Perception & Psychophysics
2008, 70 (1), 1-12
doi: 10.3758/PP.70.1.1

The auditory continuity illusion: A parametric investigation and filter model

Lars Riecke
University of Maastricht, Maastricht, The Netherlands

A. John van Opstal
Radboud University, Nijmegen, The Netherlands

and

Elia Formisano
University of Maastricht, Maastricht, The Netherlands

A sound that is briefly interrupted by a silent gap is perceived as discontinuous. However, when the gap is filled with noise, the sound may be perceived as continuing through the noise. It has been shown that this continuity illusion depends on the masking of the omitted target sound, but the underlying mechanisms have yet to be quantified thoroughly. In this article, we systematically quantify the relation between perceived continuity and the duration, relative power, or notch width of the interrupting broadband noise for interrupted and non-interrupted amplitude-modulated tones at different frequencies. We fitted the psychometric results in order to estimate the range of the noise parameters that induced auditory grouping. To explain our results within a common theoretical framework, we applied a power spectrum model to the different masking results and estimated the critical bandwidth of the auditory filter that may be responsible for the continuity illusion. Our results set constraints on the spectral resolution of the mechanisms underlying the continuity illusion and provide a stimulus set that can be readily applied for neurophysiological studies of its neural correlates.

The human auditory system can identify and select meaningful sounds in loud and noisy environments in which the sensory input is a mixture of acoustic signals. One illustration of this phenomenon is the auditory continuity illusion (G. A. Miller & Licklider, 1950), in which a sound is perceived as continuous even though parts of it have been replaced by another sound—for example, a noise burst (Figure 1). The illusion has been observed for steady-state tones, frequency-modulated (FM) sweeps, familiar melodies, and even for complex speech signals. In all cases, the addition of an interrupting sound makes the overall stimulus more perceptible; thus, the phenomenon has been variously labeled perceptual restoration, synthesis, fusion, or induction. The illusion has been demonstrated in humans as well as in nonhuman species, including monkeys (C. T. Miller, Dibble, & Hauser, 2001; Petkov, O'Connor, & Sutter, 2003), cats (Sugita, 1997), and birds (Braaten & Leary, 1999), suggesting a general constructive mechanism of auditory perception that operates at multiple levels of abstraction. The illusion seems to reflect perceptual sensitivity to faint but expected sounds and robustness against contaminating noise, resulting in an enhanced perceptual signal-to-noise ratio (SNR).

But how can the continuity illusion of the target sound arise from a stimulus in which that sound is in fact discontinuous? This question is of particular interest since it may shed light on more general mechanisms of auditory perception. It is known that the omitted target can be perceptually restored only when it has been replaced by another sound that would be able to mask the target if the target were actually present (Warren, Wrightson, & Puretz, 1988; for reviews, see Bregman, 1990; Warren, 1999). *Auditory masking* refers to a perceptual phenomenon in which one sound, the masker, renders another sound, the target, inaudible. Masking occurs when the spectrogram of the masker obliterates the spectrogram of the target. This effect can be attenuated by removing the overlapping frequency band from the masker (i.e., by inserting a spectral notch) or by decreasing the intensity of the masker relative to that of the target—that is, by increasing the SNR (Bregman, 1990). Masking can result in the continuity illusion if the target precedes and follows the masking sound (Warren, 1999), indicating a tight coupling between the two phenomena (Houtgast, 1972; Warren, Obusek, & Ackroff, 1972). The salience of the continuity illusion thus depends on the degree of masking, which, in turn, depends on the degree of spectral–temporal concealment of the target by the masker (Bregman, 1990; Warren, 1999). The salience of the continuity illusion is further influenced by the du-

L. Riecke, l.riecke@psychology.unimaas.nl

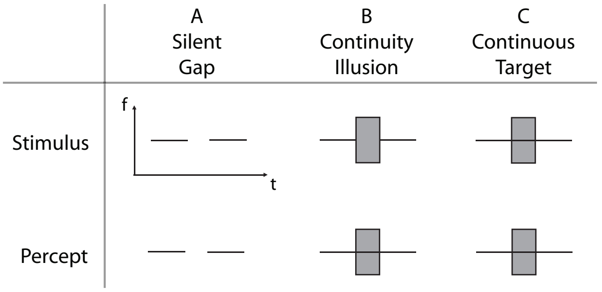

Figure 1. The auditory continuity illusion, exemplified for steady-state tones. (A) Two tones interrupted by a silent gap are perceived as two independent entities. (B) Illusion of a single entity when a broadband noise masker is added to the gap, a percept that is similar to a physically continuous tone, shown in Panel C.

ration of the masker (Kluender & Jenison, 1992). Earlier studies (reviewed in Warren, 1999) with pure tones have demonstrated prominent continuity illusions with masker durations of 10–300 msec. For longer duration maskers, however, the illusion tends to fade, evoking percepts of partially continuous targets. Thus, the illusion is not an all-or-none phenomenon, but reflects a gradual extrapolation of the preceding target that extends perceptually through (parts of) the masker (Bregman, 1990; Warren, Bashford, Healy, & Brubaker, 1994).

According to the Gestalt principles of auditory grouping (Bregman, 1990; Wertheimer, 1938), spectral and temporal proximity of the interrupted tone and masking noise burst are required to induce continuity illusions. However, these Gestalt principles ignore the effect of the relative spectral power of masker and target (as discussed above). Furthermore, despite extensive psychophysical evidence for the proximity requirement, the underlying grouping mechanisms remain poorly quantified. For example, it is unknown whether the proximity principles vary with center frequency. A conceptual problem in the study of the continuity illusion arises with the use of very brief (100 msec or less) maskers (see, e.g., Darwin, 2005; Petkov et al., 2003) and of maskers that contain power in the target's frequency band—that is, the on-frequency band (see, e.g., Darwin, 2005; Lyzenga, Carlyon, & Moore, 2005). Without comparison of continuity illusions to nonillusory continuity percepts of appropriate control stimuli, it remains unclear whether listeners could hear the actual targets in very brief maskers. Strictly speaking, if the masker contains the on-frequency band, the frequency channel of the target sound is physically continuous and no illusory filling occurs in that channel. Furthermore, previous studies have used different target sounds to investigate how individual stimulus parameters may influence the illusion (Bregman, 1990; Warren, 1999), but more abstract parameters (e.g., interactions between the spectral–temporal concealment and the relative spectral power) were not investigated and thus cannot be derived ad hoc from the individual earlier studies.

According to a current view, the continuity illusion can be considered to result from neural mechanisms that extract abstract stimulus properties in order to form perceptual objects (Darwin, 2005; Griffiths & Warren, 2004). In the present study, we apply the concept of the auditory filter to provide a constraint on such neural mechanisms. According to the auditory filter model, the auditory system is a bank of overlapping linear band-pass filters, and it accounts for the fact that masking of a tone is restricted to a narrow spectral band, the so-called critical band (CB) around the tone's frequency (Fletcher, 1940). According to the power spectrum model (Patterson & Moore, 1986), the detection of a tone in noise occurs in the auditory filter closest to the tone's frequency, and the total noise power passing through that filter determines the amount of masking. The CB is often expressed in terms of the equivalent rectangular bandwidth (ERB), which is considered to be a measure of the spectral resolution of the auditory system around the tone's frequency (Moore, 2003).

Typically, auditory filters and ERBs have been used to interpret masking threshold data from rippled- or notched-noise experiments (Patterson, 1976). Here, we consider a range of limiting stimulus parameters that lead to continuity illusions (Houtgast, 1974) as masking thresholds and apply the auditory filter concept to the continuity illusion. We propose that the illusory filter properties need not be identical to those of the classical filter. According to this idea, the auditory filter contributes to the formation of a continuity illusion by grouping all frequencies within its CB. For example, if the sensory input to the filter comprises a spectral notch smaller than the CB, and if masking conditions are met, then the frequencies that are physically present within the CB are merged to fill in the notch at the output of the filter. Such a filter might thus function as an integrator whose ERB represents only the frequencies that are capable of yielding the continuity illusion.

The present study aims to quantify the proposed mechanism involved in the continuity illusion. We designed a series of psychophysical experiments in which we systematically assessed the perceptual consequences of varying the masking noise across large parameter ranges. Noise burst interrupted, amplitude-modulated (AM) tones of different frequencies were used to generate spectrally balanced stimulus sets comprising a physically discontinuous and a physically continuous tone, respectively. Using the method of constant stimuli and a scaling procedure in a repeatedly presented paradigm, we analyzed the perceptual responses from a large pool of listeners and quantified the relation between the salience of the perceived continuity of the target tone and the duration, relative power, or notch width (NW) of the noise masker while controlling for potential frequency effects. These parameters are known to control the masking potential of the noise and, therefore, the salience of the continuity illusion. We analyzed the salience of illusions by comparing illusory and nonillusory continuity evoked by physically discontinuous and continuous targets, respectively. By fitting the psychometric results, we predicted the range over which each noise parameter could establish the illusion. Adopting the power spectrum model, we determined the ERB of the auditory filters as a function of the tone's frequency for a range of detection thresholds. Our results indicate that strong illusions involve filters similar to those reported by classical masking studies, suggesting that common masking mechanisms may account for these illusions. For partial illusions, the filters' width increase, suggesting a neural mechanism that may be different from the one involved in masking.

METHOD

Listeners

The 29 listeners (25 females and 4 males; mean age, 22 years; *SD* = ±2) were mainly undergraduate students from the University of Maastricht who were paid for their participation and gave their informed consent. All participants had normal hearing abilities as assessed by an initial hearing test before each experiment. Of the 29 listeners, 16, 12, and 12 listeners participated in the noise duration, SNR, and NW experiments, respectively, with 9 listeners participating in two experiments and 1 listener (one of the authors) participating in all three experiments. Excluding this last listener, all listeners were uninformed about the experimental background.

Stimuli

Tones interrupted by a noise burst were used to generate two different stimulus types. The experimental stimulus comprised three temporally nonoverlapping sequential segments. The target tone was removed from the center segment and replaced by a noise masker, resulting in a discontinuous target. The control stimulus was identical to the experimental one in all respects except that the target remained in the center segment while the temporally overlapping masker was superimposed, resulting in a continuous target. The nonillusory continuity percepts of targets in control stimuli served to assess the salience of illusory continuity percepts evoked by experimental stimuli. Moreover, a correct continuity percept of the control stimuli provided listeners with a reference for perceptual ratings of the respective experimental stimuli.

Stimulus duration was set to 2,800 msec. To equate for overall sound level, stimuli were equated on the root mean square (RMS) amplitude. This might have resulted in slight intensity differences among targets. According to informal observations and listeners' reports, the putative differences were virtually inaudible. Tones of five different frequencies (500, 930, 1732, 3223, and 6000 Hz) within the preferred human hearing range were used as targets to test for the generality of the continuity illusion across different frequencies. Carrier tones were amplitude modulated with a sinusoidal modulator (3-Hz frequency, 100% depth). All tones had linear rise and fall times of 3 msec. Broadband white Gaussian noise bursts were temporally and spectrally centered within the stimulus at linear and logarithmic scales, respectively. The nonmodulated noise was filtered with a two-octave band-pass finite impulse response (FIR) filter centered on the target frequency. To create a spectral notch, frequency bands around the target frequency were removed using a FIR band reject filter. Noise had linear rise and fall times of 3 msec. Ramp centers were synchronized with those of the respective tone offsets and onsets. Stimuli were digitally generated in MATLAB 7.0.1 (The MathWorks, Inc., Natick, MA) using a 44.1-kHz sampling rate and 16 bits per sample. Nonspatial monostimuli were delivered binaurally via headphones using a Creative Sound Blaster Audigy 2ZS sound card (Creative Technology, Ltd., Singapore) and Presentation 9.30 software (Neurobehavioral Systems, Inc., Albany, CA).

Three experiments were conducted (Figure 2). The noise in the stimulus was characterized by three parameters: duration (in milliseconds), relative amplitude (in decibels) given by

$$SNR(\text{dB}) = 20 \times \log_{10}\left(\frac{\text{tone amplitude}}{\text{noise amplitude}}\right), \qquad (1)$$

and NW (in octaves). In each of the experiments, one parameter was manipulated, and the other two were set to their near-limiting values still associated with continuity illusions. In the first experiment, noise duration was varied in six steps (200, 400, 600, 900, 1,400, and 2,000 msec), noise amplitude was set to equal tone amplitude (SNR = 0 dB), and the NW was set to 0. In the second experiment, noise duration was set to 600 msec (a near-limiting value in the preceding experiment; see Results), whereas SNR was varied in six steps (−8, −6, −3.5, 0, +6, and +12 dB) and NW was set to 0. In the third experiment, noise duration was set to 600 msec and SNR to −3.5 dB (near-limiting values in the preceding experiments; see Results), whereas NW was varied (0, 0.25, 0.5, 0.75, 1, and 1.25 octaves). The stimulus parameters are summarized in Table 1.

Task and Design

Listeners set the overall sound intensity to an individual hearing level (~82 dB SPL on average) that remained fixed throughout the experiment. The task was a modified version of the standard continuity illusion paradigm (Bregman, 1990) that we designed specifically for potential future applications in neuroimaging environments. Instructions appeared on a computer screen and instructed listeners to attend to targets in stimuli and to rate how likely it seemed to them that the tone continued during the entire noise burst on each trial. They used a buttonpress to rate the tone on a 4-point scale (1 = *most likely continuous*, 2 = *probably continuous*, 3 = *probably discontinuous*, 4 = *most likely discontinuous*); the rating scale remained visible on the screen throughout the task. Within each trial, a 2,800-msec stimulation period was visually indicated by a green cross that turned red during the following response period. The upper response limit was 5,000 msec; earlier responses terminated response periods earlier and initiated the next trial. After reading the

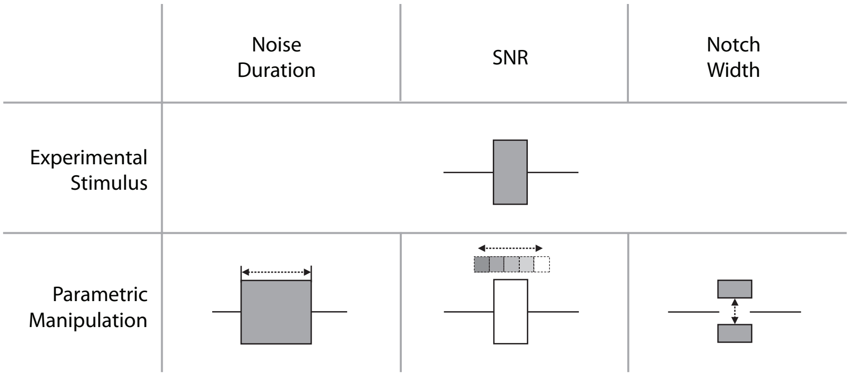

Figure 2. Experimental manipulations. In each experiment, a different noise parameter was varied in six steps across trials. Parametric manipulations were applied similarly to both experimental and control stimuli. The gray scale represents different levels of masker intensity.

Table 1
Stimulus Parameter Settings in the Experiments

	Experiment		
	Noise Duration	SNR	Notch Width
Stimulus duration		2,800 msec	
Tone frequency		500, 930, 1732, 3223, 6000 Hz	
Tone AM		3 Hz	
Noise bandwidth		2 octaves	
Noise duration	200–2,000 msec	600 msec	600 msec
SNR in dB	0	−8–+12	−3.5
Notch width in octaves	0	0	0–1.25

instructions, listeners practiced on 18 test trials. The test stimuli also included the minima and maxima of the parametric stimulus range so that listeners could adjust their rating scale to the stimulus scale available in the subsequent experiment.

In each experiment, three factors or independent variables were systematically varied: stimulus (two types: experimental and control), frequency (five values; see Stimuli), and noise parameter (duration, SNR, or NW with six levels each; see Table 1 for details). This resulted in a $2 \times 5 \times 6$ within-subjects design with 60 conditions per experiment. One stimulus was presented and one response was measured per trial. Trial duration varied from 3,300 to 8,300 msec (2,800-msec stimulus + 500-msec intertrial interval + response time of 0–5,000 msec). In total, 360 trials were presented per experiment, resulting in an average experiment duration of approximately 30 min. Trials were organized in three types of blocks, each of which included two adjacent levels of the noise parameter. More precisely, the first block type comprised stimuli at noise parameter levels one and two; the second block type, at levels three and four; and the third block type, at levels five and six. Each block type was presented three times, resulting in a total of nine blocks per experiment. Block order was balanced and pseudorandomized so that successive blocks were never of the same type. Successive blocks were always separated by a task break. Listeners were free to terminate breaks once they felt confident to resume the experiment. Within each block, 2 (stimuli) × 5 (frequencies) × 2 (noises per block) resulted in 20 different conditions, all presented twice for a total of 40 trials per block. The two noise levels and the five frequencies were both balanced and randomized within blocks. Two thirds of the total number of trials were experimental; one third were control trials; the stimulus types were randomized within and between blocks. We quantified the mean response on each condition, averaged across nine (experimental stimulus) and three (control stimulus) repetitions, ranging from value 1 (*most likely continuous*) to value 4 (*most likely discontinuous*).

Statistical Analysis and Calculation of ERBs

Group data were statistically analyzed in SPSS 12.0.1 (SPSS Inc., Chicago, IL) using general linear models (GLMs) and univariate as well as multivariate tests for repeated measures. Stimulus, frequency, and noise were included as three within-subjects factors in the model with two, five, and six levels, respectively. For all three experiments, the three-way interaction among these factors turned out to be nonexplanatory regarding the variance in the perceptual response. The nonsignificant interaction term was thus removed, and the reduced GLM was reanalyzed. Two-way interactions were treated stepwise according to the same schema. Two independent factors were analyzed separately for main effects, and two dependent factors were analyzed for simple effects (i.e., one factor was investigated separately per each level of the other factor and vice versa). Pairwise comparisons between conditions within experiments were performed using paired samples *t* tests, whereas pairwise comparisons between conditions between experiments were performed using independent samples *t* tests. Inflated Type I error probabilities caused by multiple comparisons were corrected for using Bonferroni's method.

The power spectrum model (Patterson & Moore, 1986) and the notched-noise method (Patterson, 1976) were adopted to estimate the auditory filter bandwidth from detection thresholds of the illusory tone in the notched-noise masker at two different NWs. Specifically, a fixed-tone paradigm was used in which the expected level P_s (in dB SPL) of an illusory tone at frequency f_0 (in Hz) was kept constant while the noise spectrum level N_0 (in dB SPL/Hz) varied with the NW Δf (in Hz) at detection threshold. P_s was defined as the level of the tones surrounding the noise. Thresholds of the continuity illusion in the SNR and NW experiments were defined by an average rating score of 2.5. Since the continuity illusion is a gradual phenomenon (see the introduction), the choice of a subjective criterion may have affected ERB estimation. To take this into account, a range of additional thresholds was also examined. The corresponding noise spectrum levels were predicted from fitting a third-order polynomial to the psychometric results, using the least-squares error criterion. Assuming a perfectly rectangular filter centered at f_0 with constant weighting function in its pass bands, the efficiency of the target detection process at filter output is

$$K = \frac{P_s}{W \times N_0}, \tag{2}$$

where W is the masker bandwidth within the filter bandwidth ERB at detection threshold. Note that for notched noise, W is smaller than ERB, whereas for nonnotched noise, W is smaller than or equals ERB. Assuming that masker bandwidth (BW = two octaves) exceeded ERB (Figure 3), Equation 2 becomes

$$K_{\mathrm{SNR}} = \frac{P_{s,\mathrm{SNR}}}{\mathrm{ERB} \times N_{0,\mathrm{SNR}}} \tag{3}$$

for the SNR experiment and

$$K_{\mathrm{NW}} = \frac{P_{s,\mathrm{NW}}}{(\mathrm{ERB} - \Delta f) \times N_{0,\mathrm{NW}}} \tag{4}$$

for the NW experiment.

According to the power spectrum model (Patterson & Moore, 1986), the threshold for detecting a tone corresponds to a constant ratio of tone power to total masker power at the output of the filter. Thus,

$$K_{\mathrm{SNR}} = K_{\mathrm{NW}} \tag{5}$$

at detection threshold, and Equations 3 and 4 can be solved for ERB, thus:

$$\mathrm{ERB} = \frac{\Delta f}{1 - \dfrac{P_{s,\mathrm{NW}} \times N_{0,\mathrm{SNR}}}{P_{s,\mathrm{SNR}} \times N_{0,\mathrm{NW}}}}, \tag{6}$$

where P_s and N_0 are expressed on a linear scale.

The ERBs were calculated according to Equation 6 from group-averaged data for each tone frequency, which implies that listeners used a constant rating scale between experiments. To test this assumption, ratings were first analyzed across experiments considering only conditions that included identical stimuli (i.e., noise dura-

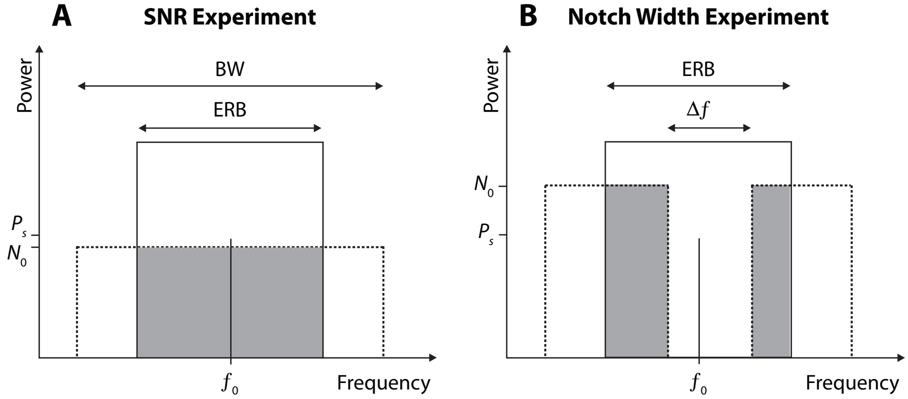

Figure 3. Auditory filter and power spectrum model. Spectra of tone targets and noise maskers at detection threshold in the SNR (A) and notch width (B) experiments are outlined in relation to the auditory filter on linear–linear scales. The black rectangles delineate the assumed shape of the auditory filter with an equivalent rectangular bandwidth (ERB). It is assumed that for detection of a tone with frequency f_0 and fixed level P_s (represented by the black vertical lines) in noise, a filter is recruited that is linearly centered on f_0. The dotted gray lines delineate the white noise masker with bandwidth (BW) and spectrum level N_0. In the notch width experiment, the masker comprised a spectral notch of width Δf placed nonsymmetrically around f_0 on a linear scale. The shaded area represents the total noise power transmitted by the filter at detection threshold, which is assumed to be constant across the two different conditions.

tion = 600 msec vs. SNR = 0 dB, and SNR = −3.5 dB vs. NW = 0 octaves). Comparison between identical conditions in different experiments revealed that rating differences between experiments did not reach significance either for the control or for the experimental stimuli at any frequency. The identical conditions were ranked either close to each other (noise duration = 600 msec and SNR = 0 dB) or more remotely (SNR = −3.5 dB and NW = 0 octaves) on the respective stimulus scale. Thus, identical stimuli were rated similarly and independently of the stimulus scale available in the various experiments, supporting the assumption of constant rating scales and justifying the application of the power spectrum model to our data.

RESULTS

Effects of Noise Duration, SNR, and NW on Perceived Continuity

Figures 4A–4C show the psychometric curves in the noise duration, SNR, and NW experiments, respectively, averaged across listeners and frequencies, whereas Figure 5 shows the corresponding curves for each frequency. The effects of noise duration, SNR, and NW on ratings differed significantly for experimental and control stimuli [stimulus × duration, $F(5,11) = 16.57$, $p < .00001$; stimulus × SNR, $F(5,7) = 43.93$, $p < .00005$; stimulus × notch, $F(5,7) = 23.06$, $p < .0005$]: Experimental stimuli were rated as progressively more continuous when noise duration, SNR, and NW decreased (Figures 4A–4C, solid circles); these effects were significant at all frequencies [duration, $F(5,11) > 5.98$, $p < .01$; SNR, $F(5,7) > 23.03$, $p < .0005$; notch, $F(5,7) > 24.25$, $p < .0005$], except for 1732- and 6000-Hz stimuli in the SNR experiment [$F(5,7) < 3.63$, $p > .05$]. Control stimuli were rated as progressively less continuous when noise duration, SNR, and NW decreased (Figures 4A–4C, open circles), but these trends did not reach significance at any frequency [duration, $F(5,11) < 1.18$, $p > .1$; SNR, $F(5,7) < 3.85$, $p > .05$; notch, $F(5,7) < 2.06$, $p > .1$]. Thus, the perceived continuity of physically discontinuous targets, but not that of physically continuous targets, depended on the properties of the noise masker.

Regarding differences between illusory and nonillusory continuity, listeners perceived physically discontinuous targets as continuity illusions (i.e., mean rating scores were 2.5 or smaller) in 73.3%, 63.3%, and 53.3% of the experimental conditions of noise duration, SNR, and NW, respectively (Figures 4A–4C; Figure 5, see asterisks). The control stimuli were generally rated as continuous, irrespective of noise duration, SNR, or NW. Occasional incorrect discontinuity ratings in individual listeners were observed in 6.7%, 6.1%, and 2.5% of the control conditions of noise duration, SNR, and NW, respectively, and occurred mainly at short noise durations and low SNRs. Thus, the short noise durations and low SNRs evoked the most continuity illusions as well as the most incorrect discontinuity ratings. The perceptual differences between experimental and control stimuli (i.e., the vertical distances between solid and open circles in Figures 4A–4C) decreased with decreases in noise duration, SNR, and NW, suggesting that listeners had illusions that gradually assimilated the "real" continuity percepts of the control stimuli. Control stimuli were generally rated as more continuous than experimental stimuli, a difference that was evident for 81.8% of the conditions associated with continuity illusions [duration, $t(15) > 4.1$, $p < .005$; SNR, $t(11) > 4.9$, $p < .0005$; notch, $t(11) > 3.39$, $p < .01$]. Only for low SNRs of −8 and −6 dB did these stimulus type differences not reach significance [$t(11) < 1.7$, $p > .1$]. Thus, except for very intense noise maskers, listeners could implicitly differentiate between illusory and nonillusory continuity.

Regarding limiting stimulus parameter values, continuity illusions were reported for noise durations up to about

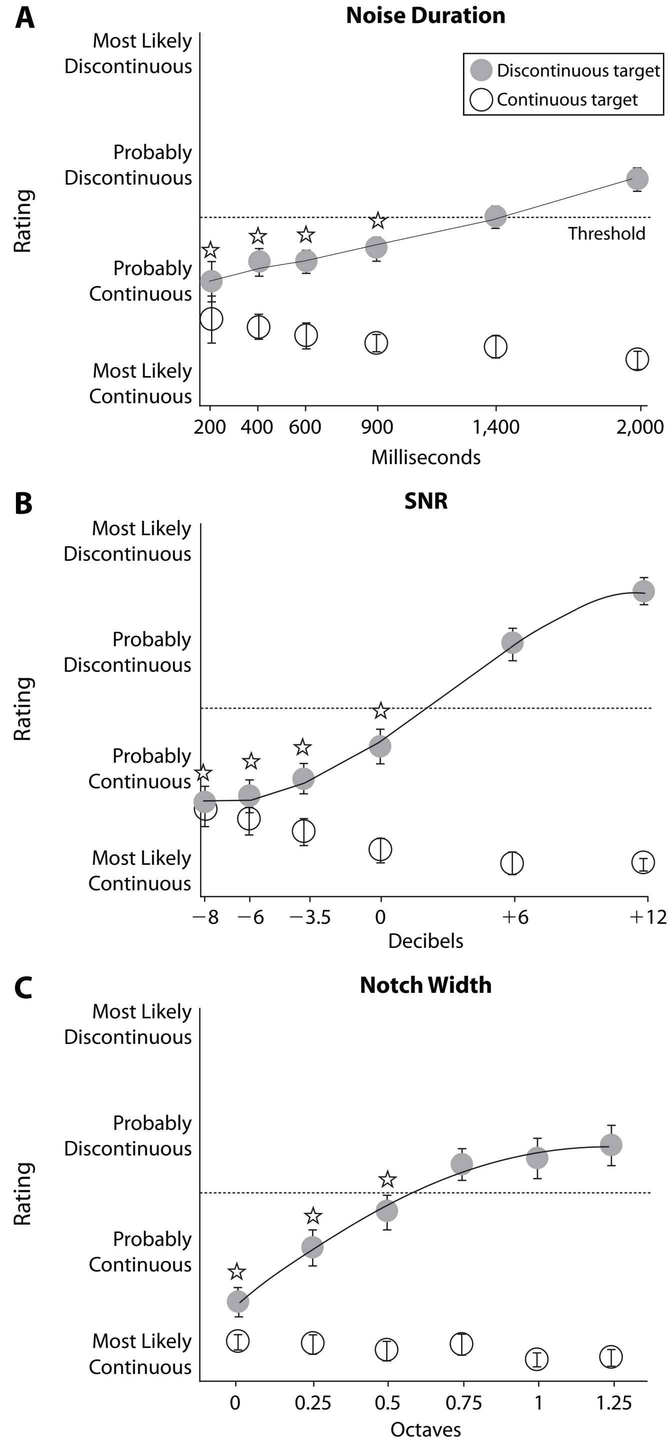

Figure 4. Mean percept (± *SEM*) of experimental stimuli (solid circles) and control stimuli (open circles) in the noise duration (A), SNR (B), and notch width (C) experiments, averaged across listeners and frequencies. The solid lines represent the fitted polynomial functions and the dotted horizontal lines represent perceptual ambiguity between discontinuity and continuity. Illusory stimuli are indicated by asterisks.

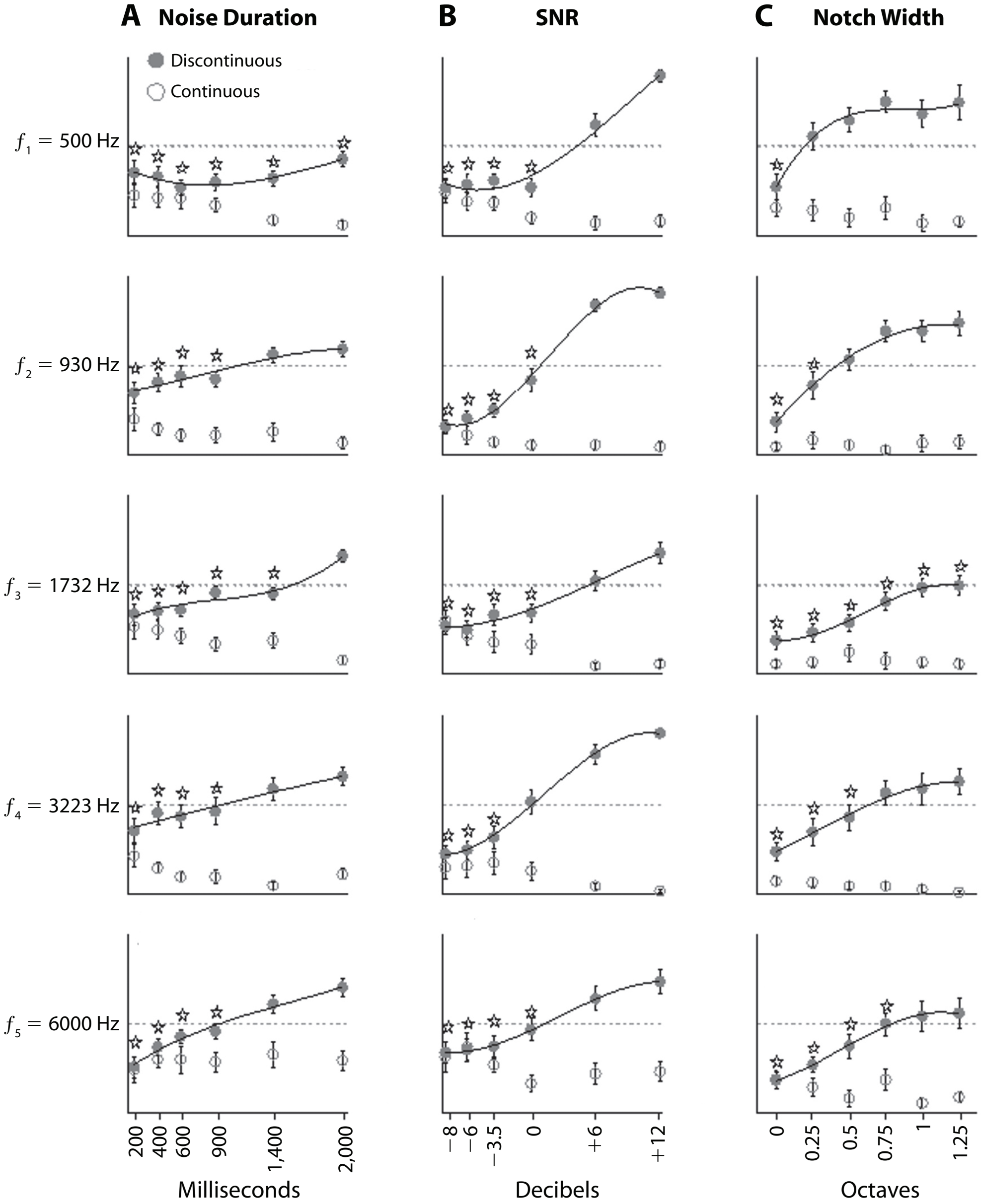

Figure 5. Mean percept (± *SEM*) of experimental stimuli, representing discontinuous conditions (solid circles), and control stimuli, representing continuous conditions (open circles), per frequency across listeners in the noise duration (A), SNR (B), and notch width (C) experiments. The solid lines represent the fitted polynomial functions and the dotted horizontal lines represent perceptual ambiguity between discontinuity and continuity. Illusory stimuli are indicated by asterisks. The plots have the same scales as those in Figures 4A–4C.

900 msec, for noise intensities at least as high as tone intensity (i.e., SNR $\leq$ 0 dB), and for NWs up to half an octave, pooled across frequencies (see asterisks in Figures 4A–4C). The limiting noise parameter values at which percepts of experimental stimuli would shift between nonillusory and illusory continuity were predicted by the fitted functions and are shown in Table 2. Fitting the polynomials to the experimental psychometric results yielded a mean coefficient of determination $R^2 = .99$ ($SD = \pm.01$) for the frequency-pooled data and an $R^2 = .96$ ($SD = \pm.03$) for the nonpooled data.

Critical Bandwidth of the Auditory Filters

The predicted limiting SNR and NW values (i.e., those with rating scores of 2.5) were considered as detection thresholds (Table 2). For these conditions, the average testing level P_s was estimated as 81.7 dB SPL. Small testing level differences between experiments (ΔP_s) might have been induced by stimulus level normalization (average ΔP_s = 1.4 dB SPL) and thus could be neglected (Glasberg & Moore, 1982; Moore & Glasberg, 1981). The average noise levels were estimated at 79.7 and 84.5 dB SPL in the SNR and NW experiments, respectively. These values

Table 2
Predicted Limiting Noise Parameter Values Inducing Shifts Between Nonillusory and Illusory Continuity Percepts (i.e., Detection Threshold = 2.5) of Physically Discontinuous Targets and Estimated Auditory Filter Bandwidths in Octaves, Displayed for Each Frequency and Pooled Across Frequencies

Frequency	Noise Duration (msec)	SNR (dB)	Notch Width (octaves)	ERB (octaves)
f_1 = 500 Hz	>2,000	1.7	0.19	0.23
f_2 = 930 Hz	1,100	1.2	0.41	0.56
f_3 = 1732 Hz	1,568	1.9	>1.25	1.40
f_4 = 3223 Hz	956	1.0	0.64	0.96
f_5 = 6000 Hz	938	1.2	0.79	1.02
Pooled f	1,406	1.3	0.58	

corresponded to noise spectrum levels (power densities) N_0 of 45.6 and 52.1 dB SPL/Hz, respectively. The ERB values at the individual frequencies were estimated as 78, 356, 1571, 2072, and 4084 Hz and are plotted in Figure 6 (circles). The corresponding ERB values in units of octaves were 0.23, 0.56, 1.4, 0.96, and 1.02 (Table 2).

Fitting of a linear function revealed that the obtained ERB values could be approximated by the equation

$$\mathrm{ERB}(f_0) = 0.7 \times f_0 - 124.3 \tag{7}$$

with an accuracy of $R^2 = 0.97$, where ERB and f_0 are expressed in Hz. The obtained ERB values exhibited a monotonic increase with f_0, consistent with filter widths obtained from classical masking experiments (crosses in Figure 6; Glasberg & Moore, 1990). Thus, the bandwidth of the masker frequencies that was required for tonal continuity illusions increased with the center frequency of the illusion. Application of additional detection thresholds was constrained to those rating scores that were common to SNR and NW experiments for each center frequency. Figure 7 shows that when threshold was increased (i.e., the continuity illusion faded), the estimated ERB values increased consistently across center frequencies.

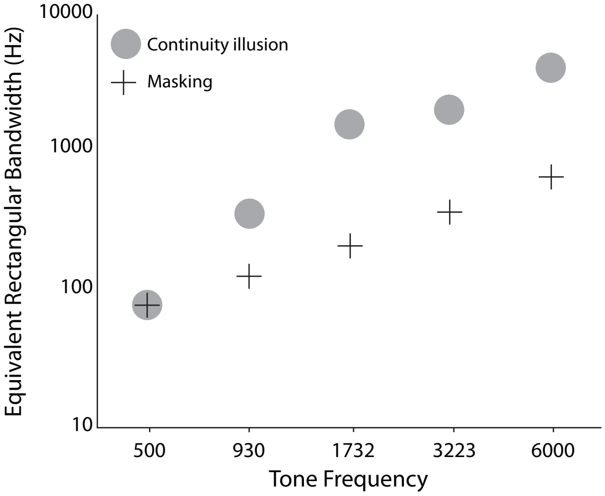

Figure 6. ERB of the auditory filters underlying continuity illusions (circles) as a function of tone frequency f_0, plotted on logarithmic–logarithmic scales. The fitted linear function, ERB = $0.7 \times f_0 - 124.3$, approximates the obtained ERB values, exhibiting a monotonic increase with f_0 (circles). A similar psychometric function, ERB = $0.1 \times f_0 - 24.7$, was suggested by Glasberg and Moore (1990) on the basis of classical notched-noise masking studies. The ERB values predicted by this function (crosses) exhibit a similar trend, but the increases are smaller at high center frequencies.

Frequency Effects

As suggested by Figure 5, the center frequency had no effect on the effects of noise duration, SNR, and NW, except for experimental conditions in the noise duration and SNR experiments [frequency × duration, $F(1,15) = 4.52, p < .05$ ($>.1$); frequency × SNR, $F(1,11) = 8.59, p < .01$ ($>.1$); frequency × notch, $F(1,11) = 2.11, p > .1$ ($>.1$); p values for control stimuli in parentheses]. The absence of a general frequency × noise interaction supported the pooling of the results across frequencies (Figures 4A–4C). As indicated by the asterisks in Figure 5, stimuli of 500, 930, 1732, 3223, and 6000 Hz were rated as continuity illusions in 61.1%, 50%, 83.3%, 55.6%, and 66.7% of the experimental conditions across experiments. Regarding the respective control conditions, 3.8%, 1.7%, 5.8%, 2.5%, and 11.25% were rated incorrectly as discontinuous. There was no significant effect of frequency on the number of illusory continuity percepts or incorrect discontinuity percepts, but there was a high correlation (Spearman's $R = .9$) between the two percept types across frequencies. Listeners perceived the longest continuity illusions mainly at 500 Hz, whereas the most filled in illusions (i.e., illusions at the largest NW) were perceived mainly at 1732 Hz (Figure 5). Remarkably, these illusions lasted up to 2,000 msec or involved noise maskers with spectral gaps of up to 1.25 octaves.

DISCUSSION

The aim of our research was to quantify the mechanisms that may underlie the continuity illusion. Based on our psychometric results, we estimated detection thresholds for continuity illusions for different noise maskers at different center frequencies and calculated the critical bandwidth of the proposed auditory filters that may underlie continuity illusions. By including continuous control stimuli, we assessed the salience of illusory continuity percepts relative to that of real (nonillusory) continuity percepts.

Masker Duration, Level, and Bandwidth Influence Illusory but Not Nonillusory Continuity

Our results show that the duration, level, and bandwidth of a noise masker influenced the perceived continuity of physically discontinuous tones (Figures 4A–4C). As expected, the most salient continuity illusions were observed for short gaps that were strongly masked. For longer gaps or weaker maskers, the illusions gradually shifted to nonillusory discontinuity percepts. The physically continuous tones were always perceived as continuous, independent of the noise maskers. The absence of a significant masker effect for the control stimuli suggests that listeners could not differentiate between masked and nonmasked continuous tones. Thus, the auditory system might smoothly embed continuous sounds of interest in the ongoing context irrespective of the background noise level.

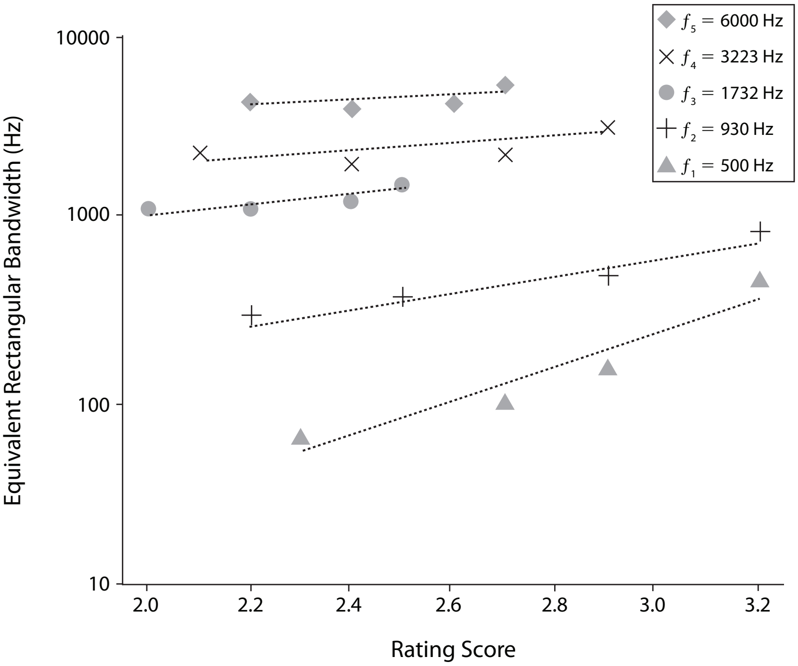

Figure 7. ERB of the auditory filters underlying continuity illusions of varying strength as a function of detection threshold, plotted on logarithmic–linear scales for each center frequency. The fitted linear functions (dotted lines) approximate the obtained ERB values (represented by various symbols; see figure legend), exhibiting an increase at higher detection thresholds (i.e., at weaker continuity illusions) consistently across center frequencies. Detection thresholds of 2.0 and 3.0 correspond to the ratings *probably continuous* and *probably discontinuous*, respectively. The ERB values predicted for threshold 2.5 correspond to the circles in Figure 6.

The finding that the continuity illusion becomes increasingly prominent with decreases in SNR and NW is consistent with previous results (Houtgast, 1972; Kluender & Jenison, 1992; Petkov et al., 2003; Sugita, 1997; Warren et al., 1972; Warren et al., 1988) and supports the spectral proximity principle. In the SNR experiments, the masker contained the on-frequency band and thus had spectral–temporal overlap with the target. The results indicate that the continuity illusion requires an average SNR of 1.3 dB or less, depending on the frequency. Thus, mere acoustic power within the on-frequency channel is not sufficient for the illusion to arise. Unless the target is masked by a sound of similar or greater intensity, the target's offset might induce an unexpected spectral edge that might be interpreted as an object offset, thereby yielding a discontinuity percept (Bregman, 1990).

In the NW experiments, the masker was sufficiently intense to mask the target (i.e., SNR = −3.5 dB), although the spectral notch did not conceal the spectrogram of the interrupted target. Interestingly, despite the physical discontinuity in the on-frequency band, our data from the notched-noise experiment predicted continuity illusions for average NWs of up to 0.58 octaves, which supports the notion that physical continuity within the target frequency band is not required in order for the illusion to arise (Houtgast, 1972). We observed the strongest effects at 1732 Hz, for which a 1.25-octave notch still produced continuity illusions. The perceived continuity and masking thus cannot be explained solely on the basis of concealment between two spectrograms. Rather, the missing on-frequency band must have been filled in by a mechanism that may have been related to masking.

A Proposed Role for the Auditory Filter in the Continuity Illusion

Our notched-noise experiments show that the continuity illusion of a tone requires only the frequencies that match and/or surround the tone's frequency, whereas more remote frequencies do not seem to have an influence. In addition, the SNR experiments indicate a minimal noise power below which the continuity illusion disappears. The results of these two experiments can be jointly understood through the concept of the auditory filter.

The auditory filter is a physiologically plausible model, since the frequency-tuning curves of auditory neurons have a certain bandwidth around the cell's best frequency. This bandwidth appears to increase along the ascending auditory pathway. Given this neuronal property, a notched-noise stimulus may be represented as a neurally filtered version of its spectrogram (Shamma, 2001) in which sharp edges and narrow notches have been smoothed and partially restored. Depending on the size of the neurons' spectral–temporal receptive fields, the processing of notched noise during an interruption of a less intense target sound might induce spatial–temporal overlap of activations in representations of proximate frequency bands. Given the continuity in the target frequency band before and after the noise, this may account for the perceptual filling in of the preserved continuous activation in the target frequency representation (Beauvois & Meddis, 1996; Warren et al., 1972). Electrophysiological research (Fishman, Arezzo, & Steinschneider, 2004) has recently reported a possible neural correlate of such a mechanism in monkeys' primary auditory cortex during the integration of auditory streams.

We found that the reconstructed critical bandwidth of spectral integration (i.e., ERB) increased monotonically with the filter's center frequency (Figure 6). Comparison of the ERBs at different center frequencies in octave units (Table 2) showed that the highest ERB occurred at 1732 Hz. This result is also reflected by listeners' ratings in the NW experiments, which showed the largest ratio of illusions as well as the largest range of filled in notches for these stimuli. Presumably, frequencies around the 1732-Hz band (which is at the logarithmic center of the human hearing range) are more likely to be perceptually grouped than are more peripheral frequencies. Stated differently, the spectral resolution of the mechanisms underlying continuity illusions may be low when they operate on bands that are otherwise well resolved.

Our results are qualitatively consistent with classical masking studies (for a review, see Glasberg & Moore, 1990) and with an earlier pulsation threshold study (Houtgast, 1974), both of which also reported monotonic increases of ERB with center frequency. Our results show that this increase is more pronounced for continuity illusions than for masking (slope 0.7 vs. 0.1; Figure 6). Note that Houtgast (1974) reported ERB values that were two times smaller for pulsation thresholds than for simultaneous masking thresholds, irrespective of the center frequency. Several causes may underlie this apparent difference. First, Houtgast (1974) investigated the perceived temporal character of pure tones that alternated repeatedly with rippled-noise bursts of very short duration (125 msec). Second, the testing levels in Houtgast's (1974) study were about 40 dB lower than they were in our study. Previous research has shown that the ERB increases with the testing level (see, e.g., Lutfi & Patterson, 1984; Moore & Glasberg, 1987; Weber, 1977), especially at high center frequencies (Baker & Rosen, 2006; Rosen & Stock, 1989). However, the reported effects of level were smaller than those observed in our study. Third, listeners in Houtgast's (1974) study were aware of the tone's absence and received feedback about their performance in the form of adjusted noise levels on each trial; these two factors may have lowered the detection threshold.

Differences in detection threshold between pulsation and masking were already reported by Warren et al. (1988), who also alternated maskers and targets of short (300-msec) duration and provided listeners with feedback during threshold estimation. The estimated detection thresholds for illusions of infratonal sounds in noise were lower than those for masking and were about 8 dB SPL lower than those reported in our study. Since the continuity illusion is a gradual phenomenon (see the introduction) and masking filters are typically estimated from more objective criteria, the reported difference in pulsation and masking threshold may reflect a difference between estimation techniques (i.e., detection of a perceptually restored vs. a physically present sound). Interestingly, the detection threshold for the illusion was reported to increase when the target's amplitude fluctuated below 10 Hz, which may also explain the observed increases in filter width for our illusory tones, which were amplitude modulated at 3 Hz (for a potential neural account, see Warren et al., 1988). Investigating whether the choice of a particular detection threshold affected our estimation of filter widths, we found that increases in detection threshold (i.e., focusing on less complete illusions like those given by less complete illusions; Figure 4) were indeed associated with qualitative increases in ERB estimation, whereas with stricter criteria for continuity, the width of the illusory filter may assimilate that of the masking filter (Figure 7).

In sum, our results suggest that decreases in the strength of the continuity illusion can be accounted for by filters of increasing bandwidth. Such wide-band filters may smooth the spectrogram of tone and noise more and, therefore, facilitate their integration across larger bands while weakening the noise's local masking effect. This may lead to drops in the perceptual SNR—that is, to fuzzier and less certain continuity percepts. For very strong continuity illusions, narrow-band filters seem to be involved. Such filters may integrate the stimulus within narrower bands while preserving the noise's masking power, which supports the idea that masking-related mechanisms may underlie salient illusions. More research is needed to investigate whether illusory perceptual grouping and tonal masking obey different principles at different stages of processing along the auditory pathway.

A Proposed Role for an Acoustic Short-Term Buffer in the Continuity Illusion

Our finding that the illusion became increasingly prominent for decreases in masker duration is consistent with previous findings (Kluender & Jenison, 1992; Warren, 1999) and supports the temporal proximity principle. Although earlier pure tone studies have reported continuity illusions of up to 300 msec, our results show that appropriate stimuli can evoke illusions of up to 900 msec on average, even extending up to 1,400 msec. One potential reason for these long illusions may be the amplitude modulation of our target sounds. The possibility of an amplitude modulation effect on the duration of the illusion has so far not been investigated, but the modulation rate and depth of the continuity illusion are preserved with nonmodulated maskers (Lyzenga et al., 2005) and may influence the strength of masking (Warren et al., 1988). A second contributing factor to long illusions might be the explicit instruction to listeners to attend to targets. Attention has also been shown to facilitate perceptual grouping of auditory events in streaming tasks (Alain & Arnott, 2000; Carlyon, Cusack, Foxton, & Robertson, 2001; Cusack, Deeks, Aikman, & Carlyon, 2004).

We observed that the upper noise duration limit and thus the temporal proximity principle depended on the center frequency of the continuity illusion (Figure 5). In particular, we obtained the longest continuity illusions of 2,000 msec for 500-Hz tones. Since the illusion arises post hoc—that is, on the basis of the continuity of the target after the masker (Warren, 1999)—an acoustic short-term buffer (Cowan, 1984) is likely involved. Specifically, the proposed buffer may retain the premasker target and match it with the postmasker target within a critical window of temporal integration. Our results put constraints on the proposed buffer's latency and suggest that within the preferred human hearing range, the buffer performs best for low-frequency bands.

Interestingly, we observed that the ratio of continuity illusions correlated with the ratio of incorrect discontinuity percepts of physically continuous tones. Presumably, listeners were more prone to interpret discontinuous targets as continuity illusions when the tone, if present during the same masker, was difficult to identify. This was indeed the case for the shortest noise duration and the lowest SNR. In terms of the proposed acoustic short-term buffer (Cowan, 1984), the perceptual difficulties with 200-msec noise bursts might be ascribed to the time scales at which unified identifiable auditory objects are represented: The time scales might be too large to perceptually resolve partial sensory information occurring within such a short time window. The proposed mechanism might sample the continuity illusion stimuli more globally as integrated abstract objects, rather than as redundant continuous signals (see, e.g., Darwin, 2005).

Potentially Confounding Ranging Effects

A limitation of the method of constant stimuli is that the observed effects of the stimulus parameterization might be contaminated by listeners' response biases. Moreover, the blocked design of our experiments might have encouraged listeners to adjust their rating scales to the different stimulus scales available within different blocks, rather than to the entire experiment, thus confounding between-condition comparisons. However, listeners were more likely to adjust their rating scales to the entire experiment, for two reasons. First, our results show a significant monotonic trend across conditions in all three experiments (Figures 4A–4C), which would not be expected for ratings based on within-block scaling. Second, before each experiment, listeners were trained on 18 nonblocked trials that included the most extreme conditions on the stimulus scales, which familiarized them with the entire stimulus scale presented in the subsequent experiment. Our finding that ratings of identical conditions did not differ significantly between experiments further suggests that listeners used a relatively stable rating scale independent of the available blocked stimulus scales. Thus, the assumptions underlying the between-condition and between-experiment comparisons were supported by our data.

A Well-Adapted Stimulus Set for Neurophysiologic Studies on the Continuity Illusion

So far, human neurophysiological data on the neural mechanisms underlying the continuity illusion are scarce (Micheyl et al., 2003), and further research (Husain, Lozito, Ulloa, & Horwitz, 2005) is much needed. Our results provide a well-adapted stimulus set for future neurophysiological studies of the continuity illusion. Specifically, the center frequencies are logarithmically centered within the humans' best hearing range and have representations roughly equidistant along the tonotopic gradient on the cortical surface (Merzenich, Kaas, & Roth, 1976), rendering these frequencies ideal for experiments on tonotopy (see, e.g., Formisano et al., 2003). Moreover, the stimuli evoke AM tone illusions of several hundreds of milliseconds—meaning that the putative neural correlates may be sampled even with low temporal resolution techniques. AM stimuli were previously reported to enhance the SNR of fMRI signals evoked by auditory stimuli (Hart, Palmer, & Hall, 2003). Furthermore, the salience of the illusions can be parametrically altered by NW changes in the noise, providing a paradigm that can be readily applied. A similar paradigm has already been applied successfully by Davis and Johnsrude (2003), who investigated the neural correlates of speech intelligibility across different maskers and masking levels with fMRI.

A potential problem is that brain signals related to percept changes are difficult to dissociate from those related to stimulus changes. However, one could exploit our paradigm to define perceptually ambiguous stimuli that were rated equally often as continuous and discontinuous (Table 2). Such a repeatedly presented ambiguous stimulus would allow researchers to define the experimental protocol post hoc according to the different perceptual responses, which is an efficient strategy for eliminating confounds from physical stimulus changes (see, e.g., Cusack, 2005).

AUTHOR NOTE

We thank Peter de Weerd and Noël Staeren for comments on the experimental design, Gerard van Breukelen for support with the statistical analysis, and Hanna Renvall, Noël Staeren, Nicolette Siep, Jasper van den Bosch, and the anonymous reviewers for their constructive comments on the manuscript. Funding for the present research was contributed to E.F. and A.J.V.O. by Grant 051.04.020 from the NWO Cognition program of the Netherlands Organization for Scientific Research. Correspondence concerning this article should be addressed to L. Riecke, Maastricht University, Faculty of Psychology, Department of Cognitive Neuroscience, P.O. Box 616, 6200 MD Maastricht, The Netherlands (e-mail: l.riecke@psychology.unimaas.nl).

REFERENCES

Alain, C., & Arnott, S. R. (2000). Selectively attending to auditory objects. *Frontiers in Bioscience*, **5**, D202-D212.

Baker, R. J., & Rosen, S. (2006). Auditory filter nonlinearity across frequency using simultaneous notched-noise masking. *Journal of the Acoustical Society of America*, **119**, 454-462.

Beauvois, M. W., & Meddis, R. (1996). Computer simulation of auditory stream segregation in alternating-tone sequences. *Journal of the Acoustical Society of America*, **99**, 2270-2280.

Braaten, R. F., & Leary, J. C. (1999). Temporal induction of missing birdsong segments in European starlings. *Psychological Science*, **10**, 162-166.

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound* (4th ed.). Cambridge, MA: MIT Press.

Carlyon, R. P., Cusack, R., Foxton, R., & Robertson, I. H. (2001). Effects of attention and unilateral neglect on auditory stream segregation. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 115-127.

Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin*, **96**, 341-370.

Cusack, R. (2005). The intraparietal sulcus and perceptual organization. *Journal of Cognitive Neuroscience*, **17**, 641-651.

Cusack, R., Deeks, J., Aikman, G., & Carlyon, R. P. (2004). Effects of location, frequency region, and time course of selective attention on auditory scene analysis. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 643-656.

Darwin, C. J. (2005). Simultaneous grouping and auditory continuity. *Perception & Psychophysics*, **67**, 1384-1390.

Davis, M. H., & Johnsrude, I. S. (2003). Hierarchical processing in spoken language comprehension. *Journal of Neuroscience*, **23**, 3423-3431.

Fishman, Y. I., Arezzo, J. C., & Steinschneider, M. (2004). Auditory stream segregation in monkey auditory cortex: Effects of frequency separation, presentation rate, and tone duration. *Journal of the Acoustical Society of America*, **116**, 1656-1670.

Fletcher, H. (1940). Auditory patterns. *Reviews of Modern Physics*, **12**, 47-65.

Formisano, E., Kim, D. S., Di Salle, F., van de Moortele, P. F., Ugurbil, K., & Goebel, R. (2003). Mirror-symmetric tonotopic maps in human primary auditory cortex. *Neuron*, **40**, 859-869.

Glasberg, B. R., & Moore, B. C. J. (1982). Auditory filter shapes in forward masking as a function of level. *Journal of the Acoustical Society of America*, **71**, 946-949.

Glasberg, B. R., & Moore, B. C. J. (1990). Derivation of auditory filter shapes from notched-noise data. *Hearing Research*, **47**, 103-138.

Griffiths, T. D., & Warren, J. D. (2004). What is an auditory object? *Nature Reviews Neuroscience*, **5**, 887-892.

Hart, H. C., Palmer, A. R., & Hall, D. A. (2003). Amplitude and frequency-modulated stimuli activate common regions of human auditory cortex. *Cerebral Cortex*, **13**, 773-781.

Houtgast, T. (1972). Psychophysical evidence for lateral inhibition in hearing. *Journal of the Acoustical Society of America*, **51**, 1885-1894.

Houtgast, T. (1974). *Lateral suppression in hearing*. Unpublished doctoral dissertation, Vrije Universiteit Amsterdam.

Husain, F. T., Lozito, T. P., Ulloa, A., & Horwitz, B. (2005). Investigating the neural basis of the auditory continuity illusion. *Journal of Cognitive Neuroscience*, **17**, 1275-1292.

Kluender, K. R., & Jenison, R. L. (1992). Effects of glide slope, noise intensity, and noise duration on the extrapolation of FM glides through noise. *Perception & Psychophysics*, **51**, 231-238.

Lutfi, R. A., & Patterson, R. D. (1984). On the growth of masking asymmetry with stimulus intensity. *Journal of the Acoustical Society of America*, **76**, 739-745.

Lyzenga, J., Carlyon, R. P., & Moore, B. C. J. (2005). Dynamic aspects of the continuity illusion: Perception of level and of the depth, rate, and phase of modulation. *Hearing Research*, **210**, 30-41.

Merzenich, M. M., Kaas, J. H., & Roth, G. L. (1976). Auditory cortex in the grey squirrel: Tonotopic organization and architectonic fields. *Journal of Comparative Neurology*, **166**, 387-402.

Micheyl, C., Carlyon, R. P., Shtyrov, Y., Hauk, O., Dodson, T., & Pulvermüller, F. (2003). The neurophysiological basis of the auditory continuity illusion: A mismatch negativity study. *Journal of Cognitive Neuroscience*, **15**, 747-758.

Miller, C. T., Dibble, E., & Hauser, M. D. (2001). Amodal completion of acoustic signals by a nonhuman primate. *Nature Neuroscience*, **4**, 783-784.

Miller, G. A., & Licklider, J. C. R. (1950). The intelligibility of interrupted speech. *Journal of the Acoustical Society of America*, **22**, 167-173.

Moore, B. C. J. (2003). *An introduction to the psychology of hearing* (5th ed.). San Diego: Academic Press.

Moore, B. C. J., & Glasberg, B. R. (1981). Auditory filter shapes derived in simultaneous and forward masking. *Journal of the Acoustical Society of America*, **70**, 1003-1014.

Moore, B. C. J., & Glasberg, B. R. (1987). Formulae describing frequency selectivity as a function of frequency and level, and their use in calculating excitation patterns. *Hearing Research*, **28**, 209-225.

Patterson, R. D. (1976). Auditory filter shapes derived with noise stimuli. *Journal of the Acoustical Society of America*, **48**, 640-654.

Patterson, R. D., & Moore, B. C. J. (1986). Auditory filters and excitation patterns as representations of frequency resolution. In B. C. J. Moore (Ed.), *Frequency selectivity in hearing* (pp. 123-177). London: Academic Press.

Petkov, C. I., O'Connor, K. N., & Sutter, M. L. (2003). Illusory sound perception in macaque monkeys. *Journal of Neuroscience*, **23**, 9155-9161.

Rosen, S., & Stock, D. (1989). Auditory filter bandwidths as a function of level at low frequencies (125 Hz–1 kHz). *Journal of the Acoustical Society of America*, **92**, 773-781.

Shamma, S. (2001). On the role of space and time in auditory processing. *Trends in Cognitive Sciences*, **5**, 340-348.

Sugita, Y. (1997). Neuronal correlates of auditory induction in the cat cortex. *NeuroReport*, **8**, 1155-1159.

Warren, R. M. (1999). *Auditory perception: A new analysis and synthesis*. Cambridge: Cambridge University Press.

Warren, R. M., Bashford, J. A., Jr., Healy, E. W., & Brubaker, B. S. (1994). Auditory induction: Reciprocal changes in alternating sounds. *Perception & Psychophysics*, **55**, 313-322.

Warren, R. M., Obusek, C. J., & Ackroff, J. M. (1972). Auditory induction: Perceptual synthesis of absent sounds. *Science*, **176**, 1149-1151.

Warren, R. M., Wrightson, J. M., & Puretz, J. (1988). Illusory continuity of tonal and infratonal periodic sounds. *Journal of the Acoustical Society of America*, **84**, 1338-1342.

Weber, D. L. (1977). Growth of masking and the auditory filter. *Journal of the Acoustical Society of America*, **62**, 424-429.

Wertheimer, M. (1938). Laws of organization in perceptual forms. In W. D. Ellis (Ed.), *A source book of Gestalt psychology* (pp. 71-88). London: Kegan Paul, Trench, Trubner & Co. (Original work published 1923)

(Manuscript received July 7, 2006;
revision accepted for publication June 7, 2007.)