SEQUENTIAL EFFECTS IN LOUDNESS

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Abstract

This paper reviews the effects of one sound on the loudness of a following sound. The following sound is usually perceived as softer than when presented in isolation. At least five sequential effects can be identified. (1) Simple loudness adaptation: the earlier part of an ongoing sound results in a decline in the loudness of later parts. (2) Ipsilaterally induced adaptation: increments in the level of an ongoing sound induce a decline in the loudness of the ongoing sound. An intermittent louder sound at a nearby frequency also causes a decline in loudness. (3) Loudness recalibration: the stronger and weaker sounds of induced adaptation are separated by a silent interval, but otherwise the decline in the loudness of the weaker sound, called recalibration, seems to follow much the same rules as induced adaptation. (4) Temporary loudness shift: a very intense sound often causes a temporary decline or shift in the loudness of a following weaker sound. This temporary shift is attributed to fatigue of the cochlear hair cells. (5) Loudness enhancement: a brief sound is louder when it follows a stronger sound within 200 ms or so. These various sequential effects are largely perceptual, but their physiological bases can only be guessed at.

This paper is about changes in the loudness of one sound caused by exposure to a preceding sound. With no silent interval between the two sounds and with no stimulus change, such sequential effects are generally referred to as loudness adaptation. With a silent interval, among the notable sequential effects are loudness recalibration, temporary loudness shifts, and loudness enhancement. Except for loudness enhancement, the effect of the preceding sound is either to leave unchanged or to diminish the loudness of the following sound.

Fechner had little to say about loudness, no doubt because control of sound intensity was so difficult in the 19th century. He did refer to sequential effects in psychophysics with respect to the measurement of difference thresholds but not with respect to sensory magnitudes, such as loudness. Many contemporary psychophysicists (see Baird, 1997) do consider effects of preceding stimuli and responses, even of the whole context, on responses, especially in scaling procedures. I limit myself to what appear to be sequential effects on perceiving rather than uniquely or mainly on responding.

Loudness Adaptation

Loudness adaptation is the progressive decline in the loudness of an unchanging, continuous sound. Such adaptation is relatively rare. That was the prevailing opinion when I was a graduate student in the Psychoacoustics Laboratory of S. S. Stevens. After all, you had only to listen to an ongoing steady sound to hear that loudness remained essentially the same no matter how long it continued. This view was quite contrary to the conclusions of Hood (1950) who published data purporting to show as much as a 50-phon decrease in the loudness level of a continuous tone after 3 or 4 min of exposure. The problem was in the way that Hood measured adaptation. He presented an occasional tone to the ear contralateral to the ear receiving the continuous tone. That occasional tone was to serve as a reference against which to judge the loudness of the continuous tone. However, as Canévet, Botte, and Scharf (1982) showed, the comparison tone caused the loudness of the continuous tone to diminish over time. With no tone in the other ear, loudness changed hardly at all. Although Canévet et al. were the first to study systematically the loudness changes induced by a contralateral sound, they were hardly the first to point out the problem. Nonetheless, Hood's report comforted the belief that loudness, like most other sensations, adapts strongly. Dramatic outcomes, no matter how weak their underpinnings, often take center stage and are difficult to dislodge.

To avoid interaural interactions and gain a rapid view of any changes in loudness over time, we developed the method of successive magnitude estimation. The listener assigns a number to the loudness of an ongoing sound at specified intervals (Scharf, 1983). This procedure has permitted us to define the stimulus conditions under which loudness adaptation does take place. To diminish markedly in loudness, a continuous sound must be weak--within about 30 dB of threshold--or be at a high frequency--above 10 kHz or so.

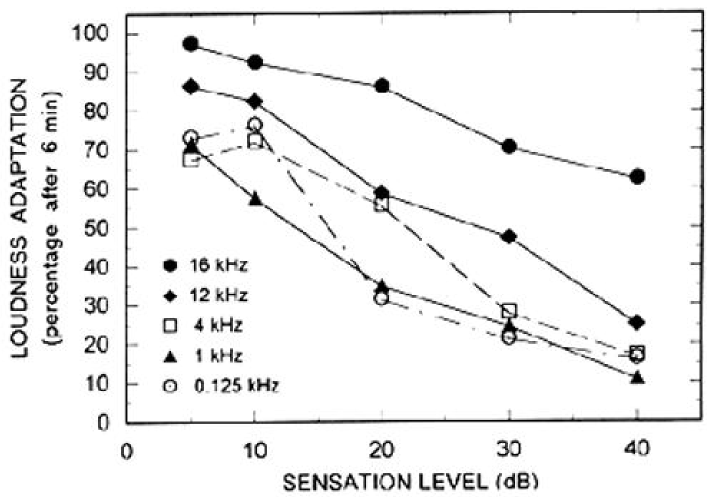

Fig. 1. Percentage decline in loudness after a 6-min exposure to a tone at various frequencies and sensation levels. (From Hellman, Miskiewicz, and Scharf, 1997.)

Figure 1 provides a broad summary of these relationships. Figure 1 shows how the amount of loudness adaptation for a pure tone depends on sensation level up to 40 dB and on frequency between 125 Hz and 16 kHz. The percentage decline in loudness at the end of 6 min is plotted against sensation level; the tonal frequency is the parameter on the curves. At 5 dB SL, loudness declines between approximately 70 and 100% at all frequencies. With increasing level, the amount of adaptation decreases at all frequencies. Above 40 dB, this 6-min adaptation is usually between 10 and 20% at the lower frequencies. These results are for steady tones. Sounds such as noise and fluctuating or intermittent tones, whose amplitude varies over time, are subject to much less adaptation. We call these declines in loudness--in the absence of any sound other than the continuous test sound—simple loudness adaptation.

The adaptation induced by a sound in the contralateral ear appears to result more from the simultaneous occurrence of the continuous test sound and the intermittent contralateral sound than from a sequential effect. However, if an intermittent sound is presented to the same ear as the ongoing sound, a true sequential effect on loudness emerges. Weiler, Sandman, and Peterson (1981) uncovered this sequential effect in their attempt to measure loudness adaptation. To avoid binaural interaction, they intermittently increased the level of a continuous tone presented monaurally. The increment, intended to serve as a reference, actually induced adaptation in the continuous tone as shown in Canévet, Scharf, and Botte (1983) and in many subsequent reports. We have named this ipsilaterally induced adaptation. Because it appears to be closely related to loudness recalibration, the two are considered together.

Loudness Recalibration and Ipsilaterally Induced Adaptation

A large number of papers and experiments by Lawrence Marks and his colleagues seemed to show that the loudness of a sound depends markedly on its "context." Context refers to all preceding sounds; usually, however, it is restricted to those in the current block of trials. For example, Marks (1994) first used the term recalibration to describe "alterations in relative responsiveness" after exposure "to a sequence of brief, weak 500-Hz tones alternating with stronger 2500-Hz tones" (p. 382). The abstract of that article begins: "Listening to relatively intense tones at 1 frequency and weak tones at another makes the latter relatively louder." The implication that you need two different frequencies for recalibration to occur is false. That other frequency may serve as a measuring device; otherwise, it is not part of the phenomenon. In all fairness to Marks, he did suggest "that recalibration may result from adaptationlike processes that are more or less specific to the signal frequencies presented" (p. 395).

My colleagues and I have begun to use the term loudness recalibration to refer specifically to the decline in the loudness of a weaker sound induced by a preceding stronger sound. Mapes-Riordan and Yost (1999) came close to such a definition when they assumed that "recalibration operates by attenuating lower-level tones with high-level tones within the same frequency channel" (p. 3509). Our broad definition includes the ipsilaterally induced adaptation described above and other such paradigms.

Most of the experiments by Marks and his colleagues were not designed to permit a direct test of such a relatively simple phenomenon. One exception is Marks’s (1993) experiment 15 in which a 500-Hz tone came on for 1 s every 4.5 s. After a 3-min exposure to a 73-dB tone, a 500-Hz tone at 63-dB was judged considerably softer. In contrast, exposure to a 500-Hz tone set 20 dB lower (to 53 dB) had little effect on subsequent loudness comparisons. Similarly, the loudness of a 2.5-kHz tone declined after having been presented repeatedly at 68 dB but not at 48 dB. The declines in loudness were equivalent to approximately 10 dB (Marks, personal communication).

Mapes-Riordan and Yost (1999) measured recalibration differently. They used an adaptive interleaved two-track procedure to match 500-Hz and 2.5-kHz tones in loudness. First came 40 trials in which the 2.5-kHz tone, varying in level from trial to trial, followed the 500-Hz tone at a fixed level; the listener reported on each trial which tone was louder. Next came 40 trials with the same sequence except that the 500-Hz tone was always preceded 1-s earlier by a more intense 500-Hz tone. The stronger tone reduced the loudness of the weaker test tone the most when the level difference was 10 or 20 dB, with the loudness reduction equivalent to 10 or 11 dB. Our own variation of this adaptive procedure is proving useful for the examination of the parameters of recalibration and an investigation into its basis (e.g. Nieder et al., 2001). In preliminary experiments, we have also used successive magnitude estimation to measure recalibration. Listeners assigned a number to a brief 500-Hz tone presented twice. They then continued to assign numbers to the same tone preceded on each trial by a stronger 500-Hz tone. After 30 trials, the loudness had declined the equivalent of 9 dB.

Loudness recalibration resembles ipsilaterally induced adaptation: both take place when a weaker tone follows a more intense tone, provided the frequencies are the same or close (Charron & Botte, 1988; Marks & Warner, 1991); both lead to a drop in loudness level of 5 to 15 phons. Could they be essentially the same phenomenon, measured with stimuli that differ mainly in their temporal properties? In recalibration, the two tones have always been separated by a silent gap. In induced adaptation, a silent gap has seldom been introduced. However, nearly 20 years ago colleagues and I in Boston and in Marseille found that ipsilaterally induced adaptation occurs even when a silent gap is present. A 20-dB increment from 50 dB induced a 40 to 50% decline in the loudness of the ongoing weaker tone; the decline was the same whether the weaker tone followed the 10-s increment immediately or was delayed for 1 s or 5 s. It is not known whether ipsilaterally induced adaptation also takes place when signal durations are as short as those that have been used to measure recalibration

Why recalibration? Parker and Schneider (1994) suggested that an internal non-linear amplifier comes into operation when loud and soft sounds are presented in the same series. The amplification would serve to boost the soft signals thereby facilitating their processing. They also suggested that amplification may be controlled by efferent input to the cochlea. Although no such amplification would seem needed when an 80-dB tone causes a loudness decline in a following 70-dB tone, a role for the efferent system is not unreasonable. The olivocochlear input to the outer hair cells modulates their response to acoustic stimulation, making the auditory system more sensitive. One current hypothesis is that efferent excitation increases the nonlinear compression in the cochlea so that loudness grows more slowly with sound intensity. If sensitivity were increased linearly over all sound levels, excitation and loudness would be too great at higher levels. But this means that the compression induced by the stronger tone results in a decrease in the response to the succeeding weaker tone. Hence the decline in loudness induced by a stronger tone. We are currently preparing to test this hypothesis with patients whose olivocochlear bundle has been severed. We predict that recalibration and ipsilaterally induced adaptation will be reduced in such listeners.

Temporary Loudness Shift

The aftereffects of an intense sound exposure on threshold have been studied so often and are so well known that they are often referred to simply by the acronym, TTS (temporary threshold shift). A corollary of TTS is temporary loudness shift or TLS: Whenever threshold goes up, loudness must come down, at least near threshold. Thought to result mainly from fatigue of the cochlear hair cells, TLS may include recalibration under some stimulus conditions. Botte and Monikheim (1994) provide a good example. Thirty seconds after a 3-min exposure to a .5-, 1-, and 3-kHz tone at 65 dB, loudness declined more at the exposure frequency than at other frequencies; the decline was greater at the lowest loudness level tested, 20 phons, than at higher levels. Whereas the frequency dependency is like that of recalibration, the level dependency is not. Mapes-Riordan and Yost (1999) found that recalibration was greatest for a 10- and 20-dB decrease from 80 dB; similar results were obtained by Nieder et al. (2001). So a single 3-min exposure at 65 dB may involve both recalibration and fatigue. On the other hand, a 15-min exposure at 90 dB to a 1-kHz tone resulted in a decline in loudness that was nearly uniform over a range of frequencies up to 1 octave from the test frequency. Presumably the duration and intensity of the exposure swamped whatever recalibration was taking place.

Decruitment

Decruitment is the rapid decline in the loudness of a tone that decreases continuously in level (Canévet & Scharf, 1990; Schlauch, 1992). The decline is more rapid than expected on the basis of the sone function or than that for the same tone presented intermittently. For example, a continuous decrease from 65 to 20 dB results in a decline in loudness ten times greater than does an intermittent decrease. Although decruitment is greatest at low levels, it also occurs at levels where simple loudness adaptation is absent or nearly so. Hence, it is not just a direct consequence of adaptation. It is also unlike ipsilaterally induced adaptation or recalibration in that interrupting the decreasing tone greatly reduces the effect. Recalibration is not evident probably because the successive levels are too close to each other, differing at most by 2 or 3 dB (Canévet & Scharf, 1990). However, decruitment resembles recalibration in that the sequential effect is asymmetrical; a continuously *increasing* tone usually does not grow more rapidly than expected.

Loudness enhancement

Until now we have seen that a stronger sound or portion of a sound diminishes the loudness of later, weaker sounds. In loudness enhancement, the sequential effect is just the opposite: a strong sound causes the loudness of a following weaker sound to *increase* provided the temporal separation is no more than a couple of hundred milliseconds (Elmasian, Galambos, & Bernheim, 1990; Plack, 1996; Zwislocki & Sokolich, 1974). A necessary condition appears to be also that the weaker tone be brief, not exceeding 10 or 20 ms in duration. Enhancement is like loudness recalibration in that it may be as large as 15 phons (on average), is greatest when the stronger and weaker sounds have the same frequency, and decreases when the two sounds are in opposite ears. Could it be that with decreasing separation between the stronger and weaker sounds, recalibration changes into enhancement? Some results of Mapes-Riordan and Yost (1998) speak both for and against this possibility. They found that the amount of recalibration decreased as the delay of the weaker tone decreased from 10 s to 50 ms. However, even with only a 50-ms delay, the loudness of a 500-Hz tone declined the equivalent of 4 dB. The lack of enhancement at 50 ms was no doubt due to the long durations of the signals, which were 500 and 1000 ms.

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