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Research paper

The continuity illusion adapts to the auditory scene

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ABSTRACT

The human auditory system is efficient at restoring sounds of interest. In noisy environments, for example, an interrupted target sound may be illusorily heard as continuing smoothly when a loud noise masks the interruptions. In quiet environments, however, sudden interruptions might signal important events. In that case, restoration of the target sound would be disadvantageous. Achieving useful perceptual stability may require the restoration mechanism to adapt its output to current perceptual demands, a hypothesis which has not yet been fully evaluated. In this study, we investigated whether auditory restoration depends on preceding auditory scenes, and we report evidence that restoration adapts to the perceived continuity of target sounds and to the loudness of interrupting sounds. In the first experiment, listeners adapted to illusory and non-illusory tone sweeps (targets) and interrupting noise, and we observed that the perceived continuity of the target and the loudness of the interrupting noise influenced the extent of subsequent restorations. A second experiment revealed that these adaptation effects were unrelated to the adapted spectra, indicating that non-sensory representations of the perceived auditory scene were involved. We argue that auditory restoration is a dynamic illusory phenomenon which recalibrates continuity hearing to different acoustic environments.

1. Introduction

A major challenge for the auditory system is to ensure stability of relevant sound objects in the presence of environmental noise. This stability is facilitated by perceptual filling mechanisms that may restore noisy interruptions in a foreground sound, thereby creating a continuity illusion of the foreground. In a loud scene, for example, an interrupted voice can be illusorily heard as continuing through noise (Miller and Licklider, 1950), which may help to restore the actual speech signal and improve its intelligibility (Warren, 1970; Powers and Wilcox, 1977; Bashford et al., 1992).

Since its discovery (Miller and Licklider, 1950) the continuity illusion has been investigated extensively under several names such as pulsation threshold (Houtgast, 1972), temporal induction (Warren et al., 1972), contextual concatenation (Warren, 1984), amodal completion (Miller et al., 2001), and illusory filling (Petkov et al., 2003; for reviews, see Bregman, 1990; Warren, 1999). Early research revealed that the continuity illusion depends on the masking of the gaps in the interrupted sound (Houtgast, 1972; Warren et al., 1972), or on the absence of sensory evidence for these gaps (Warren et al., 1972; Dannenbring, 1976; Bregman and Dannenbring, 1977). Another determining factor is the similarity of the sound fragments that surround a noisy interruption. For example, when the fragments of an interrupted sweep have the same frequency trajectory or when they are proximate to each other in frequency and time, they are more likely to be grouped and to produce a continuity illusion (Ciocca and Bregman, 1987). Thus, the relevance of the fragment that follows the interruption implies that the continuity illusion depends on the acoustic context (Warren, 1983; Ciocca and Bregman, 1987). Furthermore, it has been observed that the continuity illusion may fade out or fade in during long noise interruptions (Wrightson and Warren, 1981; Warren et al., 1994). This apparent partial extension of the fragmented sound during the interruption indicates that the illusion is not an all-or-none phenomenon, but a perceptual continuum (Bregman, 1990).

More recent research on the continuity illusion has extended the previous findings and stressed the relevance of acoustic onsets and offsets (edges). When a sweep intersects with a silent interruption of a longer sweep, the gap may be misattributed to the shorter sweep while the longer sweep may appear illusorily continuous (Nakajima et al., 2000). Furthermore, two spectrally segregated sweeps that partly overlap in time may be illusorily perceived as a single continuous sweep, accompanied by an additional illusory tone during the overlap (Remijn et al., 2001; Remijn and Nakajima, 2005). This effect is observed irrespective of the presence or absence of masking noise, and persists even when the spectral gap is wider than one critical band (Fletcher, 1940), indicating the involvement of non-peripheral mechanisms.

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These findings are consistent with the previous results (see previous paragraph) and support a model of auditory grouping proposed by Nakajima et al. (2000). According to this model, the illusory continuity of a sound may emerge from the perceptual binding of spectro-temporally proximate edges of different sounds.

An aspect of the continuity illusion which has received not much attention so far is the stability of the illusion across different acoustic environments. This aspect is relevant as restoration of a given sound may be desired under certain circumstances, but not under other circumstances. For example, in quiet environments, an abrupt interference by a loud sound from the background might reflect a meaningful event and thus it should *not* be smoothed into a sound of interest in the actual foreground. To achieve appropriate levels of perceptual stability, the restoration mechanism would need to adapt its output to current environmental demands.

Auditory adaptation phenomena illustrating how hearing depends on recent acoustic input have been well described in the literature. For example, the same sound may be perceived as substantially softer when a louder sound is presented shortly before (Marks, 1994). Such contrastive aftereffects have been commonly interpreted in terms of adaptation or habituation, which can be understood as reductions in behavioral or neurophysiologic responses caused by prior or ongoing stimulation. Aftereffects may occur for various low-level stimulus properties and in various sensory modalities as evidenced by previous research. Exposure to sounds was shown to induce temporary changes in the ability to discriminate intensities (Zeng et al., 1991; Zeng and Turner, 1992; Carlyon and Beveridge, 1993; Plack et al., 1995; Zeng and Shannon, 1995; Plack, 1996; Oberfeld, 2007, 2008) or to detect target sounds in noise (Penner, 1974; Kidd and Feth, 1982; Viemeister and Bacon, 1982; Wright et al., 1993). Furthermore, amplitude- or frequency-modulations (AMs or FMs, respectively) of preceding sounds were found to temporarily increase detection thresholds for AMs or FMs of subsequent sounds (Kay and Matthews, 1972; Green and Kay, 1973, 1974; Regan and Tansley, 1979; Tansley and Suffield, 1983; Moody et al., 1984; Wojtczak and Viemeister, 2003, 2005).

These and other (Rosenblith et al., 1947; Zwicker, 1964) auditory aftereffects may reflect a ubiquitous mechanism that enables the auditory system to adapt to current probabilities in the acoustic environment. Further findings of adaptation to non-illusory higher-level sound properties such as sound source location (Frissen et al., 2003, 2005; Phillips and Hall, 2005), phonemic category (Eimas and Corbit, 1973; Cooper, 1974; Diehl et al., 1978; Samuel and Newport, 1979; Simon and Studdert-Kennedy, 1978; Ohde and Sharf, 1979; Sawusch and Jusczyk, 1981; Landahl and Blumstein, 1982) or voice gender (Schweinberger et al., 2008) have extended this hypothesis. Therefore, hearing might depend not only on the acoustic input but also on its perceptual interpretation. Such a perceptual adaptation mechanism could have ecological value because it potentially improves the ability to discriminate rare sound objects in the perceived auditory scene.

To assess whether this adaptation also applies to auditory restoration, we investigated whether the continuity of tone sweeps (targets) or the masking potential of interrupting noise influence subsequent restorations of fragmented target sounds. Listeners were presented with series of schematic auditory scenes, consisting of sweeps, noise, or both (restoration condition), and rated their continuity. An ambiguous scene (probe) created a bistable restoration condition which was presented after different series of unambiguous scenes (adaptors). In the first experiment, listeners were adapted to illusory continuous, truly continuous, or discontinuous sweeps, and to loud or soft noise. We obtained evidence that auditory restoration adapts to the perceived continuity of the sweeps and also to the loudness of the interrupting noise. In a second experiment, we investigated whether this adaptation is specific to the spectra of the adapting sounds. Listeners adapted to sweeps or noise whose spectra did not overlap with the portion of the spectrum required for illusory restoration. We found that auditory restoration adapts even when the adapted and restored spectra are incongruent, and we observed that the masking potential of the noise has little impact. The results indicate that auditory restoration depends on the perceived continuity and the loudness of preceding sounds, irrespective of their frequency content. We argue that these aftereffects can be explained by adaptation to abstract, non-sensory representations of the auditory scene.

2. Materials and methods

2.1. Participants

Twenty six volunteers (age: 24 ± 3 years, mean ± standard deviation [SD]) with normal hearing abilities, mainly students from Maastricht University, participated in the study after providing informed consent. Two different groups of 12 listeners participated in experiment 1 and 2, respectively, and two other listeners participated in both experiments. Participants were uninformed about the background of the study, except for two (one of the authors and one research assistant). The local ethical committee approved the procedure.

2.2. Stimuli

An auditory scene was simulated by stimuli of 5000-ms duration (Fig. 1A) consisting of a tone sweep, white noise, or both (Fig. 1B and C). The tone's frequency was logarithmically increased from 1 to 3 kHz and its amplitude was pulsed at 2 Hz, resulting in an ascending sweep which was repeatedly interrupted by silence. For experiment 1 (Fig. 1B), the noise was band-passed from 0.9 to 3.6 kHz (two octaves, 3-dB cutoff frequencies) so that the noise covered the sweep's spectrum. To enable the probing of restoration in these spectra, the noise was inserted in the silent gaps of the sweep such that the onsets and offsets of noise and gaps were synchronized. All onsets and offsets were linearly ramped with 10-ms rise–fall times. For experiment 2 (Fig. 1C), some sweep and noise spectra were modified such that they did not overlap with the probe spectrum described above. The sweep's frequency was logarithmically decreased from 0.8 to 0.3 kHz, resulting in a pitch modulation which was reversed relative to that in experiment 1. The noise was band-passed from 0.45 to 7.2 kHz (four octaves) and band-stopped (notched) from 0.9 to 3.6 kHz (two octaves). Stimuli were sampled at 44.1 kHz with 16 bit resolution using Matlab 7.0.1 (The MathWorks Inc., Natick, MA). Stimuli were presented diotically at maximal 80 dB sound pressure level (SPL) using Presentation 9.30 software (Neurobehavioral Systems, Inc., Albany, CA, USA), a Creative Sound Blaster Audigy 2ZS sound card (Creative Technology, Ltd., Singapore), and a Sennheiser HMD 25-1 headset (Sennheiser electronic, Wedemark, Germany).

2.3. Design and task

For each experiment, three pairs of adaptors were designed to test listeners for adaptation to three different aspects of the simulated auditory scenes (Fig. 1B and C). In the "noise-interrupted sweep" conditions, the interrupted ascending sweep was alternated with noise. For experiment 1 (Fig. 1B), the overall noise level was varied (signal-to-noise ratio (SNR) = −20 or 8 dB, respectively) and the noise and sweep spectra overlapped. For experiment 2 (Fig. 1C), the overall noise level was held constant at the higher value (SNR = −20 dB), and the noise spectrum was either congruent or incongruent with the sweep spectrum. Thus, the noise was