Perceptual asymmetries associated with changing-loudness aftereffects

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Listening to decreasing sound level leads to an *increasing-loudness aftereffect*, whereas listening to increasing sound level leads to a *decreasing-loudness aftereffect*. Measuring the aftereffects by nulling them in short test stimuli reveals that increasing-loudness aftereffects are greater than decreasing-loudness aftereffects. However, this perceptual asymmetry may be due to another illusion—the *growing-louder effect*: In the absence of any adaptation, short steady stimuli are heard as growing louder. In an experiment in which the duration of test stimuli varied from 1.0 to 2.5 sec, the growing-louder effect did not occur in the longer test stimuli, but the asymmetry in changing-loudness aftereffects remained. The aftereffect asymmetry is therefore independent of the growing-louder effect. The aftereffect asymmetry is consistent with other psychophysical and physiological evidence that is believed to concern potential collision: An approaching sound-source elicits increasing sound level. In addition, the aftereffect asymmetry parallels a well-known asymmetry regarding aftereffects of visual motion, which is also attributed to potential collision.

Changing sound level results in a number of illusory phenomena. For example, Canévet and his colleagues investigated steady decrease or increase of sound level over many seconds; listeners estimated the loudness at “snapshots” during stimulus presentation. Estimates changed more for decreasing sound level than for increasing sound level, a result that might in part reflect sensory adaptation (Canévet, 1986; Teghtsoonian, Teghtsoonian, & Canévet, 2000). Another perceptual asymmetry concerns much shorter stimuli (250 msec); fast rise followed by slow decay is heard as less loud than slow rise followed by fast decay, a result that may concern the reverberation associated with percussive sounds (Stecker & Hafter, 2000).

Whereas the preceding phenomena involve judgments of overall loudness over a short time, other phenomena involve judgments of changing loudness; arguably, the different types of judgment tap different mechanisms (Cavénet, Scharf, Schlauch, Teghtsoonian & Teghtsoonian, 1999; Neuhoff, 1999). Several studies have reported that, in stimuli lasting a second or two, increasing loudness is more prominent than decreasing loudness (Arlinger & Jerlvall, 1979; Rawdon-Smith & Grindley, 1935; Reinhardt-Rutland, 1996; Small, 1977). These studies concern small

changes of level. For example, Small reported a preponderance of “growing louder” responses from stimuli commencing at 58 dB SPL and changing by +0.2 dB/sec to –0.2 dB/sec. Reinhardt-Rutland (1996) found that a steady decrease of sound level by about 1 dB causes a 1.25-sec tone starting at 40 dB SPL to be heard as steady. The phenomenon has been labeled the *growing-louder effect* (Figure 1B; Reinhardt-Rutland & Ehrenstein, 1996).

Recently, Neuhoff (1998, 2001) has investigated much greater changes in sound level. Neuhoff’s (2001) listeners subjectively scaled the rate of loudness change of 30 dB swept increases or decreases of level over 1.8 sec: Swept increases elicited greater estimates than did decreases. Such evidence can be linked to “looming”—the potential for imminent collision between the sound source and the listener. A sound source moving in depth relative to the listener elicits increasing level toward the listener and decreasing level away from the listener (Rosenblum, Wuestefeld, & Saldana, 1993). In the visual modality, radial motion of pattern is an analogue of changing sound level. Perceptual asymmetries favor centrifugal over centripetal motion of pattern (Ball & Sekuler, 1980; Georgeson & Harris, 1978), and looming responses arise from centrifugal motion of pattern (Ball & Tronick, 1971; Schiff, 1965).

Auditory motion aftereffects have been identified. Properties include azimuthal motion of real moving sound sources (Dong, Swindale, Zakarauskas, Hayward, & Cynader, 2000; Grantham, 1989), simulated azimuthal motion employing dichotic differences of changing sound level and phase (Ehrenstein, 1984, 1994; Grantham & Wightman, 1979), and spectral filtering associated with the pinna (Kayahara, 2001; Shu, Swindale, & Cynader, 1993). In changing-loudness aftereffects—the principal concern of the present paper—listening to decreasing

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Figure 1. Schematic representation of conditions for demonstrating an *increasing-loudness aftereffect*. (A) Following decreasing-intensity adaptation, the sound level of the first test stimulus is steady, but the stimulus is reported as “growing louder” (represented by a broken line and arrow). In the second test stimulus, the increasing-loudness aftereffect has been nulled by decreasing sound level and the stimulus is heard as steady; it would elicit equal proportions of “growing louder” and “growing softer” responses. Changing-loudness aftereffects can be demonstrated by comparing this null with that following adaptation to increasing sound level. However, a fuller quantitative assessment requires comparison with the asymmetry that affects test stimuli in the absence of adaptation—the *growing-louder effect*. (B) The first test stimulus is steady but is reported as “growing louder,” whereas the second test stimulus decreases in sound level and is heard as steady.

sound level leads to a perception of increasing loudness in a steady tone heard afterward—*increasing-loudness aftereffect* (Figure 1A)—whereas listening to increasing sound level leads to a perception of decreasing loudness in a steady tone heard afterward—*decreasing-loudness aftereffect* (Kitagawa & Ichihara, 2002; Reinhardt-Rutland, 1980). Like auditory motion aftereffects, substantial components of changing-loudness aftereffects are monaural in origin (Reinhardt-Rutland, 1998). Monaural processing of changing intensity is necessary because an azimuthal component of motion introduces dichotic differences in changing sound level (Rosenblum, Carello, & Pastore, 1987).

Motion aftereffects are well known in the visual modality (Mather, Verstraten, & Anstis, 1998; Reinhardt-Rutland, 1987; Wade, 1994). Consistent with a tendency for the visual system to treat centrifugal motion as potential collision, centrifugal aftereffects are stronger than centripetal aftereffects (Harris, Morgan, & Still, 1981; Reinhardt-Rutland, 1994; Scott, Lavender, McWhirt, & Powell, 1966; Wohlgenuth, 1911). Such evidence sug-

gests that increasing-loudness aftereffects should be stronger than decreasing-loudness aftereffects. To reinforce the point, cross-modal aftereffects have been reported: Adaptation to horizontal visual motion can lead to auditory displacement afterward (Ehrenstein & Reinhardt-Rutland, 1996), and—more crucially—adaptation to radial visual motion can lead to changing-loudness aftereffects (Kitagawa & Ichihara, 2002).

Because auditory aftereffects are somewhat short lived (e.g., Kayahara, 2001), their measurement has involved nulling the aftereffect with short test stimuli lasting about a second or so. As an example, an increasing-loudness aftereffect would be nulled by decreasing sound level in the test stimulus, so that the test stimulus would be perceived as steady in loudness (Figure 1A). Comparison of nulled increasing-loudness aftereffects with nulled decreasing loudness aftereffects shows that the former can be greater in absolute terms than the latter (Reinhardt-Rutland, 1980, 1995). Kitagawa and Ichihara’s (2002) statistical analysis includes diverse data from a range of adaptation conditions, and they do not

report significance for direction. Nonetheless, perusal of their Figure 1 suggests an asymmetry like Reinhardt-Rutland's for their purely auditory changing-loudness aftereffects.

However, test stimuli for changing-loudness aftereffects may be affected by the growing-louder effect noted earlier, so direct comparison between measurements of increasing-loudness aftereffects and decreasing-loudness aftereffects is not sufficient to determine whether there is truly an asymmetry between them. Aftereffects must be compared with the rate of changing sound level required for a test stimulus to be heard as steady in the absence of an adaptation stimulus. Furthermore, the decreasing rate of sound level to null the growing-louder effect could contribute to the decreasing sound level adaptation required for the increasing-loudness aftereffect.

A possible solution to the problem of measurement is exploited in the present experiment. The growing-louder effect may not be present if the duration of test stimulus is about 2 sec or more (Reinhardt-Rutland, 1996). By choice of slightly longer test durations than often used, measurable changing-loudness aftereffects may be obtained in test stimuli that are unaffected by the growing-louder effect. This would show that the aftereffect asymmetry is independent of the growing-louder effect.

METHOD

Stimuli

The stimuli—shown schematically in Figure 1—were based on the multiplied outputs from Tektronix FG501 and Marconi 2021 function generators, in conjunction with dedicated hardware. The resulting waveform was presented via a Keletron KSA 1500 Mk.II amplifier and Koss ESP6a headphones. Sound level was measured with a Dawe 1404B meter (A weighting) via a flat plate coupler with the recording microphone at 1 cm from the headphone transducer.

The adapting stimulus was presented diotically and changed sound level at -18 dB/sec (decreasing sound level adaptation), or $+18$ dB/sec (increasing sound level adaptation). After a few seconds the former rate would lead to inaudibility, whereas the latter rate would lead to excessive loudness. To overcome this, the adapting stimulus was maintained at a mean of 40 dB SPL by rapid increase of sound level (decreasing sound level adaptation) or rapid decrease of sound level (increasing sound level adaptation) every 2 sec. Rapid changes took 0.2 msec and were heard as atonal; they are assumed not to contribute to the aftereffects. The carrier was a 1.0-kHz sinusoid.

Test stimuli were derived from the adapting stimuli by exploiting a voltage-controlled facility on the Marconi generator. Like the adapting stimuli, the test carrier was a 1.0-kHz sinusoid. Durations of test stimuli were 1.0, 1.5, 2.0, and 2.5 sec. Each test stimulus started at 40 dB SPL and steadily increased or decreased, or was constant in sound level. Sound level change ranged from $+9$ to -9 dB/sec in 1-dB/sec steps; nulls for changing-loudness aftereffects lie well within this range. For each duration of test stimulus, there were therefore nineteen test stimuli.

For stimulus sequences involving adaptation, the adapting stimulus was presented for 2 min, followed by a test stimulus, then 10 sec of the adapting stimulus to maintain adaptation, then another test stimulus, and so on. The sound level at the restart of the adapting stimulus equalled the sound level at the end of the preceding test stimulus; a difference in sound level at the switch between test and adaptation stimuli would be easily detected (Jesteadt, Green, &

Wier, 1978; Parducci & Sandusky, 1970) and might influence responses.

In nonadaptation stimulus sequences, test stimuli were presented every 10 sec—as in adaptation sequences—and intervals between test stimuli were silent. An alternative to silence might be a steady tone of 40 dB SPL to match the mean sound level of adaptation, but this would introduce problematic sound level differences—as discussed in the last paragraph—since sound level at the end of test stimuli generally differed from 40 dB SPL.

During the experiment, the listener was seated in a sound-attenuating room with only the headphones and two press-button switches to communicate responses to the experimenter, who was outside the room controlling the remaining apparatus.

Listeners

The listeners were 4 males, 1 of whom was the author. None reported any history of hearing problems. All had hearing thresholds 15 dB HL or less between 0.125 kHz and 8.0 kHz, as measured by a Kamplex Model BA2C audiometer. All were familiar with changing-loudness aftereffects, but, except the author, naive regarding the experiment's purpose.

Procedure

Each test stimulus required a response of "growing softer" or "growing louder." As intimated in the introduction, these properties might be interpreted as recession or approach, respectively; however, listeners find judgments in terms of changing loudness more pertinent.

During preliminary sessions, test stimuli were selected for each listener's experimental sessions. In each condition, the listener responded to two presentations of the 19 test stimuli in random order. On the basis of these responses, 5 stimuli were selected as being around the listener's null, that rate of sound level change for which equal numbers of "growing softer" and "growing louder" responses would be elicited.

In the main part of the experiment, each set of five test stimuli was presented a total of eight times in random order, giving a total of 40 responses per set of test stimuli. Separate experimental sessions were run for each combination of adaptation condition and test duration.

Data Analysis

The proportions of "growing softer" responses and "growing louder" responses necessarily mirror each other, so only one type of response—"growing softer" was selected—need be considered further.

The proportion of "growing softer" responses decreases in an approximately ogival pattern as rate of sound level change in the test stimulus increases. This permits the use of Engen's (1971) technique for dealing with binary responses. The proportions of "growing softer" responses were transformed into standard scores (z) to linearize their relationship with rate of sound level change. The null—the rate of sound level change eliciting 50% "growing louder" responses—corresponds to $z = 0$. Changing loudness aftereffects are indicated if the adaptation null following increasing sound level adaptation is more positive than the corresponding adaptation null following decreasing sound level adaptation. The nonadaptation null should lie somewhere between the two adaptation nulls.

In a few cases, "growing softer" responses switched from 100% to zero over consecutive values of sound level change: z values were infinite, and Engen's (1971) technique could not apply. In such cases, the null is taken as the mean of the consecutive values.

RESULTS AND DISCUSSION

Nulls derived from response functions are shown in Figures 2 and 3. The presence of aftereffects is indicated

Figure 2. Nulls for each listener. Columns patterned “\\” represent adaptation to decreasing sound level; the aftereffect is of increasing loudness nulled by decreasing sound level. Columns patterned “//” represent adaptation to increasing sound level; the aftereffect is of decreasing loudness nulled by increasing sound level. Unpatterned columns represent non-adaptation.

by the fact that nulls following increasing sound level adaptation are consistently more positive than those following decreasing sound level adaptation. Also, in absolute terms, the nulls for decreasing sound level adaptation—leading to increasing-loudness aftereffects—are

consistently higher than the nulls for increasing sound level adaptation—leading to decreasing-loudness aftereffects.

All nonadaptation nulls lie between the two sets of adaptation nulls, as expected. In the shorter test stimuli,

Figure 3. Mean nulls for the experiment. Symbolism is as for Figure 2.

nonadaptation nulls indicate that steady perception of loudness requires decreasing sound level; steady sound level is heard as increasing loudness. This reduces as stimulus duration increases and is largely or totally absent in the longer test stimuli (2.0 and 2.5 sec). This is concordant with previous data concerning the growing-louder effect (Arlinger & Jerlvall, 1979; Reinhardt-Rutland, 1996; Small, 1977).

Comparing adaptation nulls with nonadaptation nulls shows that both aftereffects reduce with the duration of the test stimulus. This is consistent with the short duration of the aftereffects. For the shorter test durations, the nonadaptation nulls suggest that some of the aftereffect asymmetry may be explained by the decreasing sound level required for an unadapted test stimulus to be heard as steady. The data were subjected to a two-way, repeated measures analysis of variance (ANOVA) (adaptation condition $\times$ test duration). Both main effects were significant [adaptation condition, $F(2,6) = 975.08$, $p < .0005$; test duration, $F(3,9) = 12.03$, $p = .002$]. The interaction between the two factors was also significant [$F(6,18) = 16.63$, $p < .0005$]. These outcomes are consistent with the comments above.

Aftereffect magnitudes are taken to be the opposite of the nulls following adaptation, as corrected by nonadaptation nulls. Decreasing-loudness aftereffects in absolute terms are obtained by subtracting the nonadaptation nulls from the nulls following increasing sound level adaptation. Increasing-loudness aftereffects in absolute terms are obtained by subtracting the nulls following decreasing sound level adaptation from the nonadaptation nulls. An asymmetry between increasing-loudness aftereffects and decreasing-loudness aftereffects in general remains. Means of these results (Figure 4) suggest an increasing asymmetry as the duration of test stimulus increases, al-

though this does not turn out to be reflected in statistical analysis. Two-way, repeated measures ANOVA for these results showed that adaptation condition was significant [$F(7,3) = 34.21$, $p = .01$], as was duration [$F(3,9) = 20.92$, $p < .0005$], but the interaction between the two factors was not [$F(3,9) = 0.88$, $p = .49$].

The principal conclusion to be drawn from this research is that the asymmetry in changing-loudness aftereffects is reported in conditions in which the growing-louder effect in test stimuli is absent. Therefore, the asymmetry in changing-loudness aftereffects is independent of the growing-louder effect.

Physiological evidence is consistent with the auditory asymmetries reported here. The responses to changing sound level in cortical evoked potentials are greater for increasing sound level than for decreasing sound level (Arlinger & Jerlvall, 1979; Martin & Boothroyd, 2000; Wedel, 1982). Two studies concerned the responses of neurons in the cat's auditory cortex to diotic changing sound level and dichotic differences in changing sound level, simulating auditory motion-in-depth and azimuthal motion, respectively. The investigated neurons were each selective for one of the simulated motion directions. The biggest proportion of neurons was selective for diotic increasing sound level, simulating approach. Indeed, of all the neurons responding to diotic changing sound level, there were over six times as many that were selective for simulated approach as were selective for simulated recession (Stumpf, Toronchuk, & Cynader, 1992; Toronchuk, Stumpf, & Cynader, 1992).

That Neuhoﬀ (1998, 2001) links his evidence to approach of sound-sources implies that his effect and the present aftereffect share mechanisms. Hence, adaptation in the present study may be affected by Neuhoﬀ's effect: A relatively strong aftereffect (of increasing loudness) is

Figure 4. Mean aftereffect magnitudes. These are obtained by appropriate correction of the adaptation nulls by the nonadaptation nulls. See text for more details. Columns patterned “\\” represent increasing-loudness aftereffects. Columns patterned “//” represent decreasing-loudness aftereffects.

preceded by relatively weak adaptation (extrapolating from Neuhoﬀ's low judgments of decreasing loudness), whereas a relatively weak aftereffect (of decreasing loudness) is preceded by relatively strong adaptation (extrapolating from Neuhoﬀ's high judgments of increasing loudness). In the visual modality, it is normally believed that the opposite applies: Strength of aftereffect correlates positively with strength of adaptation (Reinhardt-Rutland, 1981). However, this does not necessarily apply to the aftereffect asymmetry concerning visual motion, where a preference for centrifugal motion may be reported for both adaptation and aftereffect (Reinhardt-Rutland, 1994; Scott et al., 1966). This would be consistent with a role for Neuhoﬀ's effect in perceiving the adapting stimuli of the present study.

In linking the auditory aftereffect asymmetry to auditory motion-in-depth, further evidence regarding the asymmetry in visual motion aftereffects is pertinent. Using a variety of measurement techniques, visual aftereffect asymmetries have varied from negligible (Hershenson, 1982, 1987) to cases in which the centipetal aftereffect is virtually nonexistent (Harris et al., 1981; Reinhardt-Rutland, 1994). The size of the visual aftereffect asymmetry depends on the degree to which the adapting motion approximates motion-in-depth (Reinhardt-Rutland, 1994). The auditory aftereffect asymmetry might likewise be enhanced by employing closer approximations to auditory motion-in-depth. Also, Neuhoﬀ's larger asymmetries are reported for stimuli with greater starting sound levels: He suggests that the latter property can be interpreted as a sound-source closer to the listener, so collision would be more imminent. Extrapolating, the auditory aftereffect asymmetry might be enhanced by employing higher overall sound levels for the stimulus sequence.

With respect to the growing-louder effect in the present study, this phenomenon might also reflect issues regarding motion-in-depth. However, the small or zero changes in sound level relating to it (Arlinger & Jerlvall, 1979; Rawdon-Smith & Grindley, 1935; Reinhardt-Rutland, 1996; Small, 1977) suggest another explanation. Steady stimuli are rare outside the laboratory, so listeners might not respond accurately to them. However, many sounds are percussive with fast rise and slow decay. The growing-louder effect may represent compensation for the reducing level of percussive sounds. Such an explanation referring to naturalistic sound production parallels that offered by Stecker and Hafer (2000) for their perceptual asymmetry in overall loudness of stimuli differing in rise and fall times; these authors invoked the reverberation that accompanies percussive sounds.

A final point concerns the relationship between the growing-louder effect and Canévet's (1986) illusion. The latter is opposite to the growing-louder effect. However, such a conclusion implies that judgments of changing loudness inherent in the growing-louder effect are intimately related to the overall loudness judgments required by Canévet; this cannot be assumed (Neuhoﬀ, 1999). Also, Canévet's stimuli were of longer duration

than those concerning the growing-louder effect. The putative relationship between the growing-louder effect and Canévet's effect requires further investigation before any conclusions may be drawn.

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