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Research paper

The perceptual enhancement of tones by frequency shifts

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ABSTRACT

In a chord of pure tones with a flat spectral profile, one tone can be perceptually enhanced relative to the other tones by the previous presentation of a slightly different chord. "Intensity enhancement" (IE) is obtained when the component tones of the two chords have the same frequencies, but in the first chord the target of enhancement is attenuated relative to the other tones. "Frequency enhancement" (FE) is obtained when both chords have a flat spectral profile, but the target of enhancement shifts in frequency from the first to the second chord. We report here an experiment in which IE and FE were measured using a task requiring the listener to indicate whether or not the second chord included a tone identical to a subsequent probe tone. The results showed that a global attenuation of the first chord relative to the second chord disrupted IE more than FE. This suggests that the mechanisms of IE and FE are not the same. In accordance with this suggestion, computations of the auditory excitation patterns produced by the chords indicate that the mechanism of IE is not sufficient to explain FE for small frequency shifts.

1. Introduction

The auditory system tends to "enhance" acoustic changes consisting of the addition of power to a restricted part of the spectrum of a complex sound. Thus, for example, in a chord of pure tones with equal intensities, one of the tones (X) can be made to pop out perceptually by presenting, before this chord, a copy of it in which X is attenuated. Many variants of this enhancement effect have been described in the literature (Schouten, 1940; Wilson, 1970; Viemeister, 1980; Summerfield et al., 1987; Carlyon, 1989; Wright et al., 1993; Hartmann and Goupell, 2006; Serman et al., 2008; Cao and Richards, 2012; Cervantes Constantino et al., 2012). In everyday life, enhancement is presumably helpful for the perceptual segregation of new acoustic events in sound mixtures (Bregman, 1990).

A plausible explanation for enhancement is neural adaptation. In our example, the neural response to tone X in the second chord can be expected to be stronger than the neural responses to the other components of this chord because the latter responses should show more adaptation following the first chord. A related explanation is "adaptation of inhibition" (Viemeister and Bacon, 1982; Byrne et al., 2011): the first chord could reduce, in the second chord, the inhibition of neurons responding to X by neurons responding to other components of the chord. Nelson and Young (2010) have recently reported physiological data supporting the latter explanation. Remarkably, enhancement is still observable when the enhancing stimulus (hereafter called the "precursor" stimulus) and the subsequent stimulus (hereafter called the "test" stimulus) are separated by several seconds (Viemeister, 1980; Cao and Richards, 2012), or are presented to separate ears (Richards et al., 2004; Kidd et al., 2011; Erviti et al., 2011; Carcagno et al., 2012, in press), or are electrical signals directly exciting the auditory nerve through a cochlear implant (Goupell and Mostardi, 2012; Wang et al., 2012). These three facts indicate that enhancement cannot entirely originate from peripheral processes. Its main source could nevertheless be some form of stimulus-specific neural adaptation taking place at central levels of the auditory system (Ulanovsky et al., 2003; Malmierca et al., 2009; Antunes et al., 2010).

Erviti et al. (2011) observed that tones within chords can be strongly enhanced perceptually not only as a result of shifts in relative intensity – i.e., changes in "spectral profile" (Green, 1988) – but also as a result of shifts in frequency. In an array of frequency-selective neurons acting as bandpass filters and tuned to a wide range of frequencies, a shift in frequency will increase the excitation of some neurons, like an increase in intensity. In theory, therefore, it could be that the mechanism underlying the enhancement produced by frequency shifts (called "frequency enhancement" (FE) by Erviti et al. (2011) is the same as the mechanism underlying "classical" enhancement (called "intensity

Abbreviations: FE, frequency enhancement; IE, intensity enhancement; NE, no enhancement; FSD, frequency-shift detector.

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enhancement" (IE) by Erviti et al.). However, Erviti et al. provided one argument against that view. They found that presenting the precursor and test stimuli to opposite ears rather than to the same ear significantly diminishes IE but has little effect on FE.

In the present paper, we provide two additional pieces of evidence against the idea that FE can be fully explained in the same manner as IE. First, we report a psychophysical experiment comparing FE with IE regarding their sensitivity to a *global* attenuation of the precursor stimulus relative to the test stimulus. In most of the past experiments on enhancement, the background components of the stimuli (i.e., the stimulus components which were not the target of enhancement) had the same intensity in the precursor and the test stimulus. The effect of a global attenuation of the precursor on IE has been investigated by Carlyon (1989) and Viemeister et al. (in press). These two studies led to discrepant conclusions: while Carlyon (1989) found very little effect of precursor intensity in a 30-dB range, Viemeister et al. (in press) found that a 10-dB attenuation of the precursor background relative to the test background was sufficient to reduce IE substantially. The effect of such manipulations on FE has not been documented up to now.

We also report here the results of computations based on the excitation pattern model of Moore et al. (1997), revised by Glasberg and Moore (2006). Using this model, it is possible to estimate how any stationary sound stimulus excites a bank of filters consistent with the frequency selectivity of masking in humans. One can therefore compute the difference between the excitation patterns of two pure-tone chords, P and T, identical to each other except for one tone and such that the sequence P–T enhances this tone. For a given T chord and enhancement target, consider the case of two P chords, P_F and P_I, eliciting respectively FE and IE with the same strength. If FE and IE originate from the same process, namely some form of frequency-selective neural adaptation, the spectrally local increases of excitation produced by the sequences P_F–T and P_I–T should be similar in magnitude. Our computations were intended to test this prediction.

2. Experiment

2.1. Method

2.1.1. Overview

The experimental task was the same as that used by Erviti et al. (2011). On each trial, the listener was presented with three successive stimuli: a precursor chord, a test chord, and a probe tone. The test chord consisted of five synchronous pure tones with the same nominal sound pressure level (SPL); the frequencies of its components were renewed from trial to trial, according to rules specified below (Section 2.1.2). The following probe tone was, equiprobably, either identical in every respect to one component of the test chord, or different in frequency (but not duration or SPL) from all of the test chord components. In the former case, the probe matched in frequency one of the three "inner" components of the test chord; a random choice was made between these three options. In the latter case, the frequency of the probe tone was equal to the geometric mean of the frequencies of two adjacent components of the test chord; a random choice was made between the four corresponding options. The listener had to indicate if the probe tone was present in the test chord or absent from it. As argued by Roberts (1998), such a task is probably the best methodological choice for the assessment of the relative perceptual salience of a tone presented simultaneously with other tones. Note that renewing the test chord from trial to trial was necessary to prevent listeners from basing their judgments on the probe tone alone.

The precursor chord, like the test chord, consisted of five synchronous pure tones. On two thirds of the trials, the precursor chord was intended to enhance a component of the test chord; this was the component identical to the probe tone in the trials for which the correct response was "present". Fig. 1 illustrates how enhancement was elicited. IE was elicited in experimental conditions where the components of the precursor chord did not differ in frequency from the components of the test chord but the spectral profile of the precursor chord was notched, unlike the profile of the test chord; one component of the precursor chord – the target of enhancement – was attenuated by ΔI dB relative to the other components of the precursor chord. FE was elicited in conditions where the precursor chord had a flat spectral profile, like the test chord, but one component of the precursor chord was lower in frequency, by one semitone (i.e., a factor of $2^{1/12}$), than the target of enhancement in the test chord; the other components of the precursor and test chords had the same frequencies. One third of the trials were run in IE conditions, and another third were run in FE conditions. The remaining trials were run in "no enhancement" (NE) conditions where the precursor chord had a flat spectral profile and none of its components differed in frequency from those of the test chord. In each condition, performance was measured in terms of the sensitivity index *d*' (Green and Swets, 1974).

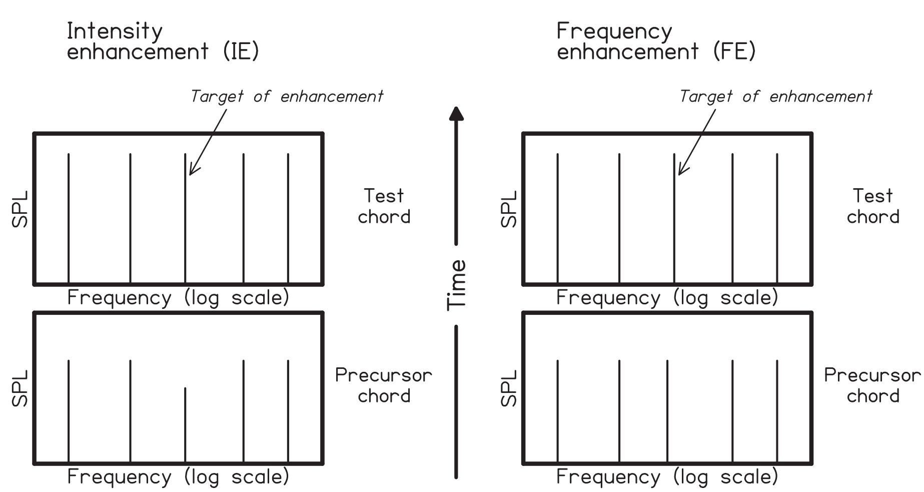

Fig. 1. Illustrations of the enhancement phenomenon. In a "test" chord of pure tones with a flat spectral profile, a tone can be perceptually enhanced in two different ways. One way (intensity enhancement) is to present, before the test chord, a copy of it in which the target of enhancement is less intense than the other tones. Another way (frequency enhancement) is to shift the frequency of the enhancement target in the precursor chord.