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Illusory Auditory Continuity Despite Neural Evidence to the Contrary

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Abstract

Many previous studies have shown that a tone that is momentarily interrupted can be perceived as continuous if the interruption is completely masked by noise. It has been suggested this “continuity illusion” occurs only when peripheral neural responses contain no evidence that the signal was interrupted. In this study, we used a combination of psychophysical measures and computational simulations of peripheral auditory responses to examine whether the continuity illusion can be experienced under conditions where peripheral neural responses contain evidence that the signal did not continue through the masker. Our results provide an example of a salient continuity illusion despite evidence of an interruption in the peripheral representation, indicating that the illusion may depend more on global features of the interrupting sound, such as its long-term specific loudness, than on its fine-grained temporal structure.

1 Introduction

The auditory continuity illusion refers to the illusory perception of a physically interrupted sound as “continuing through” another sound that occludes the interruption (Miller and Licklider 1950). The results of numerous studies during the last 40 years have led to the widespread view that an important prerequisite for the occurrence of the illusion is that peripheral auditory responses to the occluding sound contain no evidence that the signal was absent (e.g., Duifhuis 1980; Kluender and Jenison 1992; Plack and Oxenham 2000; Riecke et al. 2008; Warren et al. 1972, 1988). In particular, the results of these studies suggest that the illusion does not occur if the peripheral excitation produced by the occluder does not completely mask the excitation that would have been produced by the signal, had the latter physically continued through the occluder (Bregman 1990, p. 352; Warren et al. 1972). We refer to this as the “peripheral masking” theory of the continuity illusion (for reviews, see Bregman 1990; Petkov and Sutter 2010; Warren 1999). The interpretation of the previous

findings has focused on time-averaged measures, such as the long-term power spectrum of the target and masker, or their excitation patterns, whereas relatively little attention has been paid to the fine-grained temporal characteristics of these sounds, i.e., their temporal fine structure and fast fluctuations in their temporal envelope. In this study, we investigated the importance of fine-grained temporal information in the generation of the continuity illusion.

2 Method

2.1 Stimuli, Tasks, and Procedure

To test the influence of differences in fine-grained temporal information in the generation of the continuity illusion, we used harmonic complex tones with positive and negative phase curvatures (Schroeder 1970) as occluders. These so-called Schroeder-phase complexes (abbreviated M+ and M−) have identical long-term power spectra but different phase spectra, set specifically to evoke different temporal response patterns in the auditory periphery, taking into account the curvature of the phase response of cochlear filters (Carlyon and Datta 1997a, b; Kohlrausch and Sander 1995; Lentz and Leek 2001; Oxenham and Dau 2001a; Smith et al. 1986). This is illustrated in Fig. 53.1a, c, which shows simulated temporal response patterns of an auditory nerve (AN) fiber to M+ and M− complexes consisting of the first 33 harmonics of a 100-Hz fundamental frequency.

These simulations were produced using a model of peripheral processing, including cochlear filters with phase responses estimated based on psychophysical data in humans (Oxenham and Dau 2001b) and cochlear compression (for details, see Riecke et al. 2012). It can be seen that the M+ complex evokes a markedly “peakier” temporal response pattern than the M− complex—an effect due to the positive phase curvature of M+ compensating for the negative phase curvature of cochlear filters—whereas the negative phase curvature of M− adds to the negative phase curvature of the cochlear filters, resulting in an accentuated phase-dispersion effect (Recio and Rhode 2000; Summers et al. 2003). This effect has been used to explain why the masked threshold of a pure tone embedded in an M− complex is markedly higher than its masked threshold when embedded in an M+ complex having the same overall physical level (Kohlrausch and Sander 1995; Lentz and Leek 2001; Oxenham and Dau 2001a; Smith et al. 1986; see Fig. 53.1b, d).

Based on these simulation results, we predicted that if the continuity illusion depends on a fine-grained analysis of peripheral activity, then the level of the target below which the continuity illusion occurs (the “continuity-illusion threshold”) should be considerably lower for the M+ masker than for the M− masker, in line with the differences in simultaneous-masked threshold. Conversely, if the continuity illusion depends on a relatively coarse representation of the masker (e.g., a representation of its overall level or specific loudness), the illusion thresholds measured with the M+ and M− maskers should be reasonably similar, i.e., their difference should be considerably smaller than the differences in masked threshold.

This prediction was tested in three experiments. In the “continuity-illusion” experiment (C), a 1,500-Hz target tone (T) and a masker (M+ or M−), each lasting 200 ms, were played in an alternating sequence (TMTMTMT), and the listener’s task was to indicate whether the target

was heard as continuing through the masker or not. The level of the target was varied adaptively to determine the continuity-illusion threshold (defined as the target level corresponding to the 50 % point on the psychometric function). The level of the masker was fixed at 50-dB SL per harmonic (relative to the listener's hearing threshold at the frequency of the target).

In the “simultaneous-masking” experiment (S), the 200-ms target was presented simultaneously with, and temporally centered in, the 600-ms masker in one of two consecutive observation intervals (selected at random with equal probability), while the other observation interval contained only the masker. The task of the listener was to indicate which interval contained the target. The goal of this experiment was to provide a direct measure of the amount of simultaneous masking produced by the masker.

Lastly, the “forward-masking” experiment (F) was similar to experiment S, except that a 10-ms target was presented 5 ms after a 200-ms masker. The aim of this experiment was to provide an estimate of the strength of the long-term internal excitation produced by the masker (Carlyon and Datta 1997b). Thresholds in experiments S and F were measured with an adaptive two-alternative forced-choice procedure and a two-down one-up tracking rule estimating the 70.7 % correct point on the psychometric function (Levitt 1971). The level of the signal was varied, while the level of the masker was kept constant, as in experiment C.

In all adaptive-tracking procedures, the step size was initially set to 6 dB and reduced to 3 dB after the second reversal in the direction of change of the target level (from increasing to decreasing or vice versa) and to 0.5 dB after the fourth reversal. Each measurement began with the target level set sufficiently high (62-dB SL) so that the listener did not hear the target continue through the masker in experiment C and that the listener could easily detect the target in experiments S and F. The procedure was terminated after the tenth reversal. Threshold was computed as the arithmetic mean of the target levels at the last six reversals. For each listener and each masker condition, nine, six, and six thresholds were measured in experiments C, S, and F, respectively, in fully randomized order. Only in experiments S and F, visual feedback was provided to the listener after each trial.

Target and maskers were ramped on and off with 20-ms linear ramps, except for experiment F, in which the 10-ms target was ramped with 5-ms ramps (no steady state). In experiment C, the amplitude midpoints of the ramps of consecutive elements (T and M) were made to coincide so that the audibility of the gaps in the TMTMTMT sequence was reduced. The two observation intervals in experiments S and F were separated by a 500-ms gap.

Stimuli were generated digitally and presented monaurally via a soundcard and headphones (MDR-V900HD, Sony) in a sound-attenuating chamber. Stimulus presentation and response collection were controlled using the AFC software package (developed by Stephan Ewert at University of Oldenburg).

2.2 Participants

Eleven paid volunteers (five females, ages 20–35 years) participated in the study after providing written informed consent. Except for one participant who had a slightly elevated

threshold (35-dB HL) at 4,000 Hz, all participants had normal hearing (pure-tone hearing thresholds less than 20-dB HL at octave frequencies between 125 Hz and 4 kHz, including the frequency of the target) and no history of hearing disorders.

3 Results

As shown by Fig. 53.1e, the M+ complex yielded lower thresholds than the M− complex, both overall ($F_{1,10} = 44.05, p < 0.001$) and for each experiment taken separately (C: $t_{10} = 1.94, p = 0.049$; S: $t_{10} = 15.07, p < 0.001$; F: $t_{10} = 4.05, p = 0.0018$). Importantly, this threshold difference was significantly smaller in experiment C than in experiment S ($t_{10} = -7.34, p < 0.001$), but did not differ significantly between experiments C and F ($t_{10} = -0.97, p = 0.36$).

4 Discussion

Using maskers with identical long-term power spectra but different temporal peripheral representations, we found that differences in continuity-illusion thresholds are (1) considerably smaller than differences in simultaneously masked threshold and (2) relatively similar to differences in forward-masked thresholds.

Our first finding shows that although the real tone was much easier to detect in the M+ complex than in the M− complex, this difference existed much less for the illusory tone. Together with our simulation results, this indicates that the illusion can occur under conditions where peripheral neural responses contain evidence that the target was interrupted. Our second finding shows that the occluder had similar effects on the continuity illusion and forward masking. Based on the notion that forward masking depends primarily on the long-term internal excitation evoked by the masker (Carlyon and Datta 1997b; Wojtczak and Oxenham 2009), this suggests that the illusion depends on a neural representation of the average excitation evoked by the occluder—possibly related to the specific loudness of the occluder, i.e., its loudness within the critical band centered on the frequency of the target sound (Mauermann and Hohmann 2007).

Recent studies have demonstrated the occurrence of the continuity illusion under conditions where the target was not interrupted by any sound (Remijn et al. 2007, 2008) or the occluder was briefly interrupted (Haywood et al. 2011). Two other studies investigating dynamic aspects of the illusion found that a modulated target was perceived as continuing through an interrupting noise, although listeners were unable to track the phase of the illusory modulation through the interruption (Carlyon et al. 2004; Lyzenga et al. 2005). Together with these previous findings, our results provide accumulating evidence against the peripheral masking theory (Warren et al. 1972) and for the notion that the fine-grained temporal structure of the target and occluder are not preserved during the illusion (but see also Plack and Watkinson 2010).

The proposed role of the occluder's long-term features (e.g., its specific loudness) for the continuity illusion implies that the illusion arises at or beyond neural processing stages that integrate the fine-grained temporal structure of the peripheral sound representation. This

outcome suggests a relatively central origin, in line with claims from previous studies (Elfner and Homick 1967; Hellstrom and Young 1989; Petkov et al. 2007; Schreiner 1980).

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Fig. 53.1.

Simulated peripheral activities and psychophysical results. (a–d) The *upper row* shows sound waveforms for a portion of the stimuli denoted above. As shown by the *lower row*, the M+ complex evoked “peakier” simulated peripheral responses than the M– complex (compare panels a and c). Thus, the target should be considerably easier to detect in the M+ complex than in the M– complex (compare panels b and d). (e) Psychophysical thresholds (mean $\pm$ s.e.m. across 11 listeners) obtained with the M– complex were markedly higher than those obtained with the M+ complex, in each experiment. Importantly, this difference was substantially smaller in experiment C than in experiment S and rather similar in experiments C and F. Thus, thresholds for the continuity illusion agreed better with the pattern of forward-masked thresholds than with that of simultaneous-masked thresholds (modified from Riecke et al. (2012))