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Effects of auditory enhancement on the loudness of masker and target components

Ningyuan Wang*, Andrew J. Oxenham

Department of Psychology, University of Minnesota, Minneapolis, MN 55455, USA

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ABSTRACT

Auditory enhancement refers to the observation that the salience of one spectral region (the “signal”) of a broadband sound can be enhanced and can “pop out” from the remainder of the sound (the “masker”) if it is preceded by the broadband sound without the signal. The present study investigated auditory enhancement as an effective change in loudness, to determine whether it reflects a change in the loudness of the signal, the masker, or both. In the first experiment, the 500-ms precursor, an inharmonic complex with logarithmically spaced components, was followed after a 50-ms gap by the 100-ms signal or masker alone, the loudness of which was compared with that of the same signal or masker presented 2 s later. In the second experiment, the loudness of the signal embedded in the masker was assessed with and without a precursor using the same method, as was the loudness of the entire signal-plus-masker complex. The results suggest that the precursor does not affect the loudness of the signal or the masker alone, but enhances the loudness of the signal in the presence of the masker, while leaving the loudness of the surrounding masker unaffected. The results are consistent with an explanation based on “adaptation of inhibition” [Viemeister and Bacon (1982). J. Acoust. Soc. Am. 71, 1502–1507].

1. Introduction

The perceptual salience of a spectral region can be enhanced if it is preceded by its spectral complement. This auditory enhancement effect has been investigated using psychoacoustic masking techniques (e.g. Viemeister, 1980; Thibodeau, 1991; Wright et al., 1993; Viemeister et al., 2013) and vowel-identification paradigms (Summerfield and Assmann, 1987; Wang et al., 2012). The auditory enhancement effect is probably related to the spectral contrast effects that have also been reported using both speech (Holt and Lotto, 2002; Holt, 2006b) and non-speech (Holt, 2006a; Stilp et al., 2010) stimuli. These phenomena demonstrate how the auditory system adapts to long-term spectral properties, and how any changes relative to the long-term spectrum of the preceding sounds are enhanced. More generally, enhancement and contrast effects can be interpreted in terms of a normalization process, which may help establish auditory perceptual invariance in the face of different talkers, changing acoustic environments, and varying background noises.

One possible neural implementation of auditory enhancement involves adaptation. Preceding sounds lead to adaptation of neurons responding to those spectral regions that are most stimulated. Thus, when energy appears in new spectral regions, the neurons responding to the new energy are not in an adapted state and so respond more strongly than the neurons that also responded to the preceding sound. In terms of auditory enhancement experiments, a precursor with the same spectral properties as the masker will therefore lead to a reduced neural response to the masker but not the signal (Viemeister, 1980; Summerfield et al., 1987; McFadden and Wright, 1990). Note that this “adaptation alone” account implies that the precursor does not produce an *absolute* enhancement of the signal, relative to its response in the absence of the precursor, but rather an enhancement *relative* to the response to the masker. Relative enhancement of this nature has been observed in neural responses at the level of the auditory nerve (Palmer et al., 1995). However, it is difficult to explain all the available psychophysical results with adaptation alone. For instance, Viemeister and Bacon (1982) found that the amount of forward masking produced by the signal component increased when a precursor (which itself produced little or no forward masking) was added, suggesting an *absolute* enhancement of the signal component. To account for this phenomenon, Viemeister and Bacon (1982) proposed an

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Abbreviations: IC, inferior colliculus; PSE, point of subjective equality.

* Corresponding author.

E-mail address: wang2087@umn.edu (N. Wang).

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“adaptation of suppression” or “adaptation of inhibition” hypothesis, whereby the inhibition usually produced by adjacent components adapts over time, so that when the signal is introduced, it is not inhibited as much as it would have been if all the components had begun at the same time. This proposal was further supported by a more recent study (Byrne et al., 2011). Neural responses consistent with this hypothesis have been identified at the level of the inferior colliculus (IC) (Nelson and Young, 2010), and predictions of a model developed by Nelson and Young (2010), based on adaptation of inhibition, have been tested directly with psychophysical data (Shen and Richards, 2012).

Although adaptation and adaptation of inhibition may combine to produce the overall auditory enhancement effect, their relative contributions remain unknown. To gain more insight into the mechanisms underlying auditory enhancement, the present study investigated enhancement in terms of the changes in loudness produced by preceding stimuli. The effects of precursors on loudness have been studied over many decades (e.g. Elmasian and Galambos, 1975; Elmasian et al., 1980; Scharf et al., 2002; Arieh and Marks, 2003; Oberfeld, 2007; Wang et al., 2015). These effects have been termed “loudness enhancement,” “loudness decrement,” “loudness recalibration,” and “loudness context effect,” but have not often been related to the literature on auditory enhancement effects discussed above.

One popular method for measuring the effects of a precursor on the loudness of a tone has been to present a sequence of three tones at the same frequency: a precursor, followed by the signal, followed some time later by the comparison tone. The subject's task is to judge the loudness of the signal relative to the comparison tone (e.g. Elmasian and Galambos, 1975; Elmasian et al., 1980). In general, an intense tone preceding a weak tone can lead to substantial increases in the perceived loudness of the weak tone, relative to the comparison tone, termed “loudness enhancement” (Elmasian and Galambos, 1975). Experiments using a comparison tone at a different frequency from the precursor and signal have suggested that the precursor may enhance tones close in time to a more intense precursor, but may also reduce the loudness of tones that follow more than about 100 ms after the precursor (Scharf et al., 2002; Oberfeld, 2007). The reduction in loudness has been termed “loudness recalibration” (Marks, 1994). These effects appear to be greatest when the precursor is about 20 dB higher in level than the signal (e.g. Elmasian and Galambos, 1975; Mapes-Riordan and Yost, 1999; Oberfeld, 2007). In all cases, precursor tones presented at the *same* level as the signal tone seem to have very little effect on the loudness of the signal.

Because studies of loudness context effects have found little effect of a precursor on the loudness of a signal if they are presented at the same level, it may be tempting to conclude that loudness context effects have little or no relation to auditory enhancement effects, where large enhancement effects are observed when the precursor and masker (and sometimes target) are all presented at the same level (e.g. Shen and Richards, 2012; Viemeister et al., 2013). However, there is one important difference between the two paradigms: studies of loudness context effects have used pure tones in isolation, whereas auditory enhancement studies have used broadband stimuli. To the extent that auditory enhancement relies on lateral inhibition or suppression, such effects would not be observed in the studies that have only used isolated pure tones.

The present study investigated auditory enhancement using a paradigm similar to those used in previous studies of loudness context effects, with the important distinction that complex (broadband) stimuli were used. The use of broadband sounds allowed an assessment of the potential effects and interactions of suppression or inhibition, and allowed us to test some basic properties of the loudness of the stimuli used in auditory enhancement studies. Four basic possibilities are distinguished: 1) The precursor enhances the loudness of the signal in isolation; 2) the precursor reduces the loudness of the masker in isolation; 3) the precursor enhances the loudness of the signal in the presence of the masker; and 4) the precursor reduces the loudness of the masker in the presence of the signal. Experiment 1 measured the effect of the precursor on the loudness of the signal tone, when it was presented in isolation (i.e., without the flanking masker tones), and the effect of the precursor on the loudness of the flanking masker tones, when the signal was not present. These two conditions address possibilities 1 and 2. Experiment 2 measured the effect of the precursor on the relative loudness of the signal and the flanking masker tones, and on the overall loudness of the signal-plus-masker complex, thereby addressing possibilities 3 and 4. Our results rule out possibilities 1, 2, and 4, and provide constraints concerning possibility 3.

2. Experiment 1: effects of a precursor on the loudness of the signal and masker in isolation

2.1. Methods

2.1.1. Subjects

Experiment 1 was divided into two parts. In experiment 1A, eleven subjects (6 males, 5 females) with normal hearing participated. Their ages ranged from 18 to 22 years (mean age 20.8 years). In experiment 1B, six subjects (2 males, 4 females) with normal hearing participated. Their ages ranged from 20 to 65 years (mean age 29.7 years). Normal hearing was defined as audiometric thresholds less than 20 dB HL at octave frequencies between 0.25 and 8 kHz. All subjects were compensated for their time and all provided written informed consent. All protocols were approved by the Institutional Review Board of the University of Minnesota.

2.1.2. Stimuli

Schematic diagrams of the stimuli are shown in Fig. 1. Three sounds were presented on each trial: a precursor, a target, and a comparison. Their total durations were 500 ms, 100 ms, and 100 ms, respectively, including 10-ms raised-cosine onset and offset ramps. The precursor and target were separated by a silent gap of 50 ms. This gap is within the range known to elicit strong enhancement effects (e.g. Carcagno et al., 2012), and is sufficiently long to avoid potential confusion between the two stimuli. The target and comparison were separated by a relatively long silent gap of 2 s, to reduce any potential interactions between the precursor and the comparison. The precursor was an inharmonic complex tone, similar to the one used by Byrne et al. (2011), consisting of pure tones with nominal frequencies (before roving) evenly spaced on a logarithmic scale between 250 and 8000 Hz. In experiment 1A, the precursors had spacing between components of 0.1, 0.3, and 0.5 octaves, leading to a spectral gap between the masker components on either side of the signal of 0.2, 0.6, and 1 octave, respectively. These three spacings were selected to investigate the effects of the spectral gap between components on loudness comparison. The central (median) on-frequency component (corresponding to the signal frequency) could be present or absent in the precursor. In experiment 1B only the 0.3-octave component spacing was tested, leading to a spectral gap between the masker components on either side of the signal of 0.6 octaves, as this spectral gap was reported by Viemeister et al. (2013) to produce the largest auditory enhancement effects. In experiment 1A, both the target and comparison stimuli were pure tones at the frequency of the central component in the precursor; in experiment 1B, the target and comparison were complex tones with the same spectral content as the precursor. The precursor and the