RESEARCH REPORT

When long appears short: Effects of auditory distraction on event-related potential correlates of time perception

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Abstract
Attentional models of time perception assume that the perceived duration of a stimulus depends on the extent to which attentional resources are allocated to its temporal information. Here, we studied the effects of auditory distraction on time perception, using a combined attentional-distraction duration-discrimination paradigm. Participants were confronted with a random sequence of long and short tone stimuli, most of which having a uniform (standard) pitch and only a few a different (deviant) pitch. As observed in previous studies, pitch-deviant tones impaired the discrimination of tone duration and triggered a sequence of event-related potentials (ERPs) reflecting a cycle of deviance detection, involuntary attentional distraction and reorientation (MMN, P3a, RON). Contrasting ERPs of short and long tone durations revealed that long tones elicited a more pronounced fronto-central contingent negative variation (CNV) in the time interval after the expected offset of the short tone as well as a more prominent centro-parietal late positive complex (LPC). Relative to standard-pitch tones, deviant-pitch tones especially impaired the correct discrimination of long tones, which was associated with a reduction of the CNV and LPC. These results are interpreted within the theoretical framework of resource-based models of time perception, in which involuntary distraction due to a deviant event led to a withdrawal of attentional resources from the processing of time information.

KEYWORDS
attentional resources, auditory distraction, duration discrimination, event-related potentials, time perception

List of Abbreviations: ANOVA, analysis of variance; CNV, contingent negative variation; EEG, electroencephalography; ERP, event-related potential; IC, independent component; ICA, independent component analysis; LPC, late positive complex; MMN, mismatch negativity; RON, reorientation negativity; RT, response time; SET, scalar expectancy theory.

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1 | INTRODUCTION

The perception of time depends on numerous factors: Waiting for a delayed train on a windy platform can seem like a very long time, while the same period of time seems to ‘fly when we are having fun’ (Block & Gruber, 2014). One possible reason for this effect is that we are probably attending more to time in the former case (e.g., Cahoon & Edmonds, 1980). In a comprehensive review of factors affecting time perception, Matthews and Meck (2016) provided a systematic taxonomy of how external stimulation and internal processing of temporal information affect the representation of time. In addition to the characteristics of the incoming sensory information, internal moderating factors are detailed, such as the extent to which mental resources are allocated to the processing and whether representations of the temporal information are present. From empirical studies on prospective timing (i.e., in which the participants know in advance that a temporal judgment will be required) the authors conclude that generally ‘attending to a stimulus improves its subjective vividness and facilitates information processing, with a corresponding expansion in apparent duration’ (Matthews & Meck, 2016, p. 880). In other words, and in line with a resource-allocation approach of time processing (for review, Block & Gruber, 2014), it is assumed that allocating more attentional resources toward a temporal judgment task should subjectively lengthen the perceived time.

On a theoretical level, this interaction of time perception and attention can be modelled within the framework of information-processing models of timing (for review, Brown, 2008; Wittmann, 2013). Based on the scalar expectancy theory (SET; Gibbon et al., 1984), the attentional-gate model of time perception (Zakay & Block, 1997) assumes several cognitive instances to play specific roles in time perception: In short, it is postulated that a pacemaker generates pulses that are passing an attentional gate into an accumulator, whose current value is continuously compared with a stored value in a reference memory value by a comparator. In an experimental task, in which the duration of a stimulus has to be evaluated relative to a reference duration, the comparator finally decides whether the current duration has to be categorized as ‘short’ or ‘long’. Critically, allocation of attention to a to-be-timed stimulus should close the attentional gate, so that pulses can reliably be gathered in the accumulator. However, when attention is not intentionally focused on time perception, it is assumed that the gate is not completely closed so that pulses are missed and not gathered in the accumulator, resulting in the perception of a shorter time interval (Gibbon et al., 1984, 1997; for an introduction into this model of time perception, see Brown, 2008).

There is some empirical evidence supporting this assumption, indicating that perceived stimulus duration indeed appears to be shorter when attention is directed onto another, not task-relevant event or task (e.g., Brown, 1997; Macar et al., 1994). For example, using an auditory dual-task paradigm, in which either tone duration or tone pitch were task relevant, Liu et al. (2013) showed that a tone was perceived as shorter, the more the attention was directed onto tone pitch, that is, away from tone duration. Focusing attention on the relevant stimulus feature thus appears essential for time processing, as well as the suppression of competing, task-irrelevant stimuli. However, beside this kind of endogenous orienting of attention to time via a ‘top-down’ route, attentional processes triggered by external stimuli in a more ‘bottom-up’ fashion also seem to be relevant (Corbetta & Shulman, 2002; Katsuki & Constantinidis, 2014). In other words, not only the voluntary focusing of attention on stimulus characteristics other than stimulus duration can influence time perception, but that also the involuntary distraction of attention away from duration should negatively influence the perception of time.

Empirical evidence for such a relationship stems from an experimental paradigm that was not originally designed to study time perception but the effect of a distraction on the processing of an ongoing task. According to a three-stage model of distraction (e.g., Schröger & Wolff, 1998; Escera et al., 1998; for review, Wetzel & Schröger, 2014), at the first stage, an automatic deviance (or novelty) detection against the background of an ongoing task occurs, signalling a (potentially important) event in the environment. In the second stage of the model, this leads to an involuntary shift of attention to the event, and thus to a deduction of attentional resources away from the task-relevant information, before in the third stage a voluntary, resource consuming reorienting of attention to the task at hand occurs. The deviance–distraction–reorientation cycle has been experimentally operationalized in a paradigm, in which participants are presented with stimuli containing two different features, one task relevant and one task irrelevant (Schröger & Wolff, 1998). In the well-established auditory version of this paradigm, a sequence of randomized short and long tones is presented, and the participants continuously decide whether the current tone is long or short, thus performing a speeded two-alternative forced-choice duration-discrimination task. Importantly, while most of these tones has a uniform pitch (the standards), a few tones differ in pitch (the deviants), and the occurrence of these pitch-deviant tones typically causes an impairment of performance in the primary task, indicated by increased response times (RTs) and more errors.
in the evaluation of the tone durations (Wetzel & Schröger, 2014).

One important aspect that has received little attention so far lies in the nature of the task itself, which actually combines auditory distraction and time perception paradigms. To perform the task quickly and correctly, in each single trial, the participant has to compare the duration of the ongoing tone with an internal representation of the short-tone duration. If the end of the current tone coincides with the (internally stored) duration of the short tone, the decision is ‘short’; as soon as the current tone exceeds the (internally stored) duration of the short one, the decision is ‘long’. The critical moment has thus arrived when the duration of the current tone has reached the internal reference duration. Variations in both the perceived current tone duration and the stored reference duration can lead to errors, namely, if the current short tone is considered too long (and erroneously answered ‘long’) or if the current long tone is considered too short (and answered ‘short’). Regarding the above-introduced resource model of time processing, it can be hypothesized that a withdrawal of attentional resources from the processing of temporal information due to distraction should make a current stimulus appear shorter. Thus, the occurrence of a deviant-pitch tone among standard tones should mainly affect the correct discrimination of the long tones, being perceived as shorter than they actually are, and less the short tones. Indeed, this observation has been reported in a few studies (e.g., Horváth, 2014) but not directly related to time perception.

The aim of the present analysis was to verify predictions from the combined attentional-distraction duration-discrimination paradigm and to explore the underlying neurocognitive mechanisms. We analysed data from the Dortmund Vital Study, a long-term study on the development of cognitive functions over age (Gajewski et al., 2021). The Dortmund Vital Study includes—among other electroencephalography (EEG)-based tasks—a task on auditory time perception and distraction, which was investigated here in a subgroup of younger participants. In particular, ERP correlates of auditory distraction and time estimation were derived. For auditory distraction, we focused on a prominent sequence of event-related potentials (ERPs) which have been observed in a large number of studies and are generally assumed to reflect the essential stages of the above-described cycle of deviance detection, distraction and reorientation. First, the mismatch negativity (MMN), a negativity over fronto-central areas at about 100 ms after the deviant stimulus, which is regarded as the electro-physiological correlate of preattentive deviance detection (Nätänen et al., 2005; for review, Paavilainen, 2013). Second, the fronto-central P3a at about 300 ms, assumed to be a correlate of an involuntary attention-switching mechanism (Escera et al., 2000; Friedman et al., 2001). Finally, a late fronto-central negativity with latencies of about 400–600 ms, the reorientation negativity (RON), which is assumed to reflect the reallocation of attentional resources to the relevant task after distraction by the deviating characteristics (e.g., Berti, 2008; Schröger et al., 2000; Schröger & Wolff, 1998).

For time perception, the focus was on a slow fronto-central negativity that has often been observed in time perception experiments (for review, Ng & Penney, 2014; Wittmann, 2013). In auditory duration-discrimination paradigms, this negative wave typically starts with the tone onset and reaches a plateau after the expected offset of the shorter tone (e.g., Macar & Vidal, 2003; Pfeuty et al., 2005). It resembles the contingent negative variation (CNV; Walter et al., 1964), a slow negative fronto-central brain potential associated with expectation and anticipation of an upcoming event or response (Brunia & van Boxtel, 2001). It is still under debate in how far this negative wave (which is termed here as CNV for the sake of simplicity) can be regarded as an electrophysiological correlate of time perception (Kononowicz & Van Rijn, 2011; Praamstra, 2010; Van Rijn et al., 2011). However, attention-based modulations of the CNV have frequently been observed (e.g., Gontier et al., 2013; Liu et al., 2013), less in form of an overall reduction in amplitude (as initially believed), but in form of a reduced slope and increased onset latency (for review, Ng & Penney, 2014). As a second correlate of time perception, a posterior late positive complex (LPC) was analysed that typically emerges after the offset of a probe stimulus in duration-discrimination tasks (e.g., Bannier et al., 2019; for review, Ng & Penney, 2014). The LPC is associated with stimulus evaluation and context updating (like the late P3b, to which there are functional and structural similarities, e.g., Polich, 2007), with stimulus discrimination and categorization (e.g., Mecklinger & Ullsperger, 1993) as well as with decision processes involved in temporal judgements (Paul et al., 2011).

In contrast to most previous studies, the behavioural and ERP analyses were performed separately for long and short tones, and cluster-based permutation tests were applied to gain a more holistic picture of the effect of auditory distraction on the processes of time perception. It was expected that the occurrence of a deviant tone induces distraction indicated by the deviance-related MMN, P3a and RON components. As a consequence, this should reduce attention to the task-relevant stimulus feature, resulting in a reduced CNV and LPC differences between short and long tones and finally a deviance-induced error in duration discrimination especially of the long tones.
2 | METHODS

2.1 | Participants

All participants took part in context of the Dortmund Vital Study (Gajewski et al., 2021), an ongoing large-sample cohort study on the development of cognitive functions over an age range from 20 to 70 years. Because the focus of the current study was on the general mechanisms of the interplay of auditory distraction and time perception, we only considered young participants aged between 20 and 40 years \((N = 200)\). We thereby aimed to reduce potential effects of age-related changes in sensory and attentional functions that are usually found when younger and older people are compared (e.g., Getzmann et al., 2015). The development of auditory distraction from youth to old age is topic of another study not reported here. The participants were recruited from local companies, public institutions and through advertisements in newspapers and public media. The participants reported to be healthy and free of medication during the experimental sessions. All participants passed a pure-tone standard audiometry \((0.125–8 \text{ kHz}; \text{Oscilla USB100, Inmedico, Lystrup, Denmark})\) indicating no or only slight hearing impairments (hearing level <40 dB). All participants gave their written informed consent before any study protocol was commenced. The study conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the local Ethical Committee of the Leibniz Research Centre for Working Environment and Human Factors, Dortmund, Germany.

2.2 | Stimuli, task and procedure

The auditory stimuli were generated digitally (CoolEdit 2000, Syntrillium Software Co., Phoenix, AZ, USA), stored offline and presented binaurally using stereo headphones (AKG, K271 Studio) at an intensity of 70 dB(A). The stimuli consisted of pure sine tones of frequencies of either 500, 1000 or 2000 Hz. Stimuli were short (200 ms) and long (400 ms) tones, including 5 ms rise and fall times, presented with equal probability. Eighty per cent of these tones were frequent standard stimuli (1000 Hz), and 20% were rare deviant stimuli (either 500 or 2000 Hz, each 10%). Two different deviant tones—one with a higher and one with a lower frequency than the standard tone—were chosen to reduce possible confounding influences of physical stimulus properties on attentional processes. In the analysis, data were then averaged across both deviant tones to compensate for possible differences between a frequency increase and a frequency decrease, relative to the standard frequency. The sequence of long and short tones and standard and deviant stimuli were presented in a pseudorandomized order (Figure 1), with the number of standard stimulus trials between the deviant stimuli ranging from 0 to 13 (mean 4.05, SD 3.73). The stimulus onset asynchrony was 1400 ms.

The experiment took place in a quiet, electrically shielded room, where the participants were seated on a comfortable chair. In a two-alternative forced-choice duration-discrimination procedure, that has also been used in several previous studies (e.g., Getzmann et al., 2013), the participants had to decide as fast and as accurately as possible whether a tone was short or long, while ignoring the tone pitch. While empty intervals are usually considered to be more suitable for the investigation of time perception (for potentially confounding effects of non-temporal cues on duration discrimination, see not only Rammsayer & Lima, 1991 but also Rammsayer, 2010), filled intervals were used here. The reason was that the stimuli should contain both the task-relevant feature (i.e., duration) and the task-irrelevant features (i.e., pitch), which could not be easily realized with an empty interval. The participants had to press one out of two response buttons with their left and right index fingers. The duration-hand assignment was counterbalanced between the participants, so that half of the participants pressed the left button with their left index fingers for the short tones and the right button with their right index fingers for the long tones (and vice versa).

![Figure 1: Schematic representation of the experimental paradigm. A sequence of short and long tones was presented, which had either a standard frequency (sta; 1000 Hz) or a deviant frequency (dev; 500 or 2000 Hz). Participants rated the duration of the sound stimuli](image-url)
versa). They had to keep their eyes open and to focus on a visual fixation point presented on a computer screen placed in front of them. No feedback was given at any time during the experiment. The experiment started with a few training trials to familiarize the participants with the task. Thereafter, two test blocks consisting of 120 trials each (48 short and 48 long standard tones and 12 short and 12 long deviant tones) were completed. RTs were measured by a high-resolution timer interface connected with the external response buttons.

2.3 EEG recording and data preprocessing

The continuous EEG was sampled using 30 electrodes mounted on an elastic cap according to the International 10–20 system and a BioSemi amplifier (Active Two; Biosemi, Amsterdam, Netherlands; amplifier band-pass 0.01–140 Hz; sampling rate 2048 Hz). Electrode impedance was kept below 10 kΩ. For offline data preprocessing, the open-source toolbox EEGLAB (v14.1.2b, Delorme & Makeig, 2004) for Matlab (R2018a) was employed. The raw data were resampled at 1024 Hz, re-referenced to the average of all electrodes, digitally band-pass filtered (cut-off frequencies 0.1 and 40 Hz; IIR Butterworth filter; filter order 6) and segmented into 2000-ms stimulus-locked epochs covering the period from –500 to 1500 ms relative to stimulus onset, with a 200-ms prestimulus time window serving as baseline. Artefacts channels were rejected using the EEGLAB pop_rejchan command and probability and kurtosis criteria (mean number of rejected channels per subject 0.59, SD 0.93). For independent component analysis (ICA), a second dataset was generated, and data were band-pass filtered (cut-off frequencies 1 and 30 Hz) and down-sampled to 256 Hz. Artefacted epochs were detected in this second dataset using the pop_autorej command and then removed from both datasets (mean number of removed epochs per subject 27.91, SD 10.39). After calculating the ICA, independent components (ICs) representing artefacts were identified using ICLabel (Pion-Tonachini et al., 2019). The ICs were then copied to the first dataset, and the ICs identified as artefactual were removed (mean number of removed ICs per subject 12.5, SD 3.98). Epochs in which the participants responded correctly in a time range from 100 to 1100 ms (relative to the offset of the short tone) were averaged, separately for each participant, for standard and deviant stimuli and for short and long tones.

2.4 Behavioural data analysis

The time between stimulus onset and the press of a response button was determined. Given that the decision whether the tone was short (200 ms) or long (400 ms) could be made not before 200 ms after the tone onset, raw RTs were corrected for this time lag by subtracting 200 ms from the measured individual values. Rates of correct and false responses (i.e., the number of correct and false responses divided by the number of trials with short standard [96], long standard [96], short deviant [24] and long deviant [24] stimuli) as well as mean RTs were determined, separately for standard and deviant stimuli and for short and long tones. Individual RTs of less than 100 ms and more than 1100 ms, as well as error trials, were excluded from RT analysis. Participants differing in standard trials more than three standard deviations in error rates (n = 4) from the whole sample of participants were excluded from further analysis, leaving 196 participants (128 female; age range 20–40 years, mean 29.6 years) for analysis. Rates of correct responses and mean RTs were subjected to two-way analyses of variance (ANOVArs) with within-subject factors Duration (short vs. long tones) and Deviance (standard vs. deviant stimuli). In order to explicitly test whether participants were more likely to confuse long or short tones (i.e., incorrectly rate long sounds as short or short tones as long) as a function of deviance, the rates of commission errors were also analysed. These are the rates of correct responses minus the rates of missing responses, determined for each participant, and separately for standard and deviant stimuli, and for short and long tones. Effect sizes were computed to provide a more accurate interpretation of the practical significance of the findings, using the adjusted partial eta-squared (η²p) coefficient (Mordkoff, 2019). Post hoc t tests were corrected for multiple testing using false discovery rate correction (Benjamini & Hochberg, 1995) and only corrected p values were reported.

2.5 EEG data analysis

For each participant, ERPs were calculated for each electrode and experimental condition, ranging from –200 to 1000 ms relative to the onset of the auditory stimulus. Trials with false responses were not analysed, because rates of false responses were overall very low (see results). For the ERP analysis, the data were re-referenced to the average of the mastoid channels (M1 and M2). Statistical testing of the data was performed using cluster-based permutation tests (Maris & Oostenveld, 2007) on
channel × time data using fieldtrip (Oostenveld et al., 2011). In cluster-based permutation tests, \( t \) statistics are computed for each data point. A clustering algorithm then identifies clusters of adjacent data points associated with a \( t \) value corresponding to \( p < .01 \) and the sum of all \( t \) values within each cluster constitutes the cluster’s test statistic. Type I error is controlled for by comparing the observed test statistics with a \( H_0 \)-distribution of test statistics. This distribution is obtained from a randomization procedure with 1000 iterations, in which the mapping of data and experimental condition gets permuted. Clusters with a probability of \( p < .05 \) of belonging to this \( H_0 \)-distribution were regarded as significant. Cluster-based permutation tests were calculated for the main effects of the factors Duration and Deviance, as well as for the interaction. To perform the cluster-based permutation test for the interaction, the differences between the long and short target tone condition in standard and deviant-pitch conditions were contrasted. Effect size estimates are reported according to Mordkoff (2019).

3 | RESULTS

3.1 | Effects of tone duration and stimulus deviance on performance

RTs were higher with long than with short tones (474 vs. 399 ms; main effect Duration: \( F_{1,195} = 556.10; \ p < .001; \ \eta^2_p = .74 \)) and with deviant relative to standard stimuli (453 vs. 420 ms; main effect Deviance: \( F_{1,195} = 280.73; \ p < .001; \ \eta^2_p = .59 \)). There was also an interaction of Duration and Deviance (\( F_{1,195} = 15.42; \ p < .001; \ \eta^2_p = .07 \)), with RTs being highest with long and deviant tones (Figure 2a). However, post hoc \( t \) tests indicated deviance-related increases in RTs for both short (+25 ms; \( t_{195} = 9.41; \ p < .001 \)) and long (+35 ms; \( t_{195} = 13.30; \ p < .001 \)) tones.

Rates of correct responses were lower with long than short tones (88.9% vs. 93.5%; main effect Duration: \( F_{1,195} = 64.09; \ p < .001; \ \eta^2_p = .25 \)) and with deviant relative to standard stimuli (88.6% vs. 93.8%; main effect Deviance: \( F_{1,195} = 140.81; \ p < .001; \ \eta^2_p = .42 \)). Moreover, there was an interaction of Duration and Deviance (\( F_{1,195} = 84.72; \ p < .001; \ \eta^2_p = .30 \); Figure 2b). Post hoc \( t \) tests revealed that a deviance-related decrease in rates of correct responses occurred only with long tones (−10.08%; \( t_{195} = 11.80; \ p < .001 \)) but not with short tones (+0.03%; \( t_{195} = 0.79; \ p > .05 \)).

The rates of commission errors (i.e., ‘short’ responses to long tones and vice versa) were relatively low for short standard tones (3.9%), long standard tones (4.0%) and short deviant tones (3.2%) but increased when the long tone was of deviant pitch (10.3%) (Figure 2c). Accordingly, there was an interaction of Duration and Deviance (\( F_{1,195} = 64.20; \ p < .001; \ \eta^2_p = .35 \)), besides main effects of Duration (\( F_{1,195} = 36.65; \ p < .001; \ \eta^2_p = .16 \)) and Deviance (\( F_{1,195} = 101.11; \ p < .001; \ \eta^2_p = .34 \)). Post hoc \( t \) tests indicated a deviance-related increase in commission errors with long tones (being
rated as ‘short’; \( +7.05\%; t_{195} = 10.20; p < .001 \) but not short tones \( (+0.04\%: t_{195} = 0.10; p > .05) \).

### 3.2 Effects of stimulus duration on ERP measures

Comparing ERPs to short and long tones averaged over standard and deviant tone frequencies revealed quite similar patterns up to 250 ms after tone onset (Figure 3a, left and middle panel). These were dominated by a fronto-central negativity at about 100 ms, corresponding to the N1 component. Thereafter, however, differences appeared in the time range from about 250 to 500 ms in the form of a more pronounced fronto-central (CNV-like) negativity for long tones. Finally, from about 500 ms on, there was a centro-posterior late positive component (LPC) also being stronger for long tones. Accordingly, the plot of long-minus-short difference-ERPs showed a more pronounced negativity in the time range from 250 to 500 ms over fronto-central, central and posterior areas (\( \Delta CNV \)) as well as a stronger posterior positivity (\( \Delta LPC \)) with a maximum at 550 ms. Finally, there was a stronger fronto-central negativity around 700 ms (Figure 3a, right panel).

![Figure 3](attachment:image_url)
The statistical comparison of ERPs to short and long tones via cluster-based permutation tests revealed three significant clusters (Figure 3b): first, an early cluster ranging from frontal to parietal areas in the time range 250 to 500 ms (Cluster 1), and second, a broad parietal cluster in the time range from about 550 to 1000 ms (Cluster 3). These clusters closely correspond to the CNV and the LPC, both being more pronounced to long than short tones. Finally, a small frontal cluster was found at about 700 ms (Cluster 2).

To provide a reference to more conventional ERP visualizations than with the analysis via cluster-based permutation tests employed here, single waveform ERPs were plotted for the fronto-central (FCz) electrode and the posterior (Pz) electrode (Figure 3c). The ERP differences between long and short tones were also clearly visible in the classical visualization of ERP waveforms. There was a (CNV-like) negativity peaking at about 400 ms at FCz and a positivity peaking at about 600 ms.
at Pz. Both ERPs were more pronounced to long than short tones, as indicated by the ΔCNV and ΔLPC peaks in the long-minus-short difference waveforms.

### 3.3 Effects of stimulus deviance on ERP measures

ERPs to the tones of the standard frequency averaged over short and long tones showed the typical pattern of a fronto-central negativity at about 150 ms after stimulus onset, followed by positivity at 200 ms and a broadly pronounced posterior positivity reaching its maximum at about 600 ms (Figure 4a, left panel). In addition, there was a prolonged fronto-central negativity in the range 250 to 500 ms. For deviant tones, the early fronto-central negativity appeared to be stronger than for standard tones (Figure 4a, middle panel). Even more striking is a fronto-central positivity beginning 250 ms after stimulus onset and spreading to posterior areas within about 100 ms and a more frontal negativity in the range of 400 to 600 ms. The three fronto-central components are

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**FIGURE 5**  
(a) ERPs to short standard, long standard, short deviant and long deviant tones. ERPs are shown relative to tone onset for all 30 electrodes, arranged from prefrontal (Fp, bottom) to occipital (O, top) electrode positions (F, frontal; FC, fronto-central; C, central; CP, centro-parietal; P, parietal; PO, parieto-occipital), with left-to-right electrode position corresponding to top-to-bottom within the marked electrode lines. Bars indicate the duration of short and long tones for standard (black) and deviant (red) stimuli. Relevant ERPs (N1, CNV, LPC) are marked. The horizontal lines in the ERP plots refer to the electrode positions shown separately in Figure 6. (b) Difference-ERPs for long-minus-short standard tones (difference standard) and long-minus-short deviant tones (difference deviant). Bars indicate the differences in durations of short and long tones for standard (black) and deviant (red) stimuli. Relevant long-minus-short difference-ERPs (ΔCNV, ΔLPC) are marked. (c) Difference-ERPs for deviant-minus-standard short tones (difference short) and deviant-minus-standard long tones (difference long). (d) Results of cluster-based permutation test of interaction effects (effect sizes), indicating three significant clusters in which difference-ERPs differed.
even more evident in the difference plot of deviant-minus-standard waveforms and can be identified as MMN, P3a and RON (Figure 4a, right panel). In addition, the positivity migrating from frontal to posterior is recognizable, while the difference plot revealed only minor differences in the later P3b around 600 ms.

Statistical comparison of standard and deviant tones indicated three significant clusters corresponding to MMN (Cluster 1), P3a (Cluster 2) and RON (Cluster 3) (Figure 4b). The latter, however, not only encompasses fronto-central areas but also evidences significantly increased positivity with deviants relative to standards over posterior areas. Differences in the amplitude of this positivity occurred both in the time range of the classic P3b, which reached its maximum around 600 ms after stimulus onset, and at a time range much earlier at around 350 ms, suggesting an early, deviance-related P3b.

These findings were also evident in the classical ERP waveforms (Figure 4c). The deviant-minus-standard difference waveforms at the fronto-central (FCz) electrode indicated the well-known MMN, P3a and RON components. In addition, there was a pronounced positivity at the posterior (Pz) electrode at about 350 ms, which occurred for deviant, but not standard, stimuli. This deviance-related P3b therefore became manifest especially in the deviant-minus-standard difference waveforms.

### 3.4 Interaction stimulus duration and deviance on ERP measures

The plot of the ERPs separately for long and short tones as well as for standards and deviants showed the processing of the tone duration when it is undisturbed (i.e., with standards) and disturbed (with deviants). For standards, a more pronounced fronto-central negativity in the time range from 250 to 500 ms and a stronger posterior positivity between 500 and 800 ms after stimulus onset occurred for long, relative to short tones (see ‘short standard’ and ‘long standard’, Figure 5a, upper row). This became especially evident in the long-minus-short difference-ERPs, ∆CNV and ∆LPC (see ‘difference standard’, Figure 5b). In deviants, a pronounced pattern of MMN, P3a and RON was observed compared with standards (see ‘short deviant’ and ‘long deviant’, Figure 5a, lower row) as well as in the deviant-minus-standard difference-ERPs (see ‘difference short’ and ‘difference long’, Figure 5c). Differences between long and short tones, on the other hand, seemed to be less pronounced in deviants than in standards (see ‘difference standard’ and ‘difference deviant’, Figure 5b). Accordingly, there was an interaction of deviance and duration mainly with two significant clusters (Figure 5d). These showed a reduction in fronto-central negativity in the range 350 to 500 ms and in centro-parietal positivity in the range 550 to 700 ms. This suggests a reduction in ∆CNV (especially toward its end) and in ∆LPC with the deviant stimuli.

In addition to this effect of deviance on time processing, the deviance processing appeared to be modulated by duration as well: Here, the comparison of the deviance-minus-standard differences revealed an earlier and more pronounced RON with short compared with long tones (see ‘difference short’ and ‘difference long’, Figure 5c), while no significant differences occurred at the time of MMN and P3a. Accordingly, significant
interactions only occurred later in the process of deviance processing but not before about 350 ms (Figure 5d).

The effects of tone deviance and duration became also visible in the single ERP waveforms, when plotted separately for short and long tones and for standards and deviants at electrode positions FCz and Pz (Figure 6a). Regarding the effects of deviance, the comparison waveforms for deviant and standard stimuli at FCz indicated (a) a stronger negativity at about 100 ms, (b) a pronounced positivity around 300 ms and (c) a stronger negativity between 400 to 600 ms with deviants, corresponding to the MMN, P3a and RON. At Pz, the early, deviance-related P3b peaking at about 350 ms is clearly visible, in addition to the LPC in the time around 600 ms. Regarding the effects of duration, the comparison of waveforms for short and long tones mainly showed a more pronounced negativity at FCz in the time range between about 200 and 500 ms and a stronger positivity at FCz and Pz around 600 ms with long (especially standard) tones, corresponding to ΔCNV and ΔLPC.

Finally, to visualize the effect of tone deviance on ERP waveforms related to tone duration, the long-minus-short difference waveforms were plotted separately for standard and deviant stimuli (Figure 6b). Both ΔCNV (at FCz) and ΔLPC (at Pz) were reduced with deviant stimuli relative to standard stimuli, corresponding with the significant interaction effects of deviance and duration shown in Figure 5d.

4 | DISCUSSION

The aim of the present study was to determine the mechanisms by which distracting (task-irrelevant) stimulus features influence time perception in a combined attentional-distraction duration-discrimination paradigm. Participants had to distinguish short and long tones, most of which having a uniform (standard) pitch and only a few having a different (deviant) pitch. The analyses indicated several specific effects of pitch deviance on time perception mechanisms that are discussed in detail in the following.

4.1 | Impaired time perception and subjective shortening of long deviant tones

As has been shown in previous studies, a deviance-induced deterioration in time estimation occurred in form of increased RTs and a decrease in the rates of correct responses when a deviant tone occurred (e.g., Schröger et al., 2000; for review, Wetzel & Schröger, 2014). A comparison with previous studies, in which the same paradigm had been used (Beste et al., 2014; Getzmann et al., 2013), revealed comparable effect sizes for RTs ($\eta_p^2 = .48$ to .50) and response accuracies ($\eta_p^2 = .37$ to .51). More important, however, is the pattern of results when short and long tones were analysed separately: While RTs to deviant stimuli increased for both long and short tones (relative to standard stimuli), the deviance-induced decrease in the rate of correct responses occurred exclusively for long tones. More specifically, the analysis of the rate of commission errors (i.e., without any missing responses) showed long tones—when of deviant pitch—were often mistaken for shorter, whereas short tones were rated as ‘short’ irrespective of tone pitch. These results are in line with some earlier observations from similar experimental paradigms (e.g., Horváth, 2014; Horváth & Winkler, 2010; Schröger, 1996).

These findings are in line with resource-based models of time perception, assuming that the processing of temporal information requires mental processing capacity (for review, Brown, 2008; Wittmann, 2013). If resources required for time processing are withdrawn (as in the present task for processing of the distraction triggered by the deviant stimulus), time perception should be impaired. In other words, in the presence of a deviant pitch, resources had to be allocated to two different processes, (a) the ‘top-down’ controlled task-relevant duration discrimination and (b) the ‘bottom-up’ triggered involuntary processing of pitch deviance. According to theories of limited cognitive resources (Kahneman, 1973), this should lead to a mutual impairment, from which both processes suffer. In line with this interpretation, there is evidence that time perception shares the same processing resources as basic executive functions (Brown et al., 2013) but appears to suffer more from being performed simultaneously than the second non-temporal task (according to the asymmetrical interference effect in timing, Brown, 1997).

Impaired time perception should become more evident in the processing of long versus short tones: The decision about the presence of a short tone could be made immediately after its offset, whereas that about the presence of a long tone could only be made after the expected end of the short tone. The latter decision contained greater uncertainty and thus required more cognitive control (for a similar argumentation referring to the amount of information provided by the short and long tones, see Lange et al., 2003). Thus, a higher amount of mental resources required for processing long tones could result in the behavioural finding that longer tones were perceived as shorter, while short tones were not perceived as longer.

This relationship is even more explicit in the attentional-gate model (Zakay & Block, 1997; for review, Brown, 2008; Wittmann, 2013), assuming that duration
discrimination (at least in short time intervals in the seconds range considered here) is based on the number of pulses generated by a pacemaker which—after having passed an attentional gate—are collected over time in an accumulator (Wearden, 2004). Crucially, when attentional resources are allocated to non-time-related tasks, the attentional gate should let fewer pulses enter the accumulator, so that the duration of a stimulus appears shorter. There is some empirical evidence supporting the predictions of the attentional-gate model (e.g., Casini & Macar, 1997; Coull et al., 2004; Polti et al., 2018). However, the present findings of significantly prolonged reaction times also with short tones suggest that deviation-induced impairments in time perception were—at least in part—indeed connected to the duration of the stimulus. This is not explained by the strict attentional-gate model. Furthermore, the attentional-gate model makes numerous theoretical assumptions that can hardly be tested empirically, and it has received some criticism in the past (e.g., Lejeune, 1998; Zaky, 2000).

4.2 Attention-based modulation of ERP correlates of time processing

The behavioural results were largely reflected in the derived electrophysiological measures. With the standard tone pitch, the comparison of the ERPs of short and long tones yielded mainly two components: a fronto-central negativity in the time range of about 250 and 400 ms (which roughly corresponds to the duration difference of the short and long tones) and a posterior positivity around 600 ms after tone onset. The first component can be identified as CNV the second as LPC (for review, Ng & Penney, 2014). The CNV has often been observed in tasks with time perception and reproduction (e.g., Elbert et al., 1991; Macar & Besson, 1985; Macar & Vitton, 1982; Ruchkin et al., 1977) and has been associated with monitoring and temporal accumulation of the current time interval (e.g., Macar & Vidal, 2003, 2009; for a critical discussion, Van Rijn et al., 2011), as well as decision processes involved in duration discrimination (Kohononowicz & Van Rijn, 2011). Specifically, the CNV develops with the duration of the tone to be judged, with its amplitude correlating with the judged duration of a stimulus (e.g., Bendixen et al., 2005; Macar et al., 1999; Pfeuty et al., 2003). Thus, the CNV appears as on-line index of timing (e.g., Macar & Vidal, 2003, 2009), with the neural representation of a time interval being reflected in form of a ‘climbing neuronal activity’ (Pfeuty et al., 2005). In this regard, it should be noted that the CNV has traditionally been associated with the preparation for an imperative stimulus or response induced by a warning stimulus (Brunia & van Boxtel, 2001; Walter et al., 1964), with different subcomponents reflecting anticipatory attention and motor preparation and with time courses usually being much longer than a few 100 ms. It is therefore debatable whether the negativity observed in time perception paradigms with relatively short stimulus durations like in the present study should be referred to as CNV. However, the negativity fits well with the CNV from a functional and conceptual point of view. The second component, the LPC, clearly emerged after the offset of the long tone and extended over central and posterior areas. The LPC has been related to decision processes involved in temporal judgements (Paul et al., 2011) and has functional and structural similarities with the late P3b, associated with stimulus evaluation and context updating (e.g., Polich, 2007; Verleger, 2020), stimulus discrimination and categorization (e.g., Mecklinger & Ullsperger, 1993), as well as integration of stimulus and response processing (Verleger et al., 2005). All of these functions are relevant for duration-discrimination tasks (for review, Ng & Penney, 2014). The latency of the LPC peaking about 200 ms after the offset of the long tone fits well to previous observations indicating that the processing of temporal information mainly takes place after stimulus offset (Bannier et al., 2019; Tarantino et al., 2010; for review, Kononowicz et al., 2016).

Both ERPs were more pronounced to long relative to short tones, as also observed previously (Gontier et al., 2009). In line with the resource-based model of time perception, this could reflect a ‘climbing neuronal activity’ (Pfeuty et al., 2005) indicated by the CNV and a stronger allocation of processing resources indicated by the LPC (Paul et al., 2011). The fact that both frontal CNV and posterior LPC were equally modulated by tone duration corresponds to the assumption of a close functional link between prefrontal and parietal brain areas during time discrimination (Gontier et al., 2007, 2009; Le Dantec et al., 2007). The higher amount of effort for processing long tones fits well also with the behavioural finding that longer tones resulted in longer RTs and more errors than the short ones (regardless of whether the pitch was standard or deviant).

For deviant tones, the classical components were found, that is, the MMN, P3a and RON (Schröger et al., 2000). According to the three-stage model of auditory distraction, these should be associated with the detection of deviance, the subsequent (involuntary) shift of attention to tone pitch (i.e., away from tone duration) and, finally, the reorientation toward the task-relevant dimension (Schröger & Wolff, 1998; Escera et al., 1998; for review, Wetzel & Schröger, 2014). More important in the context of the present study are the observed interaction effects of tone duration and deviance (cf. Figure 5d).
These show that ERP differences between short and long standard tones (∆CNV and ∆LPC, Figure 5b) were modulated by tone deviance, being mainly reduced with deviant pitch compared with standard-pitch tone.

Such attention-dependent ERP differences in duration discrimination have also been observed in previous studies. Comparing sound offset-related ERPs when attention was focused on either task-relevant or task-irrelevant sound features revealed ERP differences in the post-offset time interval, especially an offset-related negativity was much more pronounced with attention being focused (Horváth, 2016). Also, when attentional resources were involuntarily distracted from the duration-discrimination task, offset-related ERPs were found to be attenuated relative to a non-distracted condition. In particular, a sequence of P1–N1–P2 ERPs observed in the short-minus-long difference waveform was significantly reduced when attention was distracted by a deviant stimulus, (Horváth, 2014; Horváth & Winkler, 2010). These findings basically correspond to the reduction in ∆CNV and ∆LPC observed in the present study.

Furthermore, attention-based influences in timing tasks have been observed on CNV and LPC (e.g., Gontier et al., 2013; Liu et al., 2013). For example, comparing dual-task and single-task conditions, amplitudes of the CNV and the parietal P300 complex were reduced when an interference with a (resource-consuming) second task occurred (Gontier et al., 2007). In addition, increasing task difficulty modulated both CNV and LPC (Paul et al., 2011). Even more striking, in a duration-discrimination task, lower CNV amplitudes were associated with a subjectively shorter duration of (physically equal) tone stimuli (Bendixen et al., 2005). Taken together, the deviance-induced reduction of ∆CNV and ∆LPC matches well with the observed impairment in time perception and—in particular—the shortening of the subjective duration of the long tones.

4.3 Influence of duration discrimination on ERP correlates of deviance processing

The findings suggest a reciprocal influence of the two processes of time perception and deviance processing. Interesting in this context is the comparison of the ERPs of standard and deviant tones, separately for short and long tone durations (cf. Figure 5C, ‘difference short’ vs. ‘difference long’). This comparison resulted in the same interaction as the comparison of the ERPs to short and long tones (cf. Figure 5b, ‘difference standard’ vs. ‘difference deviant’). While this is statistically trivial, it led to a different interpretation: up to about 350 ms after stimulus onset, the difference-ERPs did not differ between long and short tones. That is, MMN and P3a occurred equally. However, in the time range of fronto-central RON (400 to 600 ms), an amplitude reduction occurred for long tones. This interpretation represents the inverse of the impairment of duration processing by pitch deviance. The other side of the coin seems to be an influence of tone duration processing on pitch perception, suggesting a mutual influence of two simultaneous cognitive processes that use the same cognitive resources.

Evidence for this assumption was provided by a study in which participants had to pay attention to either spatial or temporal stimulus features and in which the other stimulus dimension functioned as a distracting stimulus (Roebber et al., 2003). It was shown that performance in both the temporal and spatial task was negatively affected by deviant stimulus features in the other dimension. This interpretation also corresponds to the results of two previous studies, in which Go/NoGo short–long tone duration-discrimination tasks with infrequent pitch distractors were employed and in which reduced amplitudes of P3a and RON were observed for long as compared with short tones (Horváth, 2014; Horváth et al., 2009). The authors assumed that detecting long tones could be more resource consuming (due to the lack of a clear transient offset relative to the sharp transient offset of the short tones), leaving less capacity for processing the deviant feature. To further test this hypothesis, a dual-task setting would be revealing in a future study, in which both processing of deviance and time perception require open responses. Here, the hypothesis would be that deviance detection would be easier (and performed better) with shorter, than longer, tones.

4.4 An early P3b to deviant tones

An additional finding from the ERP analysis was an early posterior P3b that appeared with deviant stimuli at about 300 ms after tone onset (and thus temporally well before the ‘classical’ P3b with a latency of about 600 ms, cf. Figure 6a). This deviance-related P3b could be interpreted as the posterior portion of the fronto-central P3a. While the latter is associated with the attentional shift to the deviant stimulus (corresponding to the three-stage model of auditory distraction; for review Wetzel & Schröger, 2014), the deviance-related P3b could be associated with the allocation of cognitive resources for deviant processing. This assumption is supported by the fact that this P3b occurred only with deviant and not with standard stimuli. Its spatio-temporal dynamics suggest that posterior brain areas are activated after frontal ones. In
the context of the three-stage model of auditory distraction, one could assume that after the (more or less) pre-attentive deviance detection (indicated by MMN), first, the attentional orientation takes place (P3a), which then leads to a mobilization of processing resources (deviance-related P3b), and finally concludes with reorientation (RON). It might be worth to analyse the role of the early, probably deviance-related, P3b in future studies on auditory distraction.

4.5 Limitations and future directions

Some limitations of the present analysis have to be mentioned. First, the analysed data originate from a larger study, the Dortmund Vital Study, which investigates the development of cognitive abilities over the lifespan using several EEG-based tasks (Gajewski et al., 2021). For this reason, a large number of participants could be included in the analyses. The tasks themselves, however, were kept short overall, which means that a relatively small number of short and long deviant stimuli were provided. A replication of our findings in a longer version of the duration-discrimination task therefore seems reasonable. Second, the experimental paradigm was oriented to previous studies on auditory distraction (e.g., Berti, 2008; Schröger et al., 2000; Schröger & Wolff, 1998), in which fixed interstimulus-onset intervals were used. This could be suboptimal for studying time perception, because a fixed interval could act as a supratemporal cue for duration discrimination. However, given that long and short tones as well as standard and deviant tones were presented in a random order, potential confounding effects of supratemporal cue on the relationship of distraction and duration discrimination should be marginal. Finally, a finer resolving paradigm with tones of different durations (instead of only short and long tones) could be employed. This would allow for a better quantification of timing sensitivity, for example, by determining the point of subjective equality in a staircase procedure (e.g., Meese, 1995).

4.6 Conclusion

The present study related previous findings of deviance-induced impairments in a primary duration-discrimination task to attentional models of time perception. Separate analyses of short and long tones indicated that especially the processing of long tones was affected by pitch deviance. On the electrophysiological level, this was associated with a reduction of CNV and LPC in time perception. In terms of resource-based models of time perception, the deviance-related impairment of duration discrimination appears to be associated with a withdrawal of attentional resources from processing of the time information.

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CONFLICT OF INTEREST

All authors disclose no actual or potential conflicts of interest including any financial, personal or other relationships with other people or organizations that could inappropriately influence (bias) their work.

AUTHOR CONTRIBUTIONS

SG, PG and EW were responsible for the design of the study. SG and SA analysed the data. SG wrote a first version of the manuscript. SG, SA, PG and EW contributed to the completion of the final version of the manuscript.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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