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Journal

Clinical Neurophysiology, 118(5)

ISSN

1388-2457

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Publication Date

2007-05-01

DOI

10.1016/j.clinph.2007.01.005

Clinical Neurophysiology 118 (2007) 1078–1087

www.elsevier.com/locate/clinph

The N_1 complex to gaps in noise: Effects of preceding noise duration and intensity ☆

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Accepted 15 January 2007
Available online 26 February 2007

Abstract

Objective: To study the effects of duration and intensity of noise that precedes gaps in noise on the N-Complex (N_{1a} and N_{1b}) of Event-Related Potentials (ERPs) to the gaps.

Methods: ERPs were recorded from 13 normal subjects in response to 20 ms gaps in 2–4.5 s segments of binaural white noise. Within each segment, the gaps appeared after 500, 1500, 2500 or 4000 ms of noise. Noise intensity was either 75, 60 or 45 dBnHL. Analysis included waveform peak measurements and intracranial source current density estimations, as well as statistical assessment of the effects of pre-gap noise duration and intensity on N_{1a} and N_{1b} and their estimated intracranial source activity.

Results: The N-Complex was detected at about 100 ms under all stimulus conditions. Latencies of N_{1a} (at ~90 ms) and N_{1b} (at ~150 ms) were significantly affected by duration of the preceding noise. Both their amplitudes and the latency of N_{1b} were affected by the preceding noise intensity. Source current density was most prominent, under all stimulus conditions, in the vicinity of the temporo-parietal junction, with the first peak (N_{1a}) lateralized to the left hemisphere and the second peak (N_{1b}) – to the right. Additional sources with lower current density were more anterior, with a single peak spanning the duration of the N-Complex.

Conclusions: The N_{1a} and N_{1b} of the N-Complex of the ERPs to gaps in noise are affected by both duration and intensity of the pre-gap noise. The minimum noise duration required for the appearance of a double-peaked N-Complex is just under 500 ms, depending on noise intensity. N_{1a} and N_{1b} of the N-Complex are generated predominantly in opposite temporo-parietal brain areas: N_{1a} on the left and N_{1b} on the right.

Significance: Duration and intensity interact to define the dual peaked N-Complex, signaling the cessation of an ongoing sound.

Keywords: Event-related potentials; N-Complex; Offset response; Change detection; Low-resolution electromagnetic tomography; Functional imaging

1. Introduction

1.1. N_1 to speech and acoustic temporal cues

Component N_1 (~100 ms from stimulus onset) and the immediately following P2 of ERPs have been suggested as a means for studying the initial auditory processing of speech signals (Ostroff et al., 1998; Tremblay et al., 2002, 2003). N_1–P_2 amplitudes have been related to changes in speech perception accompanying aging (Tremblay et al., 2002), sensory-neural hearing loss (Oates et al., 2002), training-related plasticity (Reinke et al., 2003; Tremblay and Kraus, 2002; Tremblay et al., 2001) and performance decrease by noise masking (Martin et al., 1999; Whiting et al., 1998). The discrimination of temporal cues in speech has been studied with N_1 as a marker of detecting time-varying changes within a signal (Martin and Boothroyd, 1999) as well as the transition from friction noise to the following vowel (Ostroff et al., 1998; Tremblay et al., 2003).

☆ Some of these results were presented at the NHS2006 Conference, June 2006, Cernobio, Italy.

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1388-2457/$32.00 © 2007 Published by Elsevier Ireland Ltd on behalf of International Federation of Clinical Neurophysiology.
doi:10.1016/j.clinph.2007.01.005

The ability of the auditory system to encode temporal cues is critical for many auditory functions including speech perception and localization. Measuring auditory temporal resolution is often based on the psychoacoustic threshold for detecting gaps in continuous broadband noise, which reduces the confounding effects of spectral change. Gap detection threshold in comfortably loud broadband noise is typically 2–3 ms (Plomp, 1964; Penner, 1977; Eddins and Green, 1995; Moore, 1997; Zeng et al., 1999), increasing to 20 ms with noise intensities near hearing threshold (Irwin et al., 1981; Zeng et al., 1999).

Recently, psychoacoustic and evoked potential measures of auditory temporal processes have been compared in normal-hearing individuals and in patients with an auditory temporal processing disorder (auditory neuropathy) using gaps in continuous noise (Michalewski et al., 2005; Zeng et al., 2005). Evoked potentials in normal subjects (N_1 components) were recorded in response to gaps as short as 5 ms in both active and passive listening conditions, close to the behavioral thresholds of 2–3 ms. Gap-evoked potentials in the patients with a temporal processing disorder appeared only with prolonged gap durations (10–50 ms) and in close agreement with gap detection thresholds measured psychoacoustically. In normals, the N_1 complex, particularly to gaps between 20 and 50 ms, consisted of two separate components: an early component peaking at 90 ms, similar in latency to a stimulus onset N_1 and a later component peaking at approximately 150 ms.

In a companion study (Pratt et al., 2005), the scalp distribution and generator sources for the two negative potentials to gaps in continuous noise were defined in normal subjects. Waveforms to clicks in pairs and to offsets of long gaps (onsets of noise at the end of the gap) were similar and single-peaked, while potentials to gaps of between 10 ms and up to several 100 ms were double-peaked, consisting of two negativities, approximately 60 ms apart, regardless of gap duration. The first peak (N_{1a}), occurring at ~100 ms, was frontal in distribution and similar to N_1 of clicks. The following peak (N_{1b}) occurred at ~150 ms with a central/temporal scalp distribution, with distinct sources and time course of their activity. No effects of attention on the constituents of N_1 were observed and N_{1b} was therefore suggested to reflect pre-attentive perception of the cessation of an ongoing sound.

In contrast to the double peaked N_1 complex to gaps in continuous noise, two studies on gaps in short (tens of msec) tones (Alain et al., 2004; Heinrich et al., 2004) have reported a single-peaked N_1 to the gaps. In one of these studies (Heinrich et al., 2004), dipole source estimation suggested that the bilateral generators of the N_1 were in the superior temporal gyrus near the primary auditory cortex, in general agreement with sources of the double-peaked N_1 to gaps in continuous noise (Pratt et al., 2005). However, the stimulus differences underlying the double-peaked N-Complex to gaps in continuous noise (Michalewski et al., 2005; Pratt et al., 2005) and the single-peaked N_1 to gaps in short tones (Alain et al., 2004; Heinrich et al., 2004) will be examined below.

1.2. Purpose

We examined, in normal subjects, the effects of duration and intensity of the noise preceding gaps on the latency, amplitude and generator sites of the N-Complex (N_{1a} and N_{1b}). The results are relevant for defining brain activity to the cessation of an ongoing "constant" stimulus and the stimulus parameters that define an acoustic transient.

2. Methods

2.1. Subjects

Thirteen right-handed 18–25-year-old normal-hearing subjects participated in the study. Subjects were recruited only if their thresholds for the noise used in the study were within 15 dB of the average threshold of an audiometrically verified, normal-hearing age-matched jury of 4. Subjects were paid for their participation and all procedures were approved by the Institutional Review Board for experiments involving human subjects (Helsinki Committee).

2.2. Stimuli

Binaural stimuli were used throughout this study to avoid affecting the scalp distribution of evoked potentials by contralateral or ipsilateral stimulation. Thus, any lateralization of brain activity would be attributed to lateralized processing, independent of the stimulated ear. Binaural white noise segments (2500–4500 ms in duration, square onset/offset) with gaps of 20 ms (Fig. 1) were presented through earphones (Sony MDR-CD770). Gap duration was set at 20 ms to assure detectability at low intensities without the possible confounding effects of gap onset and offset with longer gaps. The spectral content of the noise

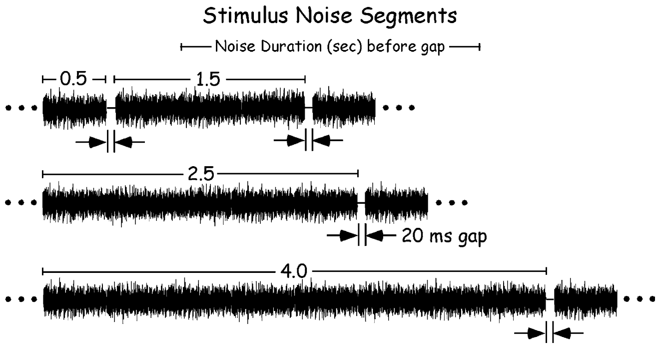

Fig. 1. Examples of noise segments with 20 ms gaps that were used in this study. Note that gap durations are not drawn to scale, for clarity. Noise segment durations varied randomly among the values detailed in the text such that post gap noise durations were never shorter than 500 ms and pre-gap noise durations were 500, 1500, 2500 or 4000 ms. Noise intensity varied randomly between 75, 60 and 45 dBnHL. Inter-segment intervals were 2 s.

was flat within 10 dB across the frequency range 100–10,000 Hz, and the gaps had abrupt (square) onsets and offsets.

The noise segments were presented at 3 intensities (75, 60 and 45 dBnHL) and the timing of the gap in each burst was such that pre-gap noise duration was 500, 1500, 2500 or 4000 ms and post gap noise duration was at least 500 ms. Noise segments were roughly of equal duration, with the following constraints: Pre-gap noise durations were not shorter than 500 ms to avoid possible temporal overlap and interaction of the responses to the noise segment onset and to the following gap. Noise segment durations were selected to minimize possible adverse results of noise exposure while assuring at least 500 ms of noise before and after each gap, and pre-gap noise durations as detailed above. At these durations temporal integration is already saturated (Loveless et al., 1996; McEvoy et al., 1997; Budd and Mitchie, 1994) and the duration does not affect intensity perception. Some noise segments included two gaps, when the above constraints allowed it. Segments with the different intensity and pre-gap duration combinations were presented in random order. The interval between noise segments was 2000 ms (Fig. 1), and each stimulus condition was randomly repeated 150 times.

Noise segments, rather than continuous noise (as in our earlier studies), were used to be able to include intensity as a variable without the adverse effects of prolonged exposure to noise.

2.3. Procedure

Each session started with the attachment of 9 mm silver disc electrodes on the scalp at 22 locations: F_{p1}, F_{p2}, F_7, F_3, F_z, F_4, F_8, T_3, C_3, C_z, C_4, T_4, T_5, P_3, P_z, P_4, T_6, O_1 and O_2, according to the 10–20 system, on the left and right mastoids (M_1 and M_2), as well as below the left eye to monitor eye movements (EOG). In total, EEG was recorded from 21 electrodes referenced to the center of the chin and EOG was recorded from one diagonal differential recording below the left eye referenced to F_z. An electrode on the left forearm served as ground. Impedance at each electrode was maintained below 5 kΩ.

Subjects were then seated in a comfortable adjustable reclining armchair in a sound proof chamber and passively listened to gaps in noise segments while reading a complicated text on which they were later examined. Stimuli were delivered in blocks of 10 min, and the total duration of the recording session, including electrode application and breaks, was 5 h.

2.4. Data acquisition

2.4.1. Electrophysiological recording

Potentials from the EEG (100,000×) and EOG (20,000×) channels were amplified, digitized with a 12 bit A/D converter at a rate of 256 samples/s, filtered (0.1–100 Hz, 6 dB/octave slopes) and stored for off-line analysis. The EEG was epoched beginning 100 ms before until 1000 ms after gap onset, followed by eye movement correction (Attias et al., 1993) and artifact rejection (±150 μV). Average waveforms were computed for each experimental condition, for each subject, and across subjects to obtain grand mean waveforms. Thus, for each subject, 12 averaged waveforms (3 intensities × 4 pre-gap noise durations) were obtained. After averaging, the data were low-pass filtered (FIR rectangular filter with a low-pass cutoff at 24 Hz) and baseline (average amplitude across the 100 ms before stimulus onset) corrected.

2.5. ERP data analysis

Analysis focused on the effects of pre-gap noise duration and intensity on peak latencies and amplitudes as well as on source current densities of N_{1a} and N_{1b} of the N-Complex to the gaps in noise.

2.5.1. Peak analysis

The amplitudes and latencies of the N_{1a} and N_{1b} components in the various stimulus conditions (pre-gap noise durations and noise segment intensities) were measured for each subject in each channel at the point of maximum negativity of each peak (or inflection and peak). These points were approximately 60 ms apart, between 90 and 180 ms. N_{1a} was fronto-central in its scalp distribution while N_{1b} had a central-temporal scalp distribution.

ERP peak amplitudes and latencies were subjected to a repeated measures analysis of variance (ANOVA) with Geisser–Greenhouse correction for violation of sphericity and Bonferroni post hoc comparisons corrected for multiple comparisons. ANOVA factors were: Pre-gap noise duration with 4 levels (500, 1500, 2500 and 4000 ms); noise intensity with 3 levels (75, 60 and 45 dBnHL); and scalp laterality group with 3 levels (Left – F_7, T_3, T_5 ; Right – F_8, T_4, T_6; and Midline – F_z, C_z, P_z); or scalp frontality group with 3 levels (Frontal – F_{p1}, F_{pz}, F_{p2}; Central – C_3, C_z, C_4; and Temporo-parietal – T_3, P_z, T_4). Probabilities below 0.05, after Geisser–Greenhouse corrections, were considered significant.

2.5.2. Functional imaging

Low Resolution Electromagnetic Tomographic Analysis (LORETA, Pascual-Marqui et al., 1994) was applied on the 21-channel ERP records to image the estimated source current density throughout the duration of the N-Complex components (N_{1a} and N_{1b}) in response to all noise intensity/duration combinations. Low resolution electromagnetic tomography (Pascual-Marqui et al., 1994, 1999, 2002; Vitacco et al., 2002) is a functional brain imaging method that estimates the distribution of current density in the brain, displaying it in a 3D Talairach space. It computes current density, converging on the solution in which each voxel's current density is the closest to the average current density of the neighboring voxels (smoothness assumption).

In addition to imaging current density distributions, LORETA current density values were subjected to a repeated measures analysis of variance (ANOVA) with Geisser–Greenhouse correction for violation of sphericity and Bonferroni corrections for multiple comparisons. The effects of stimulus parameters and of the active brain area on intracranial current density were assessed for the factors: Pre-gap duration with 4 levels (500, 1500, 2500 and 4000 ms); noise intensity with 3 levels (75, 60 and 45 dBnHL); and Brodman area (BA) with 6 levels corresponding to the most active regions (BA21, 22, 37, 40, 31 and 10), separately for left and for right hemisphere activity. Probabilities below 0.05, after Geisser–Greenhouse corrections, were considered significant.

3. Results

3.1. Evoked potentials to gaps in noise and their sources

Clear N-Complex components were obtained at about 100 ms in response to gaps in noise with all combinations of preceding intensity and duration (Fig. 2) from all subjects. N_1 was double-peaked or showed an inflection across all stimulus conditions, with the exception of the shortest duration of preceding noise at the lowest intensity (500 ms of 45 dBnHL noise). Overall, amplitudes of the N-Complex were lower (e.g., average amplitude of 1.5–2.5 μV at C_z) compared to an earlier study (average amplitude of 3–5 μV at C_z), most probably because of the interrupted nature of the noise segments used in this study, as compared to continuous noise in the previous study (see Section 4.1).

The earlier (N_{1a}) of the two negative peaks of the N-Complex, at about 90 ms, was midline fronto-central in scalp distribution, while the second (N_{1b}), at about 150 ms, was more right central/temporal (Fig. 3). Except for a partial trend toward increased amplitude with increasing intensity, by both constituents of the N-Complex, the effects of noise duration and intensity on both amplitudes and latencies of N_{1a} and N_{1b} interacted and did not show a consistent trend (Fig. 4).

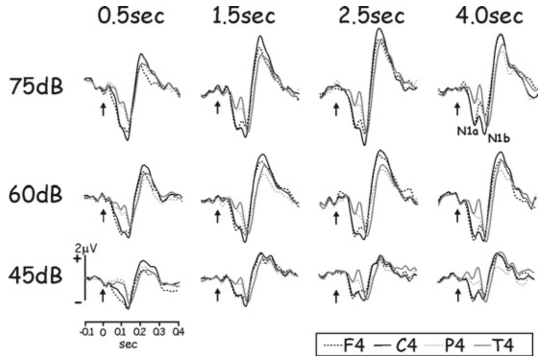

Fig. 2. Event-related potentials in response to gaps in noise with all combinations of intensity and pre-gap durations, recorded from the electrodes with best definition of the N-Complex constituents N_{1a} (fronto-central) and N_{1b} (right temporo-parietal). Grand averaged waveforms across all 13 subjects. Arrows mark the time of gap onset.

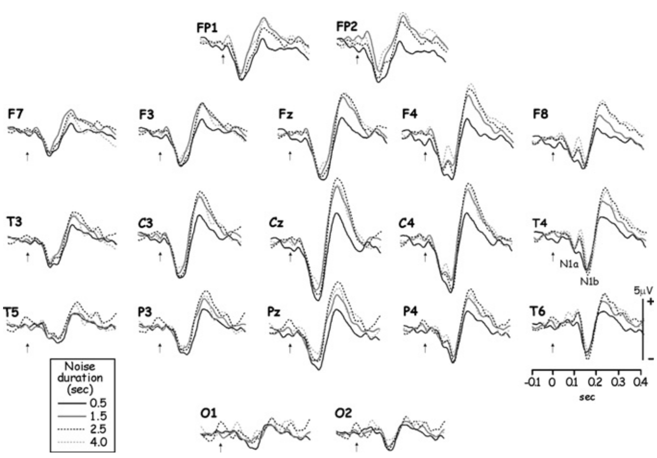

Fig. 3. Scalp distribution of potentials in response to gaps following 4 durations of noise presented at 75 dB intensity. Grand averaged waveforms across all 13 subjects. Arrows mark the time of gap onset.

When the intracranial sources of the surface activity were estimated, activity under all stimulus conditions was bilateral, with left hemisphere prominence of N_{1a} and right hemisphere prominence of N_{1b} (Fig. 5). The time course of current density in the temporo-parieto-occipital region, in the vicinities of BA20, 21, 22, 37 (Fig. 6, top), and to a lesser extent BA40 (Fig. 6, bottom), was double-peaked, corresponding in latency and hemispheric prominence to N_{1a} and N_{1b}. Current density was more bilaterally symmetrical more anteriorly, in the general locations of the Paracentral Lobule, Cingulate Gyrus (BA 31), Medial and Superior Frontal Gyrus (BA10) and Precuneus (BA7), where a single current density peak of lower magnitude was noticed throughout the duration of the N-Complex (Fig. 6, bottom).

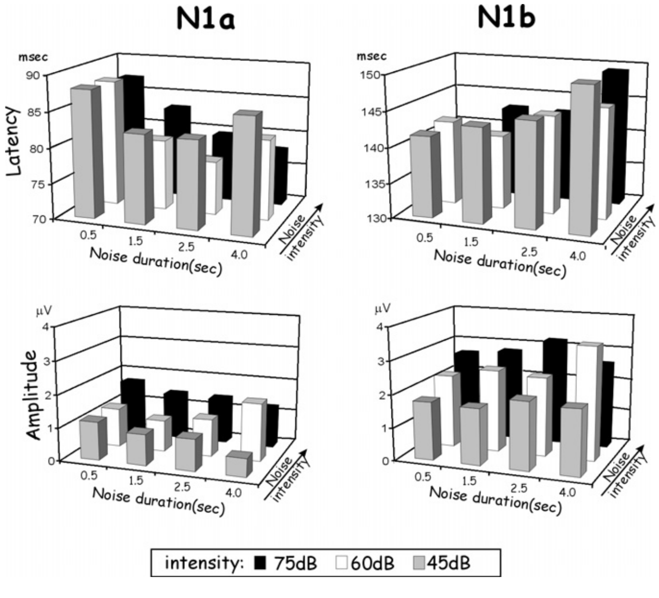

Fig. 4. Average latencies (top) and amplitudes (bottom) of N_{1a} (left) and N_{1b} (right) from their respective optimal recording electrodes, in response to gaps in noise at three intensities with four pre-gap durations.

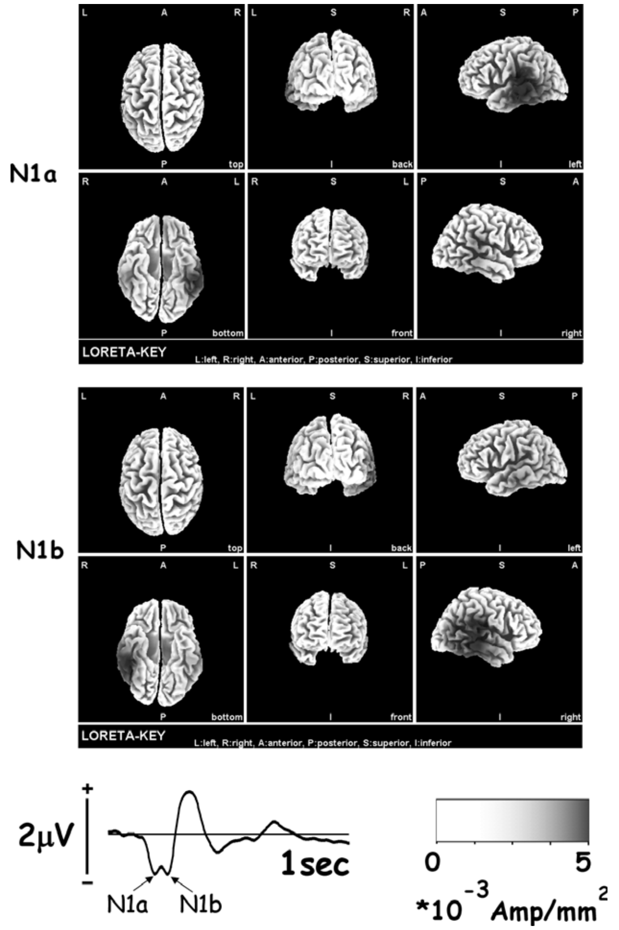

Fig. 5. Six orthogonal views of intracranial current density distributions at the peaks of N_{1a} (top) and N_{1b} (bottom). The times at which current densities were determined are indicated by arrows on the waveform in the bottom left. Note the shift of lateralization from left (N_{1a}) to right (N_{1b}).

3.2. Main effects of preceding noise duration

Duration of the noise preceding the gap affected both N_{1a} [$F(3,39) = 4.96$, $p < 0.002$] and N_{1b} [$F(3,39) = 12.91$, $p < 0.001$] peak latencies. The trends in these latency changes were not always linear or regular (Fig. 4, top), most probably due to the influence of additional factors such as noise intensity. Peak amplitudes of N_{1a} and N_{1b} were not significantly affected by duration of the noise preceding the gap (Fig. 4, bottom).

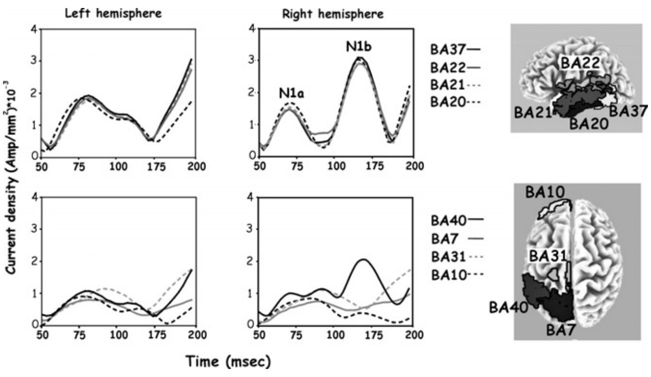

Fig. 6. Time course of activity (current density) in the most active brain regions during components N_{1a} and N_{1b}. Note the shift in hemispheric prominence from left (N_{1a}) to right (N_{1b}) in Brodman areas (BA) 20, 21, 22, 37 and 40.

To assess the effects of stimulus parameters on intracranial current density, the values in each of the most active regions (BA 21, 22, 31, 37, 40 and 10) were analyzed, separately for each hemisphere. Current density was significantly affected and tended to increase with longer duration of the preceding noise (Fig. 7) for both N_{1a} [Left – $F(3,36) = 3.73$ $p < 0.02$; Right – $F(3,36) = 10.44$ $p < 0.001$] and N_{1b} [Right only – $F(3,36) = 10.65$ $p < 0.001$].

3.3. Main effects of preceding noise intensity

Intensity of the noise preceding the gap significantly affected the latency of N_{1b} [$F(2,26) = 9.34$ $p < 0.001$], which tended to decrease with higher levels of noise intensity (Fig. 4, top), as well as the amplitudes of both N_{1a} [$F(2,26) = 44.53$ $p < 0.001$] and N_{1b} [$F(2,26) = 24.41$ $p < 0.001$], with no consistent trend (Fig. 4, bottom), indicating an interaction.

Intracranial current density values in the most active regions (BA 21, 22, 31, 37, 40 and 10) significantly increased with pre-gap noise intensity, but only in the right hemisphere, for both N_{1a} [$F(2,24) = 8.27$ $p < 0.002$] and N_{1b} [$F(2,24) = 7.49$ $p < 0.003$]. Similar trends were observed in the left hemisphere, but did not attain statistical significance ($p > 0.05$).

3.4. Main effects of scalp and intracranial distributions

Electrode laterality significantly affected latencies of both N_{1a} [$F(2,26) = 29.36$ $p < 0.001$] and N_{1b} [$F(2,26) =$

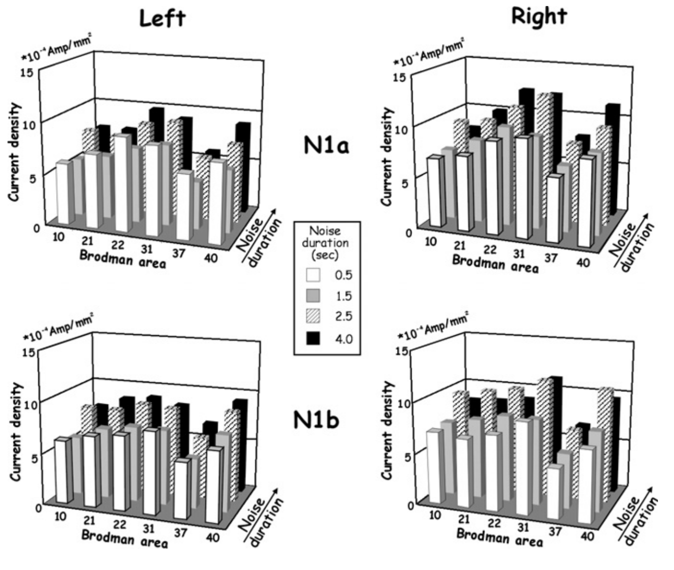

Fig. 7. Magnitude of intracranial activity in the most active brain regions, in the left (left) and in the right (right) hemispheres, during components N_{1a} (top) and N_{1b} (bottom) to gaps following different noise durations.

69.41 $p < 0.001$], N_{1a} latency being longest on the left and shortest on the right, while N_{1b} latency was longest on the right and shortest along the midline. Laterality also affected the amplitudes of N_{1a} [$F(2,26) = 175.38$ $p < 0.001$] and N_{1b} [$F(2,26) = 44.83$ $p < 0.001$]. N_{1a} amplitude was largest at the midline and smallest on the right, while N_{1b} amplitude was largest on the right and smallest on the left (Fig. 3). The latency of N_{1b} was significantly affected by electrode frontality [$F(2,26) = 23.65$ $p < 0.001$] being shortest in the central electrodes and longest over the temporo-parietal scalp. Electrode frontality affected the amplitude of both N_{1a} [$F(2,26) = 88.44$ $p < 0.001$], which was largest frontally and smallest posteriorly, and N_{1b} [$F(2,26) = 13.63$ $p < 0.001$], which was largest centrally and smallest frontally (Fig. 3).

In order to assess intracranial current density distributions, the values in each of the most active regions (BA 21, 22, 31, 37, 40 and 10) were analyzed separately for each hemisphere. Current density was significantly different across these Brodman areas for both N_{1a} [Left – $F(5,60) = 2.58$ $p < 0.004$; Right – $F(5,60) = 6.23$ $p < 0.001$] and N_{1b} [Left – $F(5,60) = 5.17$ $p < 0.02$; Right – $F(5,60) = 6.04$ $p < 0.001$] (Fig. 7).

3.5. Interactions in the effects of preceding noise duration, intensity and scalp distribution

Interactions of duration and intensity of the pre-gap noise affected the amplitudes of both N_{1a} [$F(6,78) = 2.56$ $p < 0.02$] and N_{1b} [$F(6,78) = 3.58$ $p < 0.002$] as well as N_{1b} latency [$F(6,78) = 2.41$ $p < 0.003$]. The effects of pre-gap noise duration on amplitudes were most pronounced with the intermediate intensity for N_{1a} and with the high intensity for N_{1b}. The effect of noise intensity on N_{1b} latency was most pronounced with the longest noise duration, and the effect of noise duration was the most pronounced with the lowest noise intensity.

Noise intensity and scalp laterality effects on the amplitude of N_{1a} interacted significantly [$F(4,52) = 5.65$ $p < 0.001$] with the largest laterality differences observed at the high and medium noise intensity and the most prominent noise intensity effects observed in the midline and left electrodes. Amplitudes on the right side of the scalp were the least affected by noise intensity. Current density distributions across the Brodman areas examined did not exhibit a significant interaction of the effects of noise parameters.

3.6. Summary

Distinct N_{1a} and N_{1b} of the N-Complex to gaps in noise were obtained under all stimulus conditions, except with the combination of the shortest duration (500 ms) and the lowest intensity (45 dB) pre-gap noise. Pre-gap noise duration and intensity interacted in their effects on the scalp-recorded N-Complex peaks. Intracranial estimated current density time courses were double-peaked and large in the temporo-parietal region, with left hemisphere prominence of N_{1a} and right hemisphere prominence of N_{1b}. Time course was single-peaked, more symmetrical and lower in magnitude more anteriorly.

4. Discussion

4.1. The N-Complex to gaps

In this study, potentials to 20 ms gaps in noise were recorded following different pre-gap noise durations and intensities. These gaps evoked a sequence of P_1, N-Complex (N_{1a}, N_{1b}) and P_2 (Fig. 2). Because the gaps used in this study were 20 ms, the accompanying P_1 and N-Complex to gaps could not be attributed distinctly to either gap onsets or offsets. However, in our previous study (Michalewski et al., 2005; Pratt et al., 2005) longer gaps (e.g., 500 ms) were used such that the N-Complex components to gap onsets and offsets could be separately distinguished: gap onsets evoked a double-peaked N-Complex whereas gap offsets evoked a single-peaked N_1. The differences in P_1 between gap onset (a diminished P_1) and offset are detailed in a separate report (Pratt et al., in preparation). This report focuses on the effects of pre-gap noise duration and intensity on the N-Complex.

In this study, the N-Complex was double-peaked, or had a peak and inflection, except when the pre-gap noise had both the shortest duration (500 ms) and the lowest intensity (45 dB), to which only a single N_1 peak was noted. The double-peaked N_1 in response to 20 ms gaps is mostly the N-Complex to gap onsets (double-peaked) with a markedly diminished, or absent due to refractoriness, N_1 to gap offsets (single-peaked). A single-peaked N_1 to 20 ms gaps therefore indicates a single-peaked N-Complex. Such a single-peaked N_1 has also been described to suprathreshold short gaps in 60 ms duration tone bursts (Alain et al., 2004; Heinrich et al., 2004; rare and frequent waveforms before MMN derivation). The N_1 in those studies is a composite of the N_1 to tone onset and to the gap. Its single peak therefore indicates a single-peaked N-Complex to gaps that are preceded by short (<60 ms) tones.

Notably, N-Complex amplitudes in our study, using noise segments, were about half those of earlier studies that used continuous noise (Michalewski et al., 2005; Pratt et al., 2005). This difference is most probably due to the segmentation of the noise in which the gaps of the present study were embedded. In continuous noise, gaps and their durations are the only change in the auditory environment, whereas with short tones or noise segments – the onsets and offsets of these segments may be processed as additional auditory changes. Thus, the present study's auditory environment of noise segments included a number of additional stimulus changes (e.g., onsets and offsets of the noise segments), that likely contributed adaptation and refractoriness effects, reducing the amplitudes of the N-Complex to the gap onsets in the noise segments.

The latency of N_{1a} increased while that of N_{1b} decreased with decreasing duration of the preceding 75 dBnHL noise

(Fig. 4). These opposite effects on the two constituents of the N-Complex underscore their inherent difference: N_{1a} appears to be similar to the onset N_1 component evoked by transient stimuli such as tones and clicks while N_{1b} appears to be specific to the cessation of an ongoing stimulus – an off response. The considerable temporal overlap of these distinct components which were differentially affected by stimulus parameters resulted in the complex pattern of their changes across stimulus parameters.

4.2. The N-Complex as a function of pre-gap conditions

Effects of pre-gap durations on behavioral gap detection have been reported for durations shorter than 500 ms (Penner, 1977; Forrest and Green, 1987; Phillips et al., 1998; Schneider and Hamstra, 1999; Snell and Hu, 1999) showing that thresholds are unaffected by pre-gap durations of a few hundred ms. A study on the electrophysiological correlates of gap detection with pre-gap durations of 5, 20 and 50 ms found correlations between the detection thresholds and the Middle-Latency fields (Rupp et al., 2004). The effects on the N-Complex observed in this study may have behavioral accompaniments, more subtle than gap detection thresholds, that have not been studied yet.

Pre-gap noise duration and intensity interacted with complex effects on N_{1a} and N_{1b}: effects of noise duration on amplitudes were most pronounced with the intermediate intensity for N_{1a} and with the high intensity for N_{1b}. The effects of pre-gap noise intensity on N_{1b} latency were most pronounced with the longest duration, and the effect of noise duration most pronounced with the lowest intensity. This complex pattern of intensity and duration effects and their interactions suggests that the effects are not a simple energy integration process. A magnetoencephalographic study (Gage and Roberts, 2000) using stimuli of constant intensity and constant energy also concluded that N_1 amplitude was more likely to depend on stimulus duration than on energy integration. In this study, we show that intensity is an additional factor that interacts with duration to determine the latency and amplitude of each N-Complex constituent.

4.3. N-Complex and acoustic change

N_1 has been suggested to signal the detection of acoustic change in the environment (Hyde, 1997). Change is defined as a deviation from a preceding constant or steady state with particular temporal characteristics. Perceptual constancy requires a time period after sound onset for integration of the acoustic events to occur. The time period of integration is distinct from the more general 'temporal integration', used to describe the linking of auditory information over time to form auditory objects (Loveless et al., 1996).

Over the years, temporal integration has been described and measured in electrophysiological studies, with conflicting results. Onishi and Davis (1968) showed an increase in amplitude of the single-peaked N_1 of the 'vertex potential' with increasing sound duration up to 30 ms. Alain et al. (1997) studied this effect in more detail and found N_1 amplitude to increase up to a stimulus duration of 72 ms. Different constituents of the N_1 response showed different integration time constants and low stimulus frequencies were associated with longer time constants (Alain et al., 1997). Similar integration time constants were found in a magnetoencephalographic study (Gage and Roberts, 2000) using stimuli of constant intensity and constant energy. N_1 amplitude was concluded more likely to depend on stimulus duration than on energy integration.

N_1 to transient stimuli is a limited measure which cannot reflect auditory integration over time periods beyond its onset latency of 50–80 ms. To overcome this limitation pairs of stimuli have been employed. In general, response amplitude diminished when the time interval between succeeding stimuli was shortened. However, N_1 amplitude to the second stimulus of a pair of short tone-bursts increased when the interval between stimuli was shorter than 300 ms, indicating a short-term facilitation process with a time course similar to that of temporal integration (Loveless et al., 1996). Several other studies have replicated these findings for both magnetic (McEvoy et al., 1997) and electrical recordings (Budd and Mitchie, 1994). In addition to transient-evoked recordings, auditory temporal integration was studied with the magnetically recorded Auditory Steady-State Response (ASSR) (Roß et al., 2002). ASSR amplitude increased monotonically over a 200 ms period beginning about 40 ms after stimulus onset. The time course of the ASSR phase reliably measured the duration of this transition of the steady state. The results indicated that the primary auditory cortex responds immediately to stimulus changes and integrates stimulus features over a period of about 200 ms. In another series of studies on fusion of rapid stimulus alternations (Vaz Pato and Jones, 1999; Jones et al., 2000a,b), continuous synthesized musical instrument notes oscillated between two pitches at a rapid rate (8–16 notes/s, i.e., every 63–125 ms) and the 'change-type' N_1 and P_2 potentials associated with each individual change were abolished ('fused oscillations'), indicating an integration time of around 100 ms. Thus, different approaches to determine the time span of stimulus constancy or temporal integration resulted in quite different results (between 30 and 300 ms), depending on possible confounding factors such as spectral changes, adaptation rates, refractory periods and on/off effects.

4.4. The N-Complex, On- and Off-responses

In an earlier study, the potentials evoked by onsets of long gaps in noise (sound offset responses) and those to clicks and to onsets of noise (Pratt et al., 2005) were compared. That study revealed two distinct constituents of the N-Complex: N_{1a} which is similar to the onset responses, and N_{1b} which is unique to stimulus offset. The present study extends these findings to show that the offset-like constituent (N_{1b}) is affected by the duration and intensity of the preceding sound in a different manner than the onset N_1. These findings contribute to the debate on the similarity or dissimilarity of the onset and offset N_1.

Earlier studies comparing magnetic onset and offset responses (Hari et al., 1987; Joutsiniemi et al., 1989) were at odds with each other. The first (Hari et al., 1987) showed that the offset response occurred at about the same latency as the onset responses, that their amplitudes were similarly affected by interstimulus interval and that both were generated by sources close to each other in the supratemporal plane. In contrast, the second study (Joutsiniemi et al., 1989) concluded that generators of onset and offset responses differ because their amplitudes and latencies were differently affected by stimulus duration. These conflicting findings are resolved by the findings of our study: The first study (Hari et al., 1987) used stimulus parameters that resulted in an $N100_m$ that was predominantly an onset-like N_{1a}, even to offsets. In contrast, the second study (Joutsiniemi et al., 1989) manipulated stimulus durations and thus obtained a range of contributions of the offset-specific N_{1b} to the $N100_m$. This variable contribution of the offset-specific N_{1b} was responsible for the observed difference between onset and offset responses.

The anatomical separation of onset and offset responses in the auditory pathway has been described in a study of the effects of intensity on onset and offset responses in guinea pigs (He, 2001). The study found that OFF neurons formed clusters (sheets) that were always segregated from ON neuron clusters in various divisions of the medial geniculate body. This segregation was not affected by stimulus type (noise or tones) nor by intensity.

4.5. N-Complex source estimation and hemispheric prominence

Cortical activity associated with the N-Complex of this study was located, under all stimulus conditions, bilaterally in temporo-parietal regions, with left hemisphere prominence of the first peak (N_{1a}) and right hemisphere prominence of the second peak (N_{1b}). The lateralization of source current density estimations to the left ($N_{1a)}$ and then to the right ($N_{1b)}$ hemisphere, as observed in this study, is unlikely a result of limitations of the source estimation procedure because a biased enhancement of the source estimation procedures to one hemisphere would have affected all sources at all times. In contrast, our results show, in the same subject to the same stimulus, prominent activity in both the right and in the left hemisphere, at different times. In addition to the double-peaked temporo-parietal junction activity with its shifting lateralization, a lower magnitude, more symmetrical, single broad current density peak was observed more anteriorly, in the vicinity of the Precuneus and Medial Frontal Gyrus, suggesting concurrent processing in these regions.

Hemispheric lateralization of the single-peaked N_1 has been shown to vary among different stimuli. For speech-elicited N_1 no correlation was observed (Shtyrov et al., 2000) between the right-ear advantage, determined behaviorally, and any asymmetry indices calculated. These results were concluded to suggest that N_1 to speech signals does not indicate lateralization of speech function in the brain. In a study, that compared evoked potentials to pips with those to brief interaural disparities of intensity, N_1 hemispheric lateralization varied among stimulus types and conditions (Ungan and Ozmen, 1996). Thus, N_1 hemispheric lateralization has been shown to depend on stimulus type, independent of the hemispheric specializations typically attributed to speech and non-speech processing. This study confirms the results of our previous study (Pratt et al., 2005) in which we show that lateralization varies from left (N_{1a}) to right (N_{1b}) in response to gap onset. This different lateralization of the constituents of the N-Complex most probably reflects spatio-temporal constraints of processing different attributes of the stimulus – N_{1a}, which is homologous to the onset N_1, and N_{1b} which is unique to gap onset and is associated with a specific change in the stimulus, from noise to silence – the termination of an ongoing constant stimulus.

4.6. The N-Complex and the limits of constancy

In addition to suggesting the pre-gap noise parameters that evoke a bifid N-Complex, these findings contribute to the intensity and duration aspects of change and the distinction of transient from ongoing stimuli (constancy) in auditory perception. Previous studies on temporal integration, change and constancy (Alain et al., 1997; Vaz Pato and Jones, 1999; Jones et al., 2000a,b; Gage and Roberts, 2000; Roß et al., 2002; Alain et al., 2004; Heinrich et al., 2004) used stimuli that included spectral changes due to stimulus onset and offset that may have interacted with duration. Consequently, depending on the procedures employed, different values ranging between 30 and 300 ms were obtained. This study may contribute to the issue of constancy of sound without the confounds of spectral effects (by using gaps in noise). The electrophysiological responses may be a composite of the temporally overlapping potentials to pre-gap sound onset and to the gap. In the present study such temporal overlap is unlikely since noise onset and the gap were separated by at least 500 ms.

We suggest that the appearance of the dual-peaked N-Complex signals the brain's detection of the cessation of an ongoing, constant stimulus. In the present study the N-Complex had two peaks across all stimulus conditions, except when gaps followed the shortest (500 ms) and lowest intensity (45 dB) noise. The shortest possible wide-spectrum auditory stimulus (like the noise used in this study) is a click, which evokes a single N_1 peak at all intensities. A single-peaked N_1 was also reported in studies on gaps in short (60 ms) tones (Alain et al., 2004; Heinrich et al., 2004; raw waveforms before derivation of MMN). Taken together, our and earlier findings suggest that the minimum pre-gap sound duration necessary to evoke a two-peaked N-Complex (i.e., the minimum duration of constancy) is just under 500 ms at low intensities, and shorter with higher intensities.

4.7. Summary and conclusions

The results of this study show that both duration and intensity of the noise preceding gaps affect the early components to gap onset, and interact in their effects. These components are generated mostly in temporo-parietal areas of the brain with left hemisphere prominence for N_{1a} and right prominence for N_{1b}, with a lesser contribution to both components from more anterior symmetrical activity. Both noise duration and intensity interact to determine N-Complex detectability and characteristics. Integrating the results of this study and earlier studies indicates that the sound duration required to evoke a double-peaked N-Complex varies under half a second, depending on sound intensity. Using the N-Complex as a marker of cessation of an ongoing (constant) sound, constancy of sound was shown to be determined by both intensity and duration of the sound.

Acknowledgments

This study was partially supported by the U.S.-Israel Binational Science Foundation, by Grant DC 02618 from the National Institutes of Health, by the Rappaport Family Institute for Research in the Medical Sciences and by the Eli and Yona Sternheim Research Fund.

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