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Time course of loudness recalibration: Implications for loudness enhancement

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Time course of loudness recalibration: Implications for loudness enhancement

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Loudness recalibration, the effect of a relatively loud 2500-Hz recalibrating tone on the loudness of a relatively soft 2500-Hz target tone, was measured as a function of the interstimulus interval (ISI) between them. The loudness of the target tone, assessed by a 500-Hz comparison tone, declined when the ISI equaled or exceeded about 200 ms and leveled off at an ISI of about 700 ms. Notably, the target tone's loudness did not change significantly at very short ISIs (<150 ms). The latter result is incompatible with the literature reporting loudness enhancement in this time window, but is compatible with the suggestion made by Scharf, Buus, and Nieder [J. Acoust. Soc. Am. **112**, 807–810 (2002)] that early measurements of enhancement were contaminated by the influence of the recalibrating tone on the comparison tone when the two shared the same frequency. In a second experiment the frequency of the comparison tone was changed to 2500 Hz and the results of a loudness enhancement paradigm was successfully predicted from the time course of recalibration obtained in experiment 1. [DOI: 10.1121/1.1603768]

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I. INTRODUCTION

The loudness of an auditory signal is intimately tied to the presence of other auditory signals recently presented. In loudness recalibration, listeners experience a reduction in the loudness of transient tones of relatively moderate intensity when stronger tones were recently presented (Marks, 1988, 1994). For example, Marks (1993) exposed listeners to a series of repeated tones: 500 Hz at 53 dB, 500 Hz at 73 dB, 2500 Hz at 48 dB, or 2500 Hz at 68 dB. After exposure, listeners compared previously matched test tones at 500 and 2500 Hz. Exposure to only the greater SPL at each frequency influenced the subsequent judgments. Exposure to the 500-Hz tone at 73 dB decreased the probability of judging a subsequent 500-Hz tone as louder than a 2500-Hz tone, and exposure to the 2500-Hz tone at 68 dB increased the probability. Exposure to the softer tones had essentially no effect.

Although loudness recalibration was first reported 15 years ago, not much is known about the underlying process—perhaps in part because early interpretations of loudness recalibration placed its origin in high-level cognitive processes, as numerical response bias in magnitude estimation (e.g., Marks, 1988) or as shifts in response criteria in loudness matching (see Arieh and Marks, 2001). Subsequent research, however, has shown both explanations to be inadequate. Recalibration arises in paradigms that do not ask listeners to make numerical judgments, either by having participants compare differences in loudness (Schneider and Parker, 1990) or match loudness (Marks, 1992, 1993, 1994; Mapes-Riordan and Yost, 1999; see Scharf *et al.* 2002). Both comparisons of loudness difference and direct loudness comparisons reveal recalibration, much like that observed with magnitude estimation. Finally, in this regard, Arieh and Marks (2003) found recalibration in measures of response times and errors obtained in a speeded choice task. When listeners rapidly classified 500- and 2500-Hz tones as low or high in frequency while the tones took on different SPLs in different conditions, choice responses were longer and errors generally greater under conditions in which loudness was smaller (recalibrated). The positive correlation between choice response time and error rate is the hallmark of a shift in "sensitivity" rather than a change in criterion. Thus, loudness recalibration is best conceptualized as a sensory phenomenon that influences auditory responsiveness, reducing loudness of suprathreshold tones (we note here that the term Induced Loudness Reduction has also been used to describe the phenomenon at hand, see Scharf *et al.*, 2002).

Relatively little is known, however, about several basic properties of loudness recalibration, especially its temporal properties: How long does it take for recalibration to arise? How long does it last? The current study aims to elucidate the temporal relationship between the first signal in each sequence, the relatively strong recalibrating tone, and the second signal, the weaker target tone. Here we ask: What is the shortest time interval between recalibrating and target tones that produces loudness recalibration? What time interval produces the greatest recalibration? [For a preliminary stab at some of these questions, see Mapes-Riordan and Yost (1998).]

To evaluate the time course of recalibration, we modified the paradigm used by Mapes-Riordan and Yost (1999). Figure 1 illustrates the events constituting a baseline trial and an experimental trial. Each experimental trial consists of the following sequence: recalibrating tone, interstimulus interval 1 (ISI), target tone, interstimulus interval 2, and comparison tone. The comparison tone is the yardstick for measuring recalibration of the target tone. In baseline trials, the recalibrating tone is omitted, so recalibration is computed as the difference in dB between the levels of the comparison tone

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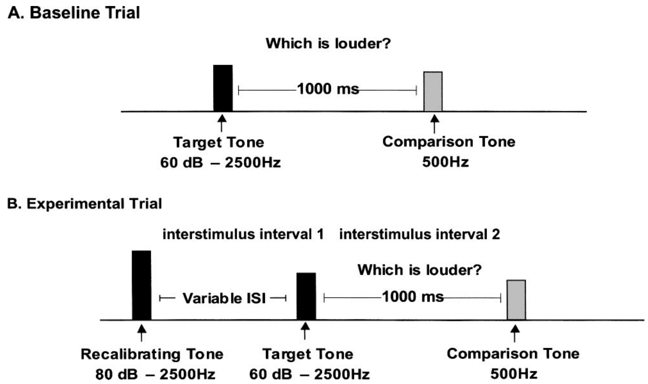

FIG. 1. Schematic illustration of stimulus sequences used to measure loudness recalibration. The upper sequence (a) shows a baseline trial, where a match was determined between the target tone and the comparison tone, and the lower sequence (b) shows an experimental trial, where the recalibrating tone precedes the target tone.

that match the loudness of the target in experimental and baseline trials.

In experimental trials, the listener's task is to ignore the recalibrating tone and judge whether the target tone or the comparison tone is louder. Note that the frequency of the recalibrating tone and the target tone is the same, 2500 Hz, while the frequency of the comparison tone is markedly different, 500 Hz. Although heterofrequency comparison of loudness is difficult, it is necessary in order to minimize the effect of the recalibration tone on the comparison tone. Marks and Warner (1991) and Marks (1994) showed that recalibration essentially affects all signals falling within roughly a critical bandwidth. The difference between the frequency of the recalibrating tone (and test tone) and the frequency of the comparison tone must be substantial, lest the recalibrating tone affect the loudness of the comparison.

In experiment 1 listeners compared the loudness of the target to the loudness of the comparison in a randomized adaptive two-track procedure. In the baseline session, we measured the matching point between the 2500-Hz target at 60 dB and the 500-Hz comparison prior to the induction of recalibration. In the experimental sessions, a 2500-Hz recalibrating tone at 80 dB preceded each comparison trial. Ten ISIs were tested, each in a different session, the shortest being 50 ms and the longest being 3300 ms.

II. EXPERIMENT 1—TIME COURSE OF LOUDNESS RECALIBRATION

A. Method

Ten listeners, six women and four men, participated in experiment 1. All were Yale undergraduates or employees of the J. B. Pierce Laboratory, 19 to 35 years of age, who reported normal hearing.

Participants sat in a sound treated booth. A Tucker-Davis System 3 Real Time processor at a sampling frequency of 50 kHz, driven by a Matlab program running on a Pentium III PC, produced the stimuli in both experiments 1 and 2. The 2500-Hz recalibration and target tones and the 500-Hz comparison tone, appropriately attenuated (Tucker-Davis PA5 module) and gated (5 msec cosine^2 rise and decay), were delivered binaurally for 50 ms through calibrated TDH-49 headphones mounted in MX41/AR cushions. The Matlab program also recorded the listeners' responses and provided all other aspects of user interface for the experimental session.

Before the start of the experiment, each listener received written and oral instructions. The baseline session always came first. A randomized adaptive two-track ascending and descending procedure [two-up, two-down, a variant of the procedure described in Jesteadt (1980)] served to estimate the value of the 500-Hz tone equal in loudness to the 2500-Hz target at 60 dB. Each baseline trial presented a fixed level of the target followed after 1 s by a comparison tone [see Fig. 1(a)]. The listener's task was to judge which tone was louder by pressing an appropriate key. The level of the comparison tone was contingent on the listener's response. If the listener indicated on two successive trials that the target was louder than the comparison, then on the next trial the level of the comparison increased. Alternatively, if the listener indicated twice in succession that the comparison was louder than the target, then on the next trial the level of the comparison decreased. The size of the step started at 4 dB, then decreased to 2 dB after three reversals of direction. In each baseline session, two tracks were randomly interleaved; an ascending track began with the comparison set below the target, at 40 dB, and the descending set above the target, at 80 dB.

The matching point between the target and comparison was calculated by averaging the last six reversal points out of the nine recorded for each track. Thus, for each listener the matching point was based on the average of 12 SPLs (6 per track). The baseline session lasted approximately 10 min.

The procedure for the ten experimental sessions was identical to that of the baseline session except that a 2500-Hz recalibration tone at 80 dB SPL preceded each trial [see Fig. 1(b)]. The ISI between the recalibrating tone and the target tone varied over the sessions: 50, 75, 150, 225, 375, 525, 675, 825, 1650, and 3300 ms. The listeners were instructed to ignore the recalibrating tone and judge which tone was louder, the target or the comparison. For each ISI, recalibration was computed as the difference between the matching levels obtained with and without the recalibrating tone.

In the experimental session, the starting points for the ascending and descending tracks were set individually 25 dB below and above that listener's baseline. Listeners took part in the 11 sessions (baseline plus ten ISIs) over three different days, with no more than four sessions on a single day. Each session lasted 10–15 min, and a mandatory 15-min break separated consecutive sessions. After the baseline session, the ten experimental sessions were given in a different random order for each listener.

B. Results

Figure 2 presents the individual data of the ten listeners who participated in experiment 1. Each panel shows how the matching SPL varied with ISI; in each case, the solid line shows the individual baseline.

The average baseline was 61.1 dB (SE=1.55). The slightly greater SPL at 500 Hz vs 2500 Hz is consistent with

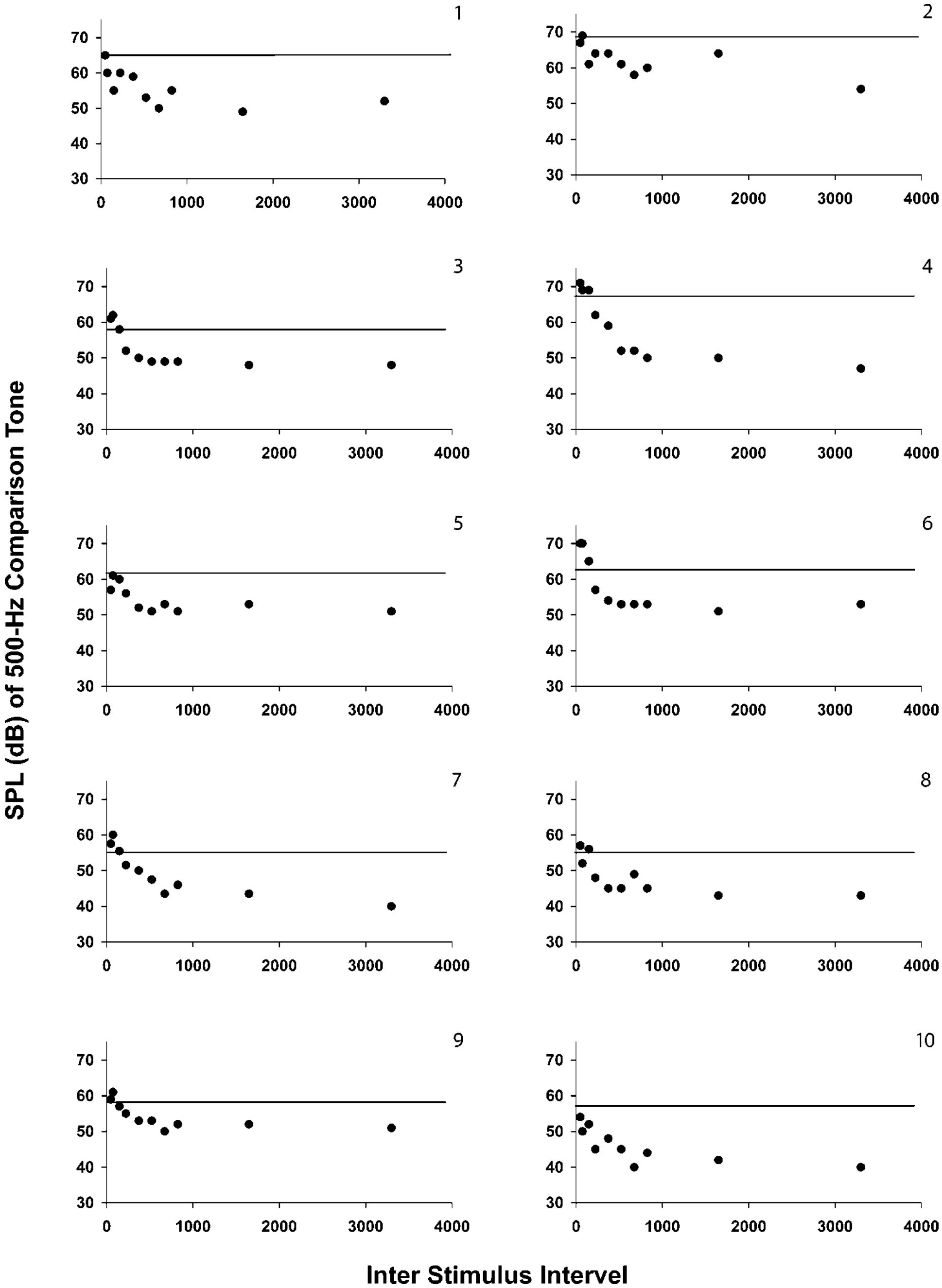

FIG. 2. Individual results from the ten listeners who took part in experiment 1. Plotted for each listener is the matching level in dB obtained for each of ten ISIs. The solid line represents, for each listener, the baseline level obtained in the absence of the recalibrating tone.

equal-loudness functions (e.g., Fletcher and Munson, 1933). In general, there is little or no evidence of recalibration (loudness below baseline) at the smallest ISIs. Recalibration becomes clear only with ISIs greater than 150 ms. The overall pattern is clarified in Fig. 3, which shows results averaged across the ten listeners. A 95% confidence interval is plotted around each mean. These within-participant confidence intervals were derived from the interaction error term of participant by conditions, as suggested by Loftus and Masson (1994). The horizontal solid line shows the mean baseline matching value and the dashed lines indicate 95% confidence intervals around that mean. Values within brackets show loudness recalibration, in dB, at each ISI.

At the three shortest ISIs (50, 75, and 150 ms), recalibration is negligible as the mean matching levels fall within or slightly below the confidence intervals at baseline. Recalibration first becomes significant, and equal to 6.1 dB, at an ISI of 225 ms. Recalibration then increases steadily until it reaches a more or less constant value of 11 dB at an ISI of 675 ms. Recalibration increases slightly again, to 13 dB, at an ISI of 3300 ms, but this increase may be spurious. Overall, this picture—the first detailed account of the time course of recalibration—reveals a temporally graded process that appears to start about 200 ms after the recalibrating tone. Recalibration then increases monotonically in magnitude for about 500 ms and then levels off for at least 3 s or so.

Of special interest is the lack of substantial change in loudness over the three shortest ISIs. Although the present results are consistent with the existence of a modest, continuous change in loudness starting with an ISI as small as 50

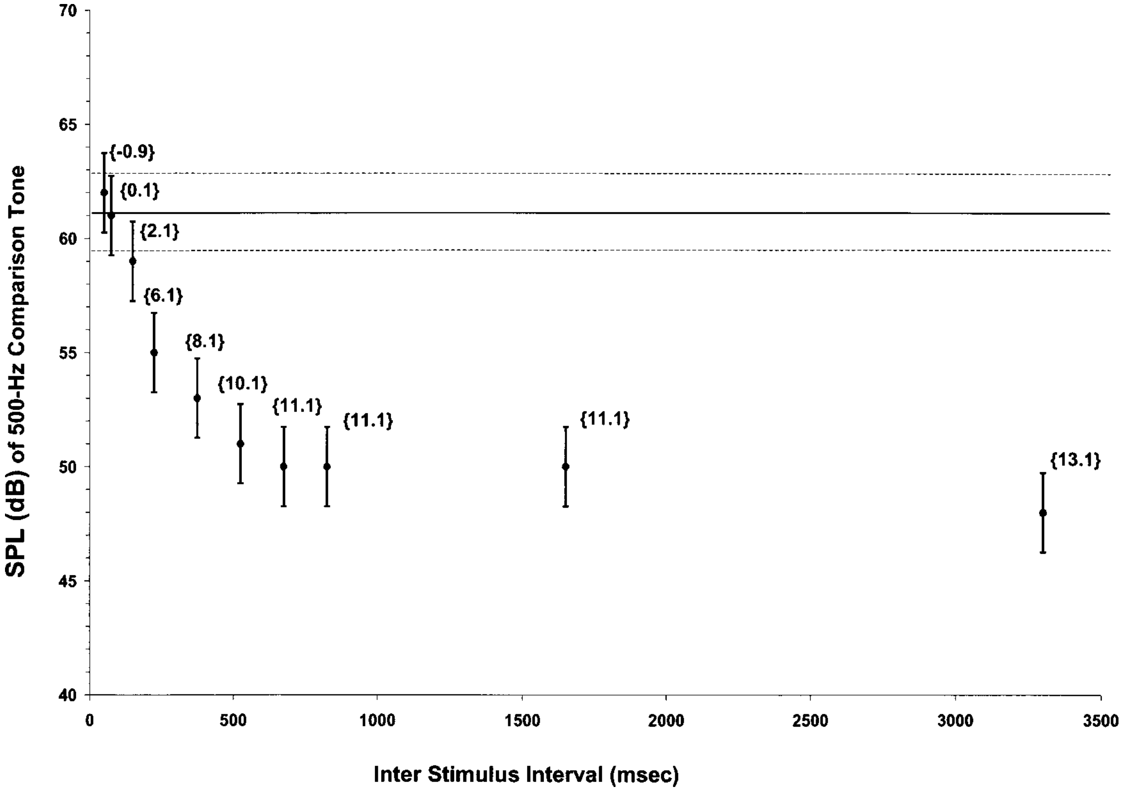

FIG. 3. Pooled matching points (in dB) for the ten listeners in experiment 1, plotted against their respective ISI. Error bars around each point indicate 95% confidence intervals. The solid line represents the mean baseline level obtained in the absence of the recalibrating tone and the dotted lines indicate its 95% confidence intervals.

ms, changes over the first 200 ms or so are small, amounting to no more than 2–3 dB. This outcome is surprising because it is at odds with reports of loudness enhancement. Several studies have shown that when two tones are presented in close temporal proximity—with ISIs$<$100 ms—the loudness of the second tone appeared to be elevated, if the first tone is more intense than the second (Elmasian and Galambos, 1975; Plack, 1996; Zeng, 1994; Zwislocki and Sokolich, 1974). Most studies of enhancement used a three-tone paradigm like that used in experiment 1. In those studies, the first tone purportedly enhances the loudness of the second, target, tone, measured by comparing its loudness to that of a third, comparison tone. Elmasian and Galambos (1975) and Zwislocki and Sokolich (1974) had listeners adjust the level of the third tone such to equal the loudness of the second tone. Plack (1996) and Zeng (1994) asked listeners to judge which tone was louder, the second or the third, in a two-alternative forced choice adaptive procedure much like ours. In both cases the outcome was the same. The loudness of the second tone was elevated in the presence of the stronger first tone. The magnitude of loudness enhancement has been reported to reach 14 to 16 dB under optimal conditions (Zeng, 1994), but is usually about 10 dB. Why the palpable discrepancy between the substantial changes in loudness at short ISIs reported in studies of loudness enhancement and the lack of any substantial change at comparable ISIs here?

The answer may lie in a suggestion recently made by Scharf *et al.* (2002). Surveying the literature on loudness enhancement, Scharf *et al.* note that virtually all studies used a comparison tone with the same frequency as the two experimental tones. By doing so, Scharf *et al.* suggest, it is possible that the loudness of the comparison tone is affected (recalibrated) by the inducing tone. For example, Zeng (1994) used 1000-Hz signals in his three-tone paradigm, the interval between the first (recalibrating) tone and the third (comparison) tone being 750 ms. When the first tone was 20 dB greater than the second (target), Zeng (1994) found loudness enhancement of 9 dB. According to Fig. 3, at an ISI of 750 ms, the loudness of the third tone would be reduced by 11 dB. In one condition of Zwislocki and Sokolich's study (1974), the interval between the first and the third tones was 575 ms (75 ms between the first tone and the target and 500 ms between the target and the comparison), and the associated loudness enhancement was reported to be about 10 dB. According to Fig. 3, however, the loudness of the comparison tone should have reduced by this same amount. In the study of Zwislocki and Sokolich, the magnitude of the loudness enhancement dropped to zero when the interval between the first tone and the second was 500 ms and so the interval between the first tone and the third tone was 1000 ms. According to Fig. 3, at these ISIs, both the target and the comparison should have been recalibrated by about 10 dB, making them equal in loudness.

This little analysis supports the suggestions made by Scharf *et al.* (2002), namely that so-called loudness enhancement is the outcome of a reduction (recalibration) in the loudness of the comparison tone. A strong first tone can reduce the loudness of the comparison, making it necessary to increase its level to make it as loud as the target. The target itself is little affected when the ISI between the initial reca-

TABLE I. Predicted and observed loudness enhancement for the four listeners in experiment 2, based on the time course of their loudness recalibration in experiment 1. The 95% confidence intervals are in parentheses.

ISI (ms)	Predicted loudness recalibration for the target tone (dB)	Predicted loudness recalibration for the comparison tone (dB)	Predicted loudness enhancement (dB)	Observed loudness enhancement (dB)
75	2	11.25	9.25(1.7)	11(1.7)
525	10	13.20	3.20(1.5)	2(1.5)

librating tone and the target is small. In their report, Scharf *et al.* (2002) presented preliminary data that tentatively supported their argument. In experiment 2 of this study, we took a more thorough look at this account of loudness enhancement, bringing back four of the listeners who participated in experiment 1 to test more explicitly the idea that the magnitude of loudness enhancement can be predicted from the time course of loudness recalibration.

III. EXPERIMENT 2—PREDICTING LOUDNESS ENHANCEMENT FROM THE TIME COURSE OF LOUDNESS RECALIBRATION

A. Method

Four listeners, two women and two men, participated in experiment 2. All four had taken part in experiment 1. The experimental apparatus and experimental paradigm were identical to those used in experiment 1 except for one crucial detail—in experiment 2, the frequency of the comparison was set to equal the frequency of the recalibrating and target tones, that is, to 2500 Hz. Only two ISIs were used: 75 and 525 ms. The order of the sessions was counter-balanced over listeners.

B. Results

We are in the unique position of being able to predict quantitatively the amount of enhancement in experiment 2 from the measurements of recalibration obtained in experiment 1. These predictions can then be compared to the actual loudness changes obtained in experiment 2. To predict loudness enhancement for each listener, we first read off, from Fig. 2, the amount of recalibration at the two ISIs used in experiment 2 (75 and 525 ms). These values represent the predicted changes in loudness of the target tone in experiment 2. Second, in the same manner we read off, from Fig. 2, the amount of recalibration predicted for the comparison tone. The comparison tone is presented 1075 ms after the recalibrating tone in the short ISI condition (75 ms between the recalibration tone and the target+1000 ms between the target and the comparison) and 1525 ms after the recalibrating tone in the long ISI condition. Finally, if recalibration is the only process that influences loudness, then the observed "enhancement" in experiment 2 should equal the difference between the predicted values of the target and the comparison tone.

Columns 2 and 3 of Table I give the average predicted values of loudness recalibration for the target tone and for the comparison tone, respectively, computed for the four listeners who served in experiment 2. Column 4 gives the predicted amount of loudness "enhancement," which equals the difference between the first two values. This is essentially the difference between the small loudness recalibration of the target and the larger recalibration of the comparison. Finally, the last column gives the average observed "enhancement."

Two features of the results are salient. First, loudness enhancement was substantially greater at an ISI of 75 ms than at 525 ms. This outcome is compatible with previous reports (Elmasian and Galambos, 1975; Zwislocki and Sokolich, 1974). Second, the measures of loudness enhancement fall very close to the predictions from experiment 1. This outcome confirms the suggestion made by Scharf *et al.* (2002) that the reported loudness enhancement of a weaker tone by a stronger one at short ISIs is the result of a reduction in loudness (recalibration) of the comparison tone. The loudness of the comparison is affected by the stronger recalibration tone when their frequencies are the same.

IV. GENERAL DISCUSSION

The present study provides two major new findings: (a) the first systematic description of the onset and time course of loudness recalibration, and (b) an empirical confirmation of the hypothesis put forward by Scharf *et al.* (2002) that loudness enhancement as measured with a three-tone single frequency paradigm reflects a reduction in the loudness of the comparison rather than an increase in the loudness of the target.

A significant amount of loudness recalibration first appeared about 200 ms after the presentation of the recalibration tone. The magnitude of loudness reduction then increased monotonically with ISI until approximately 675 ms, after which the loudness reduction leveled off at a magnitude of 11 dB. This magnitude is compatible with previous studies (Marks, 1988, 1994) that reported loudness recalibration between 17 and 22 dB when computed as the overall relative shift in loudness at two frequencies—500 and 2500 Hz. Assuming that the amount of loudness recalibration is about equal at the two frequencies, we expect to measure half as much recalibration at just one frequency. The present results do not speak to the issue of recovery from recalibration because, at the longest ISI, 3300 ms, recalibration was still substantial. Preliminary data from our lab indicate, however, that recovery times may extend over dozens of seconds and may depend strongly on the number of recalibration tones previously presented.

A. Physiological considerations

The temporal growth of loudness recalibration can serve as an important clue for identifying the underlying physiological process. Generally, the neural response to a test tone is attenuated when a louder tone precedes the test tone (but see Brosch and Schreiner, 2000). This effect is sometimes called short-term adaptation and is studied using a forward masking paradigm (Boettcher *et al.*, 1990; Shore, 1995). Numerous studies have shown forward inhibition of neural responses at several levels of the auditory system, including the auditory nerve (Smith, 1977; Harris and Dallos, 1979), cochlear nuclear complex (Boettcher *et al.*, 1990), inferior colliculus (Aitkin and Dunlop, 1969; Etholm, 1969), medial geniculate body (Aitkin and Dunlop, 1969; Schreiner, 1981), and auditory cortex (Brosch and Schreiner, 1997; Hocherman and Gilat, 1981). Recovery times of the neural response, however, are shorter by an order of magnitude than the time course of loudness recalibration found here. Recovery times average about 100 ms at the auditory nerve (Harris and Dallos, 1979; Smith, 1977), slightly longer at the cochlear nucleus (Shore, 1995) and even longer, around 200–250 ms, at the medial geniculate (Schreiner, 1981). The longest neural recovery times, recorded in the auditory cortex, extend up to only 1600 ms (Hocherman and Gilat, 1981).

These findings, however, should be interpreted cautiously. First, neural measures have been made in different species and under various kinds of anesthesia, sometimes under no anesthesia at all. Second, stimuli used in different studies varied considerably in their duration, intensity, and frequency. So direct comparison of neural recovery times across studies requires caution. This said, the general trend indicates longer recovery times as we travel from the periphery to the central auditory system. Thus, although none of the reported recovery times matches that of recalibration, the higher, central levels of the auditory system are the most promising candidates for providing neural correlates in time constants. This view is compatible with the view that recovery times are greater at higher levels of the auditory system because inhibitory processes tend to accumulate as auditory stimulation travels from the periphery to the central nervous system. This happens partly because central auditory regions show increasing numbers of local circuits and interconnecting neurons that can locally inhibit sensitivity to tones (Brosch and Schreiner, 1997). Thus, in sum, central inhibition provides one possible mechanism of recalibration.

Parker and Schneider (1994) have suggested another possible mechanism of loudness recalibration, involving descending efferent pathways. They suggest that a nonlinear amplifier, controlled by a top-down mechanism, attenuates incoming signals whenever they include loud tones. One example of descending auditory pathway is the efferent system that projects from the medial olivocochlear neurons to the outer hair cells (Liberman, 1986). Feedback through the cochlear efferent system reduces vibration at the basilar membrane (Russell and Murugasu, 1997) and activity in the auditory nerve (Guinan and Stankovic, 1996) in response to stimulation. Two features of the efferent system make it an attractive candidate for explaining loudness recalibration (Nieder *et al.*, 2003). First, the efferent system responds more vigorously to ipsilateral than contralateral stimulation (Liberman, 1988), consistent with evidence that recalibration is greater when induced ipsilaterally rather than contralaterally (Marks, 1996). Second, the efferent system can be sensitized for a few minutes by exposure to relatively intense broadband noise (Liberman, 1988). This sensitization might serve to reduce afferent responses to acoustic stimuli. But an explanation in terms of efferent activity also has some weaknesses. Because the efferent system exerts it influence early in auditory processing, one would expect to find evidence of attenuation (recalibration) at distal auditory loci. The available evidence, summarized above, fails to show the long recovery times in the auditory nerve that one would expect if recalibration resulted from efferent feedback to the cochlea. Thus, even if the efferent system contributes significantly to the loss of sensitivity following stimulation, it cannot be the sole source of loudness recalibration.

B. Loudness recalibration and loudness enhancement

The results of experiment 1 show that loudness recalibration is durable, extending more than 3 s after the presentation of a brief recalibrating tone. Further, as already mentioned, recalibration is frequency specific. The combination of durability and frequency specificity constrains the methods that can be used to measure loudness recalibration through matching procedures. Notably, one cannot use a comparison tone with the same frequency as the recalibrating tone and the target tone. If one does, the recalibrating tone will affect the loudness of the comparison tone, thereby distorting the measurements. According to Scharf *et al.* (2002), this is exactly what has happened in studies of loudness enhancement. Those studies reported that the loudness of the target tone is enhanced when presented up to 100 ms after a more intense recalibrating tone (or the conditioning tone, as it was termed). However, the frequency of the comparison was always the same as that of the recalibrating tone, which it usually followed by less than 2 s. Scharf *et al.* (2002) suggested that (a) the loudness of the comparison tone was reduced by the recalibrating tone and, therefore, (b) listeners had to raise the intensity of comparison in order to match its loudness to that of the target. Thus, loudness enhancement was an artifact of the way it was measured. In experiment 1, we used a comparison tone that lies almost seven critical bands from the recalibrating and target tones. The absence of substantial loudness enhancement at short ISIs supports Scharf *et al.*'s position.

Using loudness reduction to account for traditional measures of loudness enhancement bears consequences for other findings that have been linked to it. For example, loudness discrimination of two test tones following a ''priming'' tone is impaired (jnd's increase) when the level of the priming tone exceeds that of the first test tone by about 20–30 dB but not when the difference is larger or smaller (Plack, 1996; Zeng, 1994). Perceptual variability associated with the presumed enhancing effect of the primer on the first target was suggested as a possible source for the elevation in jnd's. Instead of enhancement, we would argue that the priming (recalibrating) tone differentially reduces the loudness of the two test tones, the second more than the first.

Note that loudness enhancement has also been reported in vibrotactile sensation. When two vibrations are presented successively to the same site, the subjective magnitude of the second is enhanced if the ISI between the two is about 100 ms (Gescheider and Verrillo, 1982; Verrillo and Gescheider, 1975, 1976). Vibrotactile enhancement resembles auditory loudness enhancement in both time course and magnitude. Unfortunately, studies of vibratory enhancement have had the same methodological flaw as studies of auditory enhancement, namely, the use of a three-stimulus paradigm in which the comparison tone had the same frequency as the recalibrating and target tones. We propose here that, as in hearing, vibrotactile loudness enhancement will disappear if measured by a comparison tone whose frequency differs significantly from that of the recalibrating and target tones.

Does all of this mean that loudness enhancement does not exist? Results of experiment 1 show that at short ISIs, any change in the loudness of the target is small. In other words, the recalibration tone substantially affects the loudness of a tone presented 200 ms later, but affects only slightly if at all the loudness of a tone presented 75 ms later. One possible explanation to this puzzle is that it takes about 200 ms for the inhibitory process responsible for recalibration to develop. But there is another possibility, one that assumes no temporal threshold for the onset of recalibration. The lack of a reliable change in loudness at short ISIs could reflect two offsetting effects: inhibition (recalibration) and a small enhancement (with the underlying processes having different time constants). This possibility is especially cogent in light of the physiological evidence showing inhibitory neural processes at all levels of the auditory system at ISIs shorter than 100 ms. The absence of a suprathreshold perceptual analog to the neural inhibition observed at short ISIs could mean that a short-lived facilitory process of loudness enhancement offsets an inhibitory process of loudness recalibration.

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Aitkin, L. M., and Dunlop, C. W. (**1969**). ‘‘Inhibition in the medial geniculate body of the cat,’’ Exp. Brain Res. **7**, 68–83.

Arieh, Y., and Marks, L. E. (**2001**). ‘‘Recalibration of loudness: sensory vs. decisional processes,’’ in *Fechner Day 2001. Proceedings of the Seventeenth Annual Meeting of the International Society for Psychophysics*, edited by T. Sommerfeld, R. Kompass, and T. Lachman (Pabst Science, Berlin), pp. 242–247.

Arieh, Y., and Marks, L. E. (**2003**). ‘‘Recalibrating the auditory system: a speed-accuracy analysis of intensity perception,’’ J. Exp. Psychol. Human Percept. Perform. **29**, 523–536.

Boettcher, F. A., Salvi, R. J., and Saunders, S. S. (**1990**). ‘‘Recovery from short-term adaptation in single neurons in the cochlear nucleus,’’ Hear. Res. **48**, 125–144.

Brosch, M., and Schreiner, C. E. (**1997**). ‘‘Time course of forward masking tuning curves in cat primary auditory cortex,’’ J. Neurophysiol. **77**, 923–943.

Brosch, M., and Schreiner, C. E. (**2000**). ‘‘Sequence sensitivity of neurons in cat primary auditory cortex,’’ Cereb. Cortex **10**, 1155–1167.

Elmasian, R., and Galambos, R. (**1975**). ‘‘Loudness enhancement: monaural, binaural, and dichotic,’’ J. Acoust. Soc. Am. **58**, 229–234.

Etholm, B. (**1969**). ‘‘Evoked responses in the inferior colliculus, medial geniculate body and auditory cortex by single and double clicks in cats,’’ Acta Oto-Laryngol. **67**, 319–325.

Fletcher, H., and Munson, W. A. (**1933**). ‘‘Loudness, its definition, measurement and calculation,’’ J. Acoust. Soc. Am. **5**, 82–108.

Gescheider, G. A., and Verrillo, R. T. (**1982**). ‘‘Contralateral enhancement and suppression of vibrotactile sensation,’’ Percept. Psychophys. **32**, 69–74.

Guinan, J. J., and Stankovic, K. M. (**1996**). ‘‘Medial efferent inhibition produces the largest equivalent attenuations at moderate to high sound levels in cat auditory-nerve fibers,’’ J. Acoust. Soc. Am. **100**, 1680–1690.

Harris, D. M., and Dallos, P. (**1979**). ‘‘Forward masking of auditory nerve fiber responses,’’ J. Neurophysiol. **42**, 1083–1107.

Hocherman, S., and Gilat, E. (**1981**). ‘‘Dependence of auditory evoked unit activity on interstimulus interval in the cat,’’ J. Neurophysiol. **45**, 987–997.

Jesteadt, W. (**1980**). ‘‘An adaptive procedure for subjective judgments,’’ Percept. Psychophys. **28**, 85–88.

Liberman, M. C. (**1988**). ‘‘Response properties of cochlear efferent neurons: monaural vs. binaural stimulation and the effects of noise,’’ J. Neurophysiol. **60**, 1779–1798.

Liberman, M. C., and Brown, M. C. (**1986**). ‘‘Physiology and anatomy of single olivocochlear neurons in the cat,’’ Hear. Res. **24**, 17–36.

Loftus, G. R., and Masson, M. E. J. (**1994**). ‘‘Using confidence intervals in within-subjects designs,’’ Psychon. Bull. Rev. **1**, 476–490.

Mapes-Riordan, D., and Yost, W. A. (**1998**). ‘‘Temporal properties of loudness recalibration,’’ J. Acoust. Soc. Am. **103**, 3020.

Mapes-Riordan, D., and Yost, W. A. (**1999**). ‘‘Loudness recalibration as a function of level,’’ J. Acoust. Soc. Am. **106**, 3506–3511.

Marks, L. E. (**1988**). ‘‘Magnitude estimation and sensory matching,’’ Percept. Psychophys. **43**, 511–525.

Marks, L. E. (**1992**). ‘‘The slippery context effects in psychophysics: intensive, extensive, and qualitative continua,’’ Percept. Psychophys. **51**, 187–198.

Marks, L. E. (**1993**). ‘‘Contextual processing of multidimensional and unidimensional auditory stimuli,’’ J. Exp. Psychol. Hum. Percept. Perform. **19**, 227–249.

Marks, L. E. (**1994**). ‘‘Recalibrating’ the auditory system: the perception of loudness,’’ J. Exp. Psychol. Hum. Percept. Perform. **20**, 382–396.

Marks, L. E. (**1996**). ‘‘Recalibrating the perception of loudness: interaural transfer,’’ J. Acoust. Soc. Am. **100**, 473–480.

Marks, L. E., and Warner, E. (**1991**). ‘‘Slippery context effect and critical bands,’’ J. Exp. Psychol. Hum. Percept. Perform. **17**, 986–996.

Nieder, B., Buus, S., Florentine, M., and Scharf, B. (**2003**). ‘‘How induced loudness reduction depends on duration, level, and laterality,’’ J. Acoust. Soc. Am.

Parker, S., and Schneider, B. A. (**1994**). ‘‘The stimulus range effect: evidence for top-down control of sensory intensity in audition,’’ Percept. Psychophys. **56**, 1–11.

Plack, C. J. (**1996**). ‘‘Loudness enhancement and intensity discrimination under forward and backward masking,’’ J. Acoust. Soc. Am. **100**, 1024–1030.

Russell, I. J., and Murugasu, E. (**1997**). ‘‘Medial efferent inhibition suppresses basilar membrane responses to near characteristic frequency tones of moderate to high intensities,’’ J. Acoust. Soc. Am. **102**, 1734–1738.

Scharf, B., Buus, S., and Nieder, B. (**2002**). ‘‘Loudness enhancement: induced loudness reduction in disguise?’’ J. Acoust. Soc. Am. **112**, 807–810.

Schneider, B., and Parker, S. (**1990**). ‘‘Does stimulus context affect loudness or only loudness judgment?’’ Percept. Psychophys. **48**, 409–418.

Schreiner, C. E. (**1981**). ‘‘Poststimulatory effects in the medial geniculate body of guinea pigs,’’ in *Neuronal Mechanisms of Hearing*, edited by J. Syka and L. Aitkin (Plenum, New York), pp. 191–196.

Shore, S. E. (**1995**). ‘‘Recovery of forward masked responses in ventral cochlear nucleus neurons,’’ Hear. Res. **82**, 31–43.

Smith, R. L. (**1977**). ‘‘Short-term adaptation in single auditory nerve fibers: Some post-stimulatory effects,’’ J. Neurophysiol. **40**, 1098–1112.

Verrillo, R. T., and Gescheider, G. A. (**1975**). ‘‘Enhancement and summation in the perception of two successive vibrotactile stimuli,’’ Percept. Psychophys. **18**, 128–136.

Verrillo, R. T., and Gescheider, G. A. (**1976**). ‘‘Effect of double ipsilateral stimulation on vibrotactile sensation magnitude,’’ Sens Processes **1**, 127–137.

Zeng, F.-G. (**1994**). ‘‘Loudness growth in forward masking: Relation to intensity discrimination,’’ J. Acoust. Soc. Am. **96**, 2127–2132.

Zwislocki, J. J., and Sokolich, W. G. (**1974**). ‘‘On loudness enhancement of a tone burst by a preceding tone burst,’’ Percept. Psychophys. **16**, 87–90.