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Attention-dependent sound-offset-related brain potentials

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Abstract

When performing sensory tasks, knowing the potentially occurring goal-relevant and -irrelevant stimulus events allows the establishment of selective attention sets, which result in enhanced sensory processing of goal-relevant events. In the auditory modality, such enhancements are reflected in the increased amplitude of the N1 event-related potential (ERP) elicited by the onsets of task-relevant sounds. It has been recently suggested that ERPs to task-relevant sound offsets are similarly enhanced in a tone-focused state in comparison to a distracted one. The goal of the present study was to explore the influence of attention on ERPs elicited by sound offsets. ERPs elicited by tones in a duration-discrimination task were compared to ERPs elicited by the same tones in not-tone-focused attentional setting. Tone offsets elicited a consistent, attention-dependent bi-phasic (positive-negative – P1-N1) ERP waveform for tone durations ranging from 150 to 450 ms. The evidence, however, did not support the notion that the offset-related ERPs reflected an offset-specific attention set: The offset-related ERPs elicited in a duration-discrimination condition (in which offsets were task-relevant) did not significantly differ from those elicited in a pitch-discrimination condition (in which the offsets were task-irrelevant). Although an N2 reflecting the processing of offsets in task-related terms contributed to the observed waveform, this contribution was separable from the offset-related P1 and N1. The results demonstrate that when tones are attended, offset-related ERPs may substantially overlap endogenous ERP activity in the post-offset interval irrespective of tone duration; and attention differences may cause ERP differences in such post-offset intervals.

Introduction

The human cognitive system features various functions to optimize the processing of sensory information based on the predictability of the sensory environment. When performing sensory tasks, if the potentially goal-relevant and goal-irrelevant stimulus events are known, we can prepare for the goal-relevant events while disregarding irrelevant ones, that is, we can establish *selective attention sets*. The selectivity of such an attention set is not perfect, however: rare or conspicuous goal-irrelevant events often capture our attention and disrupt goal-directed behavior, that is, we get *distracted*. Although such disruptions impact on task performance, bringing these events into the focus of attention is useful, because it allows us to re-evaluate our goals in the face of situational changes. In the auditory modality, processing enhancements related to establishing selective attention sets have been described across the stages of auditory processing (e.g. Paltoglou, Sumner, & Hall, 2011; Petkov, Kang, Alho, Bertrand, Yund, & Woods, 2004; Rinne, Balk, Koistinen, Autti, Alho, & Sams, 2008). Such a processing enhancement is also reflected in the auditory event-related potential (ERP) as the amplitude enhancement of the N1 waveform (Hillyard, Hink, Schwendt & Picton, 1973). Conversely, the disruption of the selective attention set is reflected in the attenuation of the N1 elicited by probe events closely following distracting auditory events (Horváth, 2014a, 2014b; Horváth & Winkler, 2010). In contrast with most previous studies, which investigated ERPs elicited by sound onsets, the latter studies investigated ERPs elicited by tone-gaps (Horváth, 2014a; Horváth & Winkler, 2010) and tone offsets (Horváth, 2014b). Because the effect of attention on offset-related ERPs has not been widely studied, the goal of the present study was to explore the influence of attention on ERPs elicited by sound offsets.

Following the seminal study by Hillyard et al. (1973), numerous studies demonstrated that auditory ERPs, specifically the N1 waveform (for a summary, see Näätänen & Picton, 1987) elicited by task-relevant sounds is enhanced in comparison to that elicited by task-

irrelevant sounds. The enhancement is present for various task-relevancy manipulations, including manipulations of the to-be attended ear (e.g. Rif, Hari, Hämäläinen, & Sams, 1991; Woldorff & Hillyard, 1991), the task-relevant tone frequency (e.g. Kauramäki, Jääskeläinen, & Sams, 2007; Okamoto, Stracke, Wolters, Schmael, & Pantev, 2007), or the time-point of task-relevant sound event (see Lange, 2013). Similarly to the N1 waveform itself, the attention-dependent N1-enhancement is composed of different sub-components. The modulation of the N1 sub-component originating from the auditory cortex (as evidenced by magnetoencephalographic – MEG – recordings, see e.g. Okamoto et al., 2007), is generally regarded as the reflection of enhanced sensory processing of the task-relevant aspects of the auditory input. The ERP enhancement is also due, however, to the superposition of a different ERP component (Alho, Paavilainen, Reinikainen, Sams, & Näätänen, 1986; Knight, Hillyard, Woods, & Neville, 1981) - termed processing negativity (PN, Näätänen, Gaillard & Mäntysalo, 1978) or negative difference (Nd, Hansen & Hillyard, 1980), which is hypothesized to reflect voluntary, task-relevant processing related to matching the event to a voluntarily maintained stimulus template (attentional trace, Näätänen, 1982, 1990).

Instead of presenting sequences of discrete tones, Horváth and Winkler (2010), and Horváth (2014a) presented a continuous tone in which pitch-glides (*glissandos*, continuous pitch changes over a short period of time) and short gaps occurred. They found that when participants performed a gap-detection task, gaps preceded shortly (in 150 ms) by rare glides elicited N1 waveforms with lower amplitudes than gaps further (at least 650 ms) away from previous glides. This was interpreted as a reflection of distraction triggered by the rare glide, that is, the glide lead to the abolishment of the attention set optimal for gap-detection for brief periods of time. Conversely, when participants watched a silent movie with subtitles, and were instructed to ignore the continuous tone, gaps shortly preceded by rare glides elicited higher amplitude N1s than those further away from glides, suggesting that in this setting, rare

glides drew the participants attention from the movie to the tone, which lead to the enhanced processing of gaps delivered within these brief, tone-oriented time-periods.

Horváth (2014b) suggested that the interplay of attention and distraction was also reflected in the ERPs elicited by sound offsets. Sound offsets elicit waveforms similar to those elicited by tone onsets (Davis & Zerlin, 1966; Hillyard & Picton, 1978; Onishi & Davis, 1978), and the offset-and onset-related N1s, and offset-and onset-related P2s respectively originate from overlapping sources as evidenced by MEG recordings (Hari, Pelizzone, Mäkelä, Hällström, Leinonen, & Lounasmaa, 1987; Pantev, Eulitz, Hampson, Ross, & Roberts, 1996; Yamashiro, Inui, Otsuru, & Kakigi, 2011, but see Noda et al., 1998). Animal studies demonstrated that there is a high proportion of offset-sensitive neurons in the auditory cortex (see e.g. Fishman & Steinschneider, 2009; Recanzone, 2000). Many of these neurons respond both to on- and offsets (Qin, Chimoto, Sakai, Wang, & Sato, 2007), although these responses are driven by different synaptic connections (Scholl, Gao, & Wehr, 2010). This supports the notion that onset- and offset-related auditory ERPs have common components, and (at least in part) reflect the same underlying information processing. Therefore, the notion that (parts of) the offset ERP response may be enhanced when attention is directed towards the sound, seems plausible. Studies investigating this hypothesis are scarce, Nishihara et al. (2014) found that the amplitude of the magnetic counterpart of the offset-related P1 of the auditory ERP waveform (P1m) was not affected when the task-relevancy of the tones was manipulated.

Horváth (2014b) administered the distraction paradigm introduced by Schröger & Wolff (1998a, 1998b). Participants performed a tone-duration discrimination task. Distraction was induced by task-irrelevant, rare, unpredictably occurring pitch-variations. Contrasting ERPs elicited by short tones with frequent and rare pitch variations showed that the offsets of tones with a frequent pitch elicited a tri-phasic waveform (termed P1-N1-P2 in Horváth,

2014b), which was reduced in amplitude for short tones with a rare pitch. It was suggested that rare pitch variations distracted participants (i.e. abolished the task-optimal attention set), and thus removed the attentional enhancement of the offset-related P1-N1-P2 waveform.

The goal of the present study was to investigate how sound-focused attention influenced offset-related ERP waveforms. In Experiment 1, the task-relevancy of the sounds was manipulated: in the active part participants performed a “short go” duration-discrimination task (i.e. they pressed a button in response to short, but not to long tones), whereas they watched a silent movie in the passive part. Offset-related ERPs elicited in the two parts by the same type of sounds were contrasted. It was hypothesized that the offset-related waveforms would be enhanced when the tones were task relevant. Although the results of Horváth (2014b) suggested that “short go” vs. “long go” response differences did not substantially affect the offset-related ERP pattern, Experiment 2 repeated the active part of Experiment 1 with a “long go” task instruction. It was hypothesized that offset-related waveforms resembling those found in Horváth (2014b) and Experiment 1 will be elicited despite the lack of overt responses to short tones. In Experiment 3, it was tested whether offset-related ERPs elicited in two, tone-focused attention settings differed as the function of the task-relevancy of the offset. The hypothesis was that offset-related ERPs would be enhanced when participants performed duration-discrimination (for which offsets are task relevant) in comparison to when they performed pitch-discrimination (for which offsets are irrelevant). The presence of such an ERP enhancement could indicate, that a task-specific attention set (attentional template) for tone offset, or for the task-relevant time point had been established.

Beside the main hypotheses described above, the present experiments allowed three further inquiries into of the nature of the attention-dependent offset-related ERP waveforms. First, tone offset timing was varied by presenting 150 vs. 750 ms; 300 ms vs. 750 ms; and 450

ms vs. 750 ms tone-durations respectively in three conditions. This allowed testing, whether the attention-dependent offset ERP showed an amplitude increase with tone duration, which is characteristic for offset-responses obtained in passive settings (Hillyard & Picton, 1978).

Second, varying offset timing also allowed the assessment of the consistency of the offset-related temporal ERP pattern. In the Horváth (2014b) study, the latency relations between P1, N1 and P2 were similar to those elicited by tone onsets, nonetheless, this may have been a coincidence only, especially since these offset-related waveforms were uniformly shifted by about 50 ms in comparison to those elicited by sounds onsets (i. e., instead of about 50 ms, the offset-related P1 peaked at about 100 ms, and instead of 100 ms, N1 peaked at about 150 ms, see Table 2). One may well hypothesize that some parts of the waveform were not time-locked to the offset, or did not directly reflect offset-related processing. If some parts of the waveform did not show a consistent, offset-locked latency pattern across the different offset timings, this would indicate that these waveforms were not directly related to offset processing.

The third line of inquiry tested a specific hypothesis regarding the offset-related N1 waveform. Because tone offsets were task-relevant in the study by Horváth (2014b, because of the tone-duration discrimination task), parts of the offset-related waveform may not directly reflect offset-processing, rather, they may actually reflect the processing of the offset in task-related terms, that is, they may reflect processes related to stimulus categorization or response selection. Specifically, the observed offset-related N1 might not be analogous to the onset-related N1, but may be actually an N2 (for a summary, see Folstein & Van Petten, 2008). Because N2 latency is known to co-vary with reaction time (Ritter, Simson, Vaughan, & Friedman, 1979), one way to test this hypothesis is to measure how the offset-related peak latencies varied with reaction time. To explore this possibility, ERPs elicited by short tones in

trials with fast and slow responses were averaged separately in Experiment 1 and 3, and the latency-dependence of the observable waveforms was assessed.

Method

Participants

In Experiment 1, 12 healthy young adult volunteers, recruited by a student part-time job-agency, participated for monetary compensation. Data from one participant were not used in the analyses, because of extensive eye-movements and alpha-activity resulting in a low number of EEG epochs after artifact-rejection. The remaining 11 participants were all right-handed, aged 20-24 years, and six of them were men.

In Experiment 2, 11 participants who participated in Experiment 1 returned for a second experimental session. Data from one participant were not used in the analyses, because of technical problems with the EEG recording. The remaining 10 participants were all right-handed, aged 20-24 years, and five of them were men.

In Experiment 3, 13 healthy young adult volunteers, recruited by a part-time student job-agency, participated for monetary compensation. Data from one participant were not used in the analyses, because of extensive alpha-activity resulting in a low number of EEG epochs remaining after artifact-rejection. The remaining 12 participants were all right-handed, aged 20-24 years, and five of them were men.

In all the experiments, participants reported normal hearing and no history of neurological disorders, and gave written informed consent after the experimental procedures were explained to them.

Stimuli and Procedures

Experiment 1. During the experiment, participants were sitting in an armchair in a sound-proofed room. Tones comprising three harmonics (700, 1400 and 2100 Hz sinusoids with the two high ones having relative amplitudes of -3, and -6 dB, similarly to the sounds used by Horváth, 2014b) were presented through headphones (HD-600, Sennheiser, Wedemark, Germany). In three conditions, pseudo-randomized sequences of tones of two equiprobable durations were presented: 150 and 750 ms, 300 and 750 ms, and 450 and 750 ms. All tones included 2.5-2.5 ms linear rise and fall times. Tone intensity was individually adjusted to 50 dB above hearing threshold level. The tone sequences were presented in blocks of 134 tones, with an onset-to-onset interval of 1300 ms.

The experiment had two parts: an Active and a Passive part, which were administered in Active-Passive order for 5 participants, and in Passive-Active order for 6 participants. In the Active part, participants were instructed to listen to the tones, and press a button held in their dominant hand when the short tone was presented, and withhold response for long tones (a go-no go task). The instruction emphasized that participants should respond as fast as possible while maintaining a low false alarm rate. In the Passive part, participants watched a self-selected movie with subtitles without sound. In both parts, four blocks were presented in each condition. The blocks of the same condition followed each other immediately, but the order of the three conditions was randomized. To minimize eye-movements, in the Active part, participants were instructed to keep their gaze on a fixation puppet placed in front of them. Short breaks were introduced between consecutive blocks as needed, as well as a longer break between the two parts. Before the Active part, participants practiced the task in a block featuring 150 and 750 ms tones. In the Active part, feedback on the correct response ratio, and average response time was provided at the end of each block.

Experiment 2. In Experiment 2, the stimulation arrangement was the same as in the Active part of Experiment 1, except for the instruction, which was to respond only to the long

tone and withhold response for the short tones. Participants were explicitly instructed to press the button as soon as they were certain that they hear the long tone, that is, not to wait with the response until the end of the long tones.

Experiment 3. Experiment 3 featured pseudo-random tone sequences comprising equal numbers of four types of tones resulting from the permutation of two durations (250 and 500 ms) and two base tone frequencies (700 and 900 Hz). All other aspects of the tones were identical to those in Experiments 1-2. In the Pitch Task condition, participants were instructed to press the button for high-pitched tones, whereas in the Duration Task condition participants were instructed to press the button for short tones. Tones were presented with random onset-to-onset intervals sampled uniformly from the 1200-1800 ms range. The two conditions were administered in a counterbalanced order (six participants started with the Duration Task, six with the Pitch Task condition). In each condition, 9 blocks of 124 stimuli were presented, which were separated by short breaks as needed. The two conditions were separated by a longer break. Before the experiment, a practice block was administered for both tasks.

Behavioral Data Extraction and Analysis

Experiment 1 & 2. Responses occurring from 50 ms following the task-relevant timepoints (i.e. the moments where the short tone offset could occur) to 100 ms before the next onset (i.e. 200-1200 ms in the 150 vs. 750 ms condition; 350-1200 ms in the 300 vs. 750 ms condition, etc.) were categorized as hits or false alarms, and trials with no responses were categorized as correct rejections or misses as the function of task instructions. These were used to calculate the d' sensitivity score (signal detection theory, see Macmillan & Creelman, 2005) for each condition and each participant. To avoid infinite values for perfect performance, hit rates of 1 and false alarm rates of zero were adjusted to $1 - (1/(2N))$ and $1/(2N)$, respectively (where N is the number of stimuli requiring a button press, see

Macmillan and Creelman, 2005). Participant's reaction times were calculated as the median of the individual reaction times for hits. (Because reaction time distributions are often skewed, the median provides a better estimate of the typical reaction time than the mean.) d' and reaction times were analyzed in one-way repeated measures analyses of variance (ANOVA) with condition as a three-level factor for both experiments. To compensate for potential sphericity-violations, Greenhouse-Geisser-correction was applied (epsilon values are reported with the uncorrected degrees of freedom). Generalized eta-squared effect sizes (Bakeman, 2005; Olejnik & Algina, 2003) are reported. Significant effects were followed-up by pairwise t tests with Bonferroni-Holm correction (Holm, 1979).

Experiment 3. The calculation of reaction times and d' scores was identical to those in Experiment 1 and 2, except for the response windows, which were 50-1000 ms in the Pitch Task, and 300-1200 ms in the Duration Task condition.

EEG Recording and Analysis

The electroencephalogram (EEG) was recorded with 500 Hz sampling rate with nose reference (100 Hz on-line low-pass filter, Synamp 2, Compumedics, Victoria, Australia) by 61 Ag/AgCl electrodes mounted on an elastic cap (EASYCAP, Herrsching, Germany) according to the 10% system (Nuwer et al., 1998). Two further electrodes were placed at the mastoids. Horizontal electrooculogram (EOG) was recorded on-line between electrodes placed close to the outer canthi of the two eyes. The signal of an electrode placed under the right eye was subtracted off-line from the signal measured at Fp2 to obtain the vertical EOG. The EEG was off-line 20 Hz low-pass filtered (Kaiser-windowed sinc finite impulse response filter, beta of 4.53, 733 coefficients, transition bandwidth 2 Hz, stopband attenuation at least 50 dB).

Experiment 1 & 2. The filtered EEG was segmented into epochs of 1300 ms corresponding to hit and correct rejection events in each condition, including a 200 ms long interval preceding tone onset. The average signal in the 200 ms pre-stimulus interval was used as a reference in the amplitude calculations. Epochs with a signal range exceeding 100 μ V on any channel were discarded. The mean numbers of the remaining epochs (and their standard deviances) in the Active part of Exp. 1. were 370 (119), 392 (123), and 399 (101) in the 150, 300 and 450 ms vs. 750 ms conditions, respectively; in the Passive part of Exp.1 these were 344 (93), 328 (90), 349 (74) in the 150, 300 and 450 ms vs. 750 ms conditions, respectively. In Exp. 2 these were 356 (146), 331 (162), and 328 (134) in the 150, 300, and 450 ms vs. 750 ms conditions, respectively. The remaining epochs were averaged for each participant, for each condition, and for hit and correct rejection trials separately.

In contrast with previous studies identifying the offset-related transient waveform in the ERPs, in the present study the ERP elicited by the long tone served as a reference for the assessment of the pre-offset waveform, that is, the offset-related ERPs were assessed in the short-minus-long difference waveforms. That is, in both experiments, in each part, and each condition, short-minus-long difference ERP waveforms were calculated. To have an unbiased estimate whether significant offset-related ERP activity was elicited, the offset-related peak times and electrode sites of maximal amplitudes as reported by Horváth (2014b) were used. Due to the obvious dominance of P3b over the offset-related P2 in the active parts, only the first two components (P1 at 98 ms at Cz, and N1 at 160 ms at Fz, Horváth, 2014b) were submitted to the analyses. Individual amplitudes were calculated as average signals in 20 ms windows centered at these time points, at these electrode sites, and were submitted to one-tailed Student's *t* tests against zero in each condition, for each short-minus-long difference waveform.

Experiment 1 allowed the assessment whether attending the sounds (i.e. having a tone-related task) resulted in ERP differences, that is, whether the offset-related ERPs identified in the short-minus-long difference waveforms of the Active condition were significantly different from the ERPs elicited in the same interval in the Passive condition. For this purpose, individual amplitudes were calculated as average signals in 20 ms windows centered at the actual latencies and sites of the peaks observed in the Active condition in the group-average difference waveforms, and were submitted to an Task (Active vs. Passive) \times Condition (150, 300, or 450 ms vs. 750 ms) repeated-measures ANOVA.

To confirm that the amplitude of offset-responses increased with tone duration, as found in previous (passive) paradigms (Hillyard & Picton, 1978), the P1-N1 (peak-to-peak) amplitudes measured at Cz were submitted to one-way Condition (150, 300, or 450 ms vs. 750 ms) repeated-measures ANOVAs in both experiments. Characterizing the transient waveform by the difference of the P1 and N1 amplitudes in these calculations allowed for the most power to detect a potential duration-effect.

To investigate whether the latencies of the offset-related waveforms differed for different tone durations, P1, N1 (both measured at T8) and P3b (measured at Pz) peak latencies in the short-minus-long difference waveforms in Experiment 1 and 2 were compared by one-way Condition (150, 300, or 450 ms vs. 750 ms) repeated-measures ANOVAs using the jackknife procedure as described by Kiesel, Miller, Jolicœur, and Brisson (2008). T8 was chosen for the assessment of P1 and N1 latencies because these peaks were more pronounced at temporal electrodes in the group-average ERP waveforms (see Fig. 2) than at central leads. It seems possible that this was caused by the overlap of the P3b, which more strongly reduced the amplitude of the negative waveform at central than at temporal leads.

To assess whether N1 was actually an N2 reflecting task-related processing, individual ERP epochs corresponding to hit trials (to short tones) with reaction times slower and faster than the individual median reaction time were averaged separately in each Active condition for each participant. Note that in contrast with the analyses presented above, this analysis was based on the transient waveforms identified in the short tone offset related waveforms (and not in the short-minus-long differences). Because of this, contributions from low-frequency ERP activities may bias the results of this analysis. P1, N1 (both measured at T8) and P3b (measured at Pz) peak latencies were compared by Condition (150, 300, or 450 ms vs. 750 ms) \times Partition (faster, or slower than the median RT) repeated-measures ANOVAs using the jackknife procedure as described by Kiesel et al. (2008).

An unexpected finding was that the P1 and N1 ERPs showed right dominance in the group-average ERPs, especially in Exp. 2., which was investigated by post-hoc paired two-tailed Student's *t* tests of the P1-N1 (peak-to-peak) amplitudes measured at the T7 and T8 electrodes in both experiments.

Experiment 3. The filtered EEG was segmented into epochs of 1200 ms corresponding to hit and correct rejection events in each condition, including a 200 ms long interval preceding tone onset. The average signal in this interval was used as a reference in the amplitude calculations. Epochs with a signal range exceeding 100 μ V on any channel were discarded. The mean numbers of remaining epochs and their standard deviations were 885 (125) and 940 (89) in the Duration and Pitch conditions, respectively. The remaining epochs were averaged for each participant, for each condition, and for short and long tones separately. The offset-related P1 and N1 were identified in the group-average short-minus-long waveform in the Duration Task. Individual P1 and N1 amplitudes were calculated as average signals in 20 ms windows centered at the group-average peaks found in the Duration Task. P1 and N1 amplitudes measured in the short-minus-long difference waveforms were

compared between conditions in Student's t tests. To ascertain that a P1 was elicited in the Pitch Task condition, the amplitudes in the P1 time range were submitted to a further t test against zero mean amplitude.

To assess the potential contribution of the N2 to the offset-related ERP similarly to Exp. 1, individual ERP epochs corresponding to hit trials (to short tones) in the Duration Task with response times in the first, second, and third tertiles of the reaction time distribution were separately averaged. As for Exp. 1 and 2., this analysis was based on the transient waveforms identified in the short-tone-offset related waveforms (and not on the short-minus-long differences). (Using tertiles was possible because each condition of Exp. 3 featured about twice as many trials as those in Exp. 1 or 2). Peak latencies for the P1, N1, N2 and P3b ERPs elicited in the three partitions were analyzed by applying the jackknife procedure described by Kiesel et al. (2008) in separate one-way repeated-measures ANOVAs. P1 and N2 peak latencies were assessed at Cz, whereas N1 was assessed at Fp2, where the overlap of N2 was lower than at other leads in the group average ERP waveforms. P3b latency was assessed at Pz.

Results

Experiment 1 & 2

Behavioral data. Group-average reaction times and d' sensitivity scores in the two experiments are presented in Figure 1. In Experiment 1, the ANOVA of the reaction times (in reference to short tone-offset) showed a significant Condition main effect: $F(2,20) = 8.019$, $\epsilon = .706$, $\eta_G^2 = .183$, $p = .008$. Pairwise t tests with Holm-correction showed that the responses were significantly slower in the 450 vs. 750 ms than in the other two conditions (p -values = .032). The ANOVA of the d' scores showed a significant Condition main effect: $F(2,20) = 5.055$, $\epsilon = .826$, $\eta_G^2 = .197$, $p = .017$. Pairwise t tests with Holm-correction showed that the d'

score was significantly lower in the 450 vs. 750 ms than in the 300 vs. 750 ms condition ($p = .025$).

In Experiment 2, the ANOVA of the reaction times (in reference to the timepoint at which the short tone would end) showed no significant Condition effect: $F(2,18) = 2.241$, $\varepsilon = .888$, $\eta_G^2 = .056$, $p = .135$. The ANOVA of the d' scores showed a significant Condition main effect: $F(2,18) = 40.640$, $\varepsilon = .861$, $\eta_G^2 = .337$, $p < .001$. Pairwise t tests with Holm-correction showed that all d' scores significantly differed from each other (p -scores $< .022$).

Although discrimination performance was high overall, these results show the expectable decline of performance for decreasing duration-differences.

ERPs – general observations. The group-average ERPs and the short-minus-long difference waveforms elicited in the Active conditions are presented in Fig. 2 for Experiment 1, and Fig. 3 for Experiment 2. In the pre-stimulus intervals, a negative trend could be observed at fronto-central electrodes, suggesting that participants were actively expecting and preparing for the stimuli, especially in the 150 vs. 750 and the 300 vs. 750 ms conditions. The tone onsets elicited the expectable pattern of P1, N1 and P2, which was followed by a sustained negativity with duration commensurate to that of the short tone in the given condition. Following the time-point of the short tone offset, a parietal positivity, identified as a P3b, could be observed. Importantly, the offsets of the short tones were followed by sharp ERPs (indicated by black arrows in Figures 2 and 3) superimposed on the slow decay of the sustained ERP, which resulted in the short-minus-long difference waveforms showing the bi-phasic (positive-negative) offset-related waveform pattern (termed P1 and N1 in the following) similar to the first part of the positive-negative-positive waveform reported by Horváth (2014b). Interestingly, the offset of the long tone was also followed by a similar, sharp bi- (positive-negative) or tri-phasic (positive-negative-positive) waveform, which was

most readily observable at the leads on the side of the head (mainly at the temporal but also at frontal and also at mastoid sites – indicated by blue arrows in Fig. 2 and 3).

The group-average ERPs and the short-minus-long difference waveforms elicited in the Passive condition of Experiment 1 are presented in Figure 4. The tone onsets elicited the expectable pattern of P1, N1 and P2, which was followed by a sustained negativity with duration commensurate to the duration of the eliciting tone. No offset-related ERPs were observed in the short-minus-long difference waveforms, and no significant short vs. long ERP differences were found in the 88-108 ms time-range (P1) at Cz, or the 150-170 ms time-range (N1) at Fz following the offset (as in the Horváth, 2014b study). Interestingly, the visual inspection of the ERPs elicited by long tones in the three conditions show a post-offset waveform at around 900 ms (i.e. at around 150 ms post-offset, indicated by blue arrows on Fig. 4). This waveform is visually similar to that obtained in the Active part of the Exp. 1, and Exp.2. (see Fig. 2 and 3), and is interpretable as the superposition of a negative-going transient waveform and a sustained activity.

ERPs – active conditions. For the Active conditions, all analyses of the ERPs (see Table 1) in the 88-108 ms P1 time-range following the offset at Cz (as in the Horváth, 2014b study) showed that the ERP for the short tone was more positive than that of the long one. The analyses of 150-170 ms N1 time-range following tone-offset at Fz (as in the Horváth, 2014b study) showed that the ERP for the short tone was more negative than that for the long one in all but the 450 ms vs. 750 ms condition of Experiment 1.

The actual peak latencies were similar to those found in the Horváth (2014b) study (Table 2). The offset-related P1s in the short-minus-long difference waveforms of the Active conditions showed midline central maxima (Cz) in both Experiment 1 and 2 (see Figure 5, first and third columns). Therefore, amplitudes at the Cz were used in the Active vs. Passive

comparisons (see below). It is also to be noted that in Exp. 1, in the 150 vs. 750 ms condition, an additional, slightly right shifted parietal maximum (peak at PO4) was also observable. The offset-related N1s in the short-minus-long difference waveforms of the Active conditions of Exp. 1 (Fig. 5, second column) showed slightly left-shifted fronto-central distributions (peaks at F3, FC3, C3), therefore amplitudes measured at FC3 were used in the Active vs. Passive comparisons (see below). In Exp. 2, N1 peaked at fronto-central sites (FC2, F2, FCz). In both Experiments, N1 also showed local maxima at similar latencies at the sides (mainly temporal, but frontal and mastoid sites as well, see Fig. 5, second and fourth columns). In Experiment 2, the transient P1-N1 waveform was elicited with higher amplitudes at the right than at the left side (see Fig. 3, left and right columns, as well as Fig. 5 right columns). This post-hoc observation was supported by paired, two-tailed Student's *t* tests of the P1-N1 (peak-to-peak) amplitudes measured at the T7 and T8 electrodes ($t[9] = 4.004, p = .003$; $t[9] = 4.1647, p = .002$; $t[9] = 3.8094, p = .004$ respectively for the 150, 300 and 450 vs. 750 ms conditions). The corresponding comparisons for Experiment 1 showed no significant differences.

The one-way Condition ANOVAs of the P1-N1 (peak-to-peak) amplitudes measured at Cz showed no significant effects in either experiments.

ERPs – Experiment 1. - active vs. passive comparisons. Short-minus-long difference waveforms from the Active and Passive parts are contrasted in Figure 6. The Task (Active vs. Passive) \times Condition (150, 300, or 450 ms vs. 750 ms) repeated-measures ANOVA of the amplitudes measured in the actual P1 time-intervals in Exp. 1 showed only a significant Task main effect: $F(2,20) = 11.297, \eta_G^2 = .29, p = .007$, indicating that the ERP in the P1 interval was more positive in the Active than in the Passive part. The same type of ANOVA for the N1 interval showed a significant Task main effect only: $F(2,20) = 10.440, \eta_G^2 = .300, p = .009$, indicating that the ERP amplitude in the N1 interval was more negative in the Active than in the Passive part.

ERPs – latency analyses. The jackknife-procedure based one-way Condition (150, 300, or 450 ms vs. 750 ms) ANOVAs of the P1, N1, and P3b latencies measured in the short-minus-long difference waveforms at T8, T8, and Pz respectively, showed no significant differences in either Exp. 1 or Exp. 2.

The group-average ERPs elicited in short tone hit trials with below- and above median reaction times in each condition are presented in Figure 7. The ERPs exhibited the same, clearly identifiable offset-related waveform patterns in all conditions. Latency-analyses utilized the jackknife procedure with Condition (150, 300, or 450 ms vs. 750 ms) \times Partition (below or above median RT) ANOVAs (in the following, jackknife-adjusted F-values, Greenhouse-Geisser epsilons if applicable, unadjusted degrees of freedom, and adjusted p-values are reported). The mean jackknife peak latencies are presented in Figure 8. For P1, only a significant condition main effect was found: $F(2,20) = 6.135$, $\epsilon = .970$, $\eta_G^2 = .917$, $p = .009$. Pairwise t tests with Holm-correction indicated that P1 peaked earlier in the 450 vs. 750 ms, than in the 150 vs. 750 ms condition: $t(10, \text{jackknife-adjusted}) = 3.475$, $p = .018$. For N1, no significant effects were found. For P3b, only a significant partition main effect was found: $F(1,10) = 6.132$, $\eta_G^2 = .920$, $p = .033$, indicating that P3b peaked earlier in trials with faster-than-median reaction times.

Apart from the offset-related waveforms, the group-average ERPs elicited in short tone hit trials with below- and above-median reaction times showed some differences which are worth mentioning. As observed post-hoc, tones in trials with faster-than-median responses elicited a higher amplitude sustained negativity preceding and overlapping the offset-related waveforms than those with slower-than-median responses (Fig. 7, shaded areas). This post-hoc observation was confirmed by paired t tests of the amplitudes measured in the 50 ms interval preceding the tone offsets at Cz: ($t[10] = 2.267$, $p = .047$, $t[10] = 3.768$, $p = .004$; $t[10] = 3.465$, $p = .006$, respectively for the 150, 300 and 450 vs. 750 ms conditions). Note

that because amplitude calculations were referred to the pre-stimulus interval (i.e. baselining was performed), the reported amplitude differences are biased to different degrees in the three conditions, because the sustained ERPs might have already differed in the pre-stimulus intervals.

Experiment 3

Behavioral data. The group-average reaction times were 299 ± 43 ms in the Pitch- (in reference to tone onset), and 271 ± 48 ms in the Duration Task (in reference to the short tone offset) condition. The group-average d' scores were 4.391 ± 0.600 in the Pitch-, and 4.376 ± 0.569 in the Duration Task condition.

ERPs – general observations. The group-average ERPs and short-minus-long difference waveforms elicited in the two conditions are presented in Figure 9. The tone onsets elicited the expectable succession of P1, N1, P2 and N2 waveforms in both conditions. The N2 was followed, and partly overlapped by a sustained negativity in the Duration Task condition. Sustained activity is also visible in the Pitch Task condition: the short-minus-long difference waveforms show a sustained, fronto-centrally maximal positivity, which (due to the subtraction) is equivalent to a long tone-related sustained negativity. In both conditions, these ERPs were followed by a P3b. Interestingly, in both conditions, a biphasic - positive-negative - transient waveform can be observed 100 and 150 ms after the offset of the long tone, most conspicuously at the right temporal and mastoid leads (Fig., 9, right column, indicated by blue arrows; in the short-minus-long difference waveform these show up as biphasic negative-positive waveforms).

The comparison of the short-minus-long difference waveforms (Fig. 9) showed a positivity following the short tone offset by about 100 ms in both conditions. In the Pitch condition, this was followed by a fronto-central sustained positivity (as explained above, this

is the reflection of the long-tone-related sustained negativity). In the Duration Task condition, a negativity (identified as superposition of the N1 and N2 ERPs, dominated by the N2, see below) was present peaking at about 230 ms following the short offset.

ERPs – between condition comparisons. In the Duration Task condition, P1 peaked at C3 at 344 ms from onset (94 ms after the offset) in the group average short-minus-long difference waveform (Fig. 10., left column shows the short-minus-long topographical differences, as well as the topographical distribution of the between-condition differences at the P1 peak). The comparison of the amplitudes measured in the two conditions in a 20 ms long window centered at this latency, at this electrode, showed no significant difference ($t[11] = 2.145, p = .055$). The amplitude in the Pitch Task condition was nonetheless significantly higher (more positive) than zero ($t[11] = 6.514, p < .001$, one-tailed).

In the Duration Task condition, N1/N2 peaked at FCz, at 484 ms (234 ms after the offset) in the group average short-minus-long difference waveform (Fig. 10., right column shows the short-minus-long topographical differences, as well as the topographical distribution of the between-condition difference at the N1/N2 peak). The amplitude was significantly higher (more negative) in the Duration Task than in the Pitch Task condition ($t[11] = 10.200, p < .001$).

ERPs –latency analyses. The group-average ERPs elicited in the short tone hit trials of the Duration Task condition with reaction times in the three tertiles are presented in Figure 11. As for Exp.1 the jackknife procedure was used to calculate one-way repeated measures ANOVAs for each component (Figure 12). Even with the selection of the Fp2 electrode for the identification of the N1 peak, in two cases no local minima, but a shoulder was observable. These shoulders were characterized by the latency of the timepoint at which the temporal derivative of the Fp2 signal (the difference of consecutive signal samples) was

closest to zero. The P3b in the fastest response tertile exhibited two peaks in all but one case; in such cases the earlier peaks were selected. For P1 and N1 no significant partition effects were found. For N2 and P3b, however, significant partition effects were present. For N2: $F(2,22) = 41.18128$, $\varepsilon = .949$, $\eta_G^2 = .993$, $p < .001$. Pairwise t tests with Holm-correction showed that N2 was elicited later in trials with slower responses (p -values $< .001$ for all comparisons). For P3b: $F(2,22) = 35.208$, $\varepsilon = .960$, $\eta_G^2 = .994$, $p < .001$. Pairwise t tests with Holm-correction showed that the P3b peaks differed significantly between all three RT-tertiles, with the one corresponding to the first tertile being the earliest, and the one corresponding to the third tertile the latest (p -values $< .05$ for all comparisons).

Similarly to Exp. 1, the waveforms corresponding to trials with faster responses elicited a sustained negativity preceding the offsets. A one-way repeated measures ANOVA of the amplitudes measured at Cz in the 50 ms long pre-offset interval showed a Partition effect: $F(2,22) = 7.256$, $\varepsilon = .931$, $\eta_G^2 = .027$, $p = .004$. Pairwise t tests with Holm-correction showed that the sustained activity was more negative for trials with RTs in the first tertile than for those in the other two tertiles (p -values $< .05$ for both comparisons).

Discussion

The goal of the present study was to investigate the attention-dependency of auditory offset-related ERPs as suggested by Horváth (2014b). He found that in a duration-discrimination task, contrasting the short-minus-long ERP difference waveform obtained in the task-focused state with that obtained in a distracted state showed a sequence of ERPs resembling that elicited by tone onsets. Based on this finding it was speculated that this waveform was an attention-dependent auditory offset response. To test this hypothesis in the present study, short-minus-long difference ERP waveforms obtained in two types of contrasts were investigated. In the first one, ERPs elicited in a tone offset-related task were compared

to those elicited when participants had no tone-related task. In the second one, ERPs elicited in a tone offset-related task were compared to those elicited in a tone pitch-related task. The results of the study replicated previous findings, and showed that tones presented in the context of tasks requiring tone-focused attention elicited an attention-dependent offset-related ERP waveform. There was, however, no evidence for an attention set established specifically for the offset or for the time-point when a task-relevant offset could occur.

Specifically, in the Active part of Exp. 1 and in Exp. 2 offset-related P1 and N1 responses were found, which were superimposed on the decaying phase of a negative sustained ERP activity with duration commensurate to the duration of the short tone (i.e., the task-relevant time-point). It is important to note that in the 450 vs. 700 ms condition of Exp.1, the *t* test of the ERP amplitude measured at the latency and site of the maximal N1 signal as in the Horváth (2014b) study showed no significant difference from zero. Nonetheless, P1 was followed by a clear cut negativity with a similar latency as in the Horváth (2014b) study and all the other conditions of Exp 1. and Exp. 2. The lack of a significant difference from zero is probably caused by the superposition of a slow positive wave on the P1-N1 in the short-minus-long difference waveform. The slow positive wave may be brought about by the asymmetry of the task: whereas the short tone offset is a clear indication that the trial is a go trial, deciding whether the time point of the offset has already passed (making the trial a no go trial) may require a longer time, especially for longer tone durations, for which estimating the time-point of the potential offset is more difficult. This may result in the later termination of the sustained negative ERP for long tones, which could be reflected in a positive contribution in the short-minus-long difference. The P1-N1 pattern could be observed irrespectively of whether short tone offsets required an overt response or not. These results closely replicate the findings of Horváth (2014b), with the exception of the P2 response, which – if present – was not separable from the P3b in the present study. Importantly, ERP amplitudes in the offset-

related P1 and N1 time ranges were significantly higher in the active than in the passive part of Exp. 1, thus confirming the hypothesis that these offset-related ERP responses were indeed attention-dependent. Whereas one could assume that the attentional enhancements reflected an offset-specific attention set, or an attention set tuned for the timepoint of the task-relevant offset, no evidence for this was found in Exp. 3., in which attending the sounds resulted in well-discernible offset-related P1 waveforms with no significant amplitude differences between settings requiring pitch- or offset-focused attention. (Because N1 was overlapped by an N2 in the offset-focused setting, no conclusions regarding N1 could be drawn). That tone-focused attention was sufficient to elicit offset-related P1 and N1 waveforms was also corroborated by the observation of such waveforms for long tone offsets (which were task-irrelevant in all conditions) in all three experiments (indicated by blue arrows at T8 in the figures).

The Attention-Dependent Offset-Related Waveform

It was hypothesized that the attention-dependent, offset-related P1-N1 amplitudes would increase with increasing tone duration, because previous studies administering passive experimental protocols showed such effects, but no such increase was found. Since no offset-related responses were observable in the passive part of Exp.1 for 150-450 ms long tones (which is on a par with previous studies which found discernible offset-responses only for sounds longer than about 0.6-1 s, Hillyard & Picton, 1978, see also Näätänen & Picton, 1987), the lack of this effect may reflect the lack of power to reveal such an effect in the given duration-range with the given ERP signal-to-noise ratio.

Since the attention-dependent responses peaked about 50 ms later than those reported in previous studies (which administered passive protocols), one may argue that the ERPs reported in the present study are unlikely reflect the modulation of the offset-related ERPs

reported previously. Nonetheless, in the passive conditions of Exp. 1, the offset of the 750 ms long tone was followed by a negative waveform resembling the N1 elicited in the active settings both in its timing and its marked presence at the temporal leads. This suggests that in the present study, the offset response was shifted by about 50 ms in the passive part as well as in the active parts. That is, the latency discrepancy between the current (and also the Horváth, 2014b) study and previous studies is not caused by task (active/passive) differences, but are related to some, yet unclear differences.

The attention-dependent P1 and N1 elicited in Exp. 1 and 2 showed a consistent, offset-locked pattern: the latency of the P1, N1, and P3b measured in the short-minus-long difference waveforms did not significantly differ between conditions in Exp. 1 and 2 (note, however, that P1 peaked slightly earlier for the 450 ms than for the 150 ms tone when P1 was identified in the short-tone related ERPs). Separating short tone trials with fast and slow responses affected only the latency of the P3b significantly. Interestingly, fast response trials featured a sustained negative shift preceding the P3b onset, which may reflect more pronounced (attentional) preparation for the task-relevant moment (see e.g. Tecce, 1972; Liu, Zhang, Ma, Li, Yin, & Luo, 2013). These response-speed related ERP differences show the involvement of preparatory and decision-related activities, but in Exp. 1 and 2, these did not significantly influence the offset-related ERP latencies when the slow, pre-offset ERP activity was controlled for (i.e. when the analyses were conducted on the short-minus-long difference wave forms).

In Exp. 3, however, the offset-related negative (N1) waveform was strongly enhanced when the offset (and not tone pitch) was task relevant. Averaging epochs from short tone trials according to response speeds allowed delineating two contributions to this enhanced negative waveform: The offset-related N1 was overlapped by an N2, presumably reflecting the evaluation of the stimulus event in task-related terms. Whereas the latency of N1,

similarly to that of the P1 was not significantly affected by response-speed differences, N2-, as well as the P3b-latency, was significantly longer in trials with longer response times. It seems likely that the dominant N2 elicitation was due to the randomized stimulus presentation (both in terms of pitch and inter-stimulus intervals), which required more cognitive control, and allowed less efficient preparation for the time-relevant moment in Exp. 3 than in Exp. 1 or 2.

Taken together, these observations give support to the notion that the observed P1 and N1 ERPs are direct reflections of offset-detection, which can be dissociated from decision-related ERPs. The results of the present study support the notion that differences in the attentional state of participants at the time of stimulus offset may significantly affect ERP waveforms in the post-offset interval. Moreover, these offset-related ERPs are not only substantial for tone durations beyond 0.6-1.0 s, but also for durations as short as 150 ms. This has profound implications for paradigms designed to contrast endogenous ERPs elicited in various conditions. In many designs, it is assumed that waveforms occurring well after the onset (and the onset-related exogenous ERPs) reflect mainly endogenous (cognitive) activity. The present study shows that these ERPs may receive substantial contributions from attention-dependent offset-related waveforms if they occur in 100-250 ms following the offset of an auditory stimulus. Importantly, if the contrasted conditions differ in the allocation of attention towards the stimuli, then the attentional modulation of these ERPs may contaminate these comparisons.

Outstanding Issues

The attention-dependency of these waveforms seems to be similar to that of the onset-related N1 waveform: When participants attended the sounds, the waveforms were enhanced, which may be interpreted as enhanced offset-processing similarly to that of the onset-related

N1 (see e.g. Hillyard et al., 1973). On the other hand, no evidence for the establishment of an offset-specific attention set was found, although this may be due to the lack of power in the present study. Further differences, however, make it difficult to relate the present findings to the attention-dependency of the onset-related N1. The present study leaves open three, possibly inter-related issues, which need further study.

First, although the attention-dependent offset P1 response seems to be a robust finding in the present study, such an ERP was not reported by most previous studies. This lack of reports may be related to the fact that in most previous studies the offset-related transient waveform was identified visually in the tone-related ERP and not in a short-minus-long difference waveform. Without an estimate of the (decay of) the preceding sustained activity, the P1 may go unnoticed. It is, however, possible that the P1 is not an independent ERP component. Rather, it may be brought about by the faster decay of the task-related sustained negativity preceding the task relevant time-point for short tones. Because the task relevant time-point is marked by a physical change for short but not for long tones, the uncertainty regarding whether the task-relevant moment has passed or not is larger for long tones. Because the sustained negativity lasts as long as the task-relevant moment is reached, the decaying slope of the sustained negativity may be less steep for long tones. In other words, the temporal uncertainty may compel participants to maintain the preparatory state for longer (than necessary) for long tones, which may result in a longer lasting sustained ERP activity, and a less steep decay in the average ERP. Such a difference in steepness would result in a positive short-minus-long difference. The results of Exp. 3, however, rule out this possibility, because P1 was elicited in the Pitch Task condition, in which a task-related sustained negativity is unlikely to be present, because the task-relevant time-point was at the onset for both tone durations. It is important to note, however, that even if no task-related sustained negativity was present at this point, the sustained negativity of the auditory ERPs was still

present for long tones (observable as a sustained positivity in the short-minus-long waveform in Fig. 9). Because this difference may have overlapped the P1-N1 time range, the possibility that the positive deflection identified as a P1 was actually brought about by the interplay of the sustained difference and the offset-related N1 cannot be dismissed. That is, despite controlling for the pre-offset ERP activity by investigating the short-minus-long difference waveform, it still cannot be unequivocally resolved whether the observed P1 waveform is an independent ERP component or it reflects short-minus-long differences in the decay of the sustained ERP activity.

Second, although the ERP latency patterns were consistent across the three experiments in the present and in the Horváth (2014b) study, the waveform was nonetheless elicited about 50 ms later than that reported by previous studies. Temporally displaced offset-related responses were also found by Kushnerenko, Fellman, Huotilainen, and Winkler (2001) in a passive experimental setting. In their study, P1 peaked at 132 ms and 142 ms following the short tone offset, respectively in the 200–minus-300 ms, and 300–minus-400 ms difference waveforms. Although this was not specifically investigated, the positivity was followed by a negativity peaking at around 250 and 270 ms following short-tone offset, respectively, in the 200–minus-300 ms, and 300–minus-400 ms group-average difference waveforms (at Cz, as observable in Figure 2, Kushnerenko et al., 2001, p. 3779). Although the ERPs may have been distorted by the application of a 1 Hz high pass filter to an ERP featuring a slow sustained response, the consistent latency pattern nonetheless suggests that these waveforms reflected some aspect of offset processing. The factors underlying the temporal displacement of these waveforms are currently not well-studied. Baltzell and Billings (2014) found that the latency of the offset-response elicited by lower intensity tones was longer, and Nishihara et al. (2014) found that the latency of the P1m (and presumably the following event-related signals) elicited by the offset of rapid click-trains (25 – 400 clicks/sec) increased from 56 to 91 ms

with decreasing click-frequency. Despite these results, it seems unlikely that the tones used in the present study would elicit markedly delayed responses compared to those used in previous studies (mainly pure tones, e.g. Pantev et al., 1996; or band-limited noise, e. g. Hari et al., 1987).

Third, some aspect of the topographical distributions of the offset-related waveforms found in the present study were not reported previously. In all three experiments, the offset-related waveforms were also clearly observable at the sides, mainly at the temporal (T7, T8), but also at the mastoid and the side frontal (F7, F8) leads, with a right dominance in Exp. 2. One speculation which could explain both the latency-related-, and the topographical peculiarity of the results is that the observed as P1-N1 waveform might receive a significant contribution from the T-complex (Wolpaw & Penry, 1975), one of the components contributing to the N1 waveform (see Näätänen & Picton, 1987). Whereas the positive Ta subcomponent (typically peaking at around 105-110 ms after tone onset at T7 and T8) would correspond to the P1, the negative Tb subcomponent (typically peaking at around 150-160 ms after tone onset at the T7 and T8) would correspond to the observed N1 waveform. Following this line of thought, one may further speculate that auditory onset- and offset-related ERPs may share the same set of sub-components, but the relative weights (amplitudes) of the sub-components differ, and for the offset-related waveform they change as a function of tone duration. At short tone durations (150-750 ms in the present study) offset-related waveforms may be dominated by the T-complex, and the prominent fronto-central N1 sub-components may become dominant only for substantially longer durations. Obviously, this issue needs further study.

Summary

In summary, by comparing ERPs elicited in a tone-focused and a not-tone-focused attention setting, the present study showed a consistent attention-dependent sound offset-related ERP pattern replicating that observed by Horváth (2014b), who compared ERPs elicited by offsets in a tone-focused and a distracted setting. Whereas the ERP featured an N2 reflecting task-related event processing, this contribution was separable from the offset-related P1 and N1 waveforms. The results highlight the possibility that offset-related ERPs may substantially overlap endogenous ERP activity in the post-offset interval irrespectively of the tone duration, and differences in the strength of tone-focused attention may contribute to ERP differences measured in such intervals.

Author notes

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Tables

	ERP	150 vs. 750 ms	300 vs. 750 ms	450 vs. 750 ms
Exp. 1.	P1	$t = 3.981, p = .001^*$	$t = 3.028, p = .006^*$	$t = 3.313, p = .004^*$
($df = 10$)	N1	$t = 2.252, p = .024^*$	$t = 3.972, p = .001^*$	$t = 0.953, p = .181$
Exp. 2.	P1	$t = 3.530, p = .003^*$	$t = 4.497, p = .001^*$	$t = 3.828, p = .002^*$
($df = 9$)	N1	$t = 3.041, p = .007^*$	$t = 2.419, p = .019^*$	$t = 2.437, p = .019^*$

Table 1. Results of the one-tailed Student's t tests comparing ERP amplitudes to zero in each condition of Experiment 1 and 2 in the P1 and N1 latency-range reported by Horváth (2014b). Statistically significant differences are marked with asterisks.

ERP	Group-average ERP peak latency (ms) in relation to tone-offset						
	Horváth, 2014	Experiment 1			Experiment 2		
	150 vs. 600 ms	150 vs. 750 ms	300 vs. 750 ms	450 vs. 750 ms	150 vs. 750 ms	300 vs. 750 ms	450 vs. 750 ms
P1	98	112	102	100	98	96	98
N1	160	172	176	182	150	156	152

Table 2. P1 and N1 peak latencies reported by Horváth (2014b), and measured in the group-average short-minus-long difference waveforms in Experiment 1 and 2.

Figures

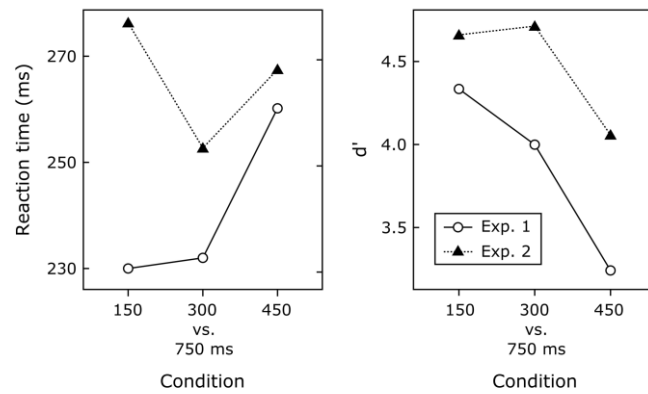


Figure 1. Group-average reaction time (left) and d' sensitivity scores (right) in the three conditions of Experiment 1 and 2. In Experiment 1, the task was to respond to the short tones and withhold response to the long tones (Short-Go); in Experiment 2, the tone-action correspondence was reversed (Long-Go).

Experiment 1 - Active - short go

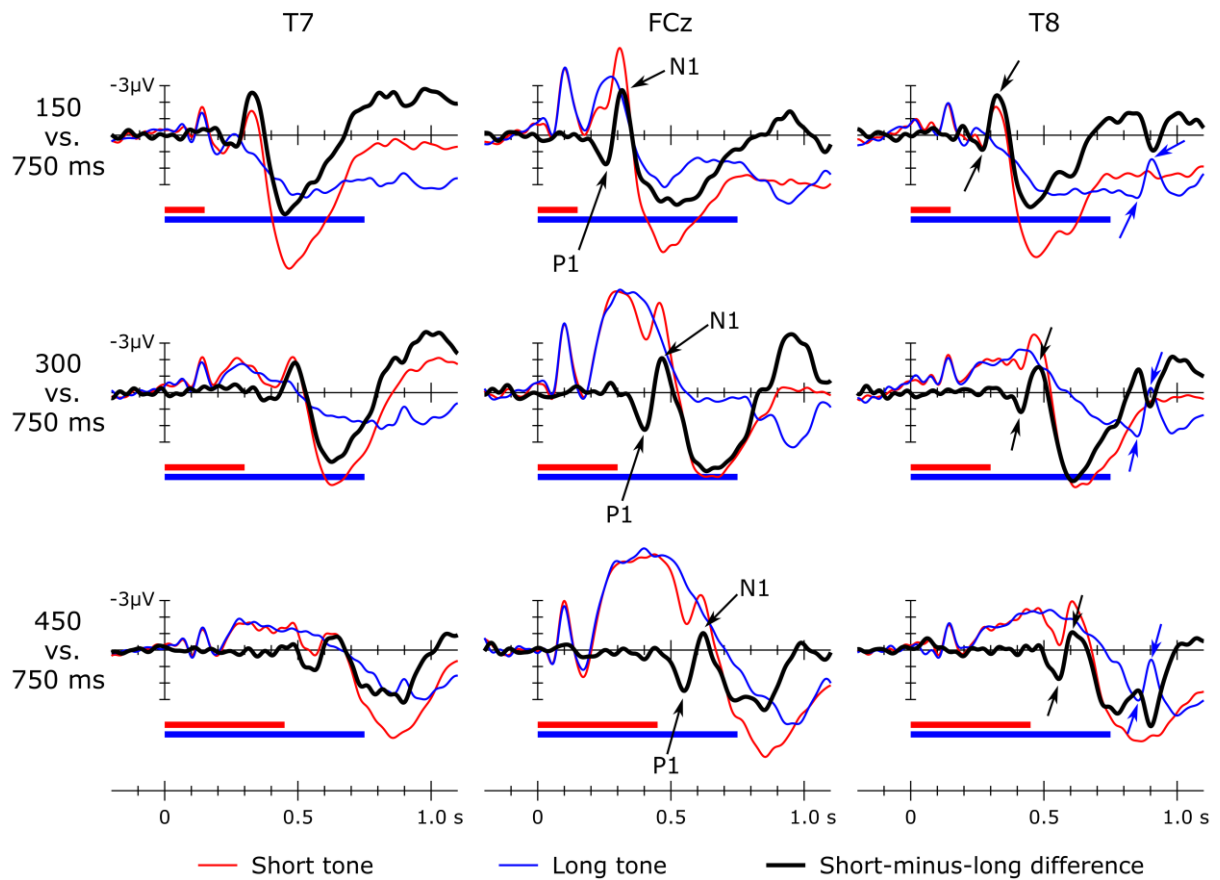


Figure 2. Group-average ERPs elicited at the T7 (left), FCz (middle), and T8 (right) electrodes for the short (red curves) and long tones (blue curves) in the three conditions (each presented in a single row) of the active part of Experiment 1 (short go), as well as corresponding short-minus-long difference waveforms (thick black curves). Tone durations are represented as red (short) and long (blue) bars under the horizontal axes. Black arrows indicate the offset-related P1 and N1 waveforms at the FCz and T8 electrodes. Blue arrows indicate the long tone offset-related waveforms at T8.

Experiment 2 - Active - long go

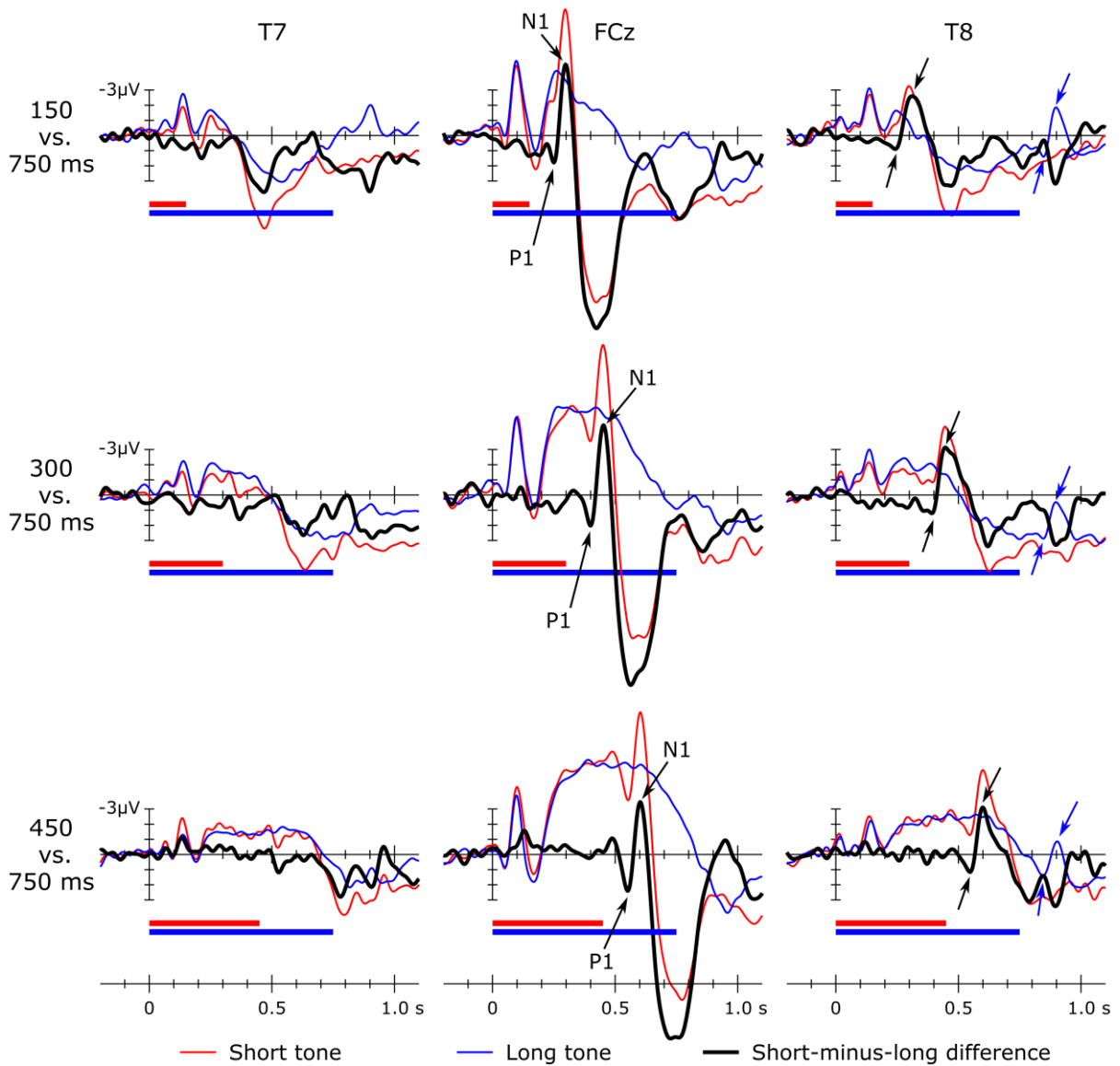


Figure 3. Group-average ERPs elicited at the T7 (left), FCz (middle), and T8 (right) electrodes for the short (red curves) and long tones (blue curves) in the three conditions (each presented in a single row) of Experiment 2 (long go), as well as corresponding short-minus-long difference waveforms (thick black curves). Tone durations are represented as red (short) and long (blue) bars under the horizontal axes. Black arrows indicate the offset-related P1 and N1 waveforms at the FCz and T8 electrodes. Blue arrows indicate the long tone offset-related waveforms at T8.

Experiment 1 - Passive

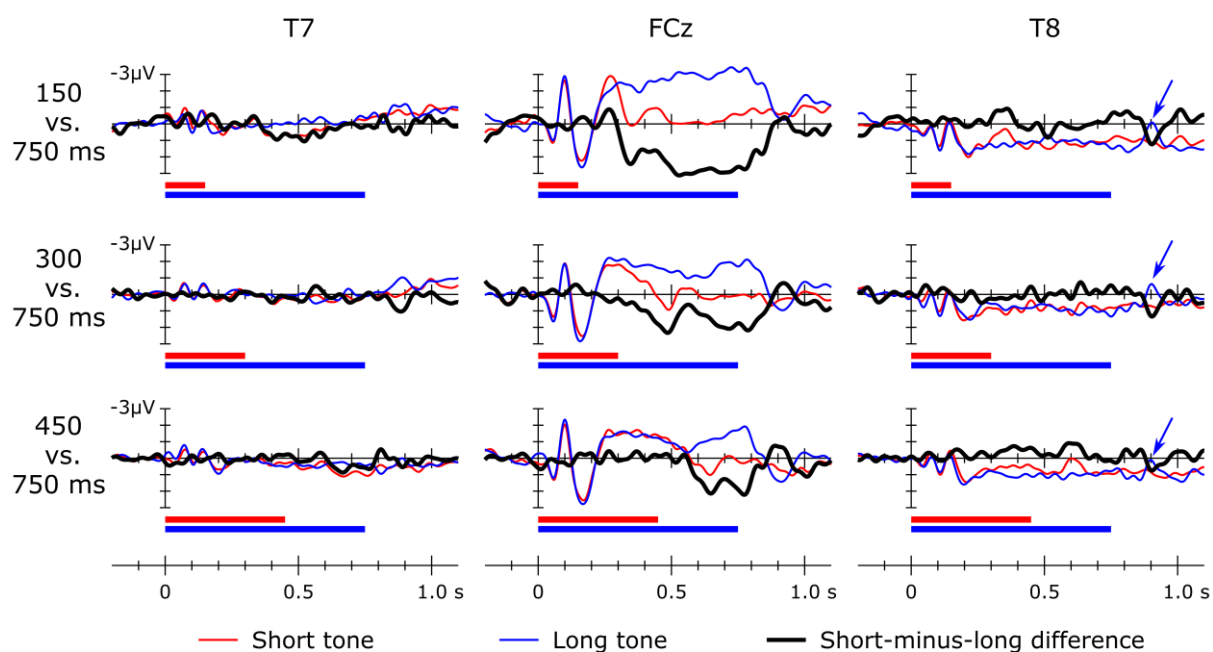


Figure 4. Group-average ERPs elicited at the T7 (left), FCz (middle), and T8 (right) electrodes for the short (red curves) and long tones (blue curves) in the three conditions (each presented in a single row) of the passive part of Experiment 1, as well as corresponding short-minus-long difference waveforms (thick black curves). Tone durations are represented as red (short) and long (blue) bars under the horizontal axes. Blue arrows indicate the long tone offset-related waveform at T8.

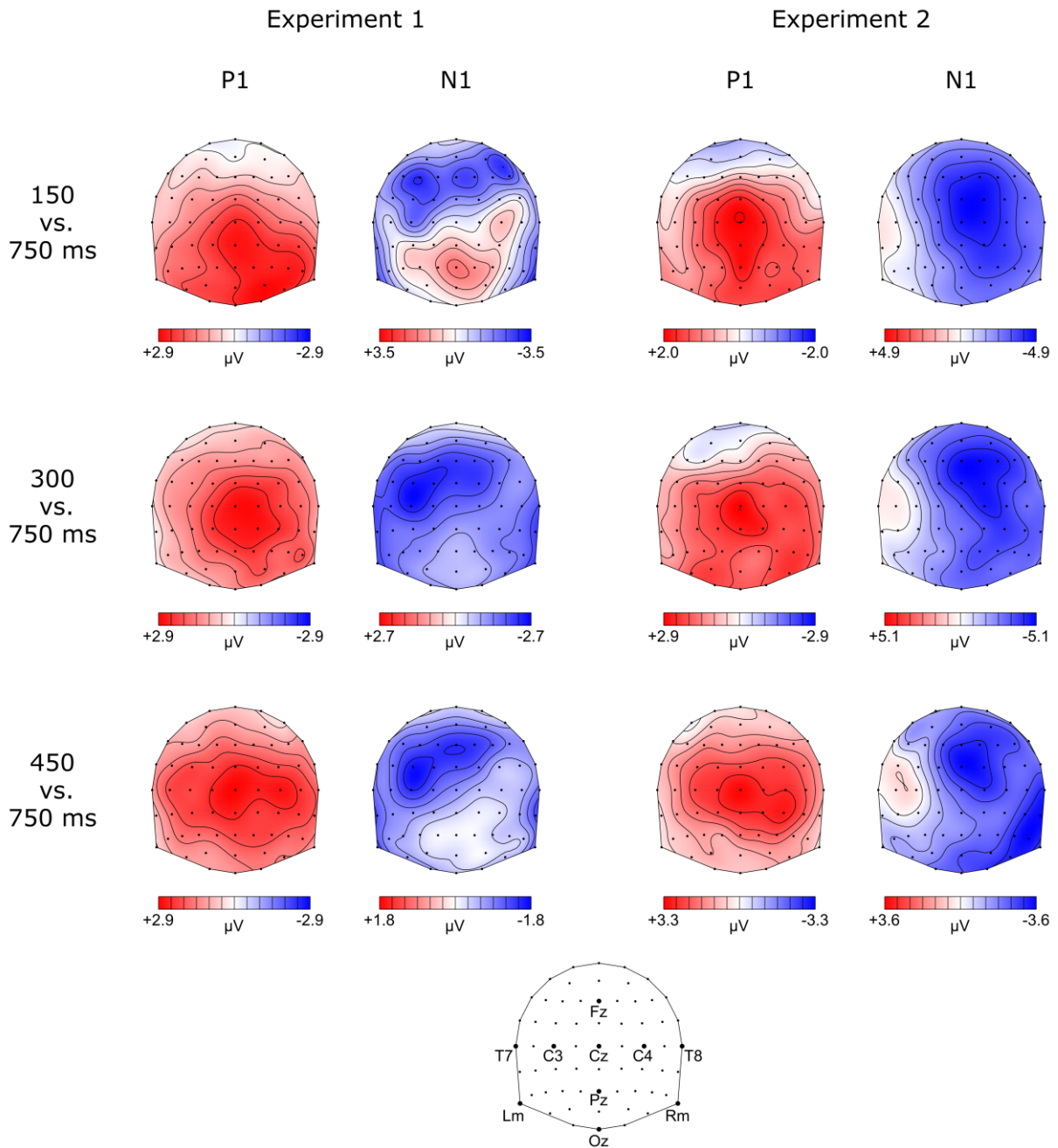


Figure 5. Topographical distributions of the group-average offset-related P1 and N1 identified in the short-minus-long difference waveforms (at the peak latencies) in the active part of Experiment 1 (short go – 1st and 2nd columns) and Experiment 2 (long go – 3rd and 4th columns). Each of the three conditions are presented in a single row. Signal ranges differ between conditions to emphasize differences or similarities in the shape of the distributions.

Experiment 1 - short-minus-long difference waveforms

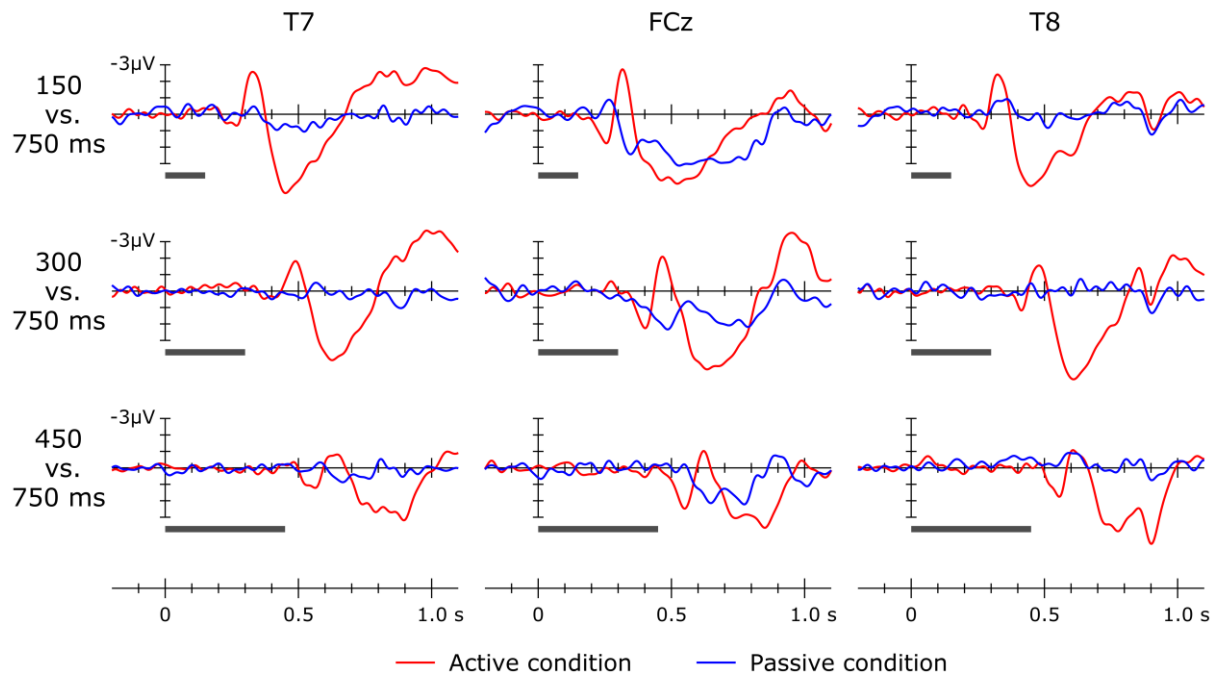


Figure 6. Group-average short-minus-long ERP difference waveforms elicited at the T7 (left), FCz (middle), and T8 (right) electrodes in the active (red curves) and passive (blue curves) parts of Experiment 1 in the three conditions (each presented in a single row). Short tone durations in the given conditions are represented as gray bars under the horizontal axes.

Experiment 1 - ERPs to short tones with above or below median reaction times

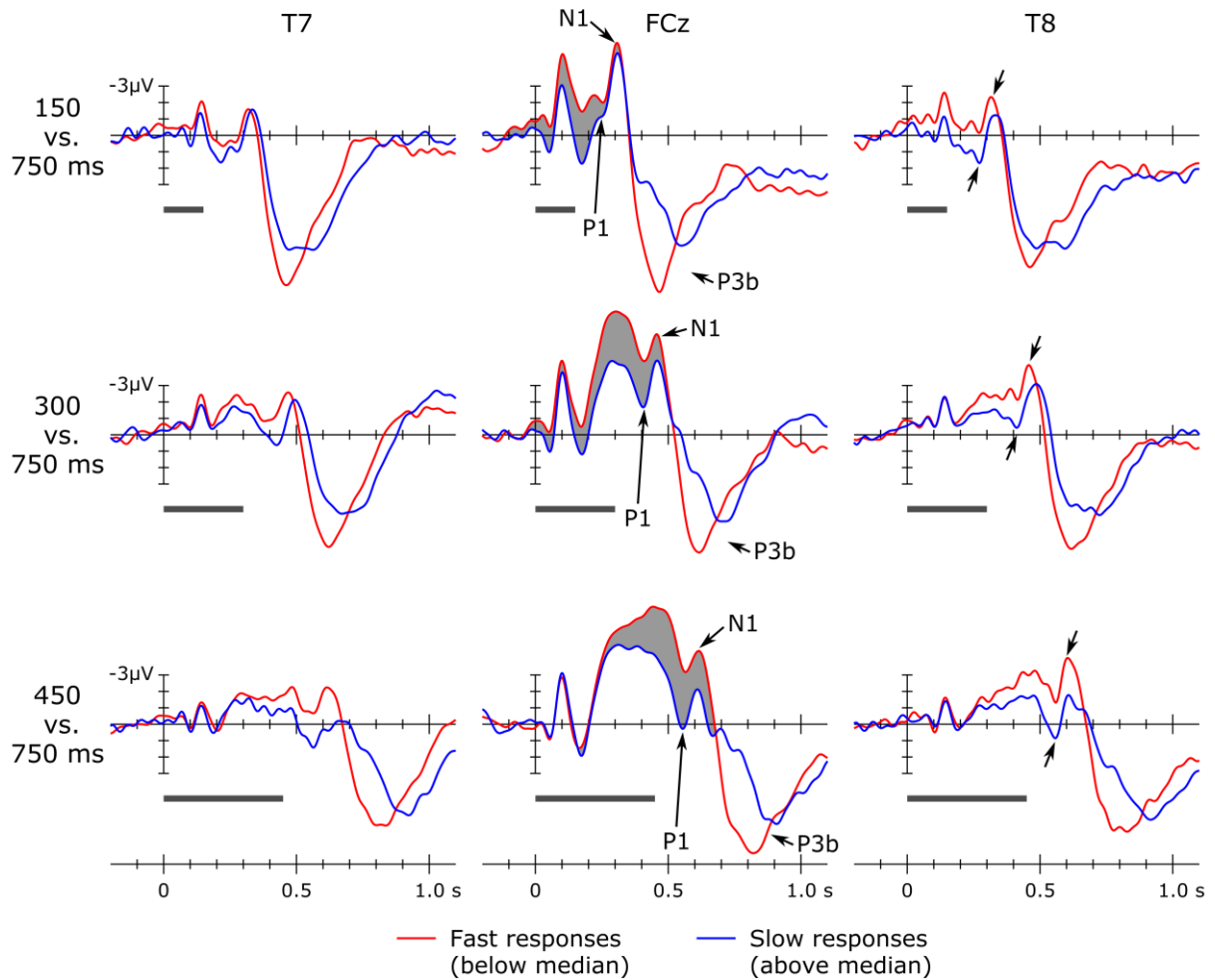


Figure 7. Group-average ERPs elicited by short tones in trials with below-median (red curves) and above-median reaction times (blue curves) at the T7 (left), FCz (middle), and T8 (right) electrodes, in the three conditions (each presented in a single row) of the active part of Experiment 1. Short tone durations in the given conditions are represented as gray bars under the horizontal axes. Offset-related P1 and N1, and also P3b are indicated by arrows at FCz and T8. The gray shading between the two curves at FCz highlight a sustained difference in ERP activity preceding the offset-related waveforms.

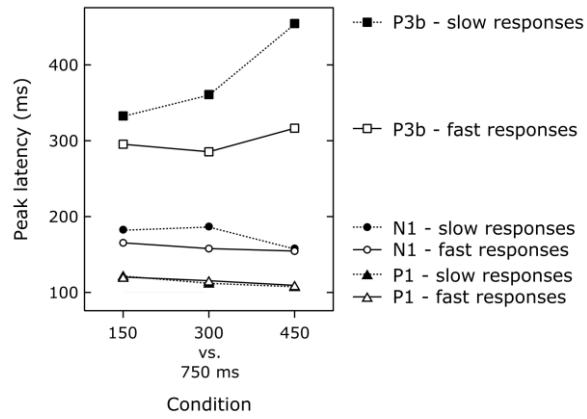


Figure 8. Group-mean jackknife peak latencies for the offset-related P1 and N1, and also for the P3b elicited by short tones in trials with fast (below-median) and slow (above-median) reaction times in the three conditions of Experiment 1.

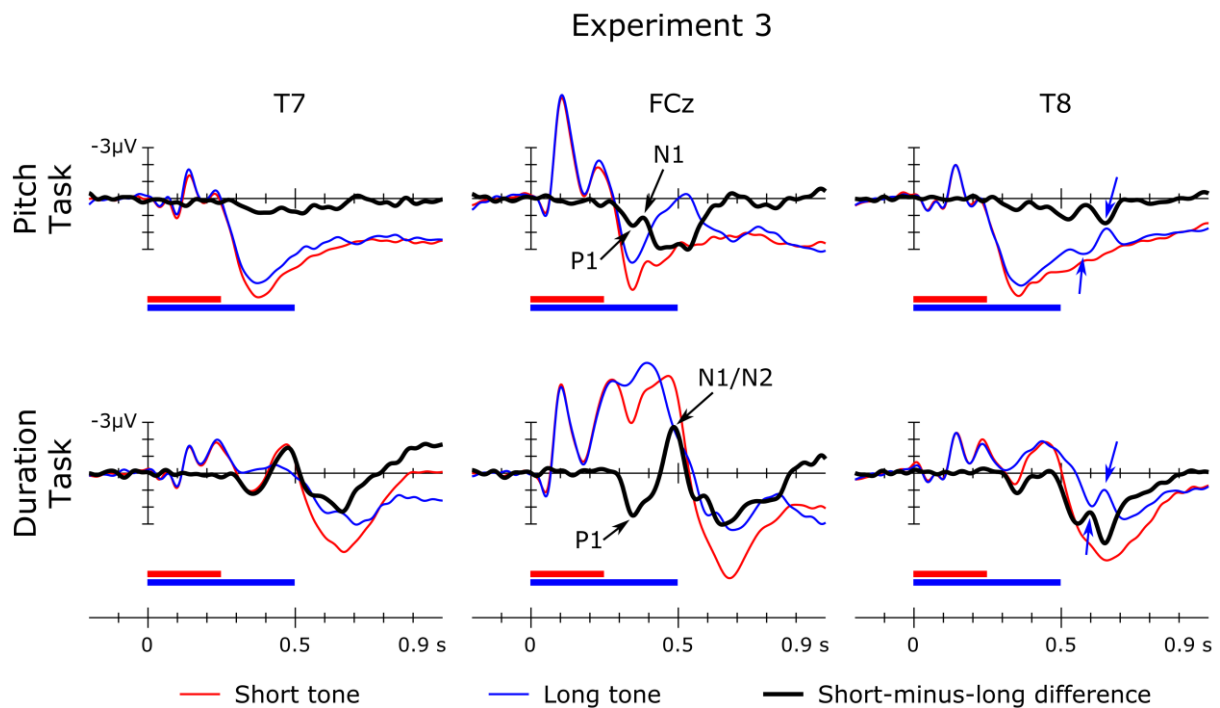


Figure 9. Group-average ERPs elicited at the T7 (left), FCz (middle), and T8 (right) electrodes for the short (red curves) and long tones (blue curves) in the two tasks (each presented in a single row) of Experiment 3, as well as corresponding short-minus-long difference waveforms (thick black curves). Tone durations are represented as red (short) and long (blue) bars under the horizontal axes. Black arrows indicate the offset-related P1 and N1 in the Pitch Task condition, and the P1 and the overlapping N1/N2 waveforms in the Duration Task condition at the FCz electrode. Blue arrows indicate the long tone offset-related P1 and N1 waveforms at T8.

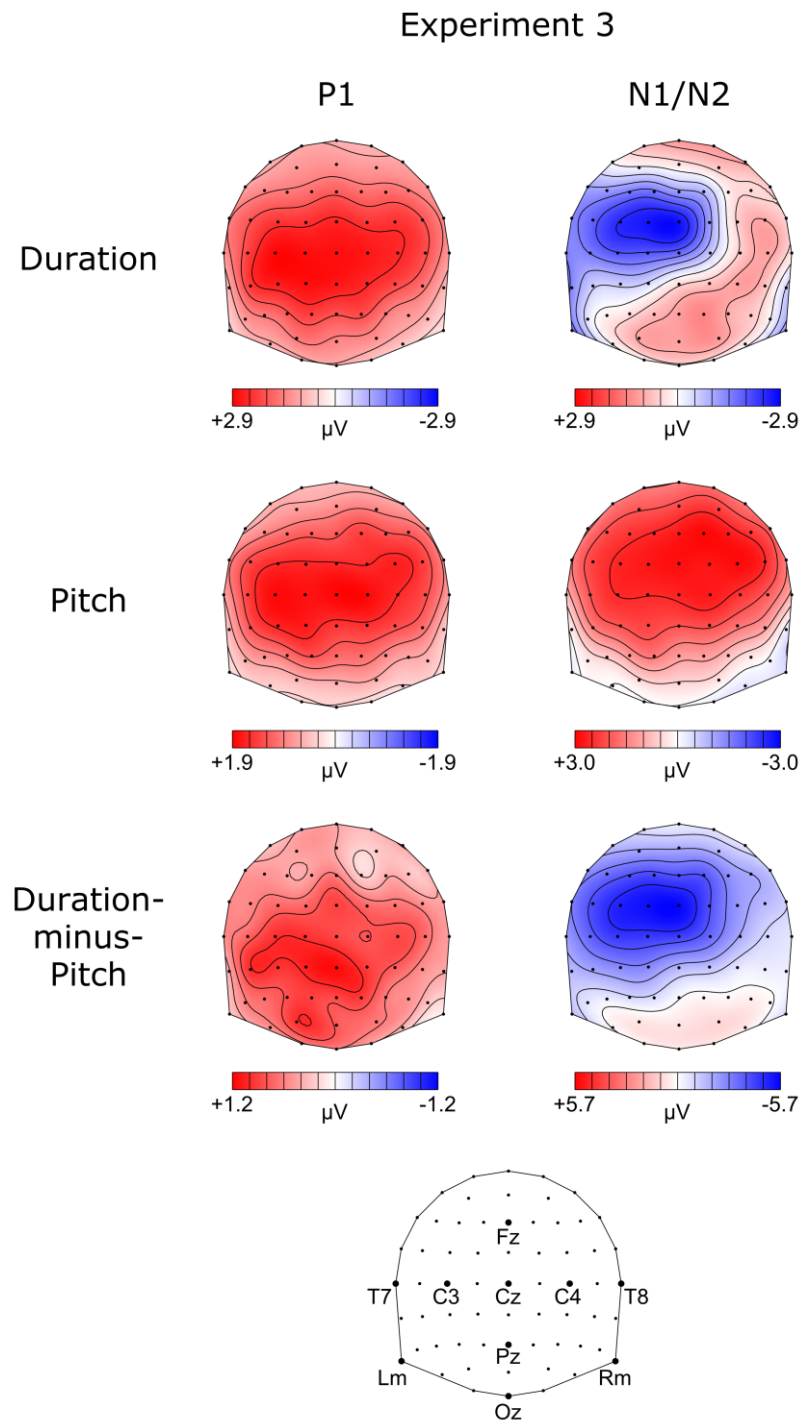


Figure 10. Topographical distributions of the group-average short-minus-long difference waveforms at the peak latency of the P1 (left column) and N1/N2 (right column) measured in the Duration Task (top row) and Pitch Task condition (middle row) of Experiment 3. The third row shows the topographical distribution of the duration-minus-pitch difference signal at the same latency (i.e. the difference of the short-minus-long differences). Signal ranges differ between conditions to emphasize differences or similarities in the shape of the distributions.

Experiment 3 - Duration Task
ERPs to short tones with fast, mid-speed, and slow responses

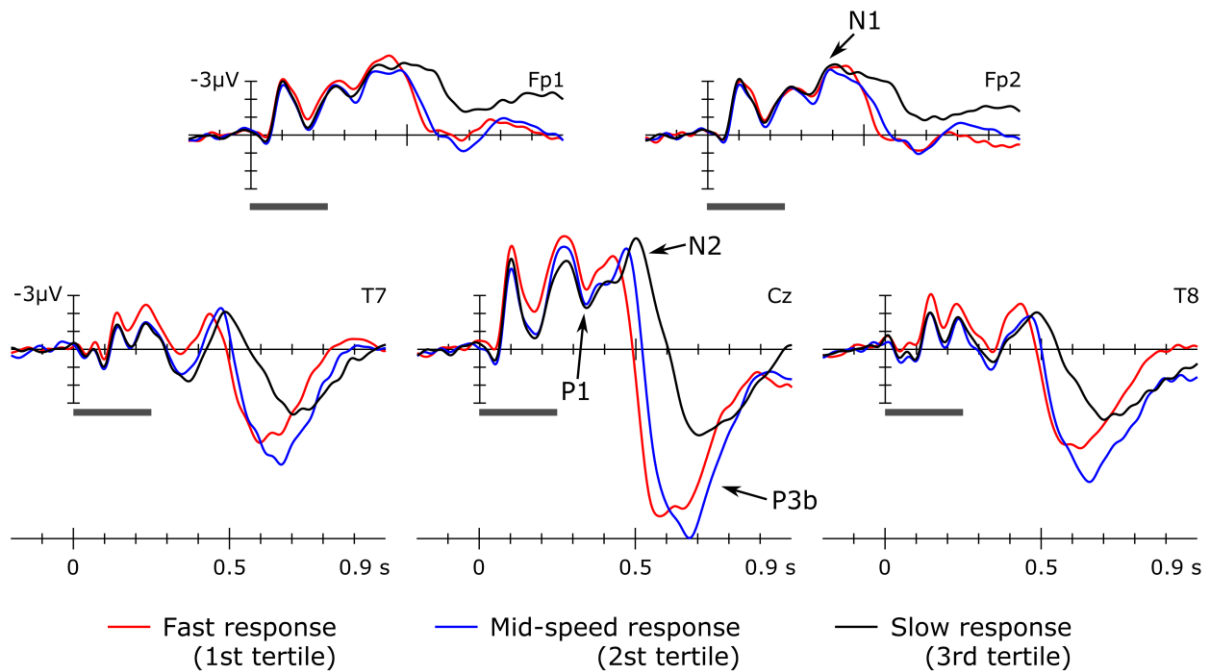


Figure 11. Group-average ERPs elicited by short tones in trials with reaction times in the first (fast responses - red curves), second (mid-speed responses – blue curves) and third tertile (slow responses – black curves) at the Fp1, Fp2, T7, Cz, and T8 electrodes in the Duration task of Experiment 3. The peaks of the offset-related P1, N1, N2 and P3b are indicated by arrows. Short tone durations are represented as gray bars under the horizontal axes.

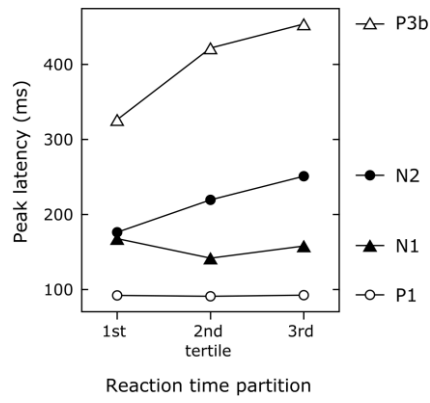


Figure 12. Group-mean jackknife peak latencies for the offset-related P1, N1, N2, and P3b, elicited by short tones in trials with reaction times in the first, second, and third tertiles (corresponding to fast, mid-speed, and slow responses, respectively) in Experiment 3.