Neural correlates of auditory distraction revealed in theta-band EEG

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Selective attention involves the exclusion of irrelevant information in order to optimize perception of a single source of sensory input; failure to do so often results in the familiar phenomenon of distraction. The term 'distraction' broadly refers to a perceptual phenomenon. In the present study we attempted to find the electrophysiological correlates of distraction using an auditory discrimination task. EEG and event-related potential responses to identical stimuli were compared under two levels of distraction (continuous broad-band noise or continuous speech). Relative to broad-band noise, the presence of a continuous speech signal in the unattended ear impaired task performance and also attenuated the N1 peak evoked by nontarget stimuli in the attended ear. As the magnitude of a peak in the event-related potential waveform can be modulated by differences in intertrial power but also by differences in the stability of EEG phase across trials, we sought to characterize the effect of distraction on intertrial power and intertrial phase locking around the latency of the N1. The presence of continuous speech resulted in a prominent reduction of theta EEG band intertrial phase locking around the latency of the N1. This suggests that distraction may act not only to disrupt a sensory gain mechanism but also to disrupt the temporal fidelity with which the brain responds to stimulus events. ***NeuroReport*** **23:240–245 © 2012 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

Focusing on one stream of auditory information while ignoring others is known as auditory *selective attention* and the failure to maintain this selection is known as the perceptual phenomenon of *distraction*. Early research [1,2] revealed that selection is sometimes incomplete such that competing information can become incorporated into the contents of auditory awareness and disrupt perception of the selected stream. Elucidating the neural correlates of attentional selection became a foundational goal of cognitive neuroscience; however, the concept of distraction has gone relatively unstudied.

Investigations of auditory selective attention using the EEG and event-related potential (ERP) revealed that the responsiveness of sensory systems depends on the attentional state of the perceiver. One prominent effect is an increase in the N1 component of the auditory ERP evoked by attended, relative to ignored, stimuli ([3,4] for review). Although the perceptual effects of attention are manifested within a few 100 ms of orienting, the augmented sensory response occurs only after attention is focused on the target stream for tens of seconds [5,6], but not when attention is frequently reoriented [7–9] as would be expected in conditions of high-distraction. Recent work has confirmed that the presence of competing auditory streams attenuates components of the auditory ERP in the 100–200 ms latency range [10–14]; however, the neurophysiological basis for this effect remains unclear.

The dynamics of oscillations in neuronal networks has come under intense scrutiny with respect to the notion of attention and selection [15,16]. In this study we investigated the neural correlates of distraction by considering the relationship between the auditory ERP and measures of brain oscillatory activity. We found not only that distraction attenuated the N1 peak but also reduced intertrial phase locking (ITPL) in the theta EEG band.

Methods

Twenty-two undergraduates participated for course credit. Participants were excluded if they screened positive for attention deficit hyperactivity disorder [17], did not follow task instructions, or made excessive eye movements. Thus 14 participants contributed data to the analysis (nine female; one left-handed; average age: 23.6). Participants provided informed written consent. Procedures were in accordance with the Declaration of Helsinki and were approved by the University of Lethbridge Human Subjects Review Committee.

Stimuli were presented on a desktop computer with sound attenuating ear-bud headphones. The OpenAL audio library was used to render sounds to 90° left or right

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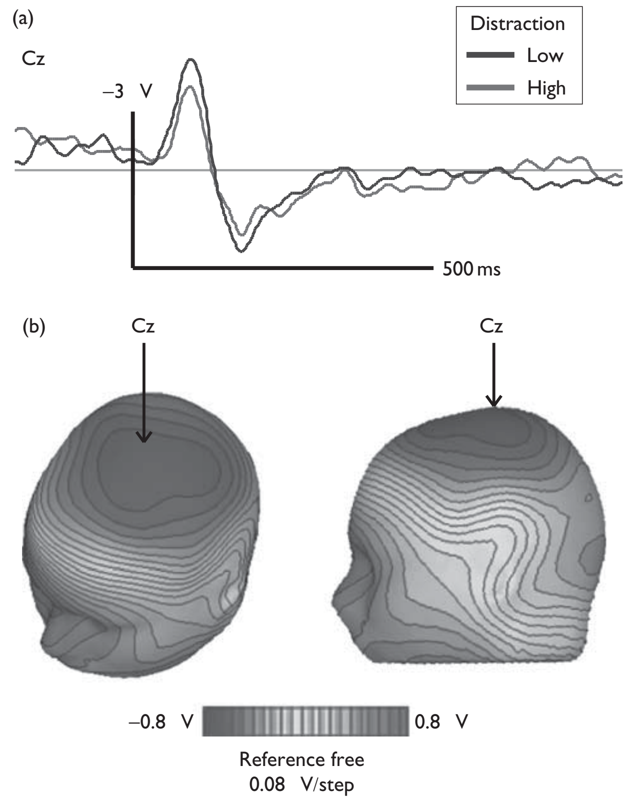
of midline. Volume was individually adjusted. Trials were presented in 28 1-minute-long blocks following a practice session. In each block participants heard target and nontarget noise bursts on one side and a distracting sound on the other side. Targets and nontargets were each 60 ms in duration and consisted of two brief noise bursts separated by a 20 or 40 ms silent gap, respectively. Ten target and 20 nontarget stimuli were pseudorandomized and intertrial intervals were randomly distributed over 1750–2250 ms. The distracting sound was either a 'low-distraction' continuous broad-band noise or a 'high-distraction' condition consisting of randomly selected segments of an audio book. The root mean square amplitude of each low-distraction stream was matched to that of each high-distraction stream. Participants were instructed to attend to the target stream, press the 'space' key when a target sound occurred and to ignore the distraction.

Mean response times, accuracy, proportion of hits and false alarms and sensitivity to detect the target sound (d') were collapsed across blocks and the side of presentation such that we tested the prediction that distraction (high vs. low) impaired perception by one-tailed t-tests.

The EEG was recorded with 128 Ag/Ag–Cl electrodes in an Electrical Geodesics Inc. (Eugene, Oregon, USA) system. The sampling rate was 500 Hz and impedances were maintained under 100 kΩ. Data were analyzed using the BESA software package (Megis Software 5.3, Grafelfing, Germany). The EEG was visually inspected for bad channels and a small number of electrodes (eight or fewer) were replaced with an interpolated signal. ERPs were time locked to presentation of target and nontarget sounds with a 200 ms prestimulus baseline [high-pass (0.5 Hz, 12 dB/octave); low-pass (30 Hz, 48 dB/octave) zero-phase Butterworth filters; re-referenced and interpolated to a standard 10–10 average-reference montage]. Epochs containing artifact (amplitude $> \pm 120\,\mu V$, gradient $> \pm 75\,\mu V/ms$, or SD of gradient $< 0.001\,\mu V/ms$) were rejected. Participants with less than 30 epochs remaining in each condition after artifact rejection were excluded from further analysis. Below we present data only for the 14 participants who met criteria on correct rejections of nontarget trials (average number of trials: low-distraction 149.7; high-distraction 135.4). A small subset of these participants ($n = 9$) also met criteria for hits on target present trials. When data from these nine participants were analyzed all of the effects reported below for correct rejections appeared as nonsignificant trends in the same direction.

The N1 peak (92 ms latency) for correct rejections in both distraction conditions was identified at electrode Cz (Fig. 1a). Mean amplitudes of the N1 (± 6 ms window spanning the peak) in each condition were compared using a two-tailed t-test. ITPL and time-spectral evolution (TSE) of power were computed using BESA and

Fig. 1



(a) Event-related potential waveform evoked by nontarget correct rejections under low-distraction and high-distraction conditions at Cz. N1 is maximal at 92 ms and is attenuated in the high-distraction condition ($t_{13} = 3.463$; $P = 0.004$). (b) An isopotential map of the N1 peak difference across distraction conditions reveals a fronto-central focus.

MATLAB (MATLAB version 7.10.0; The Mathworks Inc., 2010, Natick, Massachusetts, USA).

ITPL is defined as

$$\mathrm{ITPL}(f,t) = \frac{1}{N}\sum_{k-1}^{N} e^{j\Phi_k(f,t)},$$

where N is equal to the number of trials, and ϕ is the phase of trial k at a given frequency (f) and time (t). ITPL is a measure of the similarity of the phases of a signal over many repetitions. The values of ITPL range from 0 to 1 with 1 meaning perfect phase consistency across trials. Lower values of ITPL suggest temporal heterogeneity of brain responses across trials. ITPL differs from the traditional event-related de/synchronization measures in that it is less sensitive to (but not independent of) the amplitude of the EEG signal.

TSE of power is defined as

$$\mathrm{TSE} = \frac{A(t,f) - A_{\mathrm{baseline}}(f)}{A_{\mathrm{baseline}}(f)} \times 100\,\%,$$

where $A(t,f)$ is the activity (in power) at time t and frequency f and $A_{baseline}$ (f) is the mean activity over the baseline epoch at frequency f. TSE of power ranges from $[-100\%$ to $+\infty]$, is relative to baseline for a given frequency at time t and is relatively insensitive to phase.

The EEG was transformed into time–frequency space by complex demodulation [18] between 4 and 46 Hz from −200 to 800 ms in 2 Hz/25 ms steps. This implementation of complex demodulation applies a zero-phase Gaussian filter thereby blurring power in time. Grand averaged ITPL and TSE of power plots under low-distraction and high-distraction conditions at electrode Cz (Fig. 2a and b) were computed in MATLAB using the Fieldtrip (F.C. Donders) toolbox. We used a nonparametric random-sample permutation method and applied a Bonferroni-like false-discovery rate method to control for multiple comparisons across time and frequency bins [19].

To compare the two distraction conditions, we used a random-sample permutation method. A surrogate distribution was built for each participant by randomly shuffling trials between conditions, preserving the original number of trials in each condition and recomputing ITPL and TSE of power differences. This process was repeated 40 000 times for each participant. These surrogate distributions were then averaged to produce a grand-average surrogate distribution of differences. We compared the original grand-average difference to this surrogate distribution of differences, and obtained a two-tailed P-value (2 × the proportion of differences that fell beyond the observed difference).

Results

High-distraction reduced sensitivity to detect the target (d') ($t_{13}=2.171$; $P=0.025$) and increased the rate of false alarms ($t_{13}=2.766$; $P=0.008$). Participants made more hits in the low-distraction condition, and responded more slowly in the high-distraction condition; however, these effects were not significant.

ERP analysis revealed a prominent N1 peak in the low-distraction condition and an attenuation of this N1 peak in the high-distraction condition ($t_{13}=3.463$; $P=0.004$) (Fig. 1a). The N1 was maximal at electrode Cz with a peak latency of 92 ms. The isopotential map of the N1 difference across distraction conditions at 92 ms (Fig. 1b) revealed a fronto-central focus.

High-distraction had a pronounced effect on theta-band ITPL and a smaller effect on theta-band TSE of power (Fig. 2a and b). Also evident was a trend of more gamma power in the low-distraction condition at the N1 latency [Fig. 2b(iii)]. We observed no significant differences in the absolute amplitudes of the baselines between the low-distraction and high-distraction conditions.

Twenty-six time–frequency bins around the N1 latency/theta frequency (4–8 Hz) range for ITPL reached significance with 15 out of the 26 bins having a P-value of less than 0.0001. Unlike ITPL, none of the time–frequency bins for TSE of power passed the false-discovery rate threshold [Fig. 2a(iv) and 2b(iv)] and none of the time–frequency bins around the N1 latency/theta frequency for TSE of power reached significance when unthresholded P-values were considered (i.e. not corrected for multiple comparisons and thus much less conservative).

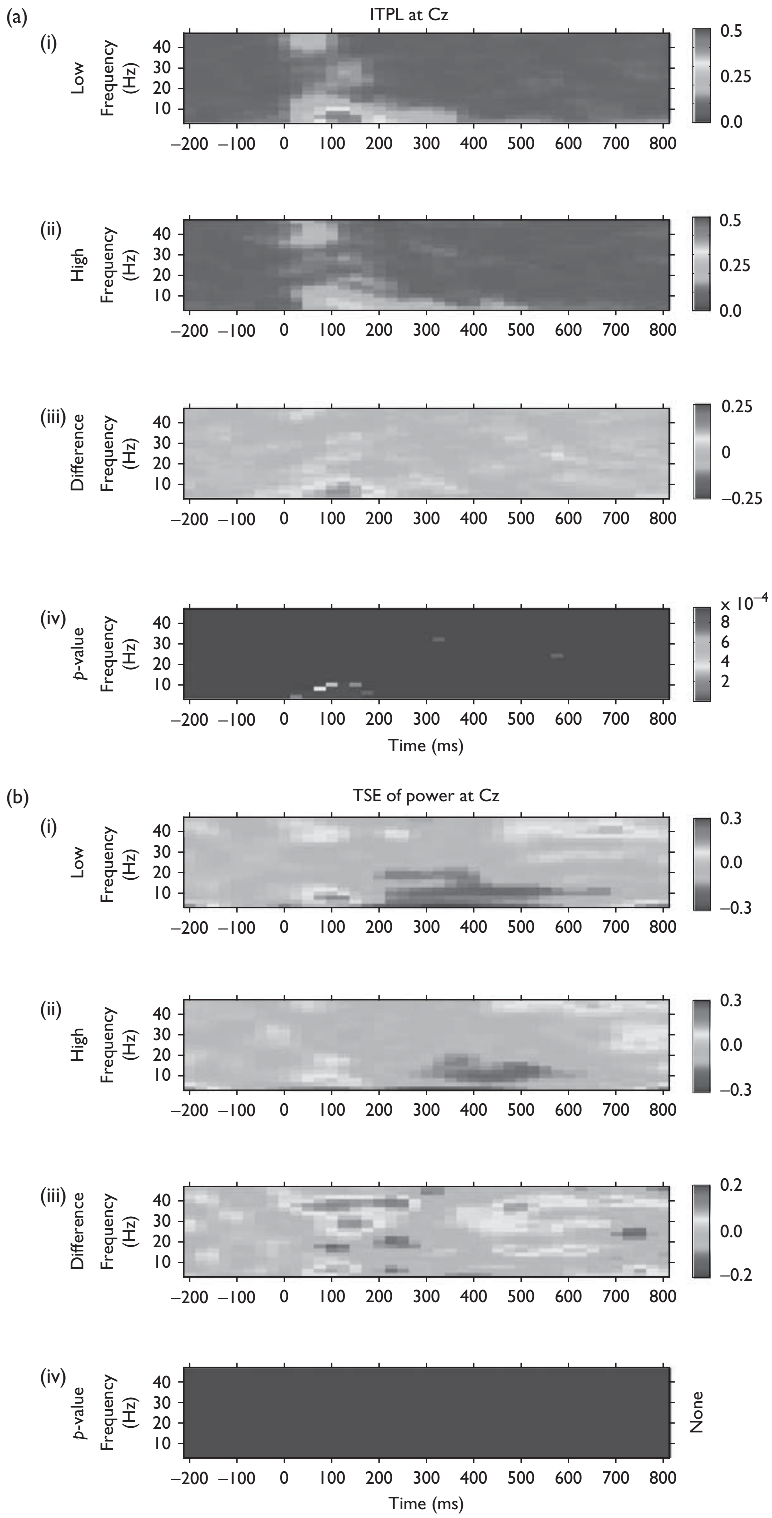
For further analysis we chose a time–frequency bin (100 ms/6 Hz) that was closest to our N1 peak and in the middle of the theta frequency range. For every participant, this time–frequency bin exhibited greater ITPL on low-distraction trials. However, in contrast to ITPL, only eight of the 14 participants showed greater theta-band power at the 100 ms/6 Hz time–frequency bin in the low-distraction relative to high-distraction condition. Across participants there was a positive correlation between ITPL and N1 mean amplitude in the low-distraction condition ($r=0.63$; $P=0.016$) and in the high-distraction condition ($r=0.77$; $P=0.001$). There was also a positive correlation between TSE of power and N1 mean amplitude in both low-distraction ($r=0.63$; $P=0.015$) and high-distraction ($r=0.66$; $P=0.010$) conditions. We therefore do not rule out the possibility that theta-band power was modulated by high-distraction at the N1 latency; however, the distraction effect seems to be primarily manifested in theta-band ITPL rather than TSE of power.

Discussion

In this study we compared the EEG and ERP responses to identical auditory stimuli under two levels of distraction. We found that the presence of distracting speech reduced the N1 peak evoked by nontarget stimuli in the attended stream relative to broad-band noise. This finding is consistent with previous investigations of the effect of auditory masking on the auditory ERP [10–14]. In addition, we found that this neural correlate of distraction seemed to reflect both a reduction in the theta phase consistency across trials and, to a lesser degree, reduced theta power. Two mechanisms could account for this distraction effect: a reduction of sensory gain afforded by attentional processes and jitter in the timing of brain responses to stimulus events.

The theory that attention acts to modulate the 'gain' of sensory systems has been argued for both the auditory and visual modalities [20]. The 'gain control' theory of attention holds that the neural responses of sensory stimuli are potentiated relative to physiological noise (e.g. neural responses to task-irrelevant events). For example, cells encoding the features of attended objects might be the target of a biasing signal enabling preselected cells to evoke a larger response [21].

Fig. 2



(a) Time–frequency plot of intertrial phase locking (ITPL) at electrode Cz in low-distraction (i) and high-distraction (ii) conditions and a time–frequency plot of the ITPL distraction difference (iii). Note the substantial increase in theta ITPL in the low-distraction condition around the latency of the N1. (iv) False-discovery rate (FDR) thresholded *P*-values for the ITPL difference generated by the nonparametric test described in 'Methods.' (b) Time–frequency plot of time-spectral evolution (TSE) of power at electrode Cz in low-distraction (i) and high-distraction (ii) conditions and a time–frequency plot of the TSE of power distraction difference (iii). Note the increases in theta and gamma power occurring around the N1 peak latency in the low-distraction condition. (iv) No time–frequency bins exceeded the FDR threshold for TSE of power difference.

Distraction may cause occasional involuntary orienting of attention away from the target source of sound, thereby abolishing the boost in early sensory gain to attended stimuli. In addition, because ITPL is sensitive to signal-to-noise ratio, small changes in the amplitude of a fixed-latency component can appear as increases in ITPL. Thus a modulation of sensory gain could explain the observed data.

Distraction could also disrupt the temporal fidelity of brain responses relative to the events that triggered them. The notion that distraction might 'jitter' brain responses in time, rather than modulate sensory gain, was suggested to explain the influence of attention on the 40 Hz auditory response [22]. Extensive effort has attempted to link the effects of selective attention to oscillatory phenomena – particularly phase locking of signals between two or more neural assemblies – to perceptual processes such as binding features into objects, attentional selection of objects from a complex scene, and entry of sensory input into consciousness [15].

A critical feature of the ERP is that the signals captured in the waveform reflect neural processes that are tightly time-locked to the sensory event of interest. We suggest that the presence of a distracting stream reduces this time locking between auditory events and subsequent brain response(s). Such a process would give rise to the pattern of data we have observed: a prominent reduction of the N1 amplitude coupled to reduced ITPL, without a prominent modulation of TSE of power. Such intertrial phase jitter might occur for one or more reasons. A prominent theory about the neurophysiological mechanisms underlying the generation of an ERP is that a sensory event can 'reset' and transiently lock the phase of various oscillating neural ensembles [23–25]. Any process that interferes with the temporal fidelity of phase resetting will increase phase variability across trials and attenuate ERP peaks. Another possibility is that distraction breaks an attentive mechanism that would otherwise tighten the temporal resolution of early perceptual systems. This view applies equally well to an 'additive fixed-latency evoked potential' model of ERP generation [23].

The reduction in N1 amplitude reported here is similar to previous reports of N1 attenuation, with the difference in N1 components between low-distraction and high-distraction resembling the difference between attended and unattended stimuli, respectively [3,4]. There are, however, important differences between the present study and that previous work. Presumably, our participants maintained a top-down attentional set on target stream stimuli in both conditions. These stimuli were 'unattended' in the high-distraction condition only in that attention was likely captured away from the target stream by the distractor. Future studies will elucidate the relationship between ITPL and attentional modulation of ERP components.

Conclusion

Relative to broad-band noise, the presence of a continuous speech signal in the unattended ear impaired task performance, attenuated the N1 peak evoked by nontarget stimuli in the attended ear and reduced theta EEG band ITPL around the latency of the N1. This suggests that distraction may act not only to disrupt a sensory gain mechanism but also to disrupt the temporal fidelity with which the brain responds to stimulus events.

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Conflicts of interest

There are no conflicts of interest.

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