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

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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”.

Keywords

auditory context effects; auditory enhancement; loudness context effects

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

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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 “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; Ariei 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.” 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 target were presented at 50 dB SPL per component, and the level of the comparison varied between trials. The overall frequency content of all sounds was roved together across trials over a 1-octave range (± 0.5 octaves) around the nominal frequencies, with uniform distribution on a logarithmic scale, so that the frequency relationships between all tones within a trial remained constant. The rove was designed to discourage listeners from using potential cues other than the loudness of the stimuli on each trial (such as a long-term representation of the target), and to avoid any long-term (across-trial) effects of enhancement (e.g. Feng and Oxenham, 2015).

The stimuli were generated digitally and presented diotically from a LynxStudio L22 24-bit soundcard at a sampling rate of 48 kHz via Sennheiser HD650 headphones to subjects seated in a double-walled sound-attenuating chamber.

2.1.3. Procedure—In both experiment 1A and 1B, a reference condition was tested first. In the reference condition, no precursor was presented. After the reference condition was completed, all other conditions were presented in random order, with each condition being repeated four times per subject. An adaptive two-interval forced-choice task was employed

in all conditions. Subjects were instructed to judge which sound was louder, the target or the comparison. The target and precursor levels were fixed. The level of the comparison was adaptively varied based on the subject's response, using an interleaved tracking procedure (Jesteadt, 1980), consisting of a 2-down 1-up track and a 2-up 1-down track starting from 60 and 40 dB SPL, respectively. The two tracks converged on the points at which the comparison was judged louder than the target 70.7% and 29.3% of the time, respectively. The initial step size for each track was 5 dB. After two reversals in one track, the step size for that track was reduced to 2 dB and the track continued for another four reversals. The threshold for each track was defined as the mean comparison level at the last four reversal points. If the stopping rule for one track was met before the other, the "completed" track would continue, but the levels were not incorporated into the threshold estimates. The threshold level of the comparison for each subject was estimated by taking the mean of the thresholds from the two interleaved tracks, which corresponds approximately to the point of subjective equality (PSE), i.e., the level at which the comparison was judged louder than the target 50% of the time.

In experiment 1A, the on-frequency component in the precursor was either present or absent. In combination with three frequency spacings, this led to a total of 6 conditions, plus the reference condition. In experiment 1B, only one condition was tested along with the reference condition.

2.2 Results and discussion

The mean PSE levels for the comparison tone in the different conditions from experiment 1A are shown in Fig. 2a. Overall, the PSE levels were somewhat lower than the level of the target tone (50 dB SPL), even in the reference condition, where no precursor was present. However, there was no clear effect of the precursor on the loudness of the target tone, with or without a spectral gap in the precursor. Effects of the precursor and component spacing were investigated in a twoway within-subjects (repeated-measures) ANOVA, excluding the reference condition, with the comparison PSE level as the dependent variable and component spacing (0.1, 0.3, and 0.5 octaves) and precursor spectral gap (present or absent) as factors. The main effect of component spacing was significant [$F(2,20) = 11.0$, $p = 0.001$, partial $\eta^2 = 0.524$], but neither the main effect of precursor spectral gap [$F(1,10) = 0.388$, $p = 0.547$, partial $\eta^2 = 0.037$] nor the interaction term [$F(2,20) = 1.59$; $p = 0.228$, partial $\eta^2 = 0.137$] was significant. Pairwise comparisons for component spacing revealed that results for the 0.1-octave spacing condition were significantly different from those for the 0.3-octave ($p = 0.001$) and 0.5-octave ($p = 0.004$) conditions, but these differences were generally less than 2 dB. Paired t-tests showed no significant differences between the reference condition and any of the other six conditions ($p > 0.05$ in all cases). These results indicate that the presence of precursor had little or no effect on the loudness of target tone when presented in isolation.

The results from experiment 1B are shown in Fig. 2b. Here again, the loudness of the target (in this case, the tones that act as the masker in a traditional auditory enhancement experiment) did not appear to be affected by the presence of the precursor. A paired-sample

t-test confirmed that there was no significant difference between the comparison PSE with or without the precursor [$t(5) = 0.127$; $p = 0.904$].

In both experiment 1A and 1B, the comparison was between 1 and 3 dB lower in level on average than the target at the PSE, even in the absence of a precursor. The reason for this systematic bias is unclear. However, similar biases have been reported in the past, but with no consistent direction of the bias [for a discussion of potential sources of bias in loudness judgments, see Marks and Florentine (2011)]. For instance, Elmasian *et al.* (1980) found that a 50-dB SPL target tone alone was matched with a comparison tone near 52 dB SPL, whereas a 70-dB SPL target tone was matched with a comparison tone near 66 dB SPL. They ascribed the differences to a central tendency. Because we only used a single target level (50 dB SPL), the bias observed in our study does not seem likely to be due to a central tendency. Systematic biases in loudness judgments were also observed by Botte (1992), albeit in the opposite direction (where the comparison tone level was higher than that of the target when their loudness was judged to be equal). Nevertheless, any such bias should not affect the conclusions of the current study, as the bias should be eliminated by comparing the comparison level in the reference condition with that measured in the test conditions.

In a typical auditory enhancement experiment, the loudness of the signal tone appears to be enhanced relative to the loudness of the flanking masker tones (e.g. Byrne *et al.*, 2011; Demany *et al.*, 2013). The results from experiment 1 show that neither the loudness of the signal in isolation (experiment 1A) nor the loudness of the flanking masking tones alone (experiment 1B) is affected by the presence of a precursor when presented at the same level as the signal and masker. This outcome suggests that the effect of the precursor in typical auditory enhancement experiments is to alter the interactions between the signal tone and the flanking masker tones. This possibility was explored in experiment 2.

3. Experiment 2: Effects of the precursor on the loudness of the masker-signal complex

3.1. Methods

3.1.1. Subjects—The same six subjects (2 males and 4 females, age from 20 to 65 with a mean of 29.7 years) were tested as in experiment 1B.

3.1.2. Stimuli and Procedure—Schematic diagrams of the stimuli used in experiment 2 are shown in Fig. 3, with the stimuli for experiment 2A and 2B shown in panels a/b and c/d, respectively. The stimuli used in experiment 2 were identical to those used in experiment 1. As in experiment 1, subjects first completed a reference condition, in which the target and comparison stimuli were presented without a precursor. In this reference condition of experiment 2A (Fig. 3a), the signal component in the target sound was increased in level by 10 dB (i.e. to 60 dB SPL), and subjects were asked to compare the loudness of the signal component in the target with the loudness of the signal component in the comparison, and judge which was louder. All the flanking masker components in the target and the comparison were presented at 50 dB SPL. A level difference between the signal and masker tones of 10 dB was selected after some pilot testing indicated that this level difference was

sufficient to allow the signal to be heard out separately from the complex, while still being within the plausible realm of enhancement. Aside from providing a reference, this condition also allowed subjects to acclimatize to the task of judging the loudness of the signal component within the masker.

In the test condition of experiment 2A (Fig. 3b), a precursor was added prior to the target. The signal component in the target sound was presented at the same level of 50 dB SPL as all of the other target (and precursor) components. The task was again to compare the loudness of the signal components in the target and comparison stimuli. The same interleaved adaptive procedure as used in Experiment 1 was employed here to determine the PSE. The average amount of enhancement (i.e., the level increase of the signal tone in the comparison stimulus relative to its level in the target stimulus) was calculated from four repetitions of each condition.

In the reference condition of experiment 2B (Fig. 3c), the flanking masker tones in the target stimulus were fixed at 50 dB SPL per component, and the signal component in the target was adjusted to match the amount of enhancement measured for each subject individually in the test condition of experiment 2A (5.8 dB on average). On average, this led to a signal component level of 55.8 dB SPL in the target stimulus. Subjects were then asked to compare the overall loudness of the target stimulus (signal and masker tones) with the overall loudness of the comparison stimulus. The level relationship between the signal and masker components within the comparison stimulus was the same as for the target stimulus (adjusted for each subject, but 5.8 dB higher for the signal component on average). All the components in the comparison were then adjusted simultaneously to compare the overall loudness of two stimuli. In the test condition (Fig. 3d), the task was to compare the overall levels, but in the presence of the precursor, so the level of the signal component in the target sound remained at 50 dB SPL. However, the comparison stimulus maintained the same level relationship between the signal and masker components as in the reference condition. The purpose of Experiment 2B was to determine the effect of the precursor on the loudness of the masker components within the target sound. However, to keep the task intuitive for the subjects, they were asked to adjust the loudness of the overall target sound. Keeping the signal component at a constant level relative to the masker components avoided any changes in the perceived timbre of the sound as the level was adjusted. Once the relative relationships between the signal and the masker of the two sounds in loudness were determined, the comparison in overall loudness was able to reflect the relationship between the loudness of the masker components in the target and the loudness of the masker components within the comparison. Both reference and test conditions were repeated four times each in experiment 2A and 2B.

3.2. Results and discussion

Average PSEs for all conditions were calculated in the same way as for experiment 1. As shown in Figure 4a, the signal component level at PSE in the comparison stimulus was 56.2 dB SPL in the reference condition of experiment 2A, which was lower than the level in the target (60 dB SPL). This apparent mismatch in the absence of a precursor is in the same direction as the bias observed in experiment 1. When the precursor was present, the signal

component in the target was presented at the same level as the masker components (i.e. 50 dB SPL), but the level of the signal in the comparison was adjusted to a mean level of 55.8 dB SPL (s.d. 2.9 dB), revealing a significant enhancement in the loudness of signal component in the target sound [paired-sample t-test; $t(5) = 5.24$; $p = 0.003$]. The PSE level for the 60-dB signal component without the precursor was not significantly different from that of the 50-dB signal component with the precursor [paired-sample t-test; $t(5) = 0.265$; $p = 0.802$], suggesting effective enhancement by the precursor of around 10 dB.

In experiment 2B, subjects were asked to compare the overall loudness of the target (signal and masker components) with that of the comparison stimulus. The average level of the masker components within the comparison at PSE with and without a precursor is shown in Fig. 4b. A paired-sample t-test revealed no significant difference between the masker component levels at PSE between the no-precursor and precursor conditions [$t(5) = 1$; $p = 0.36$], suggesting that the precursor had no effect on the overall loudness of the signal-plus-masker complex and, by inference, no effect on the loudness of the masker components. Again, however, we observed that the matched level of the comparison was a few dB below the actual level of the target stimulus. This bias was relatively consistent across conditions and subjects and was observed in both experiments 1 and 2.

In experiment 2A, we observed an enhancement of the signal component in the target sound, which is consistent with previous studies (Viemeister and Bacon, 1982; Byrne *et al.*, 2011). After our analysis of experiment 1, showing that the precursor affected neither the masker nor the signal in isolation, two potential possibilities of auditory enhancement remained. The first possibility was that the precursor reduces the loudness of the masker in the presence of the signal. The second possibility was that the precursor enhances the loudness of the signal in the presence of the masker. The results from experiment 2 are not consistent with the first explanation and instead support the second explanation: experiment 2A showed that the loudness of the signal component was enhanced, relative to that of the surrounding masker components, and experiment 2B showed that the loudness of the masker components was not reduced by the presence of the precursor. The idea that the signal component is partially masked by the masker, and then released from this partial masking effect by the influence of a precursor is in line with the original idea of “adaptation of inhibition” (Viemeister and Bacon, 1982; Carcagno *et al.*, 2013).

An alternative way to view the results is in terms of “profile analysis” (e.g. Green, 1988). As with the concept of partial loudness, the precursor can be thought to increase the effective intensity of the signal component, relative to the effective intensity of masker components. Our results suggest that the precursor does indeed alter the perceptual “profile” of the stimulus by raising the effective intensity of the signal, and not by lowering the effective intensity of the masker components.

4. General discussion

In this study, we investigated auditory enhancement from the perspective of loudness changes to the signal and flanking masker components in the target sound under the influence of a precursor. The four possibilities to be tested were: 1) The precursor enhances

the loudness of the signal in isolation; 2) the precursor reduces the loudness of the masker; 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.

In experiment 1, we examined the influence of the precursor on the loudness of the signal component in isolation, and on the loudness of the masker components in isolation. It was found that the precursor produced no significant change in the loudness of either. The situation might have been different had the level of the precursor been substantially lower or higher than that of the target. In such cases, effects known as “loudness enhancement” or “loudness decrement” have been shown to influence loudness judgments (Galambos *et al.*, 1972; Elmasian *et al.*, 1975). However, in the present study, the levels of the precursor and target components were always the same, making it less likely that such assimilative or contrastive effects would be observed. In any case, the lack of an effect of the precursor on either the signal or masker components alone rules out possibilities 1 and 2.

In experiment 2A, the comparison stimulus was judged most similar to the target stimulus (with all components at equal amplitude) when the comparison's signal component was 5.8 dB higher than that of the flanking masker components. This amount of “enhancement” is very similar to that obtained in previous studies using a variety of similar tasks. In Byrne *et al.* (2011), the estimated amount of enhancement was generally in the range 4 to 6 dB, whether it was estimated in a masker enhancement paradigm or in a binaural centering paradigm, for stimulus levels of 50 and 70 dB SPL. The “true” amount of enhancement may be somewhat greater than that, based on the systematic bias of 2-4 dB found in our reference conditions. In fact, the PSE found with the precursor was not significantly different from that found with a 10-dB level increment in the signal component, suggesting that the enhancement could be as great as 10 dB. The relative increase in the loudness of the signal is consistent with both possibilities 3 and 4. In experiment 2B, we added the estimated amount of enhancement to the signal component in the comparison sound, to make the comparison stimulus sound as similar as possible to the target in terms of spectral quality or timbre, and we asked listeners to directly compare the overall loudness of the target and comparison stimuli. According to possibility 3, the loudness of the masker components should be unaffected by the precursor, and so listeners would be expected to match the target stimulus with a comparison stimulus that had the same level per masker component. In contrast, possibility 4 predicts that listeners should match the target stimulus with a comparison that has the same signal level as the target (and hence lower masker component levels). The results showed that the precursor had no significant effect on the loudness of the overall target stimulus, ruling out possibility 4 and supporting possibility 3.

What neural mechanisms could produce the observed pattern of outcomes? The proposal of “adaptation of inhibition,” originally suggested by Viemeister and Bacon (1982), predicts that a given component within a complex sound is normally inhibited by spectrally surrounding components, but that this inhibition adapts over time. Thus, when a component that is missing from the precursor is then introduced into the target stimulus, the inhibition from all the surrounding components has adapted, leading to an enhancement in the representation of the introduced component. It is not obvious what predictions such a scheme would make regarding the loudness of the masker components themselves. No

computational models of the auditory enhancement effect have been tested for their ability to predict the effects of enhancement on the perceived loudness of the stimuli. Intuitively it would seem that any model incorporating adaptation, and relating neural firing rate to loudness, would predict a decrease in the loudness of the masker following the presentation of the precursor, in contradiction to our data. However, this and other predictions would need to be tested empirically against the new data provided by this study.

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Abbreviations

IC	inferior colliculus
PSE	point of subjective equality

References

- Arieh Y, Marks LE. Time course of loudness recalibration: implications for loudness enhancement. *J. Acoust. Soc. Am.* 2003; 114:1550–1556. [PubMed: 14514208]
- Botte, M-C.; Baruch, C.; Mönikheim, S. Memory for loudness: The role of loudness contour. In: Cazals, Y.; Demany, L.; Horner, K., editors. *Adv. Biosci.* Pergamon Press; Oxford: 1992. p. 305-311.
- Byrne AJ, Stellmack MA, Viemeister NF. The enhancement effect: evidence for adaptation of inhibition using a binaural centering task. *J. Acoust. Soc. Am.* 2011; 129:2088–2094. [PubMed: 21476664]
- Carcagno S, Semal C, Demany L. Auditory enhancement of increments in spectral amplitude stems from more than one source. *J. Assoc. Res. Otolaryngol.* 2012; 13:693–702. [PubMed: 22766695]
- Carcagno S, Semal C, Demany L. No Need for Templates in the Auditory Enhancement Effect. *PLOS ONE.* 2013; 8:e67874. [PubMed: 23826348]
- Demany L, Carcagno S, Semal C. The perceptual enhancement of tones by frequency shifts. *Hear. Res.* 2013; 298:10–16. [PubMed: 23376551]
- Elmasian R, Galambos R. Loudness enhancement: monaural, binaural, and dichotic. *J. Acoust. Soc. Am.* 1975; 58:229–234. [PubMed: 1150971]
- Elmasian R, Galambos R, Bernheim A Jr. Loudness enhancement and decrement in four paradigms. *J. Acoust. Soc. Am.* 1980; 67:601–607. [PubMed: 7358899]
- Elmasian R, Morgan R, Galambos R. Time course of loudness enhancement and intensity discrimination. *J. Acoust. Soc. Am.* 1975; 58:S35–S35.
- Feng, L.; Oxenham, AJ. New Perspectives on the Measurement and Time Course of Auditory Enhancement. *J. Exp. Psychol. Hum. Percept. Perform.* 2015. Advance online publication: <http://dx.doi.org/10.1037/xhp0000115>
- Galambos R, Bauer J, Picton T, Squires K, Squires N. Loudness enhancement following contralateral stimulation. *J. Acoust. Soc. Am.* 1972; 52(4):1127–30. [PubMed: 4638026]
- Green, DM. Profile analysis: Auditory intensity discrimination. Oxford University Press; New York, NY: 1988.
- Holt LL. The mean matters: effects of statistically defined nonspeech spectral distributions on speech categorization. *J. Acoust. Soc. Am.* 2006a; 120:2801–2817. [PubMed: 17091133]
- Holt LL. Speech categorization in context: joint effects of nonspeech and speech precursors. *J. Acoust. Soc. Am.* 2006b; 119:4016–4026. [PubMed: 16838544]

- Holt LL, Lotto AJ. Behavioral examinations of the level of auditory processing of speech context effects. *Hear. Res.* 2002; 167:156–169. [PubMed: 12117538]
- Jesteadt W. An adaptive procedure for subjective judgments. *Percept. Psychophys.* 1980; 28:85–88. [PubMed: 7413416]
- Mapes-Riordan D, Yost WA. Loudness recalibration as a function of level. *J. Acoust. Soc. Am.* 1999; 106:3506–3511. [PubMed: 10615690]
- Marks, LE.; Florentine, M. Measurement of loudness, part I: Methods, problems, and pitfalls. In: Florentine, ANPM.; Fay, RR., editors. *Loudness*. Springer Verlag; New York: 2011. p. 17-56.
- McFadden D, Wright BA. Temporal decline of masking and comodulation detection differences. *J. Acoust. Soc. Am.* 1990; 88:711–724. [PubMed: 2212295]
- Nelson PC, Young ED. Neural correlates of context-dependent perceptual enhancement in the inferior colliculus. *J. Neurosci.* 2010; 30:6577–658. [PubMed: 20463220]
- Oberfeld D. Loudness changes induced by a proximal sound: loudness enhancement, loudness recalibration, or both? *J. Acoust. Soc. Am.* 2007; 121:2137–2148. [PubMed: 17471728]
- Palmer AR, Summerfield Q, Fantini DA. Responses of auditory-nerve fibers to stimuli producing psychophysical enhancement. *J. Acoust. Soc. Am.* 1995; 97:1786–1799. [PubMed: 7699160]
- Scharf B, Buus S, Nieder B. Loudness enhancement: Induced loudness reduction in disguise? (L). *J. Acoust. Soc. Am.* 2002; 112:807–810. [PubMed: 12243166]
- Shen Y, Richards VM. Investigating the auditory enhancement phenomenon using behavioral temporal masking patterns. *J. Acoust. Soc. Am.* 2012; 132:3363–3374. [PubMed: 23145617]
- Stilp CE, Alexander JM, Kiefe M, Kluender KR. Auditory color constancy: calibration to reliable spectral properties across nonspeech context and targets. *Atten. Percept. Psychophys.* 2010; 72:470–480. [PubMed: 20139460]
- Summerfield, AQ.; Assmann, P. Auditory enhancement in speech perception. In: Schouten, MEH., editor. *The psychophysics of speech perception*. Martinus Nijhoff; Dordrecht: 1987. p. 140-150.
- Summerfield Q, Sidwell A, Nelson T. Auditory enhancement of changes in spectral amplitude. *J. Acoust. Soc. Am.* 1987; 81:700–708. [PubMed: 3584677]
- Thibodeau LM. Performance of hearing-impaired persons on auditory enhancement tasks. *J. Acoust. Soc. Am.* 1991; 89:2843–2850. [PubMed: 1918628]
- Viemeister, NF. Adaptation of masking. In: van den Brink, G.; Bilsen, FA., editors. *Psychophysical, physiological and behavioural studies in hearing*. Delft U.P.; Delft, Netherlands: 1980. p. 190-198.
- Viemeister NF, Bacon SP. Forward masking by enhanced components in harmonic complexes. *J. Acoust. Soc. Am.* 1982; 71:1502–1507. [PubMed: 7108024]
- Viemeister NF, Byrne AJ, Stellmack MA. Spectral and level effects in auditory signal enhancement. *Adv. Exp. Med. Biol.* 2013; 787:167–174. [PubMed: 23716221]
- Wang N, Kreft H, Oxenham AJ. Vowel enhancement effects in cochlear-implant users. *J. Acoust. Soc. Am.* 2012; 131:EL421–426. [PubMed: 22713016]
- Wang N, Kreft HA, Oxenham AJ. Loudness Context Effects in Normal-Hearing Listeners and Cochlear-Implant Users. *J. Assoc. Res. Otolaryngol.* 2015; 16:535–545. [PubMed: 26040213]
- Wright BA, McFadden D, Champlin CA. Adaptation of suppression as an explanation of enhancement effects. *J. Acoust. Soc. Am.* 1993; 94:72–82. [PubMed: 8354762]

- We examine auditory enhancement in terms of loudness changes to a target and masker.
- A precursor has no effect on the loudness of the target or masker presented alone.
- A precursor enhances the (partial) loudness of the target in the presence of the masker.
- A precursor has no effect on the loudness of the masker in the presence of the target.
- The results based on loudness may be explained by inhibition of adaptation.

FIG. 1.

Schematic diagrams of stimuli used in experiment 1. a. The stimuli used in experiment 1A (0.1-octave spacing, without the on-frequency component condition). b. The stimuli used in experiment 1B (0.3-octave spacing). The first stimulus (0-500 ms) is the precursor, the second stimulus (550 to 650 ms) is the target, and the third stimulus (2650-2750 ms) is the comparison.

FIG. 2.

Average level of the comparison stimulus, representing the PSE between the target and comparison stimuli. a. The results from experiment 1A, where the single center tone was the target. The unfilled bar represents the PSE for the reference condition with no precursor; black bars represent results from conditions with a spectral gap in the precursor; and grey bars represent conditions with no spectral gap in the precursor. b. Results from experiment 1B. Again, the unfilled bar represents the PSE without a precursor, and the black bar represents the PSE with a precursor (including a spectral gap at the center frequency). Error bars represent 1 s.e. of the mean. The dashed lines indicate the PSE from the reference conditions.

FIG. 3.

Schematic diagrams of stimuli used in experiment 2A and 2B. The shading of the lines indicates level, with darker lines representing higher levels. The components that were varied in level during the adaptive procedure are shown as dashed lines. a. The stimuli used in the reference condition of experiment 2A. b. The stimuli used in the test condition of experiment 2A. c. The stimuli used in the reference condition of experiment 2B. d. The stimuli used in the test condition of experiment 2B.

FIG. 4.

Average level of the comparison stimulus, representing the PSE between the target and comparison stimuli. a. The results from experiment 2A, the average PSE of the signal component in the comparison sound in the no-precursor reference condition (with the signal component in the target raised by 10 dB) and in precursor test condition (where all the components in the target, including the signal component, were set to 50 dB SPL). b. The average PSE of the masker components in the comparison stimuli in both reference (no precursor) and test (precursor) conditions of experiment 2B. Error bars represent 1 s.e. of the mean across subjects. The dashed lines indicate the PSE for the reference conditions.