Hearing Research 395 (2020) 108028

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

The effect of silent gaps on temporal weights in loudness judgments

Alexander Fischenich [a, *], Jan Hots [b], Jesko L. Verhey [b], Daniel Oberfeld [a]

[a] Department of Psychology, Johannes Gutenberg-Universität Mainz, Mainz, Germany
[b] Department of Experimental Audiology, Otto von Guericke University Magdeburg, Magdeburg, Germany

ARTICLE INFO

Article history:
Received 11 February 2020
Received in revised form
14 May 2020
Accepted 22 June 2020
Available online 8 July 2020

ABSTRACT

Human loudness judgments of time-varying sounds show a non-uniform temporal weighting pattern with increased weights at the beginning of a sound. Four experiments were conducted to investigate whether this primacy effect reoccurs after a silent gap of an appropriate duration that is inserted into a level-fluctuating sound. In three of the experiments, contiguous sounds as well as sounds containing silent gaps of different durations were presented. The temporal loudness weights were compared between the sounds that contained a gap and the sounds without a gap. The data showed that with increasing gap duration an increasingly pronounced primacy effect reoccurred on the second sound part in the sense that a) the weights assigned to the first segments after the gap were increased compared to the conditions without a gap, and that b) the following weights again showed a decrease over time. This effect was statistically significant for gap durations of 350 ms and above. To investigate whether an attenuation in level can lead to the same results as a silent gap, segments in the middle part of a sound were attenuated in the fourth experiment, and the resulting weights were compared to conditions in which the middle segments were unattenuated or where a 700 ms silent gap was presented instead of the middle segments. An attenuation of 15 dB resulted in a significant reoccurrence of the primacy effect, although the effect was more pronounced for an attenuation of 30 dB and the silent gap. The results are discussed in the light of auditory nerve responses, masking effects on intensity resolution, and assumptions based on evidence integration processes.

1. Introduction

Research on loudness judgments of time-varying sounds has shown that not all temporal portions of a sound receive equal weights. Instead, the beginning of a sound is of greater importance when judging the overall loudness of a level-fluctuating sound, compared to later parts (e.g., Fischenich et al., 2019; Oberfeld and Plank, 2011; Pedersen and Ellermeier, 2008). This primacy effect can be described by an exponential decay function where the weight assigned to a given temporal segment is determined by the segment onset relative to the onset of the sound and the duration of the segment (Oberfeld et al., 2018; Oberfeld et al., 2018).

It can be expected that the mechanisms causing the primacy effect show recovery in the sense that after one sound has ended, a subsequent sound presented after a silent gap can again produce the effect. Rather indirect evidence for this hypothesis is provided by previous studies on temporal loudness weights, where the stimuli were typically presented with inter-trial intervals of around 2 s in one-interval tasks (e.g., Fischenich et al., 2019; Oberfeld et al., 2018). If there had been no recovery of the relevant processes during the inter-trial interval, the loudness judgments in longer series of such sounds presented within an experimental block should not have shown primacy effects. Additional evidence for a recovery of the relevant processes is provided by experiments where the sounds consisted of a series of brief noise bursts or tone pulses separated by silent gaps. For a loudness judgment task, Plank (2005) reported temporal weights for sequences of ten 20-ms noise bursts separated by inter-segment gaps of between 5 and 100 ms. A clear primacy effect was observed at all of the gap durations. The weights declined more rapidly as a function of segment onset when the pause between the noise bursts was 5 or 40 ms rather than 100 ms. This is compatible with the view that during each inter-segment gap, the primacy effect recovers. The longer the gap duration, the more recovery occurs, and the less pronounced is the primacy effect. This assumption is also compatible with data by Berg (1990) for a frequency discrimination task. In conditions where all tones were equally informative (see Fig. 2 in Berg, 1990),

* Corresponding author.
E-mail address: alexander.fischenich@uni-mainz.de (A. Fischenich).

https://doi.org/10.1016/j.heares.2020.108028
0378-5955/

slightly stronger primacy effects were observed when the inter-segment gap between the 50-ms tones was 50 ms rather than 200 ms.

However, it is unclear how exactly the recovery of the primacy effect depends on the duration of the silent gap between acoustic events. Therefore, the present study investigated the relation between the duration of a silent gap within a level-varying sound and the occurrence and strength of a primacy on the second sound part after the gap.

Studies on temporal loudness weights (Fischenich et al., 2019; Oberfeld, 2015; Oberfeld and Plank, 2011) discussed the possibility that the primacy effect is caused by the response characteristics of auditory nerve (AN) fibers, which show an initial peak in their firing rate at the onset of a sound (Kiang et al., 1965). This initial peak reoccurs after silent inter-stimulus intervals of at least 300 ms (Relkin and Doucet, 1991). Thus, the present study will consider its role in the process of the recovery of the primacy effect. Another potential source of the primacy effect are forward-masking effects on intensity resolution (Zeng et al., 1991). These masking effects have found to be substantially reduced for masker-target intervals of 400 ms and above and will therefore also be considered in the present study as a potential mechanism for the recovery of the primacy effect.

In four experiments, sounds with silent gaps in the middle of the sounds were presented. The duration of the silent gaps was varied within and between the experiments. In Experiment 1, we presented sounds with a wide range of gap durations from 19 to 1400 ms. In Experiment 2, we took a closer look at relatively short gap durations below 400 ms. In Experiment 3, gap durations between 350 and 700 ms were (re)assessed. In Experiment 4, we additionally investigated whether a reduction of the sound pressure level in the middle temporal portion of a sound (rather than inserting a silent gap) is sufficient for a reoccurrence of the primacy effect on the sound part following the attenuated part.

2. Experiment 1

2.1. Method

2.1.1. Listeners

In Experiment 1, nine listeners with normal hearing participated (5 female, 4 male; age 19–31 years). They reported no history of hearing problems. Hearing thresholds were measured by Békésy audiometry with pulsed 270-ms pure tones. All listeners showed thresholds less than or equal to 15 dB HL bilaterally for all audiometric frequencies in the frequency range between 125 Hz and 8 kHz. All listeners were students from Johannes Gutenberg-Universität Mainz and received partial course credit for their participation. All of the experiments reported in this paper were conducted according to the principles expressed in the Declaration of Helsinki. All listeners participated voluntarily after providing informed written consent, after the topic of the study and potential risks had been explained to them. They were uninformed about the experimental hypotheses. The Ethics Committee of the Institute of Psychology of the Johannes Gutenberg-Universität Mainz approved the study (reference number 2016-JGU-psychEK-002).

2.1.2. Stimuli and apparatus

Level-fluctuating sounds were presented, some containing silent gaps. In the condition without a silent gap (referred to as a gap duration of 0 ms in the following), the sounds consisted of ten contiguous 100-ms Gaussian wideband-noise segments (20–20,000 Hz). Level fluctuations were created by drawing each segment's sound pressure level independently and at random from a normal distribution on each trial (see section Procedure). To investigate the influence of a silent interval within the stimulus on the temporal weights, in four additional conditions we inserted a gap in the temporal center of the sounds, i.e., between segments five and six. The duration of the silent interval was either 50, 350, 700 or 1400 ms. The total duration of the five types of sounds was thus 1000, 1050, 1350, 1700 and 2400 ms. The five types of level-fluctuating sounds are schematically shown in Fig. 1.

The stimuli were generated digitally. The digital audio output was generated by an RME DIGI 9636 audio interface with a sampling frequency of 44.1 kHz and a resolution of 24 bit. The signals were then D/A-converted by an RME ADI/S, attenuated by a TDT PA5 programmable attenuator, buffered by a TDT HB7 headphone buffer, and presented diotically via Sennheiser HDA 200 circumaural headphones. The audio system was calibrated according to IEC 318 (1970). Listeners were tested in a double-walled sound-insulated chamber. Instructions were presented on a computer screen.

2.1.3. Procedure

To estimate temporal loudness weights, we used an established experimental paradigm from previous experiments (e.g., Oberfeld and Plank, 2011; Pedersen and Ellermeier, 2008). On each trial, a level-fluctuating noise consisting of ten segments was presented. The ten segment levels were set by drawing each segment's sound pressure level independently and at random from a normal distribution on each trial.

On each trial, all segment levels were either sampled from a level distribution with higher mean ($\mu_L = 56.75$ dB SPL) or a distribution with lower mean ($\mu_S = 55.25$ dB SPL), with identical probability. The standard deviation was $\sigma = 2.5$ dB for both distributions. Extremely loud or soft segments were avoided by limiting the range of possible sound pressure levels to $\mu \pm 3 \cdot \sigma$.

On each trial, listeners decided whether the presented sound had been loud or soft in comparison to previous trials within the same experimental block. Thus, a one-interval, two-alternative forced-choice (1I, 2AFC) *absolute identification task* (Braida and Durlach, 1972) with a virtual standard (e.g., Nachmias, 2006) was used. One could also describe it as a *sample discrimination task* (Berg and Robinson, 1987; Lutfi, 1989; Sorkin et al., 1987) where the listeners decided whether the segment levels had been drawn from the "loud distribution" or from the "soft distribution". Importantly, listeners were instructed to evaluate the "global" loudness of the entire sound, that is, the loudness across the entire stimulus duration, encompassing potential silent temporal gaps.

The inter-trial interval was 1500 ms, with the restriction that the next trial never started before the response to the preceding trial had been given. Trial-by-trial feedback was given during the first five trials of each block so that listeners could easily adopt a decision criterion for the new experimental condition. Those trials were not considered for the data analysis. A summarizing feedback was provided each time 50 trials were completed. It contained the number of correct and false answers, percent correct and the number of μ_L and μ_S trials as well as the number of "loud" and "soft" responses. Note that a response was classified as correct if the response ("loud"/"soft") matched the mean of the distribution that the stimulus' segment levels were drawn from (μ_L/μ_S).

We used our usual rule of thumb from previous experiments (Oberfeld et al., 2018), according to which 100 trials per temporal segment are needed to obtain reliable weight estimates. Thus, we collected 1000 trials per condition, resulting in a total of 5000 trials per listener.

2.1.4. Sessions

Each listener participated in five experimental sessions, each containing 1000 trials of the loudness judgment task (200 per

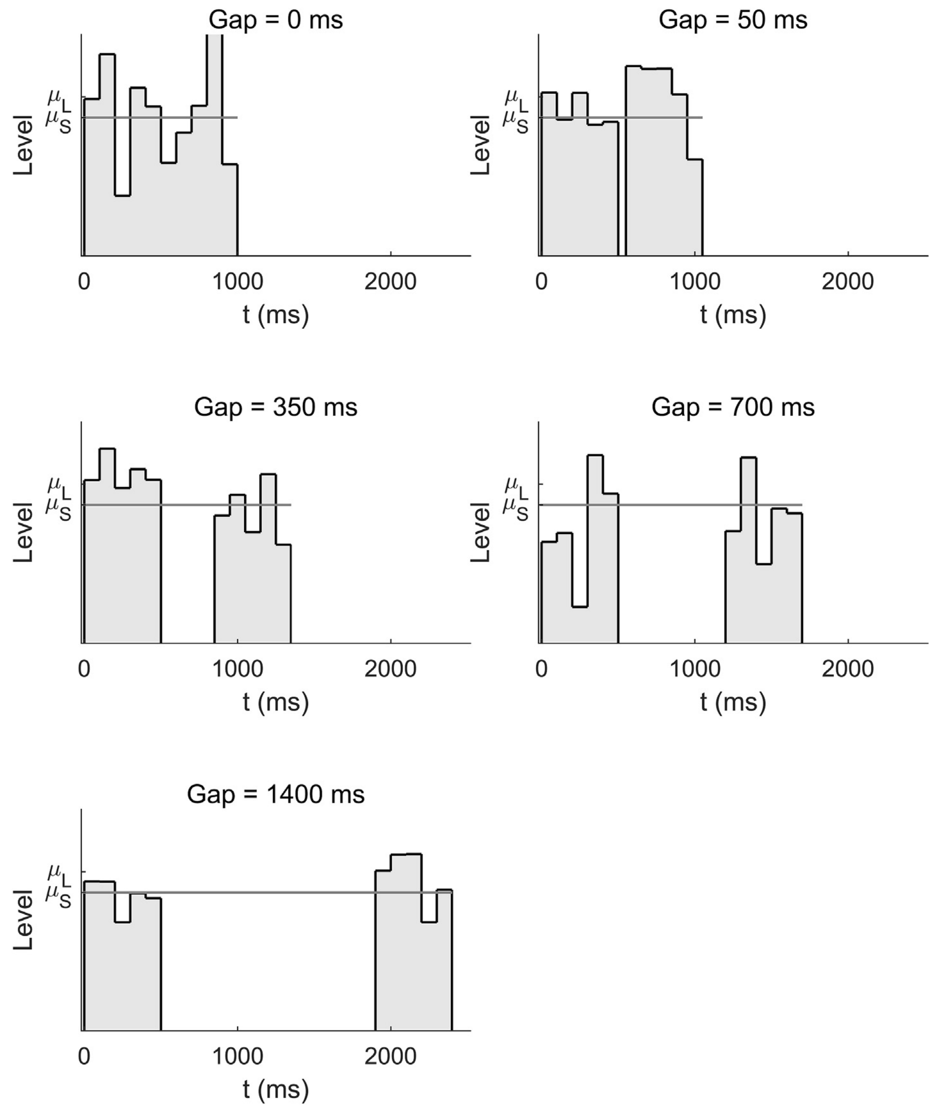

Fig. 1. Schematic representation of the temporal envelope for the five types of level-fluctuating sounds presented in experiment 1. In this example, all segment levels were independently drawn from the distribution with mean $\mu_S = 55.25$ dB and standard deviation $\sigma = 2.5$ dB. The sounds contained ten segments with a duration of 100 ms each. The duration of the silent gap between segments five and six was either 0, 50, 350, 700 or 1400 ms.

condition). Additionally, there was an initial session in which audiometric thresholds were measured, and practice blocks of the loudness judgment task were presented for all of the five conditions. The practice blocks were excluded from data analysis. Within each session, sounds of the same condition were arranged into two blocks of 100 trials. Each session was split into two parts which were separated by a mandatory pause of about 5 min. For each of the five conditions a block was presented once before and once after the pause whereas the order of conditions was chosen randomly both times. The duration of each session was approximately 60 min.

2.1.5. *Data analysis*

The perceptual weights representing the importance of the 10 temporal segments for the decision in the sample discrimination task were estimated from the trial-by-trial data via multiple logistic regression. The decision model assumed that the listener compares a weighted sum of the segment levels to a fixed decision criterion, and responds that the sound was of the “loud” type if the weighted sum exceeds the criterion (a detailed description of the decision model is provided by Oberfeld and Plank, 2011). If the weighted sum is smaller than the criterion, then the model predicts that the listener classifies the sound as “soft”. In the data analysis, the binary responses (“loud” or “soft”) served as the dependent variable. The predictors (i.e., the 10 segment levels) were entered simultaneously. The regression coefficients were taken as the decision weight estimates. For a given level of a segment, a regression coefficient equal to zero means that the segment had no influence at all on the decision. For the same segment, a regression coefficient greater than zero means that the probability of responding that the sound was of the “loud” type increased with the sound pressure level of the segment.

A separate logistic regression model was fitted for each combination of listener and gap duration. Since the *relative* contributions of the different segments to the decision were of interest rather than the absolute magnitude of the regression coefficients, the 10 regression coefficients were normalized for each fitted model such that the mean of their absolute values was 1.0.

A summary measure of the predictive power of a logistic regression model is the area under the Receiver Operating Characteristic

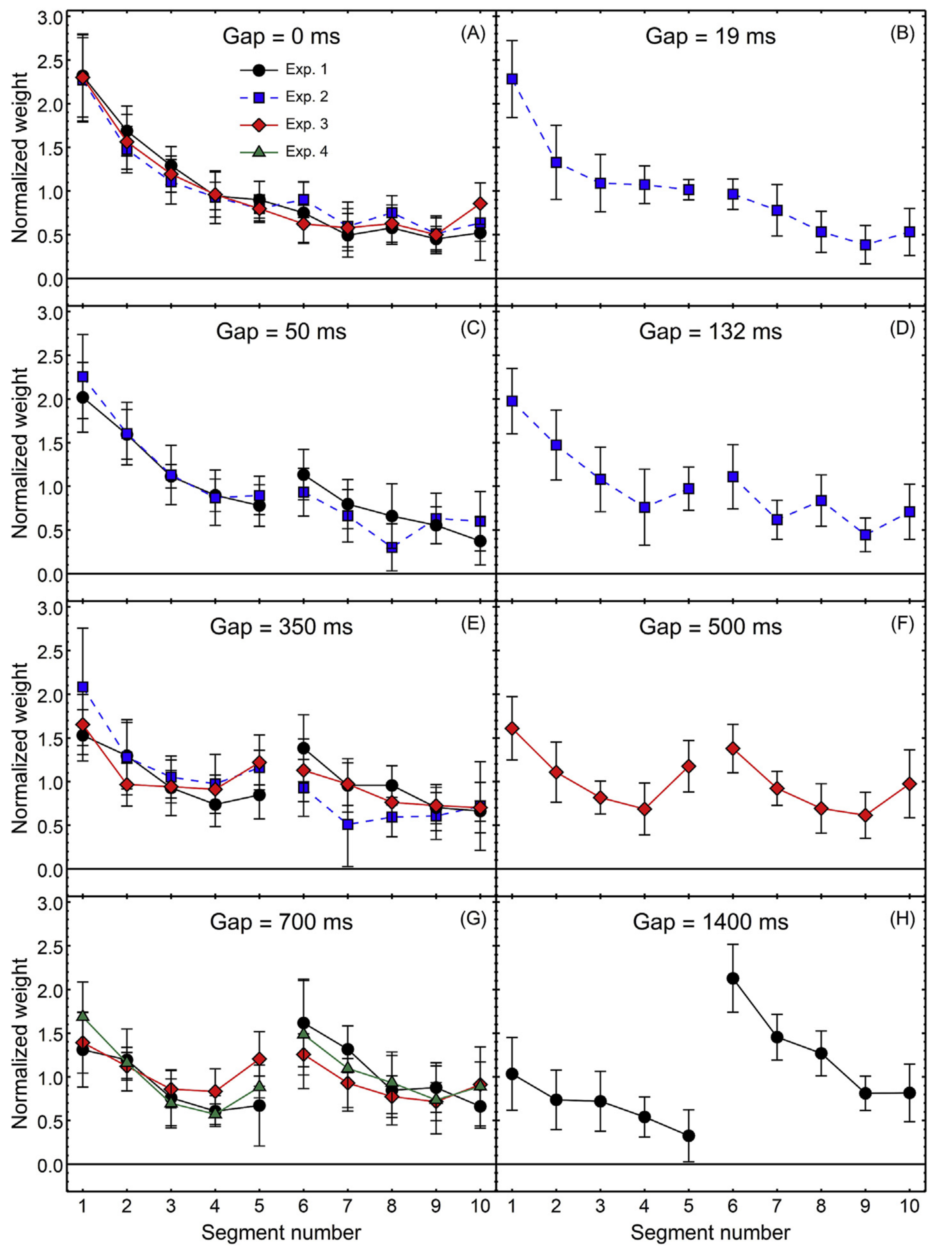

Fig. 2. Mean normalized weights as a function of segment number, for seven different gap durations. Black circles: Experiment 1. Blue squares: Experiment 2. Red diamonds: Experiment 3. Green triangles: Experiment 4. Error bars show 95% confidence intervals (CIs). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(ROC) curve (for details see Dittrich and Oberfeld, 2009). Areas of 0.5 and 1.0 correspond to chance performance and perfect performance of the model, respectively. Across the 45 fitted logistic regression models, the area under the ROC curve ranged between 0.67 and 0.90 ($M = 0.81$, $SD = 0.07$), indicating on average reasonably good predictive power (Hosmer and Lemeshow, 2000).

The individual normalized temporal weights were analyzed with repeated-measures analyses of variance (rmANOVAs) using a univariate approach with Huynh-Feldt correction for the degrees of freedom (Huynh and Feldt, 1976). The correction factor $\tilde{\varepsilon}$ is reported, and partial η^2 is reported as measure of association strength. An α-level of 0.05 was used for all analyses.

2.2. Results

The average sensitivity in terms of *d'* is shown in Table 1 for each of the five gap durations. There was no significant effect of gap duration on *d'*, $F(4, 32) = 0.973$, $\tilde{\varepsilon} = 1$, $p = .436$, $\eta_p^2 = 0.108$.

Table 1
Mean sensitivity (*d'*) in the five different conditions of Experiment 1. $N = 9$.

Gap duration (ms)	*Mean of d'*	*SD of d'*
0	0.87	0.26
50	0.96	0.29
350	0.91	0.32
700	0.93	0.28
1400	0.9	0.27

The black circles in Fig. 2 show the mean normalized weights for the five different gap durations presented in Experiment 1. At each gap duration, we observed a clear primacy effect at the beginning of the sound, in the sense that the weight on the first segment was higher than the weights on the following segments. In addition, particularly at the longer gap durations, the mean weight on the 6th segment was higher than the weights on the neighboring segments, indicating a reoccurrence of a primacy effect after the silent gap.

We conducted an rmANOVA with the within-subjects factors gap duration (0, 50, 350, 700, 1400 ms) and segment number (1–10). The effect of segment number was significant, $F(9, 72) = 14.07$, $\tilde{\varepsilon} = 0.346$, $p < .001$, $\eta_p^2 = 0.638$, indicating that the weights differed between the ten segments. The gap duration × segment number interaction was also significant, $F(36, 288) = 9.21$, $\tilde{\varepsilon} = 0.450$, $p < .001$, $\eta_p^2 = 0.535$, which confirms that the pattern of weights differed between the different gap durations, compatible with the expected reoccurrence of the primacy effect after silent gaps.

To further analyze this interaction, we conducted four post-hoc rmANOVAs, each comparing the pattern of weights for a sound containing a gap to the condition without a gap (i.e., 0-ms gap duration). The gap duration × segment number interaction was significant ($p < .001$) in all rmANOVAs involving gap durations longer than 50 ms. Thus, the pattern of temporal weights differed significantly between the sounds without a gap and the sounds with gap durations of 350, 700, and 1400 ms. Separate rmANOVAs for each gap duration with only the weights of the second sound part (segments 6–10) included showed a significant main effect of segment number for all four gap durations (all p values $< .01$, $\eta_p^2 = 0.379$, 0.520, 587 and 0.753 for the 50, 350, 700 and 1400 ms gap duration, respectively), but not for the weights in the condition without a gap ($p = .380$, $\eta_p^2 = 0.118$). Thus, for gap durations of 350 ms and above, the data show a significant primacy effect on the second sound part.

3. Experiment 2

Experiment 1 showed a significant primacy effect after a silent gap within a sound, compatible with the expected resetting of the primacy effect. Descriptively, a primacy effect on the sound portion after the gap was observed at gap durations of 50 ms or longer (see black circles in Fig. 2). Its size increased with the gap duration, and the effect was significant for gap durations of 350 ms and longer. To get a more detailed picture of the relation between gap duration and the size of the primacy effect on the second sound part (i.e., the amount of resetting of the primacy effect), we presented sounds with gap durations below 400 ms in Experiment 2.

3.1. Method

3.1.1. Listeners

In Experiment 2, eight listeners with normal hearing participated (5 female, 3 male, age 19–29 years). None of them had participated in Experiment 1. They reported no history of hearing problems. Hearing thresholds were measured by Békésy audiometry with pulsed 270-ms pure tones. All listeners showed thresholds less than or equal to 15 dB HL bilaterally in the frequency range between 125 Hz and 8 kHz.

3.1.2. Stimuli, apparatus, and procedure

Stimuli, apparatus and procedure were essentially the same as in Experiment 1, expect for the gap durations. In addition to the gap durations of 0 ms, 50 ms, and 350 ms that were already presented in Experiment 1, gap durations of 19 ms and 132 ms were also included to gain a more detailed insight into the reoccurrence of the primacy effect for gap durations below 350 ms.

3.1.3. Data analysis

Again, a separate logistic regression model was fitted for each combination of listener and gap duration. Across the 40 fitted logistic regression models, the area under the ROC curve ranged between 0.70 and 0.91 ($M = 0.83$, $SD = 0.06$), and thus was comparable to the values from Experiment 1.

3.2. Results

The average sensitivity in terms of d' in the five conditions is shown in Table 2. There was no significant effect of gap duration on d', $F(4, 28) = 0.408$, $\tilde{\varepsilon} = 1$, $p = .801$, $\eta_p^2 = 0.055$.

The blue squares in Fig. 2 show the mean normalized weights for the five different gap durations presented in Experiment 2. At each gap duration, there was a primacy effect at the beginning of the sound, in the sense that the weight on the first segment was higher than the weights on the following segments.

At a gap duration of 132 ms, the mean weight on the 6th segment was higher than the weights on the neighboring segments, indicating a reoccurrence of the primacy effect after the silent gap. This was not observed for the other gap durations.

We conducted an rmANOVA with the within-subjects factors gap duration (0, 19, 50, 132, 350 ms) and segment number (1–10). There was a significant effect of segment number, $F(9, 63) = 20.23$, $\tilde{\varepsilon} = 0.249$, $p < .001$, $\eta_p^2 = 0.743$, indicating that the weights differed between the ten segments. The gap duration × segment number interaction was not significant, $F(36, 252) = 1.50$, $\tilde{\varepsilon} = 0.476$, $p = .105$, $\eta_p^2 = 0.176$, which indicates a smaller effect of gap duration on the temporal weights compared to Experiment 1. This is not unexpected due to the shorter gap durations compared to Experiment 1.

We conducted four post-hoc rmANOVAs, each comparing the pattern of weights for a sound containing a gap to the condition without a gap (i.e., 0 ms gap duration). The gap duration × segment number interaction was not significant ($p > .05$) in any rmANOVA. Note that this also included the data for the gap duration of 350 ms, where the data from Experiment 1 showed a significant primacy effect on the second part of the sound, while in Experiment 2, this significant reoccurrence was absent.

4. Experiment 3

Experiment 1 showed a significant primacy effect after a silent gap of at least 350 ms within a sound, compatible with the expected resetting of the primacy effect. In Experiment 2, the recovery of the primacy effect was weaker than in Experiment 1. There was no significant reoccurrence of primacy effect after a 350-ms gap. Experiment 3 was conducted to provide additional data concerning the recovery of the primacy effect for gap durations between 350 and 700 ms.

Table 2
Mean sensitivity (d') in the five different conditions of Experiment 2. $N = 8$.

Gap duration (ms)	*Mean of d'*	*SD of d'*
0	1.02	0.31
19	0.96	0.28
50	0.99	0.21
132	1.02	0.18
350	0.96	0.21

4.1. Method

4.1.1. Listeners

In Experiment 3, nine listeners with normal hearing participated (8 female, 1 male, age 19–27 years). None of them had participated in Experiment 1 or 2. They reported no history of hearing problems. Hearing thresholds were measured by Békésy audiometry with pulsed 270-ms pure tones. All listeners showed thresholds less than or equal to 15 dB HL bilaterally in the frequency range between 125 Hz and 8 kHz.

4.1.2. Stimuli, apparatus, and procedure

Exactly the same stimuli, apparatus and procedure as in Experiment 1 and 2 were used, expect that gap durations of 0, 350, 500 and 700 ms were presented. Three of the gap durations (0, 350 and 700 ms) were identical to gap durations used in Experiment 1. The gap duration of 500 ms was included, in order to gain a more detailed insight into the reset of the primacy effect for gap durations between 350 and 700 ms.

4.1.3. Data analysis

Again, a separate logistic regression model was fitted for each combination of listener and gap duration. Across the 36 fitted logistic regression models, the area under the ROC curve ranged between 0.75 and 0.89 ($M = 0.83$, $SD = 0.04$), and thus was comparable to the values from Experiment 1 and 2.

4.2. Results

The average sensitivity in terms of d' in the four conditions is shown in Table 3. There was no significant effect of gap duration on d', $F(4, 32) = 1.517$, $\tilde{\varepsilon} = 0.749$, $p = .246$, $\eta_p^2 = 0.159$.

The red diamonds in Fig. 2 show the mean normalized weights for the four different gap durations in Experiment 3. At each gap duration, we observed a clear primacy effect at the beginning of the sound. In addition, particularly at the 500 and 700 ms gap durations, the mean weight on the 6th segment was higher than the weights on the neighboring segments, indicating a reoccurrence of the primacy effect after the silent gap. There also was a trend for a recency effect in the sense that the weights for the segments at the end of a sound (-part) were higher than the weights assigned to the segments in the middle of a sound part.

We conducted an rmANOVA with the within-subjects factors gap duration (0, 350, 500 and 700 ms) and segment number (1–10). There was a significant effect of segment number, $F(9, 72) = 10.63$, $\tilde{\varepsilon} = 0.373$, $p < .001$, $\eta_p^2 = 0.571$, indicating that the weights differed between the ten segments. The gap duration × segment number interaction was significant, $F(27, 216) = 6.32$, $\tilde{\varepsilon} = 0.650$, $p < .001$, $\eta_p^2 = 0.441$, which confirms that the pattern of weights differed between the different gap durations, compatible with the expected reoccurrence of the primacy effect after silent gaps.

To further analyze this interaction, we conducted three post-hoc rmANOVAs, each comparing the pattern of weights for a sound containing a gap to the condition without a gap (i.e., 0 ms gap duration). The gap duration × segment number interaction was significant ($p < .001$) in all rmANOVAs. Taken together, Experiment 3 confirmed the observation from Experiment 1 that after a silent gap of 700 ms inserted into a sound, the primacy effect on the second sound part is similar in size to the primacy effect at sound onset. As in Experiment 1, but unlike in Experiment 2, the reoccurrence of the primacy effect was statistically significant already at a gap duration of 350 ms.

Table 3
Mean sensitivity (d') in the four different conditions of Experiment 3. $N = 9$.

Gap duration (ms)	*Mean of d'*	*SD of d'*
0	0.97	0.27
350	1.05	0.22
500	1.00	0.21
700	1.06	0.14

5. Comparison across experiments and quantification of the primacy effect on the second sound part

Four of the gap durations were presented in at least two experiments, namely the 0-ms gap control condition (presented in Experiment 1, 2, and 3), 50 ms (presented in Experiment 1 and 2), 350 ms (presented in Experiment 1, 2 and 3), and 700 ms (presented in Experiment 1 and 3). Fig. 3 shows the mean normalized weights for those four conditions, averaged across experiments. Descriptively, when the sounds contained a gap, the weight on segment 6 (the first segment of the sound part following the gap) was higher than for the following segments, indicating a reoccurrence of the primacy effect on the second sound part. The size of this second primacy effect increased with the gap duration.

We conducted separate rmANOVAs, each comparing the weights in the condition without gap (gap duration 0 ms) with the weights in a condition containing a silent gap (gap duration 50, 350, or 700 ms). The within-subjects factors were gap duration and segment number (1–10), and the between-subjects factor was experiment.

When comparing the 0-ms and the 50-ms gap duration, the gap duration × segment number interaction was not significant, $F(9, 135) = 1.77$, $\tilde{\varepsilon} = 0.680$, $p = .113$, $\eta_p^2 = 0.105$. In the rmANOVA comparing the 0-ms and the 350-ms gap duration, the gap duration × segment number interaction was significant, $F(9, 207) = 11.82$, $\tilde{\varepsilon} = 0.762$, $p < .001$, $\eta_p^2 = 0.339$. This confirms the conclusion from Experiment 1 that there is evidence for a significant primacy effect on the second sound part after a silent gap of 350 ms. The experiment × duration × segment number interaction was also significant, even though the size of the effect was comparably small, $F(18, 207) = 2.38$, $\tilde{\varepsilon} = 0.762$, $p = .005$, $\eta_p^2 = 0.171$. As shown in Fig. 2, the effect of the 350-ms gap on the weighting patterns was not identical in the three experiments.

For the rmANOVA comparing the 0-ms and the 700-ms gap duration, the gap duration × segment number interaction was also significant, $F(9, 144) = 23.70$, $\tilde{\varepsilon} = 0.554$, $p < .001$, $\eta_p^2 = 0.597$. The increased effect size compared to the interaction effect in the ANOVA comparing the 350 ms gap duration with 0 ms highlights the increasing difference in the weighting patterns with increasing gap duration (see Fig. 3). The experiment × duration × segment number interaction was not significant for the comparison of 0 ms gap duration with 700 ms gap duration, $F(9, 144) = 2.03$, $\tilde{\varepsilon} = 0.554$, $p = .083$, $\eta_p^2 = 0.113$.

The statistical analyses reported so far show that the strength of the primacy effect on the second sound part increases with the duration of the silent gap. In order to provide a quantitative measure of the strength of the reoccurrence of the primacy effect after the gap, we first quantified the magnitude and time course of the primacy effect for each sound part. Following the approach developed in our previous work (Oberfeld et al., 2018; Oberfeld et al., 2018), we fitted exponential decay functions to the mean weights at each of the different gap durations, for each sound part separately. As described in Oberfeld et al. (2018), the weight assigned at the time t was assumed to be

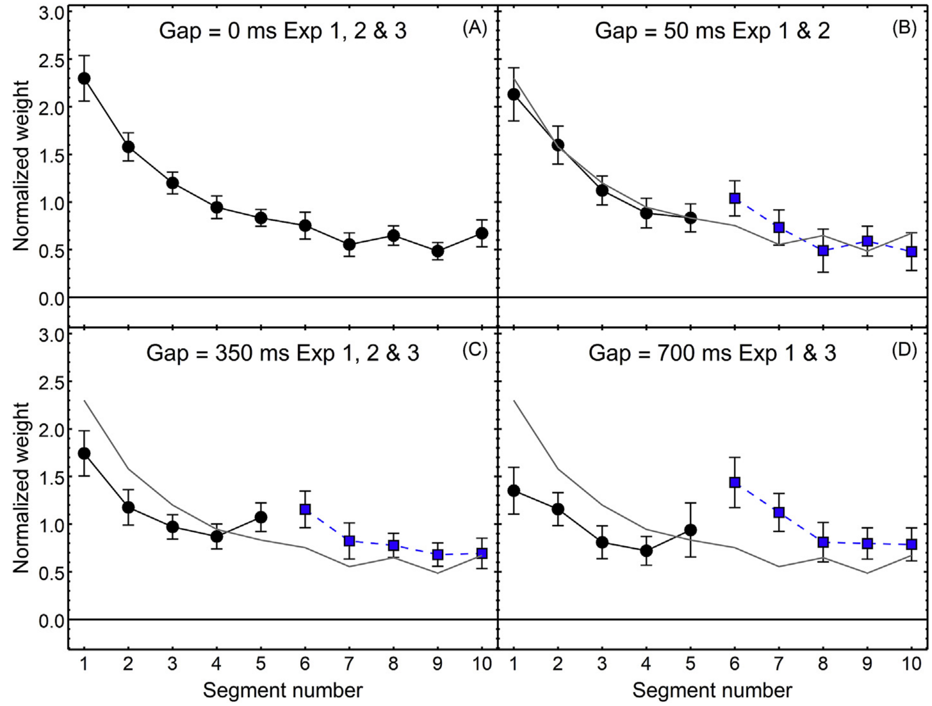

Fig. 3. Mean normalized regression coefficients averaged across experiments, as a function of segment number. Only gap durations that had been presented in more than one experiment are displayed. The average weights for the contiguous sounds (gap duration 0 ms) displayed in panel A are re-plotted in panels B–D as a gray line for comparison. Black circles: sound part 1. Blue squares: sound part 2. Error bars show 95% confidence intervals (CIs). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$w(t) = c\left(D_r \cdot e^{-\frac{t}{\tau}} + 1\right), \quad (1)$$

where $t = 0$ corresponds to the onset of the sound part, c is the asymptotic weight at $t \to \infty$, D_r is the weight at sound part onset ($t = 0$) relative to the asymptotic weight $w(\infty) = c$ (i.e., D_r is the "dynamic range" of the weights), and the time constant τ quantifies the time needed for the weight to decay to a value of $1/e$ of the weight range between $w(0)$ and the asymptotic weight c. The weight assigned to a temporal segment with onset at t_{on} and duration d was assumed to be the integral of $w(t)$ across the segment duration,

$$\overline{w}(t_{on}, d) = \int_{t=t_{on}}^{t_{on}+d} w(t)dt. \quad (2)$$

The strength of the primacy effect can be measured in terms of the difference between the weight at sound part onset, $w(t = 0)$, and the asymptotic weight, $w(t \to \infty)$. A large value of this difference indicates a strong primacy effect. According to Eq. (1), $w(0) - w(\infty) = c\, D_r$. For each gap duration, we first computed the weight difference $c\, D_r$ for each sound part separately. We then computed the reoccurence strength of the primacy effect (i.e., the relative size of the primacy effect on sound part 2 compared to sound part 1) as

$$rp = \frac{w_{SP2}(0) - w_{SP2}(\infty)}{w_{SP1}(0) - w_{SP1}(\infty)} = \frac{c_{SP2}D_{rSP2}}{c_{SP1}D_{rSP1}}, \quad (3)$$

where the indices SP1 and SP2 denote the first and second sound part, respectively.

To estimate the parameters of the decay function (Eq. (1)) per sound part, the function $\overline{w}(t_{on}, d)$was fitted to the mean weights for each gap duration and sound part separately, using the Mathematica function *NonlinearModelFit*. Constraints were set for τ (lower bound = 50 ms) and c (lower bound = 0.001). To account for the different numbers of subjects per experiment and the different within-experiment variability of the temporal weights, the weight for each data point w_i was set proportional to $1/SE^2_{w_i}$, where $SE^2_{w_i}$ is the standard error of the individual estimated weights for segment i in a given experiment. The exponential decay function provided an excellent fit to the mean weights for both sound parts for all gap

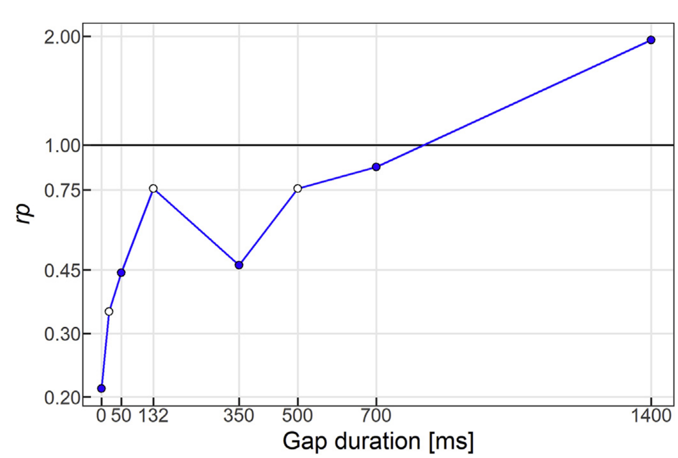

Fig. 4. Mean reoccurrence strength of the primacy effect (*rp;* defined in Eq. (3)) in Experiments 1–3, as a function of gap duration. Filled circles represent gap durations that were presented in more than one experiment (see Fig. 3). Open circles represent gap durations that were presented in only a single experiment.

durations (all $R^2 \geq 0.96$).

Fig. 4 shows *rp* as a function of gap duration. The mean strength of reoccurrence increased steadily from a gap duration of 0 ms to a gap duration of 700 ms, where on average the primacy effect on the second sound part was almost comparable in size to the primacy effect on the first sound part (mean $rp = 0.87$). The strength of reoccurrence at the 132-ms gap was higher than at the gap duration of 350 ms. However, this gap duration was studied only in one experiment, and we expect that this result reflects individual differences rather than a systematic pattern. At the 1400-ms gap, the primacy effect on sound part 2 was almost two times stronger than on sound part 1 (mean $rp = 1.95$). Again, additional data from different samples are required in order to evaluate whether this represents a systematic pattern.

6. Experiment 4

Experiments 1 to 3 showed significant changes in the temporal weighting patterns for sounds that included silent gaps. The results from all of the three experiments were compatible with the expected reoccurrence of the primacy effect after a silent gap. In Experiment 4, we addressed the question of whether for the reoccurrence of the primacy effect a completely silent gap is necessary or if it is sufficient to reduce the sound pressure level within the middle part of a sound by a certain amount.

6.1. Method

6.1.1. Listeners

In Experiment 4, eight listeners with normal hearing participated (5 female, 3 male, age 19–39 years). None of them had participated in Experiment 1, 2 or 3. They reported no history of hearing problems. Hearing thresholds were measured by Békésy audiometry with pulsed 270-ms pure tones. All listeners showed thresholds less than or equal to 15 dB HL bilaterally in the frequency range between 125 Hz and 8 kHz.

6.1.2. Stimuli, apparatus, and procedure

The same type of stimuli and the same apparatus and procedure as in Experiment 1, 2 and 3 were used, except that this time, the stimuli in three of the four presented conditions consisted of 17 contiguous broadband noise segments. In two of the latter conditions, the seven middle segments (segment numbers 6–12) were attenuated by 15 or 30 dB SPL relative to the remaining segments (see insets in Fig. 5). There was also one condition in which no attenuation was applied to the seven middle segments. This condition corresponds to the contiguous sounds (gap duration 0 ms) in Experiments 1–3. In addition, one condition with sounds consisting of ten broadband segments with a completely silent gap of 700 ms in the middle of the sound was presented.

6.1.3. Data analysis

Again, a separate multiple logistic regression model was fitted for each combination of listener and condition. Across the 32 fitted models, the area under the ROC curve ranged between 0.74 and 0.92 ($M = 0.83$, $SD = 0.04$), and thus was comparable to the values from Experiment 1, 2 and 3. The estimated weights were normalized so that the mean of the ten segments that did not receive an attenuation in any condition (i.e., segments 1–5 and 13–17 for the 17-segment sounds; segments 1–10 for the 10-segment sounds with a silent gap) was 1.0. This normalization facilitates the comparison between the weights in the 17-segment conditions and the condition containing 10 segments and a silent gap.

6.2. Results

The average sensitivity in terms of *d'* in the five conditions is shown in Table 4. This time, the effect of condition on *d'* was significant, $F(3, 21) = 6.774$, $\tilde{\varepsilon} = 0.593$, $p = .012$, $\eta_p^2 = 0.492$. Descriptively, performance was best in the condition with a silent gap. However, the difference in *d'* between the conditions with, on average, best and worst performance was only 0.15.

Fig. 5 shows the mean normalized weights for the four different attenuations of the middle segments in Experiment 4. Descriptively, the data show a clear primacy effect at sound onset for each of the four conditions. Compared to the weights obtained for the contiguous sound without an attenuated sound part, the two conditions with seven attenuated segments in the temporal center and the condition with a silent gap showed higher weights after the attenuated middle segments or the silent gap, at the unattenuated segment with onset time 1200 ms. The pattern of the weights in the two attenuated conditions and in the condition with a silent gap were quite similar. The mean weights for virtually all of the attenuated segments in the middle of the sound were not significantly different from zero (see CIs in Fig. 5).

We conducted an rmANOVA with the within-subjects factors attenuation of the middle segments (no attenuation, 15 dB, 30 dB, and 700-ms silent gap) and segment onset (0, 100, 200, 300, 400, 1200, 1300, 1400, 1500, and 1600 ms). Note that the weights estimated for the middle segments with onsets between 500 and 1100 ms were not included in this analysis. There was a significant effect of segment number, $F(9, 63) = 12.22$, $\tilde{\varepsilon} = 0.329$, $p < .001$, $\eta_p^2 = 0.636$, indicating that the weights differed between the ten unattenuated segments. The attenuation × segment number interaction was also significant, $F(27, 189) = 11.12$, $\tilde{\varepsilon} = 0.515$, $p < .001$, $\eta_p^2 = 0.614$, which confirms that the pattern of weights differed between the different conditions.

To gain further insight into the differences between the weighting patterns, we conducted separate post-hoc rmANOVAs for each pair of conditions. The weights of the segments with onsets between 500 and 1100 ms were again excluded from the analysis. Each of the separate comparisons of the weights in the unattenuated condition with either one of the conditions with attenuated middle segments or the condition with a 700 ms silent gap showed a significant condition × segment number interaction (all *p* values < .001, $\eta_p^2 = 0.550$ - 0.758). This confirms that a second primacy effect emerged after either a silent gap or a period with reduced level within a contiguous sound. Both separate comparisons of the weights in the condition with an attenuation of 15 dB with the condition with an attenuation of 30 dB and the condition with a silent gap also showed significant condition × segment number interactions ($p = .003$ and $p = .002$, respectively). As shown in Fig. 5, the condition with an attenuation of 30 dB and the condition with a silent gap both showed slightly more pronounced primacy effects after the “gap” and a stronger reduction in weights of the first part of the sound compared to the condition with an attenuation of 15 dB. However, the effect sizes for the latter comparisons were smaller ($\eta_p^2 = 0.374$ and $\eta_p^2 = 0.353$, respectively) compared to the effect sizes in the rmANOVAs comparing the weights for the sounds with “gaps” to the weights for the sound not containing attenuated segments. Taken together, results from Experiment 4 indicate that a) the pattern of the weights in both of the attenuated conditions and the condition with the 700-ms silent gap differed from the weights in the unattenuated condition, which is compatible with our hypothesis of a reoccurrence of the primacy effect, and b) that the pattern of the weights varied less substantially between the conditions with different amounts of attenuation and the condition with a silent gap.

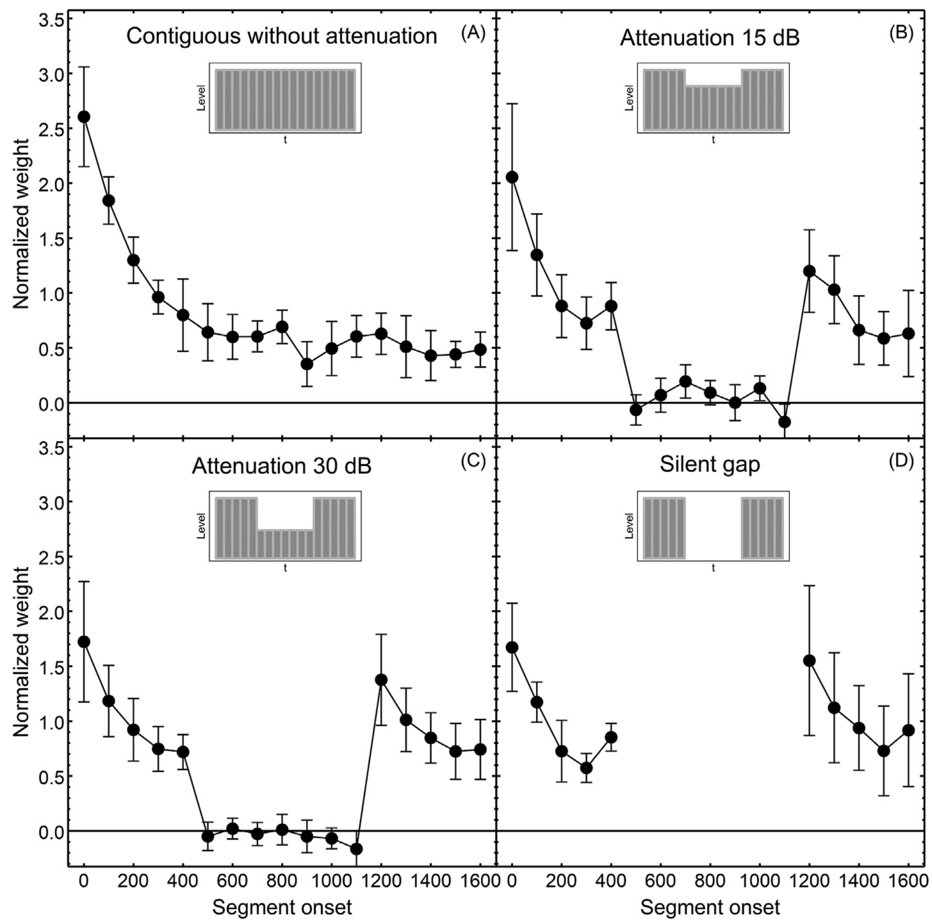

Fig. 5. Mean normalized regression coefficients in the four conditions of Experiment 4, as a function of segment number. Schematic depictions of the mean level profile of the stimuli are shown in each panel. Error bars show 95% confidence intervals (CIs).

Table 4
Mean sensitivity (d') in the four different conditions of Experiment 4. $N = 8$.

Attenuation of the middle segments	*Mean of d'*	*SD of d'*
without attenuation (0 dB)	1.08	0.17
15 dB	1.03	0.17
30 dB	1.00	0.15
silent gap	1.15	0.22

In order to provide a quantitative measure of the strength of the reoccurrence of the primacy effect in the four different conditions of Experiment 4, we computed *rp* as defined in Eq. (3), based on fits of the exponential decay function (Eq. (2)), for each condition and sound part separately. Note that we split the contiguous conditions that contained no gap into three sound parts (sound part 1 = segment 1 to 5, sound part 2 = segment 6 to 12, sound part 3 = segment 13 to 17). We then computed *rp* based on the estimated decay function parameters for sound part 3 and sound part 1. In the condition presenting a silent gap, there were only two sound parts, and we computed *rp* based on the estimated decay function parameters for sound part 2 and sound part 1. The estimated values of *rp* are shown in Fig. 6 as a function of the attenuation of the middle segments. The mean strength of reoccurrence increased steadily from the condition with no attenuation of the middle segments to the conditions with 30 dB attenuation or a silent gap. This reflects the pattern of results from the statistic tests presented above, where the pattern of the weights differed significantly between the no-attenuation condition and all remaining conditions.

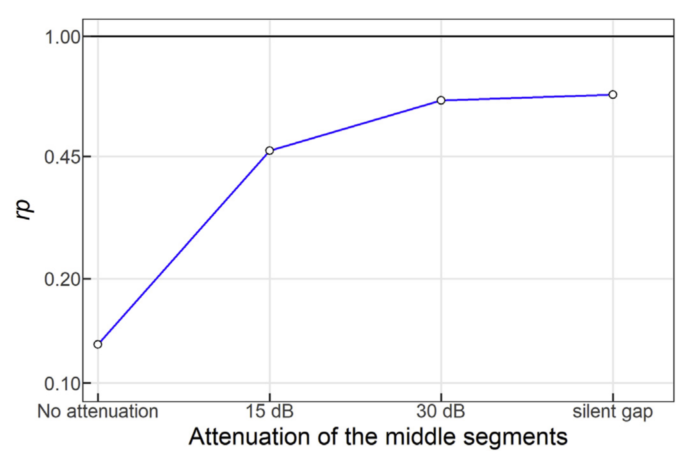

Fig. 6. Mean reoccurrence strength of the primacy effect (*rp;* defined in Eq. (3)) in Experiment 4, as a function of the attenuation of the middle segments.

7. Discussion

In Experiments 1–3, we investigated how the recovery of the mechanisms causing the primacy effect in loudness weights (higher weights assigned to the beginning of a sound than to later temporal portions) depends on the duration of a silent gap inserted into a level-fluctuation sound. We varied the duration of a silent gap inserted in the middle of a level-fluctuating sound within and between experiments. Gap durations ranging from 19 to 1400 ms were investigated. It turned out that the pattern of the weights observed when sounds contained a silent gap differed significantly from the pattern of the weights obtained for contiguous sounds already at a gap duration of about 350 ms. This primacy effect on the post-gap part of the sound became more pronounced at gap durations of 500 ms and above. In such conditions, the weighting patterns of the two parts of the sound (i.e., the first part = the part before the gap, and the second part = the part after the gap) were similar in shape as well as in the magnitude of the weights (with one exception that is discussed below). Put differently, at gap durations of 500 ms or longer, we found a significant primacy effect on both parts of the sound, and both parts contributed more or less equally to the overall judgment of loudness. The strength of reoccurrence of the primacy effect (i.e., the relative size of the primacy effect on sound part 2 after the gap compared to sound part 1 before the gap) increased monotonically with the gap duration, except for an unexpectedly large reoccurrence strength at a gap duration of 132-ms in Experiment 2. In Experiment 1, for a gap duration of 1400 ms, the second sound part dominated the loudness judgment in the sense that the weights on this part of the sound were higher compared to the weights of the first sound part. This might indicate that after a gap of this duration, listeners have difficulties in remembering the first sound part and thus focus on the second sound part when making their decision. However, the large primacy effects on the second sound part at a 132-ms gap and a 1400-ms gap remain to be replicated in future experiments. We expect that across experiments, the strength of reoccurrence of the primacy effect at a 132-ms gap would be smaller than for longer gap durations, and that the strong emphasis on the second sound part at a 1400 ms gap would also not be observed consistently.

In Experiment 4, we examined whether to trigger the reoccurrence of the primacy effect there needs to be a silent gap, or if already a reduction in sound pressure level by 15 or 30 dB SPL in the middle of a contiguous sound is sufficient. It turned out that the latter was the case. A reduction in level of the middle segments by 15 dB SPL and more resulted in effects similar to those of a silent gap. We therefore conclude that for a reoccurrence of the primacy effect to take place, a reduction in the sound pressure level in the middle part of a sound is sufficient. However, as the primacy effect after the attenuated sound part was less pronounced at the 15-dB attenuation than after the 30-dB attenuation or a silent gap, it appears that the recovery of the mechanism that causes the primacy effect was to some degree slowed down or hindered by the presence of the attenuated middle segments.

As pointed out in the Results section for Experiment 4, the attenuated middle segments received weights that did not differ statistically from zero which indicates that those segments were practically ignored in the judgment of the loudness of the sound. This occurred despite the fact that these segments did not differ in their reliability compared the segments that received no attenuation. The difference in mean level between the level distributions with higher and lower mean as well as the standard deviation of the level distributions for the attenuated and the unattenuated segments were identical, so that in theory the attenuated segments were equally predictive for the overall loudness of the sound (Berg, 1990; Oberfeld and Plank, 2011). The observed near-zero weights assigned to the attenuated segments are in accordance with a phenomenon termed *loudness dominance* (e.g., Berg, 1990; Lutfi and Jesteadt, 2006; Oberfeld, 2015; Oberfeld et al., 2013; Ponsot et al., 2013; Turner and Berg, 2007; Oberfeld, 2008). In loudness dominance, temporal portions of a sound that are relatively higher or lower in level compared to the rest of the sound receive increased or decreased weights, respectively, in the judgment of loudness or frequency.

Taken together, our data indicate a gradual increase of the primacy effect on the second sound part with the duration of the silent gap, indicating a gradual recovery of the mechanisms causing the primacy effect during a silent gap or a sound part with reduced sound level. An alternative account for the data is that a complete recovery of the mechanism causing the primacy effect occurs on a proportion of trials, while no reset occurs on the remaining trials. If the probability of the reset increases gradually with increasing gap duration, this would result in exactly the same patterns of weights as a gradual recovery.

7.1. Possible sources of the primacy effect

There are different possible sources of the primacy effect which might also contribute to a reoccurrence after a silent gap and are, at least theoretically, in accordance with the observed results. The first explanation that is compatible with some of the observed results is based on the response characteristics of auditory nerve neurons. The firing rate of the auditory nerve (AN) neurons shows a peak at the onset of a sound and a following adaptation to a lower steady-state rate (Kiang et al., 1965; Nomoto et al., 1964; Rhode and Smith, 1985). As discussed by Oberfeld and Plank (2011), the onset-peak, which typically lasts a few milliseconds, is qualitatively compatible with a higher weight on the first segment of a sound, while on the basis of the AN responses it is not immediately clear how the initial peak can account for the increased weights observed at more than 100 ms after the sound onset (see Fig. 2). Notwithstanding this unresolved question, some of the results on the response characteristics of AN fibers also seem to be in line with the observed results in the present study. One of those findings is that the difference between the initial peak in the firing rate of AN fibers and the steady-state rate was found to be reduced at short ISIs for the low spontaneous-rate (LSR) fibers in a study by Relkin and Doucet (1991). At an ISI of 100 ms, the magnitude of the onset peak was approximately only 70% of the magnitude at an ISI of 1.9 s. For ISIs of around 300 ms, this percentage increased to more than 80%. What is even more important for the explanation of the primacy effect and its reoccurrence is that the ratio between the onset peak and the steady state-rate increased even more strongly with increasing ISIs than the amplitude of the onset peak. For ISIs of around 100 ms, the probability for a spike to occur at the onset of a sound was smaller than two times the probability for a spike to occur when the neuron has reached the adapted state. In contrast, for ISIs of around 300 ms the probability for a spike to occur was well above two times the probability for a spike to occur in the adapted phase. Thus, the appropriate duration of the silent gap for a reset of the primacy effect found in our study roughly corresponds to the duration of the ISIs necessary to regain a pronounced initial peak in the firing rate of the LSR auditory nerve neurons in the study by Relkin and Doucet (1991). As the size of the initial peak in the firing rate of the LSR fibers at the onset of a sound increased with increasing ISI, these findings are also compatible with the observed effect of increasing primacy effects on the second sound part with increasing ISIs. The results from Experiment 4 are also roughly compatible with a role of the initial peak in the firing rate of AN fibers. The amplitude of the initial peak is level dependent and the same holds true for a peak in the firing rate seen when a level increment occurs in an ongoing sound (Furukawa and Matsuura, 1978; Kiang et al., 1965; Yates et al., 1985). This is compatible with more pronounced reoccurrences of the primacy effect at higher levels of attenuation of the middle segments in Experiment 4. An explanation based on the AN fiber responses can also account for the recovery of the primacy effect when the frequency spectrum changes abruptly within an ongoing sound, as reported by

Pedersen and Ellermeier (2008). Each AN fiber is only encoding a limited frequency range. Thus, when the spectrum changes, AN fibers encoding the frequencies that were exclusive to the portion after the spectral changes will show an onset response.

As noted above, the response characteristics of the AN fibers are not compatible with all results on temporal loudness weights. For instance, in a recent study from our lab (Fischenich et al., 2019), we compared temporal loudness weights for sounds presented with varying average signal levels and either in quiet or in the presence of a continuous background noise. As the amplitude of the onset-peak in the firing rate of AN fibers as well as the difference between the onset-peak and the steady-state rate have shown to be level-dependent (Kiang et al., 1965; Yates et al., 1985) and to be affected by background noise (Simmons et al., 1992), the temporal weighting patterns should be altered under different signal levels and in different background conditions if the primacy effect was due to the onset-peak in the AN firing rate. The data by Fischenich et al. (2019) did not show such an effect, but instead very similar temporal weighting patterns for different signal levels and background conditions. As a cautionary note, the neuronal auditory pathway is quite complex and involves different types of neurons as well as efferent and afferent loops. It would therefore require significant additional research to evaluate to which extent processes in the auditory periphery might contribute to the primacy effect at sound onset and after a silent gap.

A second potential explanation of the primacy effect and its observed reoccurrence are effects of non-simultaneous masking on auditory intensity processing. Zeng et al. (1991) reported that the intensity-difference-limens (DLs) for 1000 Hz pure tones that followed a narrow-band noise masker with 90 dB SPL were substantially increased when the sound pressure level of the pure tone was around 40–60 dB SPL, termed as the *mid-level hump in intensity discrimination*. To investigate the time course of the recovery of the DL, they varied the interval between the masker and the target tone. It turned out that the DLs were increased even up to masker-target-intervals of 400 ms, although the effects were substantially reduced compared to shorter masker-target-intervals. With a segment duration of 100 ms as in the present study, the first segment could potentially reduce the intensity resolution for the second or third segment due to forward masking, because the latter two segments are presented within a 200-ms window after the offset of segment 1. In such a case, a primacy effect (i.e., higher weight assigned to the first than to the second or third segment) would arise if listeners placed a higher weight on segments for which the intensity resolution is high (Green, 1958; Oberfeld et al., 2013). A silent gap inserted into the sound would reduce the effects of forward masking on the segment(s) following the gap. As mentioned above, forward masking effects have found to be still fading but already substantially reduced at 400-ms masker-target intervals. The observed significant reoccurrence of a primacy effect on the second sound part at a gap duration of 350 ms, which became more pronounced at gap durations of 500 and 700 ms, is thus roughly compatible with the time course of the forward-masking effect on intensity discrimination (Zeng et al., 1991). The results from Experiment 4, where an attenuation of the middle segments led to a reoccurrence of the primacy effect, is also in accordance with masking effects. As no DL-elevation due to forward masking is observed for masker levels below the target level (Oberfeld, 2008; Zeng et al., 1991), the 15 or 30 dB reduction in sound pressure level for a period of 700 ms within the sound should have resulted in an absence of a masker-induced DL-elevation for the first segment following the attenuated sound part. However, two issues related to the potential explanation of the primacy effect in terms of reduced intensity resolution due to non-simultaneous masking need to be discussed. First, maskers equal in level to the target show virtually no effect on intensity DLs (e.g., Zeng et al., 1991). In the present study, all segments part of the stimuli in Experiment 1–3 had the same mean level. Yet, as the sound pressure levels of the segments randomly fluctuated around the mean level from trial to trial, the probability that a given segment followed a segment with a higher level increased with the segment's serial position within the sound. As Zeng et al. (1991) reported elevated intensity DLs for masker-target-intervals of 400 ms, one could assume that in our experiment the intensity resolution was continuously reduced at least for the first four segments, after which the sensitivity might have reached a minimum for the rest of the sound. Second, a more serious restriction is that the proposed explanation based on masking so far only accounts for *forward* masking and completely neglects *backward* masking effects. However, in some studies effects of backward masking on intensity discrimination were found to be even stronger than forward masking effects (Oberfeld and Stahn, 2012; Plack et al., 1995). Using the same rationale as for forward masking, backward-masking effects would have resulted in the *opposite* temporal weighting pattern compared to forward masking effects, with pronounced recency effects (i.e., higher weights at the end of a sound) and lower weights at the onset of the sound as the probability that a segment is followed by a segment higher in level decreases with the serial position of the segment within the sound. The explanation of the primacy effect and its reoccurrence based on masking effects on the DLs thus requires that the backward masking effects do not counterbalance or even exceed the forward masking effects on intensity resolution, because otherwise, no differences in intensity resolution would occur across the segment positions. Only one study compared the time course of forward and backward masking effects on intensity discrimination and reported the backward masking effects to level off more quickly than forward masking when the masker-target interval became longer (Plack et al., 1995). This result is compatible with an assumption of forward masking exceeding backward masking in the stimuli presented in the present study, due to the longer time constant for forward compared to backward masking. However, additional experiments are required to confirm that the asymmetry in size of the forward and backward masking effects on intensity resolution are in fact sufficient to explain the consistent observation of a primacy rather than a recency effect in temporal loudness weights. Still, it is interesting to note that if backward masking effects on the DLs would, to some degree, have affected the weights observed in the present study, the insertion of an attenuated sound part in the temporal center of the sound should have led to changes in the weights assigned to segments immediately before the gap. In fact, there was at least a trend for the weights of the last segments before the gap to be slightly increased (see Panel C–D of Fig. 3). The results by Pedersen and Ellermeier (2008), who found a reoccurrence of the primacy effect when the frequency spectrum changes abruptly within a sound are also in line with an explanation based on effects of forward-masking intensity resolution, because Zeng and Turner (1992) found that maskers with frequency components two to three octaves away from the signal frequency did not affect the intensity resolution for the signal.

As proposed by Fischenich et al. (2019), a third potential explanation of the primacy effect and its reoccurrence is provided by an *evidence integration approach* (Vickers, 1970). Evidence integration suggests that when making perceptual judgments, listeners accumulate evidence for each of the possible response alternatives in a random walk process. In the initial model proposed by Vickers (1970), it is assumed that the process stops and a decision is made as soon as sufficient information has been accumulated. Information presented after the decision has been made will be ignored. However, this assumption is not shared in all variants of accumulator models. Bronfman et al. (2016), for instance, investigated accumulator models with different behaviors in the accumulation process, especially regarding the decisional thresholds, also called boundaries. They showed that models that simulate such an evidence accumulation process can produce temporal weighting patterns with either primacy or recency effects, depending on the type of decision boundaries assumed in the model. For the simplest model of evidence accumulation, one would not expect a reoccurrence of the primacy effect after a gap is inserted into a sound. Such a silent gap contains no information about the loudness of the sound and therefore no evidence integration should have taken place during the gap. Thus, one would assume that the process of evidence integration simply continues from the stage where it stopped right before the gap, unless a decision had already been made before the gap. As a result, the weight on the first segment following the gap should not be higher than the weight on the last segment preceding the gap. This prediction is incompatible with the reoccurrence of a primacy effect after a silent gap. Since primacy effects reoccurred within the loudness judgment of sounds that contained gaps as well as for sounds that contained attenuated sound parts, it can be concluded that the primacy effects found in laboratory experiments are not simply caused by the start of a new trial. Instead, it seems plausible to assume that the occurrence of a new sound triggers a primacy effect. From this perspective, an explanation of the observed effect of gap duration on the reoccurrence of a primacy effect on the second sound part is that increasing gap durations result in a higher probability that listeners perceive a sound containing a gap as two separate sounds rather than as one unitary sound. In this case, listeners might then have made a separate judgment (i.e., starting separate evidence integration processes) of the loudness for each of the two sound parts. For the decision concerning the overall loudness of the stimulus, they might have used a (weighted) average of the judgments of the two sound parts. Such a decisional strategy would result in quite similar temporal weighting patterns for both parts of a sound (pre-gap and post-gap) in conditions with longer gaps. Following this line of reasoning, the sounds with the attenuated middle sound parts presented in Experiment 4 might have been perceived as three separate sounds due to the level differences between the “regular”, unattenuated segments and the attenuated segments (i.e., a first sound containing the first five segments with the “regular” sound pressure level, a second sound containing the seven segments with attenuated level, and a third sound containing the last five segments with the “regular” sound pressure level). In the judgment of loudness, the attenuated segments were ignored, showing a loudness dominance effect. Just as for the sounds that contained a silent gap, one could assume that a separate evidence integration process was started at the onset of each perceived sound (i.e., sound part). When combining the results of the three evidence integration processes in terms of a weighted average, the data suggest that the sound part containing the attenuated segments was virtually ignored, resulting in the observed near-zero loudness weights on these segments (loudness dominance effect). A similar explanation would also account for the results by Pedersen and Ellermeier (2008) who found a reoccurrence of the primacy effect when the spectrum changes within an ongoing sound. One could assume that due to the abrupt change in frequency, the presented sounds were perceived as two distinct sounds (or auditory objects) rather than one unitary sound that changes its frequency. A separate evidence integration process might thus have been started at the perceived onset of the “new” sound (i.e., when the frequency changed) and a (weighted) average of the outcomes of the two integration processes for the two perceived sounds might then have been used for the decision.

Taken together, each of the three potential explanations of the primacy effect and its reoccurrence accounts for some aspects of the observed results, while none of them appears to be able to predict the entire pattern of results in the present and earlier studies on temporal loudness weights. Some aspects of the results may already be understood on the basis of auditory nerve responses, but all aspects can only be understood if it is assumed that higher level processes with longer time constants also contribute to loudness weights. Thus, additional research is needed to clarify which mechanisms underlie the observed temporal loudness weights.

8. Conclusion

In four experiments, we consistently found that after a silent gap within a sound, a primacy effect reoccurs on the second part of the sound following the gap, becoming more pronounced as the gap duration increases. A reoccurrence of the primacy effect is also observed when the mean signal level in the middle of a contiguous sound is reduced by 15 or 30 dB, instead of inserting a silent gap. Thus, the mechanisms that cause the primacy effect appear to recover during a silent gap or a sound part with reduced sound level. While several potential explanations of the primacy effect and its reoccurrence have been suggested, it is not yet possible to decide whether all of them contribute to the observed effects and how they interact in this process.

CRediT authorship contribution statement

Alexander Fischenich: Writing - original draft, Writing - review & editing, Formal analysis, Validation, Investigation, Methodology, Software, Data curation, Visualization. **Jan Hots:** Conceptualization, Writing - original draft, Writing - review & editing, Methodology, Software. **Jesko L. Verhey:** Conceptualization, Writing - original draft, Writing - review & editing, Methodology, Software. **Daniel Oberfeld:** Conceptualization, Methodology, Funding acquisition, Supervision, Project administration, Writing - original draft, Writing - review & editing, Formal analysis, Investigation, Software, Validation, Data curation, Visualization, Resources.

Acknowledgements

This work was supported by a grant from Deutsche Forschungsgemeinschaft (DFG; www.dfg.de) to Daniel Oberfeld (OB 346/6-1) and Jesko L. Verhey (VE 373/2-1). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. No additional external funding received. We are grateful to Lorenz Jung for his support in programming the experimental scripts and to Celine Gebbert, Jonas Krämer, Christoph Keßler, Anna-Lena Spies and Sinah Neuwardt for their assistance in data collection.

We would like to thank three anonymous reviewers for constructive comments on an earlier version of this paper, which we think improved the overall quality and depth of the analysis and discussions. Some of the figures in this article have been created using the SciDraw scientific figure preparation system [M. A. Caprio, Comput. Phys. Commun. 171, 107 (2005), http://scidraw.nd.edu].

References

Berg, B.G., 1990. Observer efficiency and weights in a multiple observation task. J. Acoust. Soc. Am. 88, 149–158.

Berg, B.G., Robinson, D.E., 1987. Multiple observations and internal noise. J. Acoust. Soc. Am. 81. S33-S33.

Braida, L.D., Durlach, N.I., 1972. Intensity perception: II. Resolution in one-interval paradigms. J. Acoust. Soc. Am. 51, 483–502.

Bronfman, Z.Z., Brezis, N., Usher, M., 2016. Non-monotonic temporal-weighting

indicates a dynamically modulated evidence-integration mechanism. PLoS Comput. Biol. 12.
Dittrich, K., Oberfeld, D., 2009. A comparison of the temporal weighting of annoyance and loudness. J. Acoust. Soc. Am. 126, 3168–3178. https://doi.org/10.1121/1.3238233.
Fischenich, A., Hots, J., Verhey, J., Oberfeld, D., 2019. Temporal weights in loudness: Investigation of the effects of background noise and sound level. PLoS One 14 (11), e0223075. https://doi.org/10.1371/journal.pone.0223075.
Furukawa, T., Matsuura, S., 1978. Adaptive rundown of excitatory post-synaptic potentials at synapses between hair cells and 8th nerve-fibers in goldfish. J. Physiol. Lond. 276, 193–209.
Green, D.M., 1958. Detection of multiple component signals in noise. J. Acoust. Soc. Am. 30, 904–911.
Hosmer, D.W., Lemeshow, S., 2000. Applied Logistic Regression, second ed. Wiley, New York.
Huynh, H., Feldt, L.S., 1976. Estimation of the Box correction for degrees of freedom from sample data in randomized block and split-plot designs. J. Educ. Stat. 1, 69–82.
IEC 318, 1970. An IEC Artificial Ear, of the Wide Band Type, for the Calibration of Earphones Used in Audiometry. International Electrotechnical Commission, Geneva.
Kiang, N.Y.S., Watanabe, T., Thomas, E.C., Clark, L.F., 1965. Discharge Patterns of Single Fibers in the Cat's Auditory Nerve. M.I.T. Press, Cambridge, Mass.
Lutfi, R.A., 1989. Informational processing of complex sound. I: intensity discrimination. J. Acoust. Soc. Am. 86, 934–944.
Lutfi, R.A., Jesteadt, W., 2006. Molecular analysis of the effect of relative tone level on multitone pattern discrimination. J. Acoust. Soc. Am. 120, 3853–3860.
Nachmias, J., 2006. The role of virtual standards in visual discrimination. Vis. Res. 46, 2456–2464.
Nomoto, M., Katsuki, Y., Suga, N., 1964. Discharge pattern and inhibition of primary auditory nerve fibers in the monkey. J. Neurophysiol. 27, 768–787.
Oberfeld, D., 2008. The mid-difference hump in forward-masked intensity discrimination. J. Acoust. Soc. Am. 123, 1571–1581. https://doi.org/10.1121/1.2837284.
Oberfeld, Daniel, 2008. Does a rhythmic context have an effect on perceptual weights in auditory intensity processing? Canadian Journal of Experimental Psychology 62, 24–32. https://doi.org/10.1037/1196-1961.62.1.24.
Oberfeld, D., 2015. Are temporal loudness weights under top-down control? Effects of trial-by-trial feedback. Acta Acustica United Acustica 101, 1105–1115. https://doi.org/10.3813/aaa.918904.
Oberfeld, D., Plank, T., 2011. The temporal weighting of loudness: effects of the level profile. Atten. Percept. Psychophys. 73, 189–208. https://doi.org/10.3758/s13414-010-0011-8.
Oberfeld, D., Stahn, P., 2012. Sequential grouping modulates the effect of non-simultaneous masking on auditory intensity resolution. PLoS One 7, e48054. https://doi.org/10.1371/journal.pone.0048054.
Oberfeld, Daniel, Jung, Lorenz, Verhey L., Jesko, Hots, Jan, 2018. Evaluation of a model of temporal weights in loudness judgments. Journal of the Acoustical Society of America 144, EL119–EL124. https://doi.org/10.1121/1.5049895.
Oberfeld, D., Kuta, M., Jesteadt, W., 2013. Factors limiting performance in a multitone intensity-discrimination task: disentangling non-optimal decision weights and increased internal noise. PLoS One 8, e79830. https://doi.org/10.1371/journal.pone.0097209.
Oberfeld, D., Hots, J., Verhey, J.L., 2018. Temporal weights in the perception of sound intensity: effects of sound duration and number of temporal segments. J. Acoust. Soc. Am. 143, 943–953. https://doi.org/10.1121/1.5023686.
Pedersen, B., Ellermeier, W., 2008. Temporal weights in the level discrimination of time-varying sounds. J. Acoust. Soc. Am. 123, 963–972.
Plack, C.J., Carlyon, R.P., Viemeister, N.F., 1995. Intensity discrimination under forward and backward masking: role of referential coding. J. Acoust. Soc. Am. 97, 1141–1149.
Plank, T., 2005. Auditive Unterscheidung von zeitlichen Lautheitsprofilen (Auditory discrimination of temporal loudness profiles). PhD thesis. Universität Regensburg, Regensburg.
Ponsot, E., Susini, P., Saint Pierre, G., Meunier, S., 2013. Temporal loudness weights for sounds with increasing and decreasing intensity profiles. J. Acoust. Soc. Am. 134, EL321–EL326.
Relkin, E.M., Doucet, J.R., 1991. Recovery from prior stimulation. I: relationship to spontaneous firing rates of primary auditory neurons. Hear. Res. 55, 215–222.
Rhode, W.S., Smith, P.H., 1985. Characteristics of tone-pip response patterns in relationship to spontaneous rate in cat auditory nerve fibers. Hear. Res. 18, 159–168.
Simmons, A.M., Schwartz, J.J., Ferragamo, M., 1992. Auditory-nerve representation of a complex communication sound in background-noise. J. Acoust. Soc. Am. 91, 2831–2844.
Sorkin, R.D., Robinson, D.E., Berg, B.G., 1987. A detection theory method for the analysis of auditory and visual displays. In: Proceedings of the 31st Annual Meeting of the Human Factors Society, pp. 1184–1188.
Turner, M.D., Berg, B.G., 2007. Temporal limits of level dominance in a sample discrimination task. J. Acoust. Soc. Am. 121, 1848–1851.
Vickers, D., 1970. Evidence for an accumulator model of psychophysical discrimination. Ergonomics 13, 37–58.
Yates, G.K., Robertson, D., Johnstone, B.M., 1985. Very rapid adaptation in the Guinea-pig auditory-nerve. Hear. Res. 17, 1–12.
Zeng, F.G., Turner, C.W., 1992. Intensity discrimination in forward masking. J. Acoust. Soc. Am. 92, 782–787.
Zeng, F.G., Turner, C.W., Relkin, E.M., 1991. Recovery from prior stimulation II: effects upon intensity discrimination. Hear. Res. 55, 223–230.