measure. The following equation shows how relative powers were computed:

$$Relative\ Power\ \%_{tf} = 100\frac{activity_{tf}-\overline{baseline_f}}{\overline{baseline_f}}$$

Here, $activity_{tf}$ is the mean absolute power across epochs at time t and frequency f. $\overline{baseline_f}$ is the mean absolute power across all epochs and time points within the baseline period at frequency f. The relative powers at all time-frequency points make up the event-related spectral perturbation (ERSP; Makeig, 1993).

2.7 | Statistics

Given the expectation of effects in the retention interval between the offset of B and the onset of X, times between −2,000 ms and 0 ms relative to the onset of X where selected. Note that this time window starts a sufficient length of time past the onset and offset of A and B stimuli (at least 500 ms) in order to minimize the influence of transient responses to those sounds (cf. Wisniewski et al., 2014). Frequencies of theta and alpha selected for analysis were within canonical bands, 4–8 Hz and 8–13 Hz, respectively. Mean relative powers within these time- frequency windows were extracted for each condition.

Linear and quadratic contrast tests were conducted on these mean relative powers. A contrast statistic, denoted ψ, was computed by multiplying the observed mean relative powers by coefficients describing a condition's role in the contrast, and then summing those values. For linear contrasts, mean relative powers for impossible, difficult, and easy conditions were associated with coefficients of 1, 0, and −1, respectively. For quadratic contrasts, the impossible, difficult, and easy conditions were associated with coefficients of -.5, 1, and -.5, respectively. The contrast ψ_{linear} reflects the degree to which the data fit a trend of increasing power with greater task difficulty, with higher values indicating a better fit. Similarly, the contrast $\psi_{quadratic}$ reflects the degree to which the data fit a trend of greater power for the difficult condition, compared to the impossible and easy conditions. Statistical significance was assessed using a nonparametric permutation-based procedure. For 1,000 iterations, condition labels were randomly shuffled and ψ was recomputed. These ψ values made up a null hypothesis distribution that was used to determine *p* values. *p* values were considered to be the proportion of iterations showing a larger ψ statistic than the actual data (for review, see Cohen, 2014).

TABLE 1 Proportion correct data

Task	Proportion correct
Impossible	.51 (.02)
Difficult	.68 (.02)
Easy	.98 (.01)

Note. Standard error of the mean appears in parentheses.

3 | RESULTS

3.1 | Behavior

Table 1 shows accuracies on impossible, difficult, and easy trials. Unsurprisingly, performance was better as task difficulty decreased. A one-way repeated measures analysis of variance (ANOVA; using the Greenhouse-Geisser correction; uncorrected *df*s reported) revealed significant differences among conditions, $F(2, 26) = 245.13$, $p < .001$, $\eta_p^2 = .95$. Accuracy was significantly higher in the easy condition compared to the difficult condition, $t(13) = 13.63$, $p < .001$, Cohen's $d = 2.56$, and the impossible condition, $t(13) = 24.03$, $p < .001$, Cohen's $d = 8.49$. Accuracy was also significantly higher in the difficult condition compared to the impossible condition, $t(13) = 7.38$, $p < .001$, Cohen's $d = 1.60$.

3.2 | Electrophysiology—channels

Figure 3 displays ERSPs averaged across levels of difficulty for frontal-midline (a) and occipital (b) electrode groups. Both theta (4–8 Hz) and alpha (8–13 Hz) power showed

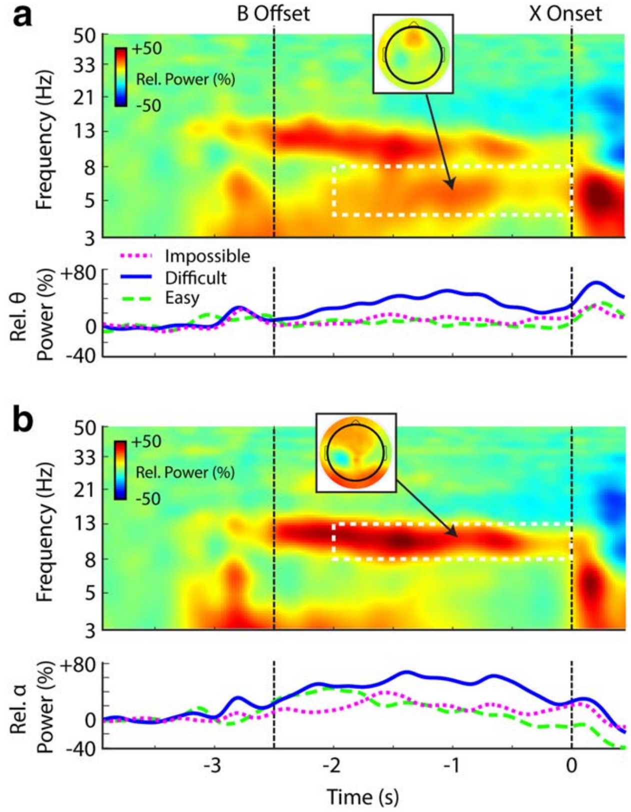

FIGURE 3 (a) Mean ERSP (across all conditions) for the frontal midline electrode group. Traces of relative theta power for each difficulty condition are shown below the ERSP. A scalp map of relative theta power within the analysis window (white dashed box) is also shown. (b) Mean ERSP for the occipital electrode group. Traces of relative alpha power for each difficulty condition are shown below the ERSP. A scalp map of relative power within the analysis window is also shown

increases relative to baseline during the retention interval between the offset of B and the onset of X. Note that relative increases in theta appear strongest at frontal sites, as is evident in the ERSPs and the scalp map of relative theta power (cf. Onton et al., 2005; Wisniewski et al., 2015). Enhancements of alpha power appear strongest at occipital sites, but these enhancements tend to be more widespread across the scalp than theta-power enhancements (cf. Wisniewski et al., 2012, 2014). Traces of relative theta and alpha power extracted from ERSPs for each difficulty condition are depicted below their respective ERSP images in Figure 3. Theta traces for the frontal midline electrode group depict greatest relative theta for the difficult condition (solid blue line). The impossible (dotted pink line) and easy conditions (dashed green line) show relative theta closer to 0% across the retention interval. The same trend is observable for relative alpha power (Figure 3b).

Time-frequency windows used for statistical analyses (see above) are depicted by the white dashed rectangles in Figure 3. Linear contrasts on mean relative powers across conditions were nonsignificant for both theta and alpha, $ps > .30$. Quadratic contrasts were significant for both theta, $\psi_{quadratic} = 27.34$, $p = .006$, and alpha, $\psi_{quadratic} = 31.35$, $p = .003$. Thus, it appears as though both theta- and alpha-power enhancements initially increase as task difficulty increases, but then decrease when the task becomes impossible. That is, a nonmonotonic relationship exists such that relative theta- and alpha-power enhancements are strongest for a sufficiently difficult listening task that is accomplishable. Theta- and alpha-power enhancements during an easy or impossibly difficult version of the same task show relatively small increases in power relative to baseline.

3.3 | Electrophysiology—IC processes

An exploratory analysis of ICs was conducted to examine the contributions of multiple independent brain processes to effects seen in the channel data. Figure 4 shows characteristics of seven different clusters of IC processes. The other clusters (not shown) displayed either less tight groupings of equivalent current dipoles or did not contain data from enough individuals to warrant further analysis. Figure 4a shows cluster spectra, 4b shows the locations of estimated equivalent current dipoles, 4c shows mean scalp maps (averaged across all ICs within a cluster), 4d shows mean ERSPs (averaged across all conditions and ICs within a cluster), and 4e shows traces of either relative theta or alpha power for each condition.

To make reference to specific IC process clusters in the following text, we named clusters based on their locations within the template brain (see Figure 4b). These were left frontal (11 participants, 15 ICs), right frontal (11 participants, 15 ICs), left central (11 participants, 15 ICs), central parietal (10 participants, 14 ICs), right parietal (10 participants, 16 ICs), right occipital (10 participants, 14 ICs), and left occipital (10 participants, 13 ICs). Note that there can be considerable error in the estimated localization of single equivalent current dipoles, especially when individualized head models are unavailable (Akalin-Acar & Makeig, 2013). We do not have individual anatomical data for the participants in this study. Accordingly, when referring to particular anatomical locations, we use the phrase "at or near" (e.g., at or near the anterior cingulate cortex). Below, we first qualitatively describe the data from each cluster. Qualitative descriptions of clusters are followed by permutation-based testing of linear and quadratic contrasts as performed above for channel data. Given that 14 tests were to be conducted (1 linear and 1 quadratic contrast for each cluster), results were interpreted with fdr corrections to the familywise error rate (corrected *p* values reported; Benjamini & Hochberg, 1995).

ICs in the left frontal cluster had estimated equivalent current dipoles centered at or near the left anterior cingulate cortex, with most dipoles falling at or near the anterior cingulate

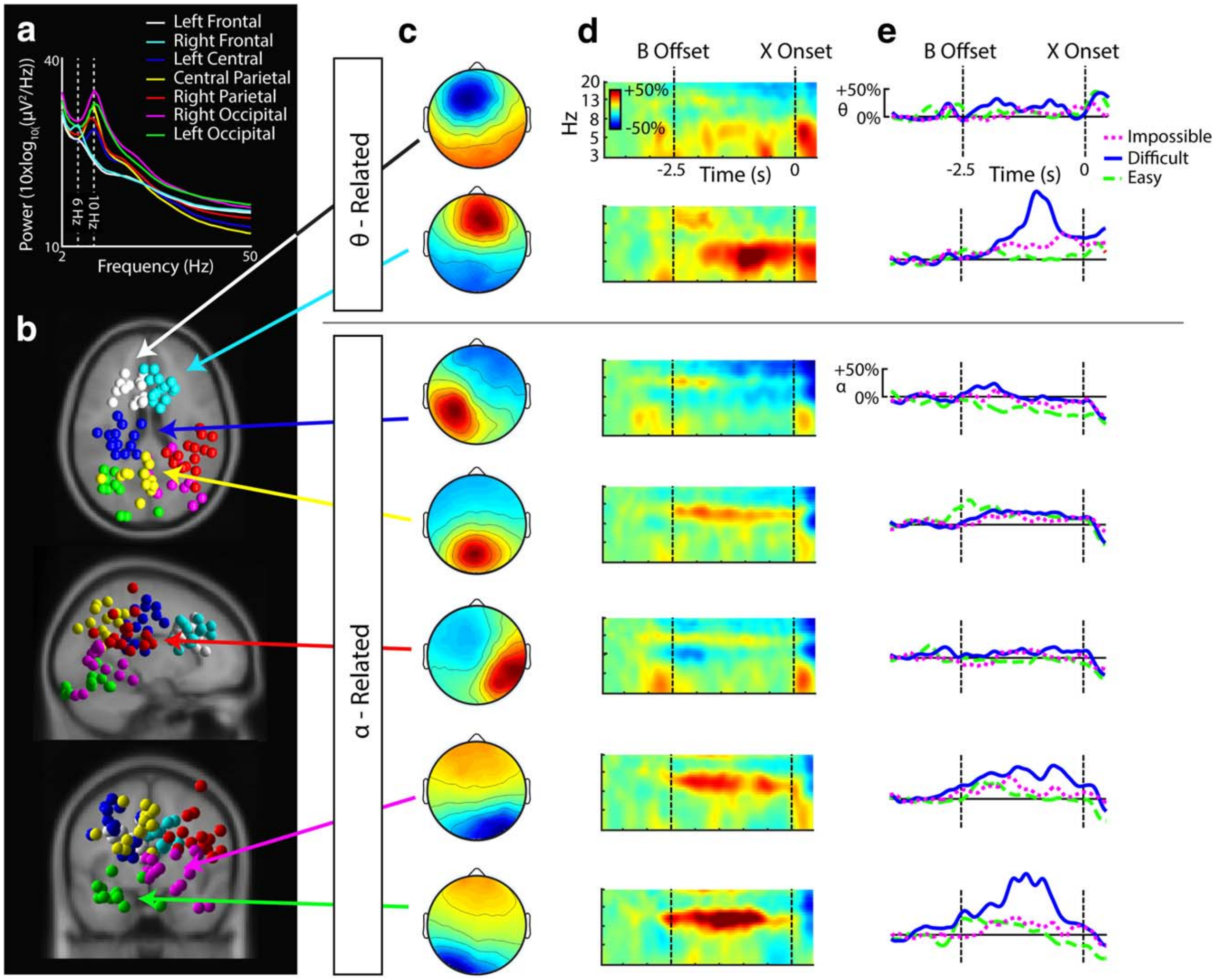

FIGURE 4 (a) Mean spectra for ICs within each cluster. (b) Estimated individual equivalent current dipoles of IC processes within each cluster. (c, d, e) From top to bottom, these clusters are referred to in the text, respectively, as left frontal, right frontal, left central, central parietal, right parietal, right occipital, and left occipital. (c) Mean scalp projection of ICs within each cluster. (d) ERSPs averaged across all difficulty conditions for each cluster. (e) Either theta or alpha relative power traces for each condition

cortex itself (white spheres, Figure 4b). The mean spectrum for ICs within the cluster showed a peak in the theta range (white line, Figure 4a), the cluster's scalp map showed strong projection of ICs within the cluster to frontal-midline scalp locations (Figure 4c), and the mean ERSP showed theta enhancement during the retention interval (Figure 4d). All of these characteristics are consistent with prior examinations of ICs corresponding to frontal midline theta (Delorme et al., 2012; Onton et al., 2005; Wisniewski et al., 2015). Traces of relative theta power for the different conditions show some hint of greater theta enhancement for the difficult condition (i.e., the solid blue line is higher than the pink and green dashed lines). The linear contrast was not significant, $p > .20$. The quadratic contrast was significant, $\psi_{quadratic} = 9.48$, $p = .045$.

The right frontal cluster was similar to the left frontal cluster in regard to dipoles (cyan spheres in Figure 4b), spectra (cyan line in Figure 4a), and scalp map (Figure 4c), but was slightly right lateralized. The mean ERSP showed even stronger theta enhancement during the retention interval than the left frontal cluster (Figure 4d). In addition, theta traces showed a striking similarity to channel data in that enhancement was stronger in the difficult condition compared to the easy and impossible conditions (Figure 4e). Like the right frontal cluster, the linear contrast was not significant, $p > .20$. The quadratic contrast was significant, $\psi_{quadratic} = 43.05$, $p = .021$.

Spectra of ICs in the left central cluster showed a clear alpha peak and a hump in the beta range (~13–30 Hz), characteristic of the motor-related mu rhythm (blue line in Figure 4a). Most dipoles were localized at or near the left precentral and postcentral gyri. Also, the mean ERSP revealed strong suppression of this mu rhythm during and after the retention interval. These characteristics are consistent with prior reports of ICs corresponding to mu rhythm features (e.g., Delorme et al., 2012; Gramann et al., 2010). Note that the motor-related mu rhythm is known to decrease in power in preparation to manual responses (Pfurtscheller & Lopes da Silva, 1999). This observation in the current data is thus unsurprising. Potentially important, however, is that alpha-power traces show that this mu suppression is strongest for the easy condition. The linear contrast for alpha power was significant, $\psi_{linear} = 20.02$, $p = .028$, suggesting that alpha suppression was strongest for the easy condition. The quadratic contrast was not significant, $\psi_{quadraic} = 18.42$, $p = .072$.

The central parietal cluster had a clear spectral peak in the alpha band (yellow line, Figure 4a), and dipoles centered in parietal cortex at or near the precuneus (yellow spheres in Figure 4b). The mean ERSP showed clear alpha-band enhancement during the retention interval (Figure 4d); however, there were no clear differences in this alpha enhancement across conditions (Figure 4e). Neither the linear nor quadratic contrasts were significant, $ps > .380$.

A right parietal cluster of ICs showed a spectral peak in the alpha band (red line, Figure 4a), and dipoles centered at or near the right parietal cortex (red spheres, Figure 4b). The cluster displayed some alpha enhancement during the retention interval. This cluster also showed a decrease in alpha power shortly after the offset of B (Figure 4d). However, there were no clear condition differences in alpha power across conditions (Figure 4e). Linear and quadratic contrasts were nonsignificant, $ps > .10$.

A right occipital cluster of ICs showed a clear peak in the alpha band (pink line, Figure 4a), and dipoles centered at or near the right occipital lobe (pink spheres, Figure 4b). A strong enhancement of alpha power is observable in the mean ERSP (Figure 4d). Relative alpha-power traces show that this alpha enhancement was greatest for the difficult condition, as it was at channels (Figure 4e). The linear contrast was nonsignificant, $p > .22$. The quadratic contrast was significant, $\psi_{quadraic} = 32.11$, $p = .035$.

A left occipital cluster of ICs also showed a clear peak in the alpha band (green line, Figure 4a). Dipoles for the left occipital cluster were centered at or near the left occipital lobe (green spheres, Figure 4b). This cluster showed the strongest enhancement of alpha power in the mean ERSP (Figure 4d). Further, relative alpha-power traces show greatest alpha enhancement for the difficult condition (Figure 4e). The linear contrast was nonsignificant, $p > .22$. The quadratic contrast was significant, $\psi_{quadraic} = 58.64$, $p = .028$.

4 | DISCUSSION

Sustained enhancements of theta and alpha power have been repeatedly observed during difficult listening tasks (Kolev, Yordanoca, Schürmann, & Başar, 1999; Mazaheri & Picton, 2005; McMahon et al., 2016; Obleser et al., 2012; Pesonen et al., 2006; Wisniewski, 2017; Wisniewski et al., 2015). In the context of listening effort research, these features have received a great deal of attention as indices of cognitive resource allocation (e.g., attention, working memory; for review, see Eckert et al., 2016; McGarrigle et al., 2014; Wisniewski, 2017). Here, we investigated how making listening impossibly difficult impacted such enhancements of theta and alpha power in a nonspeech delayed match-to-sample task (i.e., an ABX task). Given qualitative reports from clinicians that hearing-impaired individuals give up on listening under extremely difficult listening conditions (e.g., Weinstein & Ventry, 1982), and nonauditory empirical work demonstrating consistent nonmonotonic relationships between task difficulty and effort (for review, see Richter, 2016), we hypothesized that theta- and alpha-power enhancements would show a quadratic trend from the impossible, to the difficult, to the easy conditions. Indeed, relative increases in both frontal midline theta power and posterior alpha power were observed during retention in the delayed match-to-sample task. These enhancements were largest for the difficult condition, which was individually adjusted to match participants' preexperimental thresholds (70.7%). When the task was made impossible, or was sufficiently easy, both theta- and alpha-power enhancements were reduced relative to the difficult condition.

IC processes identified in the channel data were clustered based on the similarity of their equivalent current dipole models and the spectra of their time-varying activities. Several clusters of similar IC processes showed task-related modulations of theta and alpha power. Two medial frontal clusters of IC processes showed theta enhancement during the retention interval between the offset of B and the onset of X. The frontal clusters, like the channel data, showed greater theta enhancement for the difficult condition compared to the impossible and easy conditions. Task-related perturbations of the alpha band were observable for several different IC process clusters: left central, central parietal, right parietal, left occipital, and right occipital clusters. However, enhancements of alpha power were most prominent for the left and right occipital clusters of IC processes. Further, both of these occipital clusters showed trends in alpha-power enhancements across conditions that correlated with effects observed at the channel level. In addition, a left central cluster of IC processes, likely related to the mu rhythm, showed suppression during the retention interval. This suppression was greatest in the easy condition.

4.1 | Relationship to previous EEG work on theta- and alpha-power enhancements during listening

Unlike some previous studies showing either theta- or alpha-power enhancements (e.g., Obleser et al., 2012; Peterson et al., 2015; Wisniewski, 2017), we were able to see both concurrently (cf. Pesonen et al., 2006). Further, although theta- and alpha-power trends across conditions largely paralleled each other, ICA-based analyses revealed that these effects stemmed from temporally independent processes. Along with several other works (e.g., Klimesch, 1999; Klimesch et al., 2005; Pesonen et al., 2006; Strauß, Kotz, Scharinger, & Obleser, 2014), the data suggest that these two types of enhancements reflect separable processes involved in listening.

Frontal midline theta enhancements are well known to vary as a function of memory load in nonauditory paradigms (e.g., Gevins et al., 1997; Jensen & Tesche, 2002; Klimesch et al., 2005; Onton et al., 2005). Further, single equivalent current dipole models of ICs within the current frontal clusters were consistent with reports using intracranial electrophysiological methods that the frontal midline theta rhythm stems at least in part from activity in the anterior cingulate and other nearby frontal areas (Tsujimoto, Shimazu, Isomura, & Sasaki, 2010). Following work on the frontal midline theta rhythm in memory research, we suspect that the observed theta-power enhancements reflect increased utilization of working memory resources during listening (cf. Rönnberg et al., 2008, 2013). In the current task, the difficult condition entails memory for sounds (A and B) that are very similar acoustically. As a consequence, matching X to either A or B requires maintenance of a relatively detailed memory representation of previous stimulation. In contrast, in the easy condition, an individual need only remember the order of the slow and fast sounds to identify stimulus X as either slow or fast. Hence, enhancements in the theta band are weak (cf. Wisniewski, 2017).

A role for theta enhancements in working memory during listening may also potentially explain why some others have failed to find theta enhancements that correlate with task difficulty and perceived listening effort. For instance, in a task where spoken numbers separated by a retention interval are to be compared (e.g., Wöstmann, Herrmann, Wilsch, & Obleser, 2015), working memory resources may not be taxed enough to detect any enhancement in the power of the frontal midline theta rhythm. This would be similar to the lack of clear theta enhancement in the easy condition of the current study. Another study specifically manipulated the number of items to be stored in working memory and found significant effects in the alpha band (Obleser et al., 2012). Although a trend was seen for greater theta enhancement with greater memory load, this trend did not reach significance using a nonparametric cluster-based statistical method (Maris & Oostenveld, 2007). Another possibility for the lack of significance is an insensitivity of the statistical procedures employed. Such clustering procedures are biased to assign significance to data points in time-frequency-electrode space that are in large clusters of data points showing similar trends (Cohen, 2014). As our data well shows, theta effects tend to have a more focused distribution on the scalp (over frontal midline electrodes) than alpha effects (see Figure 3). Further, there may be more independent sources driving alpha dynamics at scalp electrodes compared to theta. Statistical clustering procedures (e.g., Maris & Oostenveld, 2007) may thus be less sensitive to detecting differences in theta than alpha enhancement between conditions.

Alpha-power enhancements have also been associated with memory processes (e.g., Jensen, Gelfand, Kounios, & Lisman, 2002; Klimesch, 1999, 2012; Liu, Glizer, Tannock, & Woltering, 2016), but more recently have received consideration from those studying attention processes as a mechanism of inhibition in the brain (for review, see Jensen & Mazaheri, 2010; Klimesch, 2012; Weisz et al., 2011). In this theoretical framework, alpha enhancement indicates inhibition of task-irrelevant cortical regions, whereas alpha suppression indicates release from inhibition. Inhibition of task-irrelevant processing regions can serve to route processing to regions that are important for the task at hand (Jenson & Mazaheri, 2010). That enhancements of alpha power were strongest for two occipital clusters of IC processes supports the notion that alpha enhancements reflect this type of process. In this paradigm, visual processing areas likely have little to provide and are thus inhibited. Others have made similar conclusions after finding increased parietal/occipital alpha enhancement when participants are cued to pay attention to auditory features (for review, see Foxe & Snyder, 2011). Although alpha enhancements were also seen for parietal clusters of IC processes, these enhancements did not show any clear relationship with task difficulty. If the current parietal-based enhancements reflect some sort of inhibitory top-down attentional process, this does not appear to vary as a function of difficulty as much as in other listening tasks that implicate parietal alpha rhythms (e.g., Obleser et al., 2012; Wöstmann et al., 2015).

An important consequence of the ICA-based analyses of alpha dynamics performed here is evidence that the mu rhythm can contribute to alpha-band effects observed when manipulating listening difficulty. If easy listening conditions show a stronger suppression in mu rhythm power (see Figure 4), this could be interpreted as a weaker enhancement in alpha-band power in the channel data when the mu rhythm is mixed by scalp conduction with other rhythms that show relative increases in power (cf. Wisniewski et al., 2014). One study found that presentations of speech sounds in noise were accompanied by suppression of the mu rhythm (Bowers, Saltuklaroglu, Harkrider, & Cuellar, 2013). Further, suppression was greater when SNRs were higher (i.e., when the task was easier). That study essentially showed greater alpha suppression for easy conditions rather than enhancement for harder conditions. We were able to see that alpha-band differences between conditions were not dependent upon differences in mu suppression. Nevertheless, motor-related alpha-band suppression differences between conditions should be considered and ruled out in analyses of differences in alpha-power enhancements, perhaps with an ICA approach.

4.2 | Relevance to the study of "listening effort" in cognitive hearing science

Recent years have seen an increasing focus on the role of cognition in the speech and hearing sciences, reflecting the emerging field of cognitive hearing science. A central topic of the field has been listening effort. Work has largely focused on developing methods to quantify effort, or on characterizing the stimulus factors that modulate it (for review, see McGarrigle et al., 2014). Some have begun to explore psychophysiological measures to these ends. Pupil diameter is larger in low compared to high SNRs (Zekveld, Kramer, & Festen, 2010), and speech compared to non speechmaskers (Koelewijn, Zekveld, Festen, & Kramer, 2012). Similar trends have been observed with skin conductance when varying SNR (Mackersie & Cones, 2013). In analyses of evoked MEG/EEG activity, intertrial phase locking within the time range of the auditory N1 (~100 ms poststimulus onset) shows increased amplitudes when speech sounds become increasingly difficult to discriminate (Bernarding, Strauss, Hannemann, Seidler, & Corona-Strauss, 2013; also see Wisniewski, 2017). Similar results have been obtained using components of the ERP (Bertoli & Bodmer, 2014; Obleser & Kotz, 2011). In general, increased amplitudes of these measures have been presumed to reflect greater allocation of cognitive resources to listening as difficulty increases.

These methods may prove useful as either clinically viable measures of effort, or means of testing the effects of specific clinical treatments on effort. Nevertheless, weaknesses exist for characterizing the neural and cognitive components of effortful listening. Pupil dilation is correlated with activity in various brain regions (Zekveld, Heslenfeld, Johnsrude, Versfeld, & Kramer, 2014), providing little discriminative information regarding the neural networks involved. Pupillometry and other peripheral measures also collapse effortful listening into a single measure, making it difficult to examine specific cognitive processes involved. Transient ERP features, though affected by cognitive processes associated with effort (e.g., attention; Hillyard, Hink, Schwent, & Picton, 1973), cannot fully characterize the listening brain. As the current data demonstrate, one can be utilizing cognitive resources at time points prior, and far exceeding sound onset. An exclusive focus on EEG/ERP features occurring within the first few hundred milliseconds poststimulus onset will fail to capture components of effortful listening that lie outside this small time window.

Listening effort has been defined as "the attention and cognitive resources required to understand speech," and was just recently reformed into a working definition as "the mental exertion required to attend to, and understand, an auditory message" (McGarrigle et al., 2014). Terms like *cognitive resource* and *mental exertion* entail an enormous amount of unmentioned processes (e.g., long-term memory retrieval, imagery, expectation, selective attention, maintenance, decision making, categorization, etc.). Perhaps, as a result, many studies have ignored specific processes. Studies of oscillatory dynamics of EEG and MEG can be useful in this regard. For instance, the potential for different types of listening effort that involve maintenance of information in working memory or attention-related gating of sensory information may be studied through analyses of the theta and alpha bands, respectively. Other work in auditory science shows that processes of encoding and recognition may be examined separately through enhancement or suppression of the alpha band (e.g., Krause et al., 1996). The phase of ongoing oscillations in the EEG also appears to be under some top-down control and can have modulatory effects on auditory performance (Wilsch, Henry, Herrmann, Maess, & Obleser, 2015), and may potentially relate to effort. The study of listening effort in cognitive-hearing science may benefit from a detailed investigation into the processes involved in effortful listening with the use of psychophysiological measures like EEG that are useful for detecting processing-related differences between individuals and conditions. Further, since auditory cognition is undoubtedly complex, it will behoove cognitive hearing science to consider multiple indices of listening effort.

4.3 | Conclusions

That both theta- and alpha-power enhancements during listening were found to be strongest under conditions of high difficulty, but lower under a condition where the task was impossible, supports the notion that these features relate to the effortful cognitive processes one brings to a given listening task. It is not the case that these enhancements relate monotonically to listening difficulty. ICA-based analyses support the notion that alpha-power enhancements at least partially reflect the inhibition of task-irrelevant cortical regions. Based on the nature of the employed delayed match-to-sample task, and similar nonauditory paradigms showing enhancements in frontal midline theta, we believe that the observed theta enhancements (likely stemming from medial frontal sources near the anterior cingulate cortex) are related to demands placed on an individual's use of working memory resources. Future work on listening effort will benefit from examinations that move beyond the quantification of effort as a singular phenomenon and toward a conceptualization of listening effort that qualitatively varies given the demands of a specific listening task. This approach will require examination of a fuller range of the features available in EEG and the manipulation of specific cognitive processing demands (e.g., need to utilize working memory).

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