Both frequency and interaural delay affect event-related potential responses to binaural gap

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Human listeners are extraordinarily sensitive to a transient break in interaural correlation (called binaural gap). In this study, a binaural gap embedded in interaurally correlated noise markers elicited marked scalp event-related potentials (ERPs). ERPs to the binaural gap in narrowband noise with the center frequency of 1600 Hz were significantly weaker than those for narrowband noise with the center frequency of 400 or 800 Hz. Introducing the interaural time difference (ITD) of 4 ms weakened the ERPs for either 400-Hz or 800-Hz noise. Introducing the ITD of 2 ms, however, only weakened the ERPs for 800-Hz but not 400-Hz noise. Thus central representations of a transient break in interaural correlation for narrowband noises are affected by both frequency and ITD. *NeuroReport* 19:1673–1678 © 2008 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

The interaural correlation of a sound is the correlation between the sound waveform presented to the left ear and the sound waveform presented to the right ear after one waveform is shifted in time to maximize the correlation [1]. Human listeners are sensitive to small differences between a noise delivered at one ear and its copy delivered at the other ear [2–5]. Changing the interaural correlation modifies many aspects of the sound image inside the head [6,7], such as the compactness, number, and placement.

In addition to static changes, human listeners are sensitive to dynamic changes in interaural correlation. They can detect a transient break in interaural correlation (i.e. a transient drop of interaural correlation from 1 to 0 and then return to 1) [2,3]. In this study this dynamic change in interaural correlation is called binaural gap after Akeroyd and Summerfield study [2]. Earlier psychoacoustic studies have shown that both the perceived image width of interaurally correlated band-limited noise and the sensitivity to either static or dynamic changes in interaural correlation are frequency dependent [2,6,8,9]. Reports of neurophysiological responses to the transient break in interaural correlation, however, have not been found in the literature. Particularly, it is not clear whether neural representations of the binaural gap are affected by frequency.

Moreover, the perceptual integration of interaurally correlated noise is modulated by the delay time between the two ears (interaural time difference, ITD). If identical (correlated) steady-state noises are presented at the two ears with the ITD of 0 ms, a single compact noise image is perceived at the middle point inside listeners' head. When a short ITD, for example, 0.5 ms, is introduced, the image moves to a site between the middle point and leading ear. When the ITD is increased to 1 ms, the image is perceived as coming from the site of the leading ear. With further increase of the ITD to a higher value, for example, 4 ms, a single-fused noise image is still perceived as coming from the site of the leading ear but the image compactness may reduce. Theoretically, with increasing the ITD from 0 ms to a level of a few milliseconds, listener should have more difficulty to detect the binaural gap, because the correlation between the central representation of input at the left ear and that at the right ear decreases with the ITD increase. The change in internal interaural correlation should affect the just noticeable difference in interaural correlation [3–5]. Thus it is predicted that neural representations of the binaural gap in humans are affected by ITD.

This study was to examine scalp event-related potentials (ERPs) to a binaural gap embedded in narrowband-noise markers when either the central frequency or ITD was modulated in the range where the perceptual fusion of interaurally correlated noise markers was retained. Unlike the Akeroyd and Summerfield study [2] using a constant absolute bandwidth of 100 Hz for noises with various center frequencies, this study used a constant relative bandwidth of 1/3 octaves for noises with various center frequencies.

Methods

Twenty-four young university students (18–29 years old, mean age=22.1 years, 13 females) with right handedness, determined by the hand writing the individual signature, participated in this study. They all had normal and balanced (no more than 15 dB difference between the two ears) pure-tone hearing threshold between 125 and 8000 Hz, confirmed by audiometry. All of them understood the procedure of the experiments, gave their written informed consent to participate in the experiments, and were paid a modest stipend for their participation. The participants were randomly divided into two groups with 12 for each group. Group 1 participated in Experiment 1 and group 2 participated in Experiment 2. The Committee for Protecting Human and Animal Subjects of the Department of Psychology at Peking University has approved the experiments.

Correlated Gaussian steady-state white noises with the duration of 2000 ms (including 30-ms rise/fall times) were generated for the left-ear and right-ear channels using MATLAB (The MathWorks Inc., Natick, Massachusetts, USA) at the sampling rate of 48 kHz with 16-bit amplitude quantization. The central part of the right-ear noise was replaced by a 200-ms uncorrelated noise to create the binaural gap [2]. Note that replacing the correlated noise fragment with the uncorrelated noise fragment did not change either the noise spectrum or the sound pressure level (SPL) in the monaural channel.

The Gaussian white noises were then either filtered with a 512-point low-pass FIR filter at 10 kHz to get the wideband noises or filtered with 512-point band-pass FIR filters to get the narrowband noises with a center frequency of 400, 800, or 1600 Hz (bandwidth=1/3 octaves). These noise signals were then transferred using the Creative Sound Blaster (Creative SB Audigy 2 ZS, Creative Technology Ltd, Singapore) and presented to participants by two tube phones at the level of 56 dB SPL.

To ensure that participants kept their attention on stimuli during sound presentations and ERP recordings [10], the center part of noises in some trials was replaced by a 200-ms silent gap (the energetic gap). The task for participants was to pay attention to the sound presentation and press a button in the response box as quickly as possible when they heard the energetic gap in noises. ERP responses to noises containing the energetic gap were not included in data analyses.

In Experiment 1, wideband noises and narrowband noises with the center frequency of 400, 800, or 1600 Hz were used. Stimuli were presented to participants when the ITD was fixed at 0 ms. Each noise type with the binaural gap was presented 160 times and each noise type with the energetic gap was presented 32 times. The overall 768 sound presentations were divided into 16 blocks. In each block there were 10 presentations for each of the four noise types with the binaural gap and two presentations for each of the four noise types with the energetic gap. These stimuli were presented in a random order with a constant interstimulus interval of 1000 ms.

In Experiment 2, narrowband noise with the center frequency of 400 Hz and narrowband noise with the center frequency of 800 Hz were used. They were presented to participants at the ITD of 0, 2, or 4 ms with the left ear leading. Totally 12 types of noise presentations in Experiment 2 were present. Each of the six noise types (two noise types by three ITDs) with the binaural gap was presented 120 times and each of the six noise types with the energetic gap was presented 24 times. The overall 864 noise presentations were divided into 12 blocks. In each block, each of the six noise types with the binaural gap was presented 10 times and each of the six noise types with the energetic gap was presented two times. These stimuli were presented in a random order with a constant interstimulus interval of 1000 ms.

Electroencephalogram signals were recorded in a sound attenuated chamber (EMI Shielded Audiometric Examination Acoustic Suite) that was equipped with 64-channel NeuroScan SynAmps (Compumedics Limited, Victoria, Australia). Participants were instructed to remain alert and fixate a red light in the frontal field when they listened to acoustic stimuli. During recordings (bandpass: 0.05–40 Hz; sampling rate: 1000 Hz), all electrodes were referenced to the site of the head center. For data analyses, they were all rereferenced to an average reference. For ERP signals, ocular artifacts were corrected [11] using Neuroscan Software (Compumedics Limited, Victoria, Australia). Data analyses for ERPs to the binaural gap covered the 1500-ms epoch including 100-ms prebinaural gap baseline. Data analyses for ERPs to the noise onset covered the 2400-ms epoch including 100-ms preonset baseline. Trials contaminated by excessive peak-to-peak deflection ($\pm 100\,\mu V$) at channels not adjacent to eyes were automatically rejected before averaging. For each participant, ERPs were then averaged separately for each combination of electrode site and experimental condition. Averaged ERPs were digitally low-pass filtered at the cut-off frequency of 20 Hz.

To quantitatively examine the effects of center frequency in Experiment 1 and the effects of ITD in Experiment 2, the voltage differences between the N1 (the largest negative potential 100–210 ms after the sound onset or binaural-gap onset) and P2 (the largest positive potential 210–350 ms after the sound onset or binaural-gap onset) were measured, and the averaged responses across the nine central electrode sites (F1, FZ, F2, FC1, FCZ, FC2, C1, CZ, and C2) were statistically analyzed.

Results

The mean hit rate across participants for their responses to the energetic gap reached 96.88% (SE=1.04%) in Experiment 1 and 98.59% (SE=0.50%) in Experiment 2. Thus in each of the two experiments participants were able to pay their attention to sound presentations during ERP recordings. In addition, all the participants reported that they perceived only a single-fused noise image under each of the stimulation conditions.

Experiment 1

Figure 1 shows the group mean ERP responses recorded at the FCZ site to the wideband noise and each of the three types of narrowband noises when the ITD was 0 ms. Clearly, the noise onset, binaural gap, and noise offset could elicit a marked cortical N1-P2 complex. For ERP responses evoked by the noise onset, the N1-P2 peak-to-peak amplitude was larger for the wideband noise, and the center frequency of the narrowband noises seems not to affect the ERP amplitude. For the averaged amplitude across the nine central electrode sites, a one-way analysis of variance (ANOVA) indicates that the noise-type effect on the N1-P2 peak-to-peak amplitude to the noise onset was significant [$F(3,33)=18.883$, $P<0.001$]. Post-hoc paired sample *t*-tests show that the ERP amplitude to the sound onset for wideband noises was significantly larger than that for each of the narrowband noises ($P < 0.01$). No significant differences were, however, observed between the narrowband noises ($P > 0.05$). The left panel in Fig. 2 summarizes these comparisons.

Figure 1 also shows that unlike ERP responses to the noise onset, the N1-P2 peak-to-peak amplitude to the binaural gap was affected by the center frequency for narrowband noises. The ERP amplitude to the binaural gap embedded in the 1600-Hz noise markers was much smaller than those to the binaural gap embedded in other types of noises. For the averaged amplitude across the nine central electrode sites, a one-way within-participants ANOVA shows that the effect of noise type was significant [$F(3,33)=8.998$, $P < 0.001$]. Post-hoc paired sample *t*-tests confirm that the N1-P2 peak-to-peak amplitude for 1600-Hz narrowband noises was significantly smaller than both that for 400-Hz narrowband noises ($P < 0.001$) and that for 800-Hz narrowband noises ($P=0.001$). The ERP amplitude for 400-Hz narrowband noises and that for 800-Hz narrowband noises were, however, not significantly different ($P > 0.05$) (right panel in Figure 2).

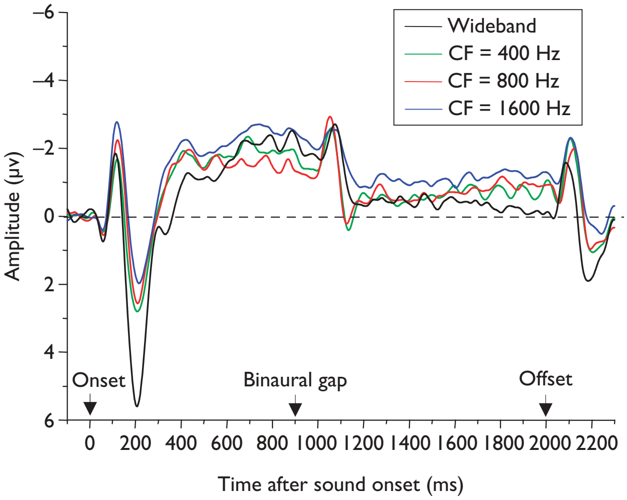

Fig. 1 The group mean event-related potential responses recorded at the FCZ site to wideband noises (black curve) and each of the three types of narrowband noises with the binaural gap (binaural gap) (400 Hz, green curve; 800 Hz, red curve; and 1600 Hz, blue curve) for participants recorded in Experiment 1. The interaural time difference was fixed at 0 ms. In this Figure and Fig. 3, the arrow under 'onset' indicates the time of the onset of the noise stimulus, the arrow under 'binaural gap' indicates the time of the onset of the binaural gap, and the arrow under 'offset' indicates the offset of the noise stimulus. The dotted line in this and following figures represents the amplitude of 0 μV. CF, center frequency.

Experiment 2

In Experiment 2, ERPs to the binaural gap embedded in 400-Hz or 800-Hz noise markers were examined when an ITD was introduced. All the participants reported that they were able to detect the occurrence of the binaural gap under each of the combinations of noise type and ITD.

Figure 3 shows group mean ERP responses recorded at the FCZ site to 400-Hz narrowband noises with the binaural gap (top panel) and those to 800-Hz narrowband noises with the binaural gap (bottom panel) when the ITD was 0, 2, or 4 ms. Clearly, ERPs to the binaural gap were affected by the ITD. Particularly, as the ITD increased from 0 to 4 ms, the amplitude of the N1-P2 peak-to-peak responses to the binaural gap markedly reduced.

Figure 4 shows the mean N1-P2 peak-to-peak amplitude to the binaural gap across the nine central electrode sites for 400-Hz noises (left panel) and that for 800-Hz noises (right panel) at each of the ITDs. A two (center frequency) by three (ITD) within-participants ANOVA shows that the interaction between the two factors was significant [$F(2, 22)=18.187$, $P < 0.001$].

For 400-Hz noise, a one-way within-participants ANOVA shows that the effect of ITD was significant [$F(2, 22)=30.257$, $P < 0.001$]. Post-hoc paired sample *t*-tests show that the N1-P2 amplitude at the ITD of 4 ms was significantly smaller than both that at the ITD of 0 ms and that at the ITD of 2 ms ($P < 0.001$). No significant difference was, however,

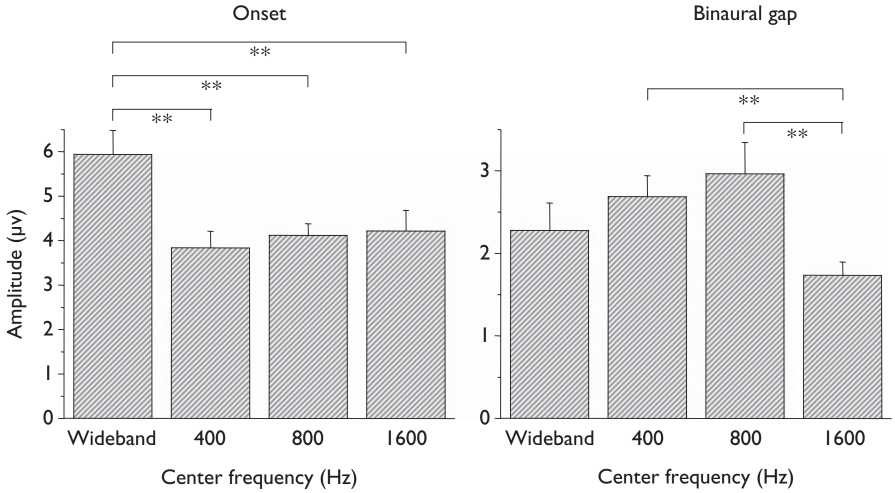

Fig. 2 Left panel: comparisons of the averaged N1-P2 peak-to-peak amplitude to the noise onset for each of the noise types across the nine central electrode sites (F1, FZ, F2, FC1, FCZ, FC2, C1, CZ, and C2) for participants recorded in Experiment 1. Right panel: comparisons of the averaged N1-P2 peak-to-peak amplitude to the binaural gap for each of the noise types across the nine central electrode sites for the same participants. The interaural time difference was fixed at 0 ms. $^{**}P < 0.01$.

observed in the amplitude between the ITD condition of 0 ms and that of 2 ms.

For 800-Hz noise, a one-way within-participants ANOVA shows that the effect of ITD was significant [F(2, 22)=15.802, $P<0.001$]. Post-hoc paired sample *t*-tests show that the ERP amplitude at the ITD of 0 ms was significantly larger than both that at the ITD of 2 ms and that at the ITD of 4 ms ($P<0.01$), but there was no significant difference between the ITD condition of 2 ms and that of 4 ms.

When the ITD was 0 ms, a paired sample *t*-test shows that the ERP amplitude to the binaural gap for 400-Hz noise was not significantly different from that for 800-Hz noise ($t_{11}=0.102$, $P=0.920$). When the ITD was 2 ms, a paired sample *t*-test shows that the ERP amplitude to the binaural gap for 400-Hz noise was significantly larger than that for 800-Hz noise ($t_{11}=5.707$, $P<0.001$). When the ITD was 4 ms, a paired sample *t*-test shows that the ERP amplitude to the binaural gap for 400-Hz noise was not significantly different from that for 800-Hz noise ($t_{11}=-0.239$, $P=0.816$).

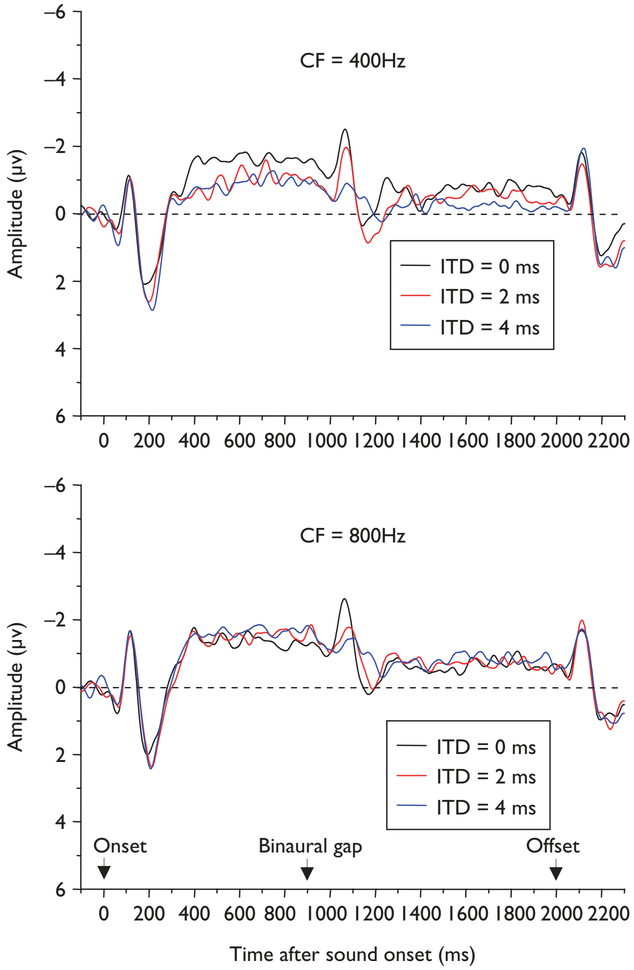

Fig. 3 The group mean event-related potential responses recorded at the FCZ site to 400-Hz noises with the binaural gap (top panel) and those to 800-Hz noise with the binaural gap (bottom panel) for participants recorded in Experiment 2, when the interaural time difference (ITD) was 0 (black curve), 2 (red curve), or 4 ms (blue curve). CF, center frequency.

Discussion

In this study the binaural gap embedded in interaurally correlated noise markers elicited a marked N1-P2 ERP complex. Although for either the left or right monaural channel, introducing a binaural gap did not change the spectrum and sound level, the binaural gap-elicited ERP responses reflect a consequence of ‘pure’ binaural processing, confirming earlier psychoacoustic reports [2,3]. Our recent unpublished observations indicate that participants’ expectation to the binaural gap does not elicit the N1-P2 ERP complex. Thus, ERPs to the binaural gap are formed by a stimulus-driven process.

This study also shows that when the three types of narrowband noises shared the same SPL, there were no differences in ERPs to the noise onset. The amplitude of the N1-P2 complex to the binaural gap in 1600-Hz noise markers was, however, significantly smaller than that in 400-Hz or 800-Hz noise markers. Thus when no interaural delay is introduced, the interaural integration for 1600-Hz noise is weaker than that for 400-Hz and 800-Hz noise. The results are generally in agreement with the Akeroyd and Summerfield study [2] showing that the threshold for detecting the binaural gap in band-limited noise markers became progressively larger as the center frequency increased from 250 to 2000 Hz. The reduction of perceptual and neural responses to the binaural gap with the increase of the center frequency can be partially explained by the loss of phase locking with the increase of frequency [12] as

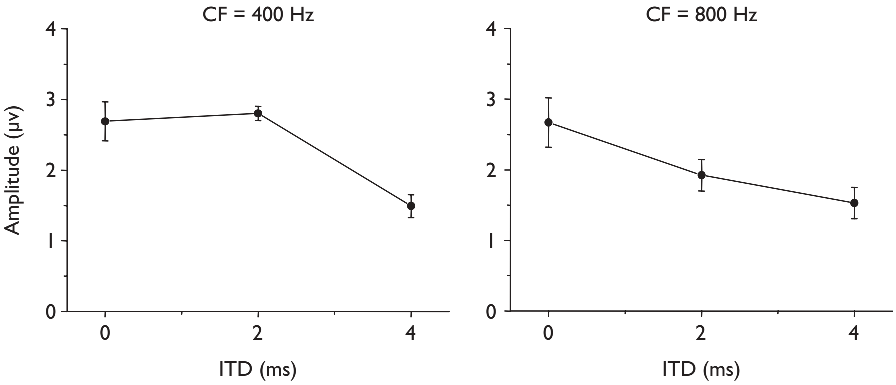

Fig. 4 Comparisons of the averaged N1-P2 peak-to-peak amplitude to the binaural gap for 400-Hz noise (left panel) and those for 800-Hz noise (right panel) across the nine central electrode sites for participants recorded in Experiment 2. The interaural time difference (ITD) was set at 0, 2, or 4 ms. CF, center frequency.

indexed with the reduction of the synchronization coefficient [13]. However, note that according to the ρ_w model for estimating the binaural window size [2], the frequency-dependent sensitivity to the binaural gap is not associated with the binaural temporal resolution.

In agreement with the prediction proposed in the introduction, results of this study show that ERPs to the binaural gap depended on the ITD. Moreover, the effect of ITD was frequency dependent. Specifically, for 400-Hz noise, introducing the ITD of 4 ms, but not the ITD of 2 ms, significantly reduced ERP responses to the binaural gap. For 800-Hz noise, however, introducing the ITD of either 2 or 4 ms significantly reduced the ERP responses. Our recent psychoacoustic studies have shown that the difference in the duration threshold for detecting the binaural gap in 400-Hz narrowband noise and that in 800-Hz narrowband noise becomes larger when an ITD is introduced [14], supporting the results of this neurophysiological study. Thus ERPs to the binaural gap are useful for estimating the degree of interaural integration.

It is not clear why the interaural integration of long-duration acoustic fine structures is still retained even the ITD of 4 ms is introduced, which is far beyond the range of interaural-delay lines as described in the Jeffress model [15]. Although the ringing responses (prolonged output decays) of the peripheral auditory filter may partially account for the preservation of acoustic signals over time, a temporal storage of fine-structure information at the central stage of auditory processing cannot be ruled out.

On the basis of results of this study, it is assumed that during the first few milliseconds after the arrival of the noise sound at the leading ear, the temporal integration of acoustic details of noise between the two ears undergoes a fast degeneration. Although at the ITD of 4 ms, a single-fused noise image is retained and particularly, the ERP responses to the binaural gap are still marked, degeneration of interaural integration is not complete after 4 ms of the arrival of the leading stimulus. In addition, the interaural integration for high-frequency acoustic components degenerates greater than that for low-frequency components.

Although ERP responses to the binaural gap depend on both monaural and binaural processing, it is worth investigating in the future whether aging-related changes in either monaural fine-structure processing (e.g. changes in filter bandwidth and phase locking or synchrony) or binaural fine-structure processing (e.g. increase of ‘binaural sluggishness’) affect the ERP amplitude to the binaural gap. In contrast, when the time interval between the wave directly coming from the source and its correlated reflections is sufficiently short, attributes of the lagging reflections are perceptually captured by the leading direct wave [16], causing a single-fused sound image that is perceived to be at or near the location of the source. This phenomenon is generally called the ‘precedence effect’ [17–20], which facilitates the recognition and localization of sources in reverberant environments by weakening auditory echoes. Although processing the similarity and dissimilarity of sound waves arriving at the two ears is critical for the formation of the precedence effect and other binaural perceptual phenomena [21], it is also important in the future to investigate the functional connection between the precedence effect and the ERP responses to the binaural gap. Moreover, when the pitch of the narrowband noise is modulated by the change of center frequency and the loudness of the binaural gap is modulated by the change of ITD, the N1 and P2 components may reflect different signal-processing stages and are driven by different intracerebral generators [22,23]. Thus further brain-imaging studies are needed for understanding the neural representations of the binaural gap.

In summary, this study established a new neurophysiological model for precisely estimating the degree of interaural integration of correlated acoustic details. ERPs to the binaural gap embedded in narrowband-noise markers are modulated by changing either the center frequency or ITD. The frequency-dependent temporal integration of correlated acoustic details is critical for perceptually separating acoustic signals (e.g. speech) from different sources in noisy, reverberant environments.

Acknowledgements

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