Hearing Research xxx (2017) 1–5

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Short communication

Sustained frontal midline theta enhancements during effortful listening track working memory demands

Matthew G. Wisniewski*, Nandini Iyer, Eric R. Thompson, Brian D. Simpson

711th Human Performance Wing, U.S. Air Force Research Laboratory, United States

A R T I C L E I N F O

Article history:
Received 9 August 2017
Received in revised form
16 October 2017
Accepted 24 November 2017
Available online xxx

Keywords:
Event-related spectral perturbation (ERSP)
Listening effort
Perceptual anchor
Event-related synchronization

A B S T R A C T

Recent studies demonstrate that frontal midline theta power (4–8 Hz) enhancements in the electroencephalogram (EEG) relate to effortful listening. It has been proposed that these enhancements reflect working memory demands. Here, the need to retain auditory information in working memory was manipulated in a 2-interval 2-alternative forced-choice delayed pitch discrimination task ("Which interval contained the higher pitch?"). On each trial, two square wave stimuli differing in pitch at an individual's ~70.7% correct threshold were separated by a 3-second ISI. In a 'Roving' condition, the lowest pitch stimulus was randomly selected on each trial (uniform distribution from 840 to 1160 Hz). In a 'Fixed' condition, the lowest pitch was always 979 Hz. Critically, the 'Fixed' condition allowed one to know the correct response immediately following the first stimulus (e.g., if the first stimulus is 979 Hz, the second must be higher). In contrast, the 'Roving' condition required retention of the first tone for comparison to the second. Frontal midline theta enhancements during the ISI were only observed for the 'Roving' condition. Alpha (8–13 Hz) enhancements were apparent during the ISI, but did not differ significantly between conditions. Since conditions were matched for accuracy at threshold, results suggest that frontal midline theta enhancements will not always accompany difficult listening. Mixed results in the literature regarding frontal midline theta enhancements may be related to differences between tasks in regards to working memory demands. Alpha enhancements may reflect task general effortful listening processes.

Excessive listening effort can discourage socializing (Kiessling et al., 2003), impact performance in concurrently performed tasks (Rabbitt, 1991), and lead to fatigue (Hornsby, 2013). Psychophysiological correlates of listening demands exist in skin conductance (Mackersie and Cones, 2011), pupil dilation (Koelewijn et al., 2015), and various M/EEG features (Bernarding et al., 2013; Weisz and Obleser, 2014; Wisniewski, 2017; Wisniewski et al., 2015). These objective measures have allowed scientists to examine how different conditions affect effort, and may eventually serve in the development of procedures for reducing it (Bertoli and Bodmer, 2014; McGarrigle et al., 2014).

Of these approaches, EEG provides an especially rich set of features for indexing the complex set of cognitive processes that underlie listening (for review, see Rönnberg et al., 2008; Strauss and Francis, 2017; Wisniewski, 2017). Some researchers have reported effort-related modulations to the power of alpha (~8–13 Hz) oscillations. Alpha has been related to attentional processes based on comparisons of active versus passive listening (e.g., Dimitrijevic et al., 2017) and different selective attention conditions (e.g., Wöstmann et al., 2016). We have reported that enhancements to frontal midline theta-band (~4–8 Hz) oscillations are affected by task difficulty and parallel self-reports of increased effort (Wisniewski, 2017; Wisniewski et al., 2015, 2017). Given non-auditory work repeatedly relating the frontal midline theta rhythm to working memory demands (e.g., Onton et al., 2005), we proposed that enhancements could reflect a working memory component of effortful listening (cf. Pesonen et al., 2006).

Though this hypothesis is viable, several reasons leave it weak. First, working memory demands have not been explicitly manipulated in our previous studies. Effects of such manipulations would provide stronger support than similarities to results from non-auditory work. Second, several studies have failed to find significant frontal-midline theta enhancements. In some of these cases, tasks did not entail a strong working memory component (e.g.,

* Corresponding author. 7108 Creek Water Dr., Centerville, OH 45459, United States.

E-mail address: matt.g.wisniewski@gmail.com (M.G. Wisniewski).

https://doi.org/10.1016/j.heares.2017.11.009
0378-5955/

Marsella et al., 2017). However, other studies have failed to find effects while using auditory working memory paradigms. For example, Wöstmann et al. (2015) had listeners compare spoken integers under varying levels of signal degradation. Listeners were asked to indicate whether an integer presented after a retention interval was larger or smaller than a prior integer. Significant relationships with signal degradation in the alpha-band were found, with no apparent effects in the theta-band. Similarly, Dimitrijevic et al. (2017) employed a task that required the retention of three consecutively presented spoken digits masked by noise. Though they did observe greater theta power in active compared to passive listening conditions, theta failed to parallel self-reports of effort in the active condition. It could be argued that, similar to non-auditory studies (e.g., Onton et al., 2005), frontal midline theta enhancements are only apparent under demanding working memory conditions. Retention of a single integer (cf. Wöstmann et al., 2015) may not be sufficiently taxing. Nevertheless, while alpha enhancements have been widely observed (for review, see Weisz and Obleser, 2014), analyses of frontal midline theta enhancements during effortful listening have yielded mixed results.

Here, we tested the hypothesis that frontal midline theta enhancements reflect working memory demands in a delayed pitch discrimination task. Listeners heard two square wave stimuli separated by a 3-s ISI at their ~70.7% correct pitch discrimination threshold. The task was to indicate which interval contained the higher pitch stimulus. In a 'Fixed' condition the low-frequency stimulus on each trial was fixed at 979 Hz. In a 'Roving' condition, the low-frequency stimulus was selected randomly on each trial. The important distinction is that in the 'Fixed' condition, listeners can accomplish the task in a single-interval manner. For instance, if a 979 Hz stimulus is heard first, the first stimulus can be designated the lowest without ever hearing the second. In contrast, the 'Roving' condition forces listeners to memorize the first stimulus long enough to compare it to the second. The 'Fixed' and 'Roving' conditions are indistinguishable on the single trial level, and have comparable accuracies, but differ in their working memory demands (Ahissar et al., 2006). We hypothesized that frontal midline theta enhancements would be stronger in the 'Roving' compared to the 'Fixed' condition. We also analyzed potential differences between conditions in the alpha band. Given the variety of tasks that have related alpha enhancements to listening difficulty, we expected to see alpha enhancements in both conditions.

1. Methods

1.1. Participants

Ten listeners (5 female, ages 19–32) were compensated for participation. Normal hearing was confirmed through audiometric testing (<20 dB HL, 0.25–8 kHz).

1.2. Stimuli and apparatus

Stimuli were square waves (250-ms, 10-ms on ramps, 240-ms linear decay) of varying fundamental frequencies ($f0$s). White noise was presented concurrently with tonal stimuli at a signal-to-noise ratio of +4 dB. Sounds were generated digitally via MATLAB 2014a and were presented over Etymotic ER-2 earphones (<81 dB SPL, fixed across listeners).

1.3. Procedures

Procedures were executed in MATLAB 2014a. A 2-interval, 2-alternative forced-choice delayed pitch discrimination task was used (see Fig. 1). On each trial an initial square wave stimulus (stimulus 1) was presented, followed by a 3-second ISI, and a second square wave stimulus (stimulus 2) with a different $f0$. White noise was gated on with stimulus 1 and off with the offset of stimulus 2. The continuation of white noise through the ISI served to mask any unintended background sounds. Listeners' task was to indicate which interval contained the higher pitched stimulus using a computer keyboard. Instructions were to withhold responding until sounds finished playing. No feedback was given. After the response, the next trial commenced after a variable ITI (uniform distribution 3.5–3.7-s).

In a 'Fixed' condition, each trial contained a 979-Hz stimulus in one interval and a higher pitch stimulus in the other. Pitch difference was adapted to track 70.7% correct accuracy. After incorrect responses, the percent frequency difference ($100 \times (f_{high}-f_{low})/f_{low}$) was doubled. After two consecutive correct responses, the frequency difference was halved. In a 'Roving' condition, the difference between the pitches of the two stimuli was also adjusted adaptively; however the low-pitched stimulus was drawn at random from trial to trial (840–1160-Hz; uniform distribution). Prior to the experiment, each listener was given a short (5 trial) practice block under each condition at a frequency separation of 25%. This served to inform participants as to the differences between conditions.

For each condition, an initial block (60 trials) was run, starting at a frequency difference of 4% to adapt an individual to his or her 70.7% correct threshold. These blocks were not analyzed. Four experimental blocks were then completed (2 'Roving' blocks, 2 'Fixed' blocks; 240 trials total). The first trial of a block started at the last set frequency difference for that condition. Blocks were pseudorandomly ordered such that the 1st and 2nd blocks were forced to be different conditions.

1.4. EEG acquisition and processing

A BioSemi Active II system (BioSemi, Amsterdam, Netherlands), recording at a 2048-Hz sampling rate, and 24-bit A/D resolution was used. Sixty-four electrodes were fixed within a cap and arranged according to the international 10–20 system. Six additional electrodes were placed at the mastoids, and on lateral sides and below each eye. Data were referenced online to the Common-Mode-Sense/Driven-Right-Leg (CMS/DRL) reference of the BioSemi system. Electrode offsets relative to CMS/DRL were brought within 25 μV or else were rejected from analysis.

Offline processing was performed using EEGLAB (Delorme and Makeig, 2004) and custom MATLAB scripts/functions. Data were referenced offline using an average reference, resampled at 256 Hz (after applying a zero-phase antialiasing filter), and then bandpass filtered between 0.5 and 100 Hz (FIR, order 1536). Channels and portions of continuous data contaminated by excessive noise or movement artifacts were removed based on visual inspection.

Full-rank extended infomax independent components analysis (ICA) was applied to each individual's data using the *binica()* function in EEGLAB. Independent components (ICs) were selected for rejection based on visual inspection of their activities and spectrum, then subsequently removed (for review and guidelines, see Makeig and Onton, 2009).

1.5. EEG analysis

Based on prior research (e.g., Wisniewski et al., 2015), a frontocentral group of channels was selected for analysis. These channels were: AFz, Fz, FCz, F1, and F2. Similarly, a group of occipital channels were selected for alpha enhancements: Oz, O1, O2, PO7, PO8 (cf. Wisniewski et al., 2017). Epochs of 7-s (from 2-s before stimulus 1 onset to 5-s after) were extracted. Each channel's event-related spectrum was computed using 7 cycle complex Morlet wavelets

Please cite this article in press as: Wisniewski, M.G., et al., Sustained frontal midline theta enhancements during effortful listening track working memory demands, Hearing Research (2017), https://doi.org/10.1016/j.heares.2017.11.009