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Attention Modulates ERP Indices of the Precedence Effect

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ATTENTION MODULATES ERP INDICES OF THE PRECEDENCE EFFECT

A Thesis Presented

By

BENJAMIN H. ZOBEL

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A Thesis Presented

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DEDICATION

To Kat and Phin

ABSTRACT

ATTENTION MODULATES ERP INDICES OF THE PRECEDENCE EFFECT

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When presented with two identical sounds from different locations separated by a short onset asynchrony, listeners report hearing a single source at the location of the lead sound, a phenomenon called the precedence effect (Wallach et al., 1949; Haas, 1951). When the onset asynchrony is above echo threshold, listeners report hearing the lead and lag sounds as separate sources with distinct locations. Event-related potential (ERP) studies have shown that perception of separate sound sources is accompanied by an object-related negativity (ORN) 100-250 ms after onset and a late posterior positivity (LP) 300-500 ms after onset (Sanders et al., 2008; Sanders et al., 2011). The current study tested whether these ERP effects are modulated by attention. Clicks were presented in lead/lag pairs at and around listeners' echo thresholds while in separate blocks they 1) attended to the sounds and reported if they heard the lag sound as a separate source, and 2) performed a difficult 2-back visual task. Replicating previous results, when attention was directed to the sounds, an ORN and LP were observed for click pairs 1 ms above compared to 1 ms below echo threshold. In contrast, when attention was directed away from the sounds to the visual task, neither the ORN nor the LP was evident. Instead, click pairs 1 ms above echo threshold elicited an anterior positivity 250-450 ms after onset. In addition, an effect resembling an ORN was found in comparing ERPs elicited by unattended click pairs with SOAs below attended echo threshold. These results indicate that attention modulates early perceptual processes in the precedence effect and may be critical for auditory object formation under these conditions.

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INTRODUCTION

Our sensory systems allow us to know what and where objects are in the world. In the visual system a great deal of spatial information is available based on where light hits the retina. However, the location of auditory objects must be calculated from the temporal and spectral cues available at the two ears. In reverberant environments, auditory localization is made even more challenging by sounds reflecting off of surfaces and arriving at the ears from locations other than the sound source. Fortunately, the auditory system can take advantage of the fact that direct sounds reliably arrive at the ears before their reflections. The stimulus onset asynchrony (SOA) between direct and reflected energy from the same sound source provides the information necessary to perceive unified auditory objects that can be accurately localized to the position of the source in a phenomenon called the *precedence effect* (Wallach, Newman, & Rosenzweig, 1949), or the *law of the first wavefront* (Lothar Cremer, 1948, as cited in Blauert, 1997).

There are several reasons to think that attention may be important for auditory object perception and localization. For example, there is evidence that other higher-level processes modulate the precedence effect. Further, attention has been suggested to be important for both visual object formation (Treisman & Gelade, 1980) and auditory streaming (Bregman, 1990). However, little is known about the role of attention in the precedence effect. In the current study, we examined whether attention modulates ERP indices of the precedence effect. It was hypothesized that if attention is required for the precedence effect to form a unified auditory object from direct and reflected sounds, we would expect to find attentional modulation of an early index of auditory object perception called the *object-related negativity* (ORN). Such a finding would support a broader definition of the precedence effect, one that extends to higher-level cognition, includes the dynamic grouping of features into auditory objects, and is consistent with the hypothesis that the precedence effect represents a process in which listeners construct complex models of acoustic space (Clifton, Freyman, & Litovsky, 1994; Clifton, Freyman, & Meo, 2002).

The Precedence Effect

The precedence effect can be demonstrated by positioning a listener in front of two spatially separated loudspeakers. When identical sounds are presented from both loudspeakers as a lead/lag pair with an SOA on the order of milliseconds—simulating a direct sound followed by its reflection—the listener will report hearing only one sound from the location of the lead loudspeaker. This *localization dominance* of the lead sound is one of three defining features of the precedence effect (Litovsky, Colburn, Yost, & Guzman, 1999). The second is *fusion*: listeners will perceive the single auditory percept as a summing of the lead and lag sounds, allowing for the accurate representation of a single source while preserving important information contained within the reflection about the composition of the surrounding space. The third feature is *lag discrimination suppression*: listeners appear to suppress location information contained within the lag sound.

The precedence effect represents a mechanism for source localization and object representation within reverberant environments. It operates at SOAs beyond the microsecond range of the interaural time differences that contribute to localizing direct sounds. Furthermore, the precedence effect has been demonstrated for sounds presented to a single ear (Hawley-Kaczka, Litovsky, & Colburn, 1997) and for sounds presented in the median-sagittal plane (Blauert, 1971; Litovsky, Rakerd, Yin, & Hartmann, 1997), establishing the lead/lag SOA as the critical cue regardless of orientation. As the lead/lag SOA is increased beyond the range of the precedence effect, the listener will begin to identify the lag sound as a separate auditory object at the location of the lag loudspeaker. The SOA at which this occurs is called the listener's *echo threshold* (Blauert, 1997). Extensive psychophysical examination of the precedence effect has shown that echo thresholds vary widely across stimulus types, from approximately 5-10 ms for clicks (Freyman, Clifton, & Litovsky, 1991) to upwards of 50 ms for music (Wallach et al., 1949) and speech (Haas, 1951). Stimulus features shown to influence echo threshold include amplitude, envelope, duration, pitch, and lead/lag correlation (Blauert, 1997; Blodgett, Wilbanks, & Jeffress, 1956; Goverts, Houtgast, & van Beek, 2000; Miller, Litovsky, & Kluender, 2009; Saberi & Antonio, 2003; Schubert & Wernick, 1969; Seeber & Hafter, 2011; Shinn-Cunningham, Zurek, Durlach, & Clifton, 1995). Additionally, echo thresholds tend to be highly variable among listeners (e.g., Yost & Soderquist, 1984). Thresholds can also vary by location of the lead sound within an individual (Sanders, Joh, Keen, & Freyman, 2008), though evidence suggests a listener's threshold profile remains relatively stable across experimental sessions (Zobel, Freyman, & Sanders, in prep).

The Precedence Effect as a Dynamic Distributed Mechanism

Since basic stimulus features can influence echo threshold, and many of the calculations involved in localizing direct sound energy occur subcortically, the precedence effect could be part of very early auditory processing. The precedence effect may be explained in part by interactions among peripheral filtering operations, hair cell responses, and binaural cross-correlations (Hartung & Trahiotis, 2001). Neuropsychological evidence in humans suggests the inferior colliculus plays an important role in fusion and lag discrimination suppression (Litovsky, Fligor, & Tramo, 2002). Single-cell recording studies in several animal models have demonstrated neural correlates of the precedence effect, in the form of suppressed response to the lag sound, within the auditory nerve, cochlear nucleus, superior olivary complex, inferior colliculus and primary auditory cortex (for review, see Litovsky et al., 1999). In addition, unilateral ablation of primary auditory cortex in cats has been shown to impair the precedence effect for lead/lag tone pairs when the lead tone is presented contralateral to the lesion, while localization of single tones remains intact (Cranford, Ravizza, Diamond, & Whitfield, 1971). What is clear from these studies is that the precedence effect does not reduce to a single mechanical or computational process within a specific anatomical region, but likely reflects a complex mechanism distributed across multiple stages of processing. Further, even multiple calculations carried out across several low-level processing steps cannot account for the entirety of the data.

Several key findings point to higher-level mechanisms involved in the precedence effect. First, infants do not begin to orient to lead/lag stimuli until approximately four months of age, despite being born with relatively well-developed lower-level auditory systems capable of localizing single-source sounds (Clifton, Morrongiello, Kulig, & Dowd, 1981; Muir, Clifton, & Clarkson, 1989). Dogs show a similar developmental delay (Ashmead, Clifton, & Reese, 1986). In humans, echo thresholds for short-duration click stimuli do not reach adult-like levels until about 5 years, and continue to be higher for longer-duration broadband sounds (Morrongiello, Kulig, & Clifton, 1984), contributing to greater localization errors in children compared to adults (Litovsky & Godar, 2010). These findings suggest the precedence effect relies upon the maturation of higher-level cortical systems.

Second, there is evidence that learning can affect echo perception. Saberi and Perrott (1990) reported that over the course of many trials, participants presented with click stimuli acquired the ability to discriminate lag location well below their initial echo thresholds. This apparent learning effect generalized to high-pass filtered clicks and sine-wave tones. Interestingly, one participant was retested three months later and had retained the ability to discriminate the lag sound. Spontaneous learning effects, however, have not been reported elsewhere. Litovsky, Hawley, Fligor, and Zurek (2000), failed to produce a learning effect after many hours of training participants on a different type of lag discrimination task.

Strong evidence for higher-level processing can be found in the contextual modulation of echo threshold. When a lead/lag pair at an SOA above echo threshold is repeatedly presented one after the other, listeners will report that the lag sound “fades out” of perception (Clifton & Freyman, 1989). This *buildup* of echo threshold is dependent on the number of presentations regardless of presentation rate or duration (Freyman et al., 1991) and has been shown to persist out to 3.5 seconds of silence

(Freyman & Keen, 2006; Keen & Freyman, 2009) and continue with declining strength out to 9 seconds of silence (Djelani & Blauert, 2001). Evidence also suggests that buildup occurs at fewer presentations and higher SOAs for right-lead compared to left-lead click pairs (Clifton & Freyman, 1989). Once buildup has occurred, presentation of an aberrant lead/lag pair, such as one in which the locations of the lead and lag sounds have been swapped, will produce an immediate *breakdown* of echo threshold, restoring perception of the lag click as a separate source. Repeated presentation of this new lead/lag configuration will produce a new buildup (Clifton, 1987; Clifton & Freyman, 1989).

This contextual, lateralized, persistent modulation of echo threshold is not likely to be wholly situated within lower-level auditory structures where bilateral symmetry and rapid response and recovery are central to processing. Indeed, single-cell recordings from the inferior colliculus in cats have failed to demonstrate neural correlates of the buildup and breakdown of the precedence effect (Litovsky & Yin, 1998). Instead, Clifton, Freyman and colleagues (Clifton et al., 1994; Clifton et al., 2002) hypothesized that the buildup of echo threshold reflects higher-level processes in which listeners construct models of auditory space based on expectations of how sound typically behaves within reverberant environments. Breakdown of echo threshold occurs when new auditory information conflicts with the established model, such as when a listener moves to a new environment, necessitating the construction of a new model. Consistent with their hypothesis, the researchers showed that buildup is maintained across changes in stimuli as long as changes are consistent with the established acoustics (e.g., a pitch change applied equally to the lead and lag sounds), whereas breakdown occurs only for changes that are inconsistent with the established acoustics (e.g., a pitch change applied only to the lag sound), signaling a structural change in the environment. Evidence that echo threshold can be modulated based on whether sounds corroborate or violate a listener's expectations about the surrounding environment strongly suggests that higher-level processes can influence the precedence effect.[1]

Within this framework, the precedence effect can be characterized as a dynamic system distributed across multiple stages of processing in which complex models of acoustic space are constructed and updated from inferences drawn about the surrounding environment. Mechanisms underlying the precedence effect not only serve to localize sound sources within reverberant environments, but also to build rich representations of the structure and composition of acoustic space and the auditory objects that occupy it.

The Precedence Effect and Auditory Objects

The process by which the auditory system identifies, segments, and groups the components of an auditory scene into representations of unified objects is not well understood. Bregman (1990)'s *Auditory Scene Analysis* posits that certain bottom-up processes automatically segregate and integrate elements based on correlations among

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[1] Some research, however, argues for a lower-level interpretation of these findings. When presenting participants with click pairs over headphones, Brown & Stecker (2013) found differential effects of interaural time differences (ITDs) and interaural level differences (ILDs) on the buildup and breakdown of the precedence effect, including replication of the finding that buildup was higher for ITD-lateralized compared to ILD-lateralized click pairs, and that swapping lead and lag locations only produced breakdown with ILD-lateralized stimuli (Krumbholz & Nobbe, 2002). These findings suggest that the buildup and breakdown operate at lower stages of processing, preceding the integration of ITD and ILD cues. The authors argue that the adaptation of echo threshold may only involve very basic expectations about how certain cues behave within reverberant environments. Further study is necessary to determine whether these effects generalize to listening conditions beyond headphones.

their spatial and spectrotemporal features. Bregman (1990) distinguishes s*equential grouping*, in which a sequence of correlated events is grouped as a segregated stream (i.e., an object tracked across time), from *simultaneous grouping*, in which correlated elements presented at one instant in time are grouped as a unified object. Additionally, top-down processes shaped by experience and knowledge play an important role in such things as auditory object recognition.

A classic example of sequential auditory object grouping can be demonstrated by presenting listeners with alternating presentations of a high and low tone. At higher presentation rates or greater spectral separation between the tones, listeners will report the tones splitting into two segregated streams as if each stream represented the activity of a separate source (Bregman & Campbell, 1971; Miller & Heise, 1950; van Noorden, 1975). This effect has been shown to generalize to complex sounds, such as noise bursts (Dannenbring & Bregman, 1976b) and speech (Cole & Scott, 1973; Lackner & Goldstein, 1974) and can be contextually modulated based on relationships among other sounds concurrently presented (Bregman, 1978b). Interestingly, listeners appear to be initially biased toward a one-stream interpretation, with stream segregation building up in strength as information is gathered (Bregman, 1978a). Furthermore, once stream segregation has been built up, it has been shown to persist with declining strength across gaps of at least 4 seconds of silence or white noise (Dannenbring & Bregman, 1976a), and can be returned to one-stream perception by a sudden change in location or increase in loudness of the presented sounds (Rogers & Bregman, 1998). The buildup in strength of auditory streaming as information is accumulated over time, its relatively slow decay in strength across gaps, and its deconstruction precipitated by sudden presentation of inconsistent information, are reminiscent of the buildup and breakdown of the precedence effect (Brown & Stecker, 2013 also note this similarity).

Harmonic integration is an example of simultaneous auditory object grouping, whereby several spectrally correlated elements are fused into a single unified object (Bregman, 1990). The timbre by which we identify and discriminate a particular auditory source emerges from the integration of its unique complex of harmonics. As such, listeners tend to have difficulty discriminating the individual harmonics within a periodic complex tone, and instead perceive a single unified sound source. Thresholds for harmonic grouping have been measured by mistuning a single harmonic within a periodic complex tone to the extent that listeners can discriminate which of two sequentially presented tones is mistuned (Moore, Peters, & Glasberg, 1985) or, in a more precise measure, can identify the frequency of the mistuned harmonic (Hartmann, McAdams, & Smith, 1990).

Alain, Arnott, & Picton (2001) used ERP measures to explore harmonic grouping. EEG was recorded while listeners were presented with 400-ms presentations of complex tones composed of 12 harmonics and reported on each trial whether they heard a single complex sound or a complex sound and a separate pure tone. When one of the harmonics was mistuned to the extent that listeners reported hearing it as a separate tone, ERPs showed an increased negativity over anterior and central electrodes that extended across the N1-P2 complex 150-250 ms after stimulus onset, a time window thought to reflect early perceptual processing. The researchers called this negative component the *object-related negativity* (ORN), suggesting that it indexed the perception of two auditory objects compared to one. In addition to the ORN, a widely distributed positivity was found 350-450 ms after stimulus onset, and was attributed to top-down processes involved in recognizing a sound and interpreting its meaning based on prior knowledge. Although this latter component is difficult to interpret precisely under these conditions, it may also reflect processes often associated with a P300 ERP effect, including target detection, stimulus categorization, and response selection (for review, see Polich, 2007). Importantly, ERP measurements from a passive-listening condition in which listeners read a book while tuned and mistuned stimuli were presented showed that the ORN was reduced in amplitude but still present, suggesting that little, if any, attention was required for harmonic grouping. The late positive component, however, was absent, suggesting that attention was important for the top-down processing of the stimuli. A follow-up study by Alain, Schuler, and McDonald (2002) showed no effect of stimulus duration on the ORN and LP. A passive-listening condition in which listeners attended to a silent movie while tuned and mistuned stimuli were presented replicated previous results. Dyson, Alain, and He (2005) also found no effect of attention on ORNs elicited by similar stimuli using zero-back and 1-back visual tasks.

If the precedence effect involves the grouping of a lead and lag sound into a unified auditory object, one would expect to see an ORN when listeners report hearing the lag sound as a separate source compared to when they report hearing a single sound source at the lead location. This is exactly what Sanders et al. (2008) found. EEG was recorded while listeners were presented with lead/lag click pairs at several SOAs around echo threshold and were asked to respond after each presentation as to whether or not they heard the lag click. ERPs constrained by behavioral responses given for click pairs at echo threshold showed an increased negativity 100-250 ms after stimulus onset for trials on which listeners reported hearing the lag click compared to trials on which they did not. Unlike the harmonic grouping studies discussed above, this study compared identical stimuli at echo threshold, ensuring that the ORN could be attributed to a shift in perceptual grouping rather than physical differences between the stimuli. Additionally, the ORN was present for trials 1 ms above echo threshold, on which listeners reported hearing the lag sound on a majority of trials, compared to 1 ms below echo threshold on which listeners did not hear the lag sound on the majority of trials. Although a late positivity was numerically noted for these comparisons when listeners heard the lag sound as a separate source, it did not reach statistical significance. Since release from the precedence effect occurs gradually as SOAs are increased above echo threshold such that listeners' thresholds for hearing the lag sound clearly or of equal loudness to the lead sound are higher than their echo thresholds (Blauert, 1997), lack of a late positivity may reflect weak lag sound recognition and low confidence in responses.

Sanders, Zobel, Freyman, and Keen (2011) found similar results examining the contextual modulation of echo threshold. ERPs from trials on which click pairs were preceded by a sequence of identical pairs designed to build up echo threshold (lag click not reported on a majority of trials) were compared to those elicited by click pairs preceded by a sequence of clicks designed to inhibit the buildup of echo threshold (lag click reported on the majority of trials). An ORN was observed in response to click pairs following the context that inhibited buildup compared to identical click pairs following the context that did build up echo threshold. Additionally, lag-click perception was associated with a posterior positivity 250-500 ms after stimulus onset, suggesting that the strong contextual manipulation of echo threshold may have produced clearer perceptual distinctions between conditions that listeners could more easily recognize and respond to with confidence.

Taken together, these studies provide strong evidence that the precedence effect involves the perceptual grouping of lead and lag sounds into unified auditory objects, and are consistent with the hypothesis that listeners are constructing complex acoustic models of auditory environments.

The Role of Attention in The Precedence Effect

Attention can be defined as the preferential processing of relevant information within a scene and is an essential mechanism for navigating perceptually challenging conditions that would otherwise overwhelm the system. Given that the precedence effect involves complex, multi-level processes that are collectively important for coherent organization of auditory objects in reverberant environments, it is striking to find that nothing is known about the role of attention in the precedence effect. The same challenging reverberant environments in which we depend upon the precedence effect for coherency are precisely those in which we are most likely to deploy attention.

Behavioral studies have shown that attended stimuli are detected more quickly and with greater discrimination accuracy while unattended stimuli are minimally processed (for review, see Pashler, 1999). ERP measures have been especially useful in determining the mechanisms underlying these behavioral effects for two reasons. First, ERPs can measure the processing of attended and unattended stimuli without requiring behavioral responses to unattended events. Requiring responses to unattended events may encourage participants to allocate attentional resources in a probabilistic or graded manner. Even when subjects do not know that behavioral responses will be required until after completing a task, their responses might only reflect instances when attention was diverted to the to-be-ignored events (for discussion of the difficulty of interpreting behavioral responses to unattended stimuli, see Pashler, 1999, chap. 2). Second, ERPs' high temporal resolution makes it possible to determine the stages of processing that are modulated by attention. ERP studies have consistently reported that endogenously directed auditory attention results in a larger amplitude first negative peak (N1) approximately 80-120 ms after stimulus onset (Hillyard, Hink, Schwent, & Picton, 1973). MEG evidence suggests the increased N1 amplitude is driven by activity within primary auditory cortex (Woldorff et al., 1993). These results are consistent with the view of attention as a high-level mechanism exerting top-down influence over early perceptual processing through feedback connections.

The current study used ERPs to examine the role of attention in the precedence effect by comparing the processing of click pairs across echo threshold under attended and unattended conditions. Of particular interest was whether attention can modulate the grouping of auditory objects as indexed by the ORN. The fact that the ORN persists across attention manipulations in harmonic grouping studies suggests that object grouping involves only automatic bottom-up mechanisms under some conditions. This interpretation would be consistent with Bregman (1990)'s view, which posits that pre-attentive processes mediate the grouping of basic features within an auditory scene. However, lack of an attentional modulation of the ORN is difficult to reconcile with ERP evidence showing that attention can modulate processing as early as 80 ms after stimulus onset, well before the ORN.

There are several notable reasons why the harmonic grouping studies may have failed to detect attentional modulation of the ORN. First, these studies employed a relatively conspicuous degree of mistuning that listeners may have been able to detect with minimal attention. Second, as Alain et al. (2002) would concur (p. 994), the passive-listening conditions in which listeners were asked to read a book or watch a silent movie may not have been challenging enough to prevent listeners from attending to the auditory stimuli. Recall that Alain et al. (2001) reported a small decrease in ORN amplitude in the passive condition, suggesting that a stronger manipulation across conditions might have resulted in a more complete modulation of the ORN. Dyson et al. (2005) used more demanding n-back tasks, but did not include a condition in which listeners attended to the auditory stimuli alone, which would have provided the strongest comparison for detecting an attentional modulation of the ORN.

Even if harmonic grouping is pre-attentive, there is little reason to assume that the underlying processes would generalize to object grouping in the precedence effect. Given that frequency is a basic feature by which the representation of sound is organized within the auditory system, one would expect object grouping across multiple pitches to occur with relative ease and a minimum of attention. Object grouping within the precedence effect, on the other hand, requires the integration of features across multiple dimensions, including those of time and space, where one might expect more computationally demanding operations to be facilitated by attention. Hall et al. (2000) and Thompson et al. (2001) provide evidence that the separable features within an auditory scene, including pitch, duration, and location, can be incorrectly grouped in a manner consistent with the illusory conjunctions predicted by *feature-integration theory*

(Treisman & Gelade, 1980; Treisman & Schmidt, 1982). These findings suggest that attention would be required for the complex object grouping across feature dimensions that we find in the precedence effect.

Can Attention Modulate ERP Indices of the Precedence Effect?

In the current study, EEG was recorded while participants completed blocks of trials in which their attention was either directed to lead/lag click pairs with SOAs spanning echo threshold (Attend condition) or diverted to a difficult 2-back visual task (Unattend condition). In both conditions, a stream of letters alternating case every two letters was presented on a computer screen in front of the participant. In the Attend condition, the participant was instructed to use the letter stream only as a fixation point and to attend to click pairs presented from loudspeakers located to the left and right, and to press a button after each presentation indicating whether or not the lag sound was heard. In the Unattend condition, participants were instructed to attend to the letters in the visual stream while click pairs were presented, and to press a button as soon as they saw a letter appear that alphabetically matched the letter presented 2 spaces back in the stream. Stimuli presented in both conditions were identical, except for the fact that the Attend condition did not contain 2-back visual targets. To further motivate our participants, the Attend and Unattend tasks were presented as a game, with points awarded for responding to every click pair in the Attend block, and points awarded for quickly identifying visual targets in the Unattend blocks. The current design allowed us to address several important questions: 1) Did the attention manipulation work? 2) Did we replicate ERP indices of the precedence effect (ORN and LP) in the Attend condition?

3) Did attention modulate these effects across conditions? and 4) Did attention shift echo threshold?

CHAPTER 2

METHODS

Participants

Twenty-three right-handed participants (9 female) 20-32 years of age (*M* = 24 years, *SD* = 3.62 years) contributed data to analysis. Six additional participants completed the initial screening session, but a clear echo threshold could not be estimated from their behavioral responses and they were not asked to return for the experimental session. Data from one participant who completed the experiment was excluded due to excessive low-frequency drift in the EEG recording. All participants reported normal or corrected-to-normal vision, having no known neurological problems and taking no psychoactive medication. When participants first arrived, they underwent a preliminary hearing screening with a Beltone audiometer to ensure normal hearing thresholds (≤20 dB HL for 1, 2, and 4 kHz tones, and ≤30 dB HL for 8 kHz tones). All participants provided informed consent and were compensated at a rate of $10/hr.

Stimuli

Auditory stimuli were pairs of "click" sounds composed of identical 181-µs positive rectangular four-sample pulses (16 bit/22.050 kHz). Twenty-two right-lead click pairs (SOAs 1, 1.33, 1.5, 1.75, and 2-19 ms in 1-ms steps) were assembled using Pro Tools audio software by placing a single click in the right channel followed by an identical click in the left channel of a stereo WAV file. The auditory stimuli were presented at 70 dBA over a matched pair of M-Audio StudioPro3 loudspeakers placed 1.4

m from the participants at 55 degrees left and right of midline, respectively. Visual stimuli consisted of single presentations of white letters (a, b, d, e, f, g, h, j, l, m, n, q, r, t) on a black background in the center of a computer screen placed 1.5 m directly in front of participants. One uppercase and one lowercase version of each letter were created and each subtended less than one degree of visual angle horizontally and vertically. All stimuli were presented from a PC using E-Prime software. Participants were seated in a comfortable chair in the center of an acoustically dampened 2.5 m x 3.5 m room.

Procedure

The experiment consisted of two separately scheduled sessions: a screening session, in which behavioral responses to click pairs across a range of SOAs were collected to estimate echo thresholds, followed by an experimental session, in which behavioral and EEG data were collected simultaneously.

Echo threshold screening session. Results from the screening session provided an estimate of a participant's echo threshold used to determine the 7 threshold-centered SOAs for the experimental session. Screening trials consisted of 1500 ms of silence followed by the presentation of a single click pair. A white fixation cross against a black background appeared in the center of the computer screen for the duration of each trial, followed by a response prompt 600 ms after click-pair offset. Participants were told that on every trial, they would hear a sound from the right side and that their task was to push a button on a button box, when prompted, indicating whether they also heard a sound from the left side. They were instructed to remain centered in the chair and to fixate on the white cross while listening. Before beginning the screening trials, participants practiced responding to trials that included SOAs of 1 ms and 25 ms to provide them with clear examples of hearing and not hearing the lag click as a separate source. Participants were told that the actual screening trials might not always be as clear as these examples, and that they should rely on their best judgment.

The initial screening included 196 trials. Fourteen click pairs with SOAs ranging from 1-14 ms in 1-ms steps were repeated 14 times in random order. Odd- and even-number SOA trials were presented in separate blocks. Results allowed the experimenter to estimate echo threshold as the SOA with closest to 50% of trials on which the lag sound was reported to be heard; reports of the lag sound as a separate source were also required to decrease across lower SOAs and increase across higher SOAs. The echo threshold estimated for each participant determined the 7 threshold-centered SOAs to be used in subsequent screening blocks: Threshold (T_0), ±1 ms (T_{+1} and T_{-1}), ±2 ms (T_{+2} and T_{-2}), and ±5 ms (T_{+5} and T_{-5}). Some participants had estimated thresholds that were too low to subtract 2 or 5 ms and still maintain a lowest SOA in which the sound from the right led by at least 1 ms. For thresholds $\leq$ 5 ms, T_{-5} was set to 1 ms; for thresholds of 3 ms, T_{-2} was set to 1.5 ms; for thresholds of 2 ms, T_{-1} was set to 1.67 ms and T_{-2} to 1.33 ms. Table 1 shows the 7 SOAs selected for each estimated echo threshold.

Next, participants received two screening blocks consisting of 5 trials at each of the 7 selected SOAs presented in random order. Additional blocks were presented to check for response consistency if needed. If estimated threshold changed with cumulative responses, the experimenter selected 7 new SOAs accordingly. Participants with echo thresholds < 2 ms, > 14 ms, or that could not be reliably estimated were not asked to return for the experimental session.

Experimental session. The experimental session consisted of two conditions: an Attend condition in which participants listened for click pairs selected from the 7 threshold-centered SOAs, and an Unattend condition, in which participants engaged in a visual 2-back task while presented with the click pairs. Both conditions included approximately 2.5-minute blocks of simultaneously presented auditory and visual streams. The auditory stream was 35 click pairs, with 5 repetitions of the 7 threshold-centered SOAs presented in random order. The auditory stream began 900-3400 ms (in 1-ms steps) after the start of the visual stream with an interonset interval (IOI) between click pairs that ranged from 2000-7000 ms in 1-ms steps. The visual stream consisted of single letters presented for 700 ms each with 900-ms IOIs. Letter case changed after every two letters such that two uppercase letters were always followed by two lowercase letters and the case of letters 2-apart in the stream never matched. In Attend blocks, letters were presented in random order with the exception that the same letter of the alphabet could not appear two spaces apart. In Unattend blocks, the visual stream included 35 2-back targets with inter-target onset intervals of 900-8100 ms in 900-ms steps. Targets were defined as the presentation of a letter that matched the letter of the alphabet two spaces back in the stream; targets and matching letters always differed in case. To keep participants motivated and entertained, the experimental session was presented as a game against the computer. For Attend blocks, participants had to respond to every click pair in order to gain 5 points and avoid having 10 points removed from their score. For Unattend blocks, participants gained 1 point for every target that elicited a button press within 3000 ms; every miss or false alarm gave the computer 1 point. The correct number of responses in every Attend and Unattend block was 35. Participants were told at the start of the session that they would have the opportunity to post their final scores to an anonymous leader board displaying their performance rankings among each other.

To begin the experimental session, participants received instructions on the Unattend task. They were then presented with a visual-only stream and practiced pressing a button as quickly as possible to targets until they had correctly identified 5 targets. After receiving instructions on how the Unattend task would be scored, they practiced responding to a visual stream containing 6 targets and viewed the resulting score. Finally, they were presented with an auditory and visual stream to practice responding to 4 visual targets under the actual conditions of an Unattend block. They were reminded that during an Unattend block, their goal was to focus on the visual letters and respond as quickly and accurately as possible.

Next, participants were reacquainted with the auditory stimuli by reviewing the instructions and practice trials that they had completed at the beginning of the previous screening session. The structure and scoring of the Attend blocks were then explained. Participants were told that during an Attend block, they should listen for each click and press a button indicating whether they heard a click from the left side in addition to the one they would always hear from the right side. They were told that the visual stream would not contain any targets and should be used as a fixation point only. They then practiced responding to 5 click pairs under the actual conditions of an Attend block. Finally, participants received two complete Attend blocks as practice with the 7 threshold-centered SOAs determined by the screening session. The experimenter examined the responses during the Attend practice before determining the 7 threshold-centered SOAs to be used in the experimental blocks.

After completing the practice, participants received 32 experimental blocks evenly divided between Attend and Unattend conditions in random order, resulting in 560 visual targets across the 16 Unattend blocks, and 560 click pairs (80 at each of the 7 threshold-centered SOAs) both across the 16 Attend and 16 Unattend blocks. Before each block, the block type along with reminder instructions were presented on the computer screen and reinforced by the experimenter. After each block, participants viewed their block and cumulative scores. After all experimental blocks were completed, participants were given the option to post and view their ranked scores on the leader board.

Behavioral Analysis

Participants' performance on the visual 2-back task was assessed by comparing the probability of a response being made within a 200-1200 ms time window following the onset of a visual target (hit rate) to the probability of a response being made within any other 1000-ms time window of the visual stream (false alarm rate). Responses on the auditory task were used to define the conditions for ERP analysis. The proportion of Attend trials on which the lag click was reported as a separate sound source was calculated at each of the 7 SOAs presented to each participant. A logistic function, free to vary by midpoint and slope, was then fit to each participant's data. Precise echo threshold (as opposed to the whole-number SOAs used for ERP analysis) was defined at the midpoint of the logistic function, predicting the SOA at which the lag click would be heard on exactly 50% of trials.

EEG Recording and Analysis

Electrical Geodesics, Inc. (Eugene, Oregon) hardware and software (Net Station) was used for EEG acquisition and analysis. Vertex-referenced EEG with a 250 Hz sampling rate and a 0.01-100 Hz bandpass filter was recorded continuously throughout each experimental block from a 128-electrode HydroCel Geodesic net. Several net sizes were available to ensure proper and consistent fit across participants. A 60 Hz notch filter was applied offline to attenuate any electrical noise within the recording. EEG time-locked to auditory stimuli was segmented into 700-ms epochs beginning 100 ms before stimulus onset. Net Station's artifact-detection algorithms were applied such that epochs exceeding voltage thresholds set individually for each participant to indicate eye movements, eye blinks, and drift were excluded from analysis. ERPs elicited by the onset of auditory stimuli were created by averaging together artifact-free epochs within specific SOA categories. ERPs were re-referenced to the average of the left and right mastoid channels, and data in the 100 ms pre-stimulus interval was used as a baseline.

ERP analyses were guided by four objectives: 1) Confirm that ERPs were modulated by attention, 2) replicate ERP indices of the precedence effect in the Attend condition, 3) examine whether the ERP effects of SOA differed in the Attend and Unattend conditions, and, if so, 4) explore whether these differences were consistent with attentional modulation of echo threshold. The effectiveness of the attention modulation was measured by comparing ERPs to the same sounds in the Attend and Unattend conditions. To examine the precedence effect in the Attend condition, all trials at each of the 7 SOAs were averaged together regardless of the behavioral response rather than including only trials on which two sounds were reported for longer SOAs and on which one sound was reported for shorter SOAs as was done in previous studies. This approach was necessary since it was not possible to collect behavioral responses to the auditory stimuli while subjects fully ignored the sounds in the Unattend condition and identical ERP processing in Attend and Unattend conditions facilitated comparisons across conditions. Central to the analysis of the precedence effect was the comparison of ERPs from trials with SOAs 1 ms above (T_{+1}) a participant's echo threshold (such that the lag sound was typically reported to be a separate source in the Attend condition) and from trials with SOAs 1 ms below (T_{-1}) that participant's echo threshold (such that the lag sound was not typically reported to be a separate source in the Attend condition). To address the possibility that echo threshold may differ for attended and unattended sounds, pairs of SOAs that were both above or both below echo threshold were compared for the Unattend condition.

Since echo threshold varies widely across individuals and since ERPs were averaged across all trials at each SOA, it was important to identify two SOAs for each participant that differed by 2 ms (or by 1.33 ms if echo threshold was 2 ms, N = 1) such that one was above echo threshold (T_{+1}) and the other was below echo threshold (T_{-1}). On Attend trials, the participant had to report that the lag click was a separate source on more than 50% of trials above echo threshold and on fewer than 50% of trials below echo threshold. When more than one pair of SOAs that differed by 2 ms met these criteria for a participant, the SOAs were selected to have the largest difference in the proportion of trials on which the lag click was reported.

To best capture the predicted ERP effects and their distributions, data from 120 electrodes were included in analysis. These electrodes were divided into 15 groups of eight electrodes designated by their scalp location within a 3 [Left (L), Medial (M), Right (R)] x 5 [Anterior (A), Anterior-central (AC), Central (C), Central-posterior (CP), Posterior (P)] grid, as shown in Figure 1. Mean amplitude of each participant's ERPs was measured at two time windows to assess early and late effects: 85-125 ms and 250-450 ms after click-pair onset. To assess the effectiveness of the attention manipulation, mean amplitude collapsed across T_{+1} and T_{-1} was analyzed in a 2 (Attention: Attend, Unattend) x 3 (Left/Right electrode position: L, M, R) x 5 (Anterior/Posterior electrode position: A, AC, C, CP, P) repeated-measures ANOVA. To assess the precedence effect within each attention condition, mean amplitude of ERPs elicited by T_{+1} and T_{-1} click pairs was analyzed with a 2 (SOA: T_{+1}, T_{-1}) x 3 (L, M, R) x 5 (A, AC, C, CP, P) repeated-measures ANOVA. Follow up ANOVAs on data collected at subsets of electrodes were largely motivated by significant ($p < .05$) condition by electrode position factor interactions. Greenhouse-Geisser corrections were applied to all p-values; uncorrected degrees of freedom are reported.

CHAPTER 3

RESULTS

Behavioral Results

Performance on the visual task in the Unattend condition was characterized by a high hit rate (*M* = .85, *SD* = .08) and low false alarm rate (*M* = .03, *SD* = .02). Eighteen participants responded to 100% of the 560 trials presented in the Attend condition and no participant failed to respond on more than three trials.

A logistic function was successfully fit to each participant's response data (*M* $Pseudo\text{-}R^2$ = .89, *SD* = .07). As shown in Figure 2, all of the logistic functions were characterized by positive slopes (*M* = .36, *SD* = .15) indicating more reports of the lag sound as a separate source with longer SOAs. Echo thresholds were defined at the midpoints of the logistic functions (*M* = 8.36 ms, *SD* = 3.23 ms). Both the average echo threshold and large variability across participants (*Range* = 2.37-14.34 ms) were typical for these stimuli and task.

Further, for 8 participants, the T_{+1} and T_{-1} SOAs selected for ERP analysis were predicted by responses on screening trials. For 10 participants, behavioral responses provided during collection of the ERP data indicated that SOAs 1 ms longer than those selected based on screening better fit the SOA categories; for the remaining five participants, SOAs that were 1 ms shorter than predicted were selected. In the resulting T_{+1} condition, listeners reported hearing the lag sound as a separate source on 81.66% of trials (*SD* = 13.55%); in the T_{-1} condition these responses fell to 17.52% (*SD* = 11.23%). Figure 3 shows the proportion of trials on which the lag click was reported to be heard across participants at each of the 7 SOAs.

ERP Results

Grand-average ERPs showed that click pairs at all SOAs in both attention conditions elicited the positive-negative-positive waveforms that are typical in response to auditory onsets. The first positive-going peak (P1) occurred at around 55 ms. The first negative-going peak (N1) occurred at around 95 ms. The second positive going peak (P2) occurred at around 180 ms.

ERP indices of attention. Figure 4 shows the comparison of ERPs elicited by attended and unattended click pairs. As expected, attended sounds elicited a larger N1 and later positivity. Across the entire scalp, there were interactions between Attention and electrode position factors on mean amplitude 85-125 ms after click-pair onset [Attention x Anterior/Posterior: $F(4,88) = 16.08$, $p < .001$; Attention x Left/Right x Anterior/Posterior: $F(8,176) = 6.34$, $p < .001$]. At central electrodes (AC, C, CP), sounds elicited a larger N1 in the Attend condition than in the Unattend condition [$F(1,22) = 8.27$, $p = .01$, $\eta_p^2 = .27$]. This effect was largest over medial regions [Attention x Left/Right: $F(2,44) = 5.18$, $p = .01$]. Attending to the sounds also resulted in a larger positivity 250-450 ms after click-pair onset [$F(1,22) = 5.77$, $p = .03$, $\eta_p^2 = .21$]. Although this effect was broadly distributed, differences in mean amplitude were numerically largest over central and posterior electrodes.

ERP indices of the precedence effect. Figure 5 shows the comparison of ERPs elicited by T_{+1} and T_{-1} click pairs in the Attend condition. Consistent with previous research, when listeners attended to the sounds, click pairs above echo threshold (T_{+1})

elicited a larger negativity 85-125 ms over anterior and central regions and a later posterior positivity beginning by 250 ms compared to click pairs below echo threshold (T_{-1}). The early effect was evidenced by a main effect of SOA across the scalp [$F(1,22) = 9.07$, $p = .01$, $\eta_p^2 = .29$] that was numerically larger at anterior and central electrodes. Although the positivity did not result in a main effect of SOA or interactions with electrode position factors on mean amplitude 250-450 ms after sound onset (p's $\geq .16$), the data motivated analysis of data collected over posterior regions (CP, P). At this subset of electrodes, sounds above echo threshold elicited a larger positivity than sounds below echo threshold [$F(1,22) = 5.1$, $p = .03$, $\eta_p^2 = .19$].

Unattended sounds. Figure 6 shows the comparison of ERPs elicited by T_{+1} and T_{-1} click pairs in the Unattend condition. The early negativity and later posterior positivity observed for the T_{+1} condition when listeners attended to the sounds were not evident when listeners directed their attention to the visual stimuli. Instead, visual comparison of the T_{+1} and T_{-1} SOAs defined by the behavioral data in the Attend condition revealed a larger anterior positivity beginning by 250 ms for the above-threshold sounds. The analyses that showed effects in the Attend condition provided no evidence for differences in the responses to the two SOAs in the Unattend condition 85-125 ms (p's $\geq .55$) or over posterior regions 250-450 ms after onset (p's $> .20$). However, there was some indication of a difference 250-450 ms across the entire scalp [$F(1,22) = 4.01$, $p = .06$]. Around the left and medial anterior sites where this effect appeared to be the largest (L, M and A, AC, C), sounds with SOAs above echo threshold elicited a larger positivity [$F(1,22) = 4.79$, $p = .04$, $\eta_p^2 = .18$]. There was no evidence of a similar effect over the same region in the Attend condition ($p > .80$).

To determine if the effects of SOA were modulated by attention, data from the Attend and Unattend conditions were included in the same analysis. The interaction of Attention and SOA on mean amplitude 85-125 ms after sound onset was marginally significant for measurements taken across the entire scalp [$F(1,22) = 3.67$, $p = .07$]; at the anterior and central regions where the effect of SOA was largest in the Attend condition (A, AC, C) there was an interaction of Attention and SOA [$F(1,22) = 4.29$, $p = .05$, $\eta_p^2 = .16$]. In contrast, similar analyses on mean amplitude 250-450 ms across the entire scalp, over the posterior regions where above echo-threshold sounds elicited a larger positivity only in the Attend condition, and over the left and medial anterior regions where above echo-threshold sounds elicited a larger positivity only in the Unattend condition, revealed no Attention by SOA interactions (*p*'s > .10).

Shift in echo threshold. One possible explanation for the differences in the effects of SOA in the Attend and Unattend conditions is that attention changes echo threshold. If so, other pairs of SOAs in the Unattend condition might reveal similar ERP effects to those observed in the Attend condition. Analysis of the shortest SOA presented to a subject (T_{-5}) and the SOA 2 ms shorter than echo threshold defined in the Attend condition (T_{-2}) included data from 18 participants; no data were collected in the T_{-2} condition for the other 5 participants who had echo thresholds below what was predicted from screening. As shown in Figure 7, consistent with the idea that directing attention to the visual stimuli lowered echo threshold, the longer of the two SOAs (T_{-2}) elicited a larger negativity 85-125 ms after onset [$F(1,17) = 8.84$, $p = .01$, $\eta_p^2 = .34$]. This effect was numerically larger over anterior and central electrodes, similar to the difference found for the T_{+1} and T_{-1} comparison in the Attend condition. Further, there was no evidence of an Attention x SOA interaction for these conditions conducted on data collected across the scalp or at anterior and central sites (A, AC, C) (*p*'s > .25). There was no evidence of the posterior positivity observed in the Attend condition 250-450 ms after sound onset in the parallel comparison for the Unattend condition (T_{-2} and T_{-5}) across the scalp or at posterior sites (CP, P) (*p*'s > .10).

CHAPTER 4

DISCUSSION

The current experiment examined whether ERP indices of the precedence effect are modulated by attention. In one condition, participants attended to click pairs presented at and around echo threshold and responded according to whether or not they heard the lag click as a separate source. In another condition, the same click pairs were presented while participants directed attention to a 2-back visual task. To assess the influence of attention on the precedence effect, analyses followed four objectives: 1) Determine that attention was manipulated across conditions, 2) replicate ERP indices of the precedence effect for the attended click pairs, 3) examine whether the ERP effects of SOA differed across attention conditions, and, if so, 4) explore whether these differences were consistent with attentional modulation of echo threshold.

The first objective was to determine that attention was indeed manipulated across conditions. The behavioral results indicated that participants attended to each task as instructed. Behavioral responses to attended sounds for each participant were consistent with the precedence effect, suggesting that participants remained engaged in judging the click pairs. Behavioral performance in the 2-back visual task was strong but not at ceiling, suggesting that participants remained focused on identifying visual targets while the task remained challenging. The comparison of ERPs elicited by identical attended and unattended sounds provided strong evidence that the tasks were effective at manipulating attention. Attended click pairs elicited larger N1 amplitudes 85-125 ms after sound onset across central regions of the scalp and larger P3 amplitudes 250-450 ms after sound onset across central and posterior regions of the scalp. These early and late effects are consistent with well-established ERP indices of attention (Hillyard et al., 1973; Polich, 2007), and provide clear evidence that participants were attending to the click pairs when judging the lag click and ignoring the click pairs while engaged in the 2-back visual task. Importantly, this shift in attention across conditions modulated both early perceptual (N1) and late (P3) auditory processing.

The second objective was to replicate ERP indices of the precedence effect for attended click pairs, namely the ORN and the LP. Attended click pairs 1 ms above echo threshold, which typically elicited reports of the lag click as a separate source, elicited a larger negativity 85-125 ms after sound onset compared to click pairs 1 ms below each echo threshold, which typically elicited reports of not hearing the lag click. The polarity, scalp distribution, and timing of this early negativity are consistent with the ORN reported in previous studies when participants reported hearing two sounds compared to one in the precedence effect (Sanders et al., 2008; Sanders et al., 2011) and pitch perception (Alain et al., 2001; Alain et al., 2002; Dyson et al., 2005). One noteworthy difference in the current study is that the ORN did not extend across the P2 time window. The length of the ORN may have been influenced by the visual stimuli or may reflect variability in ORN morphology that has not yet been fully described. Importantly, the presence of the ORN for attended sounds is consistent with the behavioral data and provides strong evidence that most of the click pairs above echo threshold were perceived as two separate auditory objects.

In addition to the ORN, attended click pairs 1 ms above echo threshold elicited a larger positivity across central and posterior scalp regions 250-450 ms after sound onset.

This effect was consistent with the LP observed in the previous studies under conditions in which participants reported hearing two sounds compared to one sound. The LP may reflect top-down processes involved in recognizing a sound and its meaning based on prior knowledge (Alain et al., 2001), and may also be related to P300 effects associated with target detection, stimulus categorization, and response selection (Polich, 2007). Although the factors contributing to the LP are difficult to specify, the presence of the LP for attended sounds indicates that at higher levels of processing, participants were able to confidently distinguish between click pairs above and below echo threshold.

Given that the attention manipulation was effective, and that the ORN and LP were replicated when listeners attended to the sounds, the third objective was to examine whether these ERP effects of SOA differed across attention conditions. In contrast with the ORN observed for attended click pairs, no difference was found for click pairs 1 ms above and below echo threshold 85-125 ms after sound onset when participants were directing attention to the 2-back visual task. Importantly, a significant interaction provided strong evidence that attention modulated the ORN. These results support the hypothesis that the precedence effect represents an active, dynamic system that extends to higher-level processes and is important for constructing perceptual models of acoustic space (Clifton et al., 1994; Clifton et al., 2002). Until now, that hypothesis has been primarily based on effects related to the contextual buildup and breakdown of echo threshold. The current experiment shows that attention also plays a role in shaping the precedence effect. Moreover, attentional modulation of the ORN was found when presenting single click pairs to participants, suggesting that higher-level processes play an important role in the basic operation of the precedence effect, regardless of auditory context.

Additionally, when listeners directed attention to the visual stimuli, there was no evidence of a late positive effect for click pairs 1 ms above compared to click pairs 1 ms below echo threshold. This was expected since the higher-level processes associated with the LP are necessarily attention-dependent; the LP was shown to be modulated by attention in previous studies of pitch perception (Alain et al., 2001; Alain et al., 2002). In the current study, however, no evidence of attentional modulation of the LP was found in testing the Attention x SOA interaction, although the differences were in the expected direction such that the positivity was larger for attended compared to unattended sounds. If the LP observed for attended sounds does indeed reflect processing associated with detecting, recognizing, categorizing, and responding to the auditory stimuli, it is probable that the interaction would have reached significance given a larger sample size.

Interestingly, a larger left and medial anterior positivity was found 250-450 ms after sound onset for unattended click pairs 1 ms above echo threshold compared to unattended click pairs 1 ms below echo threshold. This effect was unexpected and cannot be clearly linked with previously reported ERP effects. However, the fact that there was any difference in the response to sounds above and below echo threshold when attention was directed to the visual modality suggests veridical representations of the sounds were maintained in the absence of attention.

The final objective was to explore whether echo threshold may have been shifted by attention. With no evidence of an ORN for click pairs 1 ms above and below echo threshold when listeners directed attention to the visual stimuli, it was possible that echo threshold was higher in the absence of attention and that both of these sounds were heard as single, fused auditory objects. However, visual inspection of the data revealed no evidence of an ORN for pairs of sounds above echo threshold, providing no support for this interpretation. Alternatively, it was possible that echo threshold was lower in the absence of attention and that both sounds 1 ms above and below echo threshold, as defined by responses to attended click pairs, were heard as two separate sources when attention was directed to the visual modality. Consistent with this idea, when participants directed attention to the visual stimuli there was evidence of an effect resembling an ORN for click pairs 2 ms compared to 5 ms below the echo threshold established for attended click pairs. This effect was similar to the ORN measured for attended click pairs in amplitude, distribution, and timing. The exploratory nature of this analysis precludes strong conclusions. However, the possibility that attention to the auditory modality raises echo threshold is compatible with the claim that attention facilitates feature binding within the precedence effect, perhaps in a manner consistent with feature-integration theory (Hall et al., 2000; Thompson et al., 2001; Treisman & Gelade, 1980; Treisman & Schmidt, 1982). In raising echo threshold within reverberant environments, auditory attention would provide a reduction in clutter and improvement in comprehension and localization of actual sound sources.

In conclusion, ERP measures provided a unique opportunity to examine auditory object processing within the precedence effect while participants directed attentional resources toward and away from sounds. In the absence of auditory attention, ERP indices of the precedence effect disappeared. These results suggest that within complex environments, the extent to which direct and reflected sounds are grouped by the precedence effect into coherent auditory objects fluctuates as we attend to different aspects of our surroundings.

Tables

Estimated	T_{-5}	T_{-2}	T_{-1}	T_0	T_{+1}	T_{+2}	T_{+5}
2	1	1.33	1.67	2	3	4	7
3	1	1.5	2	3	4	5	8
4	1	2	3	4	5	6	9
5	1	3	4	5	6	7	10
6	1	4	5	6	7	8	11
7	2	5	6	7	8	9	12
8	3	6	7	8	9	10	13
9	4	7	8	9	10	11	14
10	5	8	9	10	11	12	15
11	6	9	10	11	12	13	16
12	7	10	11	12	13	14	17
13	8	11	12	13	14	15	18
14	9	12	13	14	15	16	19

Table 1. The 7 threshold-centered SOAs for each estimated echo threshold in milliseconds.

Figures

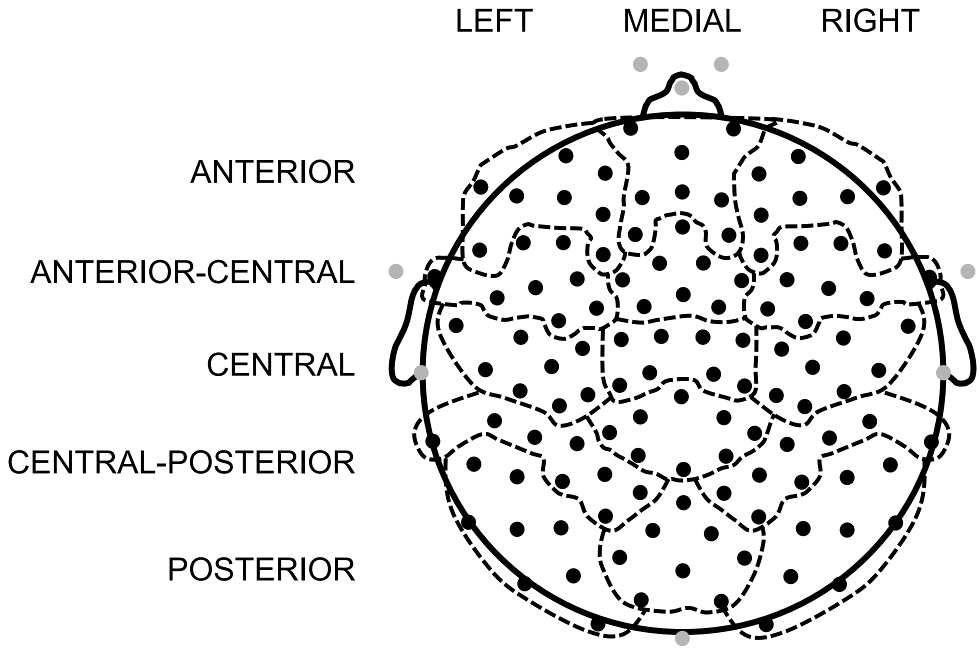

Figure 1. Approximate location of 128 electrodes used for recording EEG. Data from 120 electrodes were included in analysis (black circles) as 15 regions (dashed lines). Data were averaged across 8 electrodes within each region.

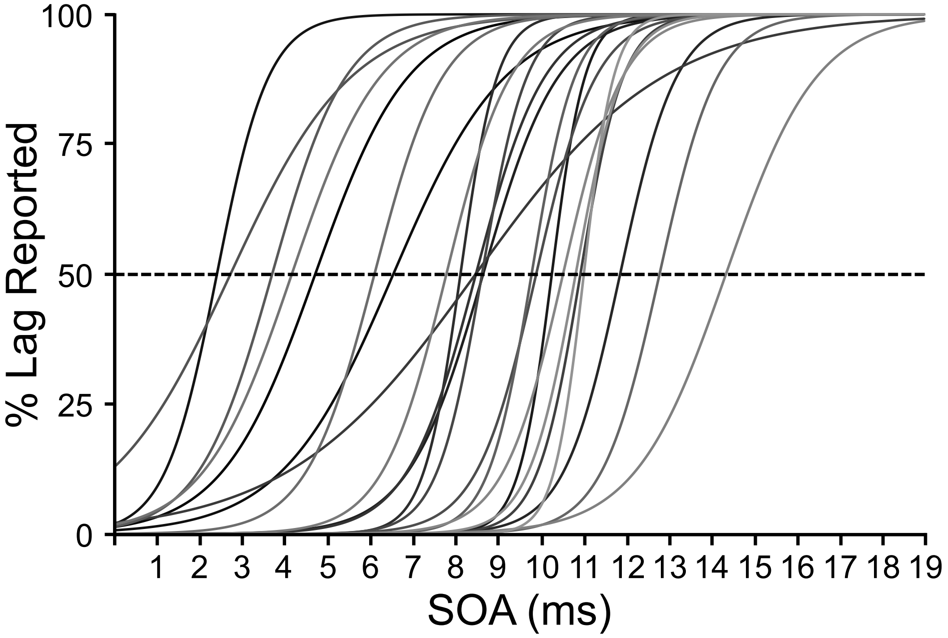

Figure 2. Logistic functions fit to each participant's behavioral responses to click pairs in the Attend condition. The dashed line indicates the SOA at which each participant is predicted to report hearing the lag click as a separate source on 50% of trials (i.e., echo threshold).

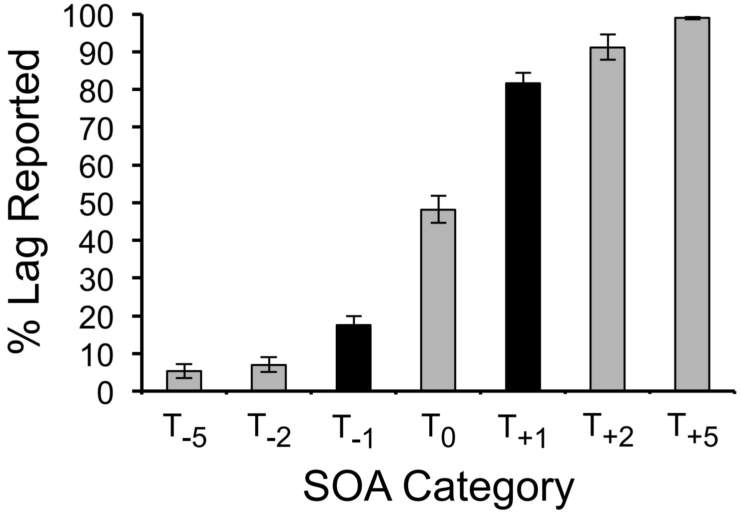

Figure 3. Percentage of trials on which participants reported hearing the lag click as a separate source in the Attend condition. SOA categories were defined for each participant based on behavioral data.

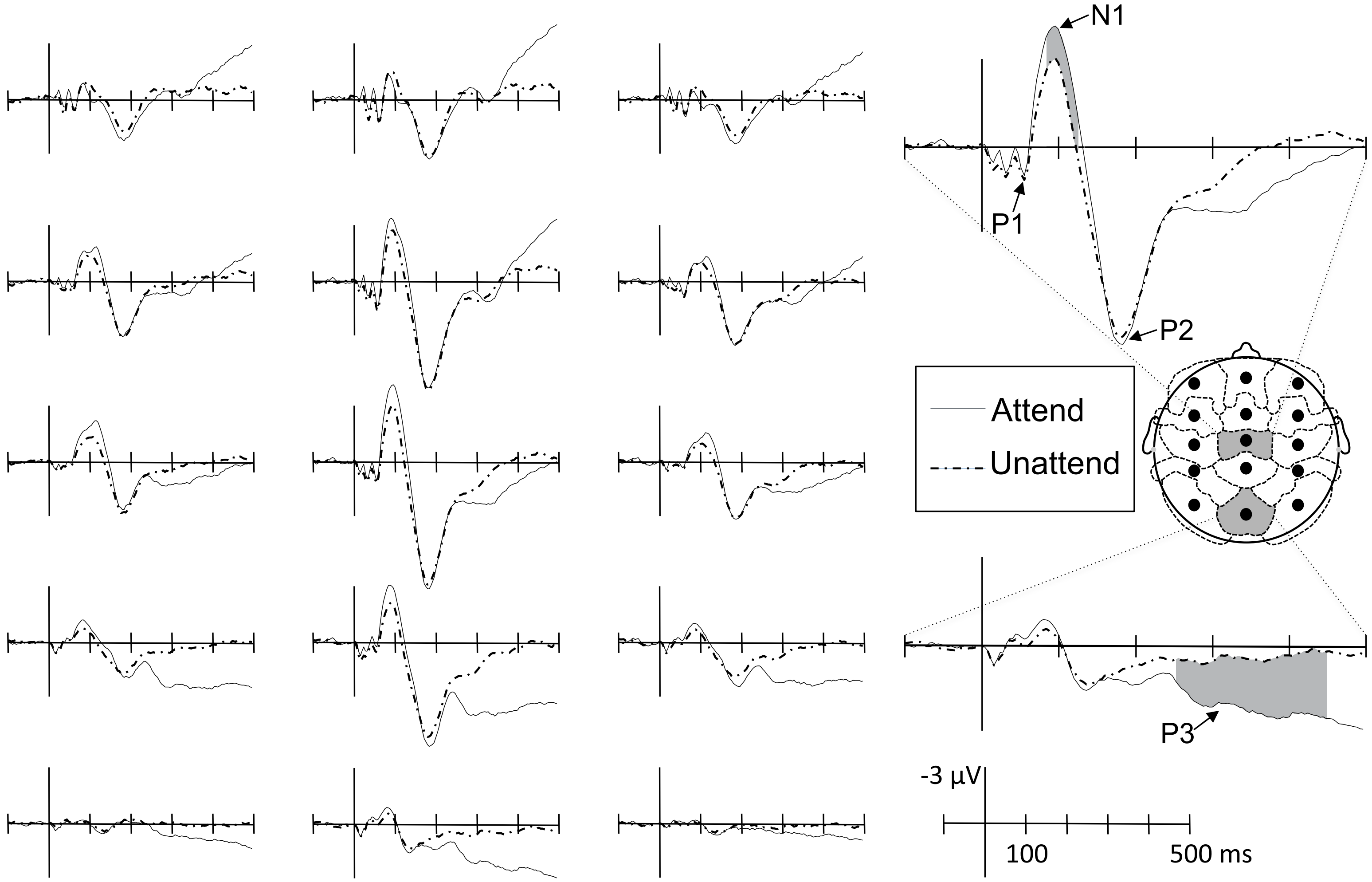

Figure 4. ERPs elicited by click pairs across T_{+1} and T_{-1} in the Attend and Unattend conditions. Data from all 15 regions are shown in the same positions depicted on the scalp map. ERPs from two locations are also shown at a larger scale. Shading indicates time windows in which there were differences between the conditions.

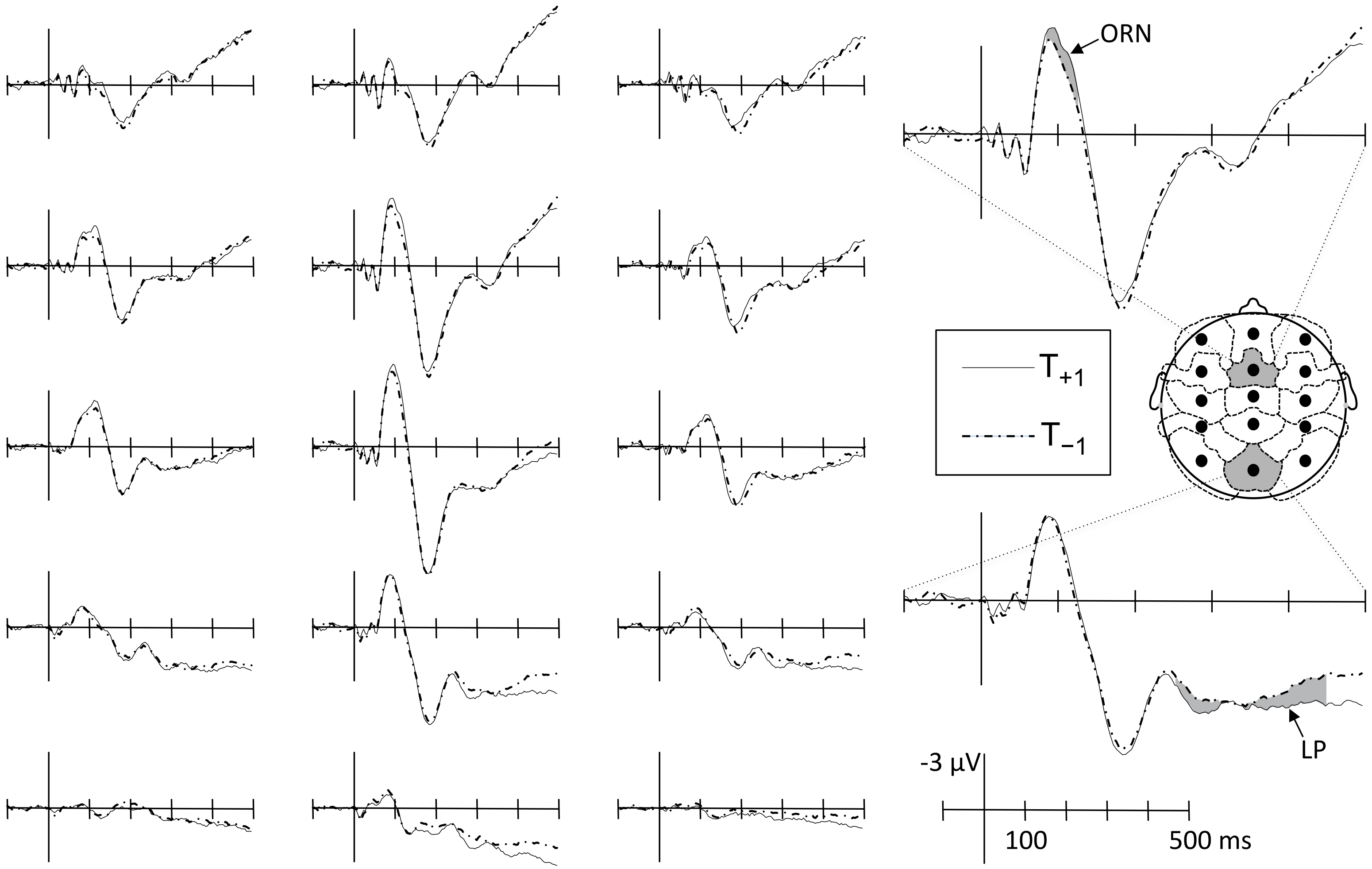

Figure 5. ERPs elicited by T_{+1} and T_{-1} click pairs in the Attend condition. Data from all 15 regions are shown in the same positions depicted on the scalp map. ERPs from two locations are also shown at a larger scale. Shading indicates time windows in which there were differences between the conditions.

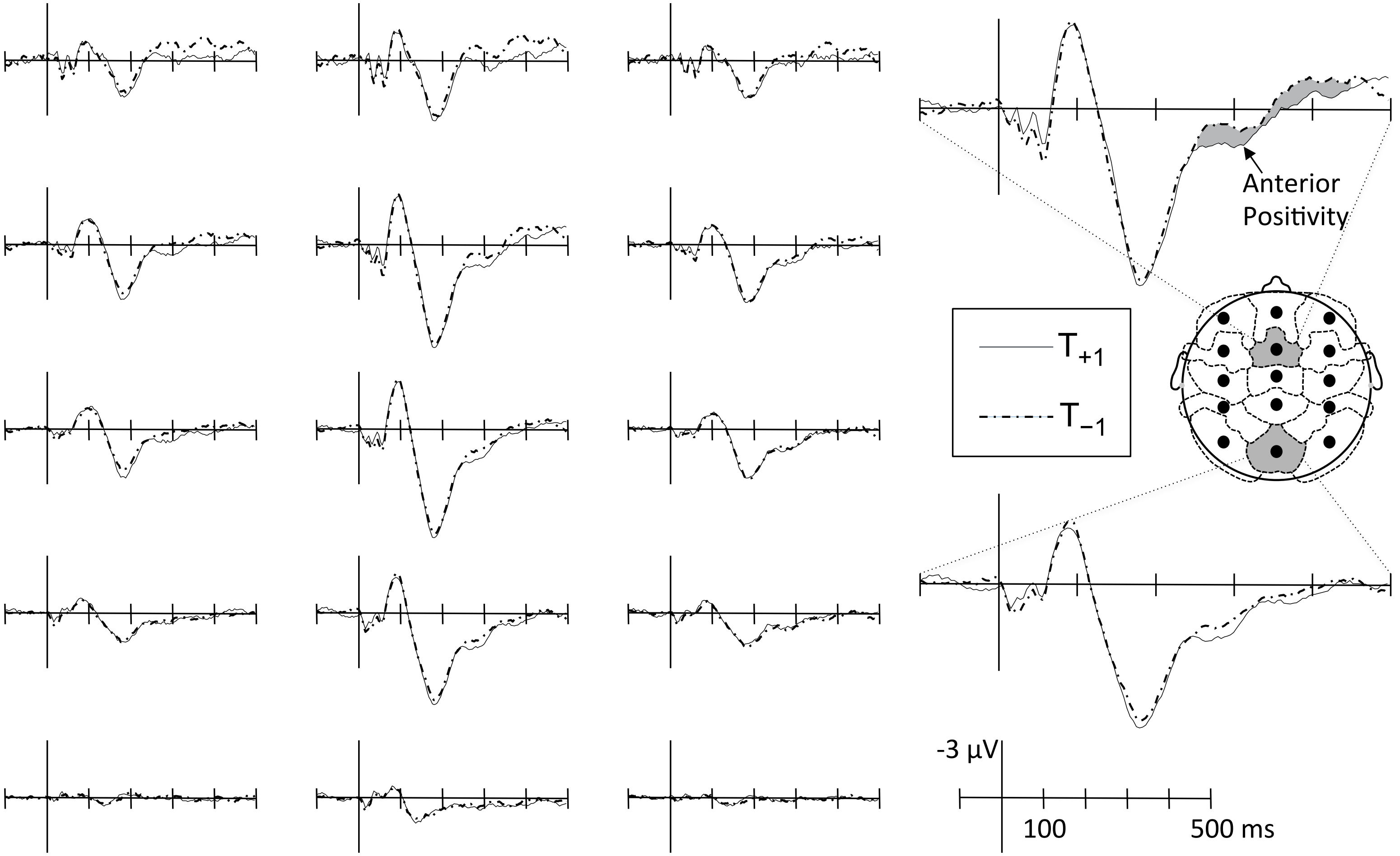

Figure 6. ERPs elicited by T_{+1} and T_{-1} click pairs in the Unattend condition. Data from all 15 regions are shown in the same positions depicted on the scalp map. ERPs from two locations are also shown at a larger scale. Shading indicates time windows in which there were differences between the conditions.

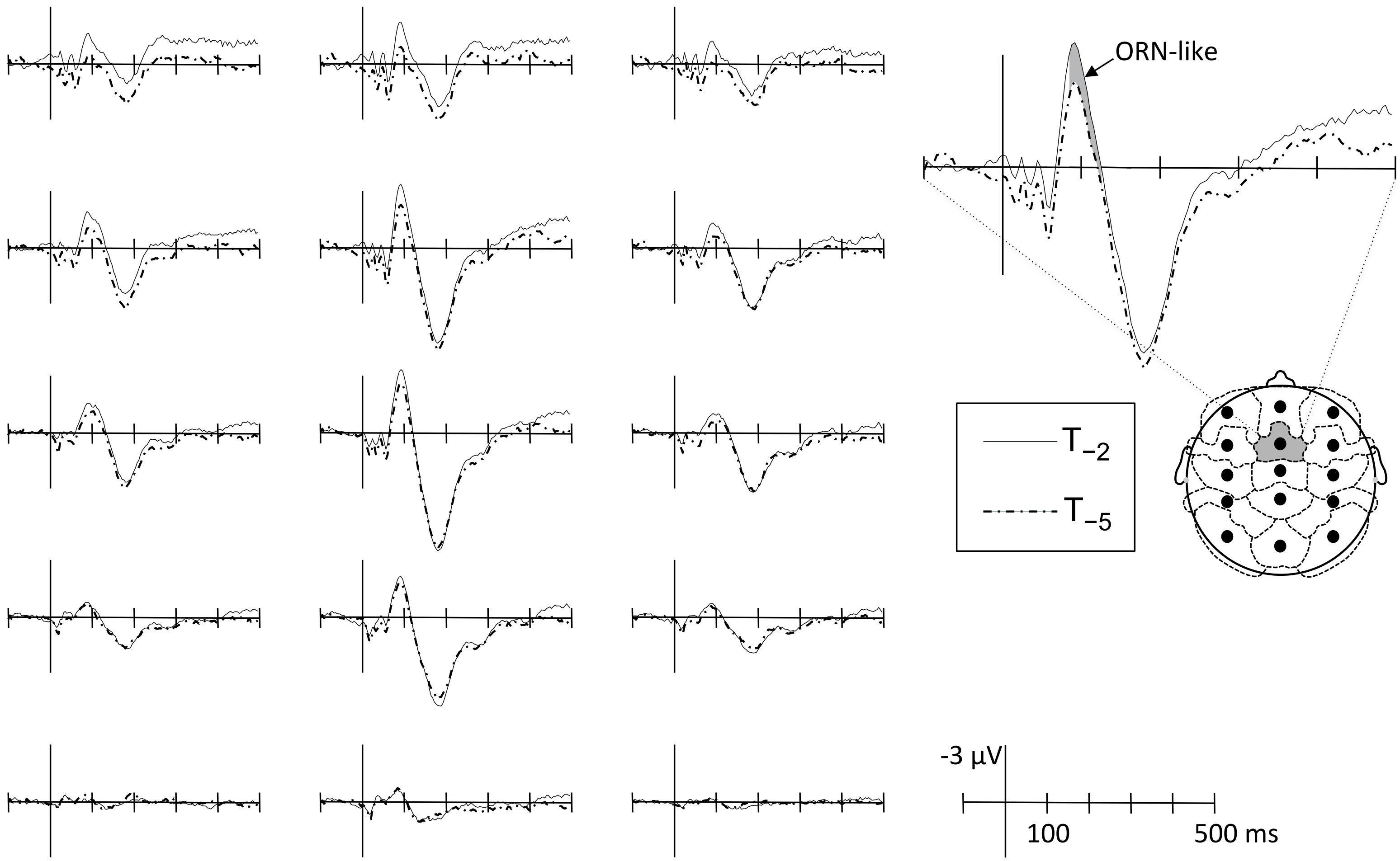

Figure 7. ERPs elicited by T_{-2} and T_{-5} click pairs in the Unattend condition. Data from all 15 regions are shown in the same positions depicted on the scalp map. ERPs from one location are also shown at a larger scale. Shading indicates time windows in which there were differences between the conditions.

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