

Duration discrimination and subjective duration for ramped and damped sounds

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The perception of stimuli with ramped envelopes (gradual attack and abrupt decay) and damped envelopes (abrupt attack and gradual decay) was studied in subjective and objective tasks. Magnitude estimation (ME) of perceived duration was measured for broadband noise, 1.0-kHz, and 8.0-kHz tones for durations between 10 and 200 ms. Damped sounds were judged to be shorter than ramped sounds. Matching experiments between sounds with ramped, damped, and rectangular envelopes also showed that damped sounds are perceived to be shorter than ramped sounds, and, additionally, the reason for the effect is a result of the damped sound being judged shorter than a rectangular-gated sound rather than the ramped sound being judged longer than a rectangular-gated sound. These matching studies also demonstrate that the size of the effect is larger for tones (factor of 2.0) than for broadband noise (factor of 1.5). There are two plausible explanations for the finding that damped sounds are judged to be shorter than ramped or rectangular-gated sounds: (1) the abrupt offset at a high level of the ramped sound (or a rectangular-gated sound) results in a persistence of perception (forward masking) that is considered in judgments of the subjective duration; and (2) listeners may ignore a portion of the decay of a damped sound because they consider it an “echo” [Stecker and Hafter, *J. Acoust. Soc. Am.* **107**, 3358–3368 (2000)]. In another experiment, duration discrimination for broadband noise with ramped, damped, and rectangular envelopes was studied as a function of duration (10 to 100 ms) to determine if differences in perceived duration are associated with the size of measured Weber fractions. A forced-choice adaptive procedure was used. Duration discrimination was poorer for noise with ramped envelopes than for noise with damped or rectangular envelopes. This result is inconsistent with differences in perceived duration and no explanation was readily apparent. © 2001 Acoustical Society of America. [DOI: 10.1121/1.1372913]

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I. INTRODUCTION

Ramped sounds (gradual attack and rapid decay) and damped sounds (rapid attack and gradual decay) are perceived differently, even though the long-term spectra of these sounds are identical. A piano produces a damped sound when played in the normal manner, but playing a recording of piano music backwards produces ramped sounds. In other words, a ramped sound is simply a damped sound reversed in time. Despite this simple manipulation of the temporal envelope, the timbre of ramped and damped sounds is quite distinct.

Berger (1964) demonstrated that playing a recording of an instrument backwards not only reduces identification, but might actually shift the label to another category. An example of this shift in labeling is heard in a widely available auditory demonstration on compact disc (Houtsma *et al.*, 1987). In this recording, the notes from a Bach chorale played on a piano in the normal manner sound like notes produced by an accordion or organ when played backwards.

Patterson and his colleagues (Patterson, 1994a, b; Akeroyd and Patterson, 1995; Irino and Patterson, 1996; Lorenzi *et al.*, 1997, 1998; Patterson and Irino, 1998) have studied the perception of ramped and damped sounds to examine ways that the auditory system might code these sounds differently. They noted that concatenated ramped and concatenated damped sounds are perceived to have a continuous component and a transient component. Matching experi-

ments between ramped and damped low-frequency tones show that the half life of a damped sinusoid has to be 4 times greater than that of a ramped sinusoid for the continuous segments to be perceived of equal strength (i.e., loudness) (Patterson and Irino, 1998). The same experiment with noise carriers showed that the perceptual asymmetry was about half that of low-frequency tones.

Stecker and Hafter (2000) measured the loudness of sounds with single-cycle envelopes with ramped and damped characteristics. On average, sounds with ramped envelopes were judged louder than sounds with damped envelopes. No statistical differences were noted for sinusoidal or broadband noise carriers.

Given this asymmetry in the strength of the continuous component for streams of ramped and damped sounds (Patterson and Irino, 1998) and in the loudness of single cycles of ramped and damped sounds (Stecker and Hafter, 2000), we decided to determine whether the temporal asymmetry in the acoustic waveform affected the perceived duration of single-cycle ramped and damped sounds.

The motivation for measuring subjective duration of ramped and damped sounds is a result of informal observations by the first author that ramped sounds are perceived to be longer than damped sounds. These observations were made while playing an ASA demonstration on compact disc (Houtsma *et al.*, 1987) of a recording of a Bach chorale

played forward and backwards during a hearing science class at the University of Minnesota.

II. EXPERIMENT 1: SUBJECTIVE DURATION OF RAMPED AND DAMPED STIMULI

A. Subjects

The listeners were young adults with hearing sensitivity of 15 dB HL or better at octave frequencies between 0.25 and 8.0 kHz. Listeners were paid for their participation. Initially, 12 listeners participated in the 1.0-kHz condition. These data were collected for a conference presentation along with intensity discrimination data for ramped and damped sounds (Schlauch *et al.*, 1998). At a later date, four additional listeners were recruited for the 1.0-kHz condition, and a second and third group of 16 listeners participated in the broadband-noise and 8.0-kHz conditions, respectively. Seven listeners from the group that judged 1.0-kHz tones also judged the noise stimulus, whereas five other listeners from the group that judged 1.0-kHz tones also judged 8.0-kHz tones.

B. Stimuli

Sounds were generated with a custom-designed 16-bit digital-to-analog converter. The sampling rates were 20 kHz for a broadband noise stimulus and a 1.0-kHz tone and 26 kHz for an 8.0-kHz tone. Antialiasing filters were set to 8.0 and 12.0 kHz for the 20.0 and 26.0-kHz sampling rates, respectively. Damped sounds were generated using a simple exponential decay with a time constant set to one-fifth the signal duration

$$x(t) = e^{(-5t/T)} w(t) \quad (1)$$

where t is time in s, w is a rectangular-gated noise or tone, and T is the duration of w . Ramped sounds were generated by simply reversing the order of the samples in the array for the damped sound prior to output. Stimulus durations were 10, 25, 50, 100, and 200 ms.

Our stimuli differ from those used by Patterson and his colleagues. Ramped and damped stimuli in Patterson and his colleagues' experiments were concatenated sequences of ramped or damped sounds with the amount of decay of damped sounds being limited by the onset of the envelope for the next sound in the sequence. For example, the 16-ms (half-life) damped stimulus in Irino and Patterson (1996) decayed 18.8 dB during its repeating, 50-ms envelope. By contrast, our 100-ms stimulus, with a half-life of 13.9 ms, decayed 42 dB over its duration, as did all of our stimuli. Our stimulus durations of 10, 25, 50, 100, and 200 ms have corresponding half-lives of 1.4, 3.5, 6.9, 13.9, and 27.7 ms, respectively.

C. Procedure

Before data collection began, potential subjects were screened with a magnitude estimation (ME) of line-length task. This line-scaling task was implemented to ensure subjects understood the instructions for the ME task and could use numbers appropriately. Subjects judged the length of 5

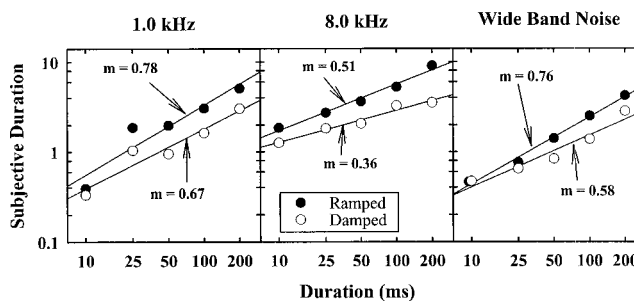


FIG. 1. ME of subjective duration for ramped (closed circles) and damped (open circles) sounds. The 1.0-kHz tones, 8.0-kHz tones, and broadband noise are shown in the left, middle, and right panels, respectively. Data points represent geometric means of assigned number for 16 listeners.

lines ranging in length from 0.64 to 447.35 cm. The lines were five pieces of tape located either on the wall of the laboratory or on the wall in the hallway outside the laboratory. Of the 51 subjects screened in this manner, only 3 were dropped from the study. These subjects either used negative numbers ($n=1$) or failed to use fractions or decimals (many lines were labeled with a "1" even though they differed by a large amount in length) ($n=2$).

After completing the line-length screening test, subjects participated in the ME of duration task. Subjects assigned numbers to the stimuli that corresponded to their subjective impression of the duration. Numerical references or standards were not provided.

Subjects listened individually to stimuli through a headphone (Telephonics, TDH-39) during a single session while seated in a sound-isolated room. Tones were 70-dB SPL (peak), whereas the noise stimulus was 80 dB SPL. Stimulus type (ramped or damped) and durations were selected randomly within a session. There was a 5-s interval between successive stimuli. A 35-ms duration warning light appeared just prior to the presentation of a stimulus.

D. Results

Figure 1 shows subjective duration (assigned number) as a function of physical duration for the three different stimuli. The data are summarized by power functions of the form,

$$D = kT^\beta, \quad (2)$$

where D is subjective duration, T is the overall stimulus duration, and β and k are fitting constants. Power functions show the same general trend for each stimulus type. For all three stimuli, the slope of the function is steeper for ramped than for damped stimuli. On average, ramped stimuli were judged to be roughly 1.5 to 2.0 times longer than damped stimuli of the same physical duration. A Wilcoxon signed-ranks test (Siegel and Castellan, 1988) was used to examine the significance of the ramped–damped difference in subjective duration. For each ranked-sign significance test, comparisons were made for ramped and damped judgments within a subject for all 16 subjects and within duration for all 5 durations (a total of 80 pairs). The logarithm of the scaled values was used. For 1.0-kHz tones, ramped was judged longer than damped 55 times, damped was judged longer than ramped 13 times, and there were 12 ties ($z=5.0$; p

$<0.000\,000\,5$). For 8.0-kHz tones, ramped was judged longer than damped 58 times, damped was judged longer than ramped 7 times, and there were 15 ties ($z=6.0$; $p < 0.000\,000\,5$). For wideband noise, ramped was judged longer than damped 50 times, damped was judged longer than ramped 14 times, and there were 16 ties ($z=3.66$; $p = 0.000\,25$). These results are significant at the 0.05 level after a Bonferroni correction (Hays, 1981) with $n=22$, the number of significance tests in this study.

E. Discussion

The differences in subjective duration observed in this study may be a consequence of a cognitive effect described by Stecker and Hafter (2000) to explain loudness differences between sounds with ramped and damped envelopes. They note that sounds with damped envelopes are perceived to have two distinct segments. Many naturally occurring sounds have the envelope of a damped sound and the perceptually different segments may represent direct and reverberant sound. They assume that direct sound provides information about the sound source and reverberant sound provides information about the listening environment. In judging the loudness of a damped sound presented in isolation, listeners may ignore the decay portion of the sound (i.e., the echo). Stecker and Hafter (2000) argue that this idea is consistent with their loudness data, and the same explanation could account for our findings that ramped sounds are judged to be longer than damped sounds.

Differences in subjective duration between ramped and damped sounds may be a result of physiological coding rather than a cognitive effect. Patterson and Irino (1998) and Stecker and Hafter (2000) have applied the “auditory image model” (AIM) to account for differences in the loudness of ramped and damped sounds. AIM models the auditory periphery, including basilar-membrane filtering, compression, and the neural response pattern (Patterson *et al.*, 1995). AIM responds asymmetrically to ramped and damped sounds. The output waveform for ramped sounds is extended in time because these sounds end abruptly, resulting in a ringing of the filter. By contrast, the abrupt onset of a damped sound results in a ringing of the filter which, when added out of phase to the decay portion of the damped sound, results in a more rapid decay of the filter output (Stecker and Hafter, 2000). This analysis is qualitatively consistent with the finding that ramped sounds are perceived to be longer than damped sounds. AIM also predicts that ramped sounds are louder than damped sounds, but this model incorrectly predicts that the loudness difference becomes smaller for high-frequency sounds (Stecker and Hafter, 2000). Although AIM does not predict all of the behavioral results, neural processing in the auditory periphery likely plays an important role in the perceptual differences between ramped and damped sounds. If the effect were entirely cognitive and a result of listeners ignoring the “echo” portion of a damped sound, the sequences of ramped and damped sounds used by Patterson and his colleagues would not show a loudness difference.

III. EXPERIMENT 2: DURATION MATCHING

The results of experiment 1 obtained with an ME procedure show that, on average, ramped sounds are judged to be about twice as long as damped sounds of the same physical duration.

A matching procedure provides an alternative means of quantifying the relative subjective impressions among different sounds. Matching functions have been derived from ME obtained for long-duration tones in quiet and in noise as a function of tonal level. These interpolated matching functions have been found to be virtually indistinguishable from the matching functions obtained directly from having listeners match the loudness of a tone presented alternately to an ear in quiet and an ear in background noise as a function of level (Hellman and Zwislöcki, 1968).

On other occasions the results of matching experiments do not agree with those of scaling (Schlauch, 1992; Botte *et al.*, 1982). Experiments where the results of matching and scaling do not agree involve judgments requiring attention. Given that a cognitive effect may be responsible for the duration and loudness differences between sounds with ramped and damped envelopes, matching and scaling procedures may not agree in this case as well. More specifically, in a natural context, as in the ME experiment, listeners may have ignored the echo portion of the damped stimulus, but in the matching task, where standard and comparison stimuli can be compared in short-term memory repeatedly, the echo may be considered in judgments of duration. To test this hypothesis, duration-matching functions were obtained and the results were compared with those of the scaling data in experiment 1.

A. Subjects

Three subjects between the ages of 25 and 30 years old participated in this study. They had normal hearing (15 dB HL or better) at octave frequencies between 0.25 and 8.0 kHz.

B. Stimuli

The stimuli were 1.0-kHz tones and broadband noise. Ramped and damped stimuli were digitally generated using the methods described in experiment 1. A rectangular-gated stimulus, with a negligible rise and fall time, was also used in this matching task.

C. Procedure

Subjects listened to a standard stimulus followed by a comparison stimulus. For each judgment, the standard stimulus was fixed in duration. The initial duration of the comparison stimulus was selected at random from a wide range of durations. A slide controlled the duration of the comparison stimulus. The subject’s task was to adjust the slide until the two stimuli were perceived to have the same duration. The standard stimulus was presented first and, following a 500-ms interstimulus interval, the comparison stimulus was presented (for one condition, rectangular vs rectangular, the standard followed the comparison for half of the matches and the comparison followed the standard for the remaining

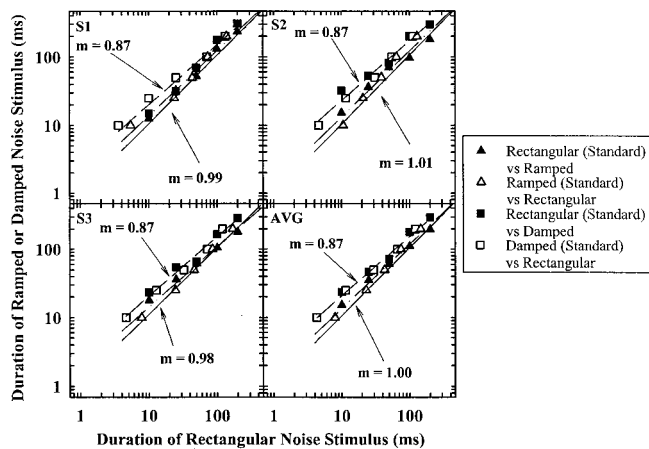


FIG. 2. Duration matching between a rectangular-gated noise and a ramped or damped noise. The dashed line is fitted to all of the data representing matches between damped noise and rectangular-gated noise. The dashed-dot line is fitted to the data representing matches for ramped and rectangular noise. The solid line represents a linear regression to data for a rectangular-rectangular condition for broadband noise (the actual data for this condition are shown in Fig. 4).

matches). The stimuli were presented continuously with about 1 s between the presentation of each standard and comparison pair. The duration of the comparison stimulus was changed during the intertrial interval, showing subjects the immediate impact of their adjustments. Subjects were instructed to bracket the point of subjective equality. When subjects perceived the durations of the standard and comparison to be equal, they pushed a button that recorded the value of the comparison duration in the computer.

Data for noise and for 1.0-kHz tones were collected for the following conditions: rectangular vs rectangular, rectangular vs damped, rectangular vs ramped, and ramped vs damped. For alternate runs, the sequence of the stimuli was reversed. Ten matches were completed by each subject for each condition. For example, in the condition comparing ramped vs damped tones, five matches were completed for the situation where the ramped tone was the standard and five were completed where the damped tone was the standard. The upper end of the range of possible comparison durations was jittered following each adjustment. A lower range offered durations from 1 to 256 ms. The upper limit varied for each adjustment between 171 and 256 ms. A higher range offered 100 to 610 ms. The upper limit for this higher range varied between 482 and 610 ms for each adjustment. Based on pilot data, the lower and upper ranges were selected for a particular condition so that the adjustments fell well within the range of possible values.

D. Results

Figure 2 illustrates data for the matching task for rectangular vs damped noise and rectangular vs ramped noise for three subjects (S1, S2, and S3) and, in the lower-right panel, the average data for these three subjects. Solid lines in each panel represent a linear regression to the matches for the rectangular vs rectangular condition. All of these lines have a slope close to 1.0 and with nearly equal values on the ordinate and abscissa for any given point on the line. For all

subjects, the dashed line fitted to the damped vs rectangular condition (squares) falls above the slope-of-one line representing equal physical durations for subjective equality. This shows that the physical duration of the noise with the damped envelope was longer than the physical duration of the noise with the rectangular envelope when the durations were perceived to be equal. By contrast, the data for the ramped vs rectangular condition fall just above and in the vicinity of the slope-of-one line representing equal physical durations. The significance of these differences was evaluated with the Wilcoxon signed-ranks test. For each significance test, the sign of each match was determined based on which stimulus in the pair (standard and comparison) was judged to be longer. Ranked pairs were evaluated across subjects and across durations. These results, shown in Table I, indicate that broadband noise with damped envelopes or ramped envelopes is perceived to be statistically significantly shorter than noise with rectangular envelopes. A small bias in the rectangular-rectangular condition resulted in adjustments that were significantly larger than the standard when the second observation interval was adjusted by the listener.

The same pattern holds in Fig. 3, where duration-matching results are shown for tones with rectangular envelopes compared with those with ramped or damped envelopes. Significance tests, shown in Table I, indicate that tones with damped envelopes are perceived to be statistically significantly shorter than tones with rectangular envelopes, but the difference between ramped and rectangular envelopes did not reach significance.

Figure 4 illustrates the results of the duration-matching task for damped vs ramped noise. Table I shows that noise with damped envelopes is judged to be statistically significantly shorter than noise with ramped envelopes. That is, the damped noise was always adjusted to a longer duration than the ramped noise for subjective equality. The same result holds for tones as shown in Fig. 5. Table I shows that this difference is statistically significant as well.

A comparison was made between the duration-matching data and the ME data for noise and tones with ramped and damped envelopes. First, equal subjective durations were derived from the ME data for the ramped and damped noise in Fig. 1. For each datum in Fig. 1. (for the group data for 1.0-kHz tones and broadband noise), an equal subjective duration was interpolated from a line drawn between two adjacent points for the corresponding condition.¹ For example, if a ramped datum was used as a reference, the equal subjective duration was interpolated using a line drawn between two damped data points in the vicinity of the equal subjective duration. These interpolated “matches” from the ME data along with group data for the duration-matching procedure (individual data points from Fig. 5 for the average data) are shown in Fig. 6 in the upper panels and lower panels, respectively. To clarify the difference in duration between sounds with ramped and damped envelopes at equal subjective durations, the ratio of the durations for these sounds (damped/ramped) at equal subjective duration are plotted as a function of the duration of the ramped stimulus.

It is clear from Fig. 6 that the two experimental procedures produced similar results. This finding is reassuring be-

TABLE I. Various conditions from the matching experiment evaluated for statistical significance using the Wilcoxon signed-ranks test. Rectangular (Rect) vs rectangular is listed twice. For the first one listed the first observation interval was adjusted by the listener, whereas for the other measure the second interval was adjusted. Bold-faced p values are significant at the 0.05 level after considering a Bonferroni correction based on 22 tests.

Stimulus	Standard	Comparison	Standard perceived longer	Comparison perceived longer	Tie	z	p
Noise							
	Rect	Damp	68	1	1	6.97	<0.000 000 5
	Damp	Rect	1	74	0	7.52	<0.000 000 5
	Rect	Ramp	56	19	0	3.30	0.000 9
	Ramp	Rect	13	58	4	5.80	<0.000 000 5
	Rect	Rect	36	38	1	1.50	0.116
	Rect	Rect	55	17	3	3.88	0.000 1
	Ramp	Damp	60	14	1	5.94	<0.000 000 5
	Damp	Ramp	8	67	0	6.90	<0.000 000 5
Tone							
	Rect	Damp	69	6	0	7.12	<0.000 000 5
	Damp	Rect	3	72	0	7.49	<0.000 000 5
	Rect	Ramp	44	29	2	1.56	0.119
	Ramp	Rect	27	45	3	1.98	0.046
	Rect	Rect	48	18	9	3.67	0.000 2
	Rect	Rect	29	40	6	1.71	0.085
	Ramp	Damp	69	5	1	7.21	<0.000 000 5
	Damp	Ramp	2	72	1	7.45	<0.000 000 5

cause different nonsensory factors can influence the data from ME procedures and matching procedures. For instance, ME procedures can be influenced by an observer's nonlinear use of numbers (e.g., Schneider *et al.*, 1974). For the matching procedure, the possibility exists that listeners were adjusting the comparison stimulus until a rhythmic pattern was produced by the entire stimulus sequence (the two observation intervals separated by a short delay repeated after a longer delay).

Figure 6 also shows that the difference in subjective duration between ramped and damped sounds is larger for tones than for noise. A Wilcoxon signed-ranks test was run on the individual data for the matching procedure to assess the significance of this difference. Within a subject and for each duration, the number of cases where the ratio of

damped/ramped at equivalent subjective duration for tones was larger than the ratio of damped/ramped at equivalent subjective duration for noise was evaluated. When the ramped stimulus was the standard, the ratio for tones was larger than for noise 60 times, the ratio for noise larger than for tones 14 times, and there was 1 tie ($z = -5.94$; $p < 0.000 000 5$). When the damped stimulus was the standard, the ratio for tones was larger than for noise 73 times and the ratio for noise was larger than for tones 2 times ($z = 7.5$; $p < 0.000 000 5$).

E. Discussion

The results of the matching experiment are in agreement with those of magnitude estimation. Both experiments found

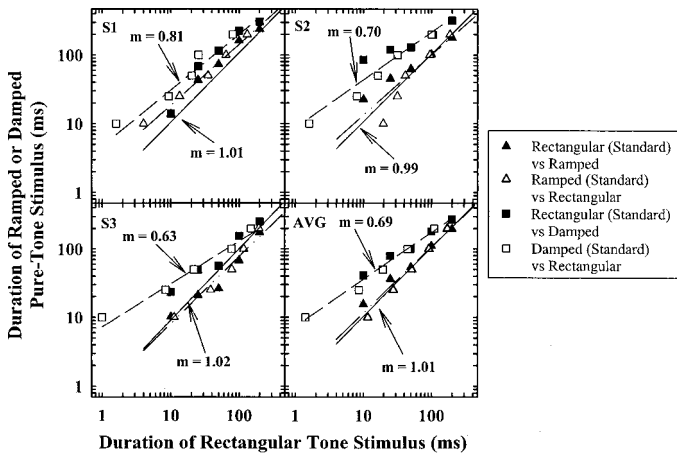


FIG. 3. Duration-matching behavior between ramped tones and rectangular-gated tones and damped tones and rectangular-gated tones. The data representation is identical to that of Fig. 2.

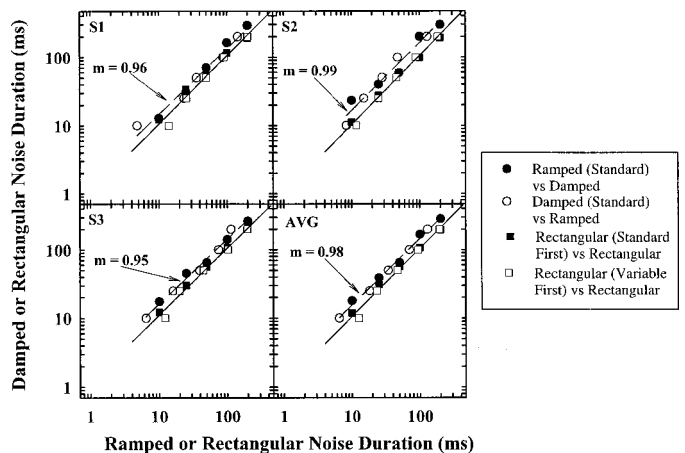


FIG. 4. Duration-matching data between ramped noise and damped noise along with data for a rectangular-rectangular control condition. The dashed line and solid line in this figure represent least-squares regression to all of the matches between ramped and damped noise and between rectangular-rectangular noise, respectively.

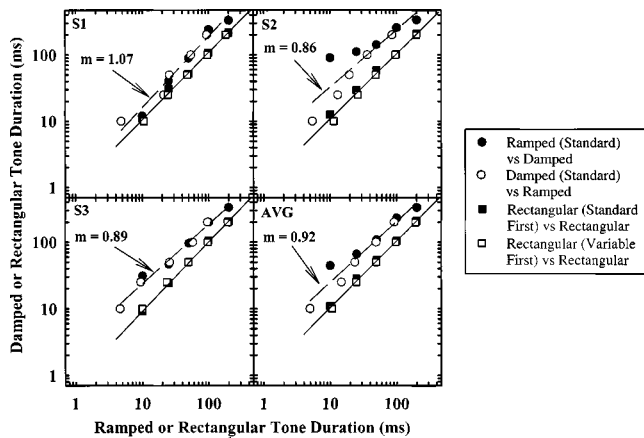


FIG. 5. Duration matching between ramped, 1.0-kHz tones and damped, 1.0-kHz tones. Also shown is a rectangular–rectangular control condition for 1.0-kHz tones. Data are represented in an identical manner as in Fig. 4 (but for 1.0-kHz tones instead of noise).

that sounds with damped envelopes are perceived to be shorter than sounds with ramped envelopes. These results are qualitatively consistent with the loudness data for ramped and damped stimuli and Stecker and Hafter's (2000) idea that listeners ignore the echo portion of a sound with a damped envelope. In other words, ignoring the echo renders a sound softer and shorter in duration than it would be if the echo were considered in the judgment. The finding of the matching experiment that sounds with damped envelopes are judged to be shorter than sounds with ramped and rectangular-shaped envelopes lends further support to this idea. A larger ramped–damped difference in the ME experiment than the matching experiment would have provided stronger support for Stecker and Hafter's (2000) cognitive explanation for this phenomenon, but the absence of a difference across experiments does not rule it out.

A more detailed comparison of the loudness and subjective duration of sounds with ramped and damped envelopes

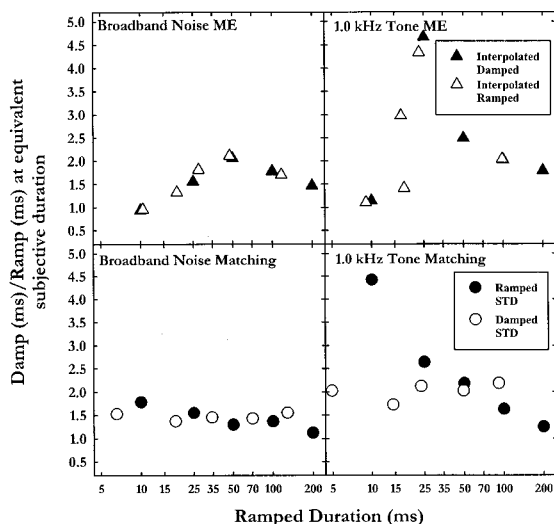


FIG. 6. The ratio of physical durations (damped/ramped) at equal subjective durations as a function of duration of the ramped stimulus. Data shown are from the matching experiment (lower panels) along with interpolated values from the ME experiment (upper panels). Data for noise (left panels) and 1.0-kHz tones (right panels) are shown for each stimulus type.

shows that these behaviors may be correlated for stimulus carrier type. Patterson and Irino (1998) found that noise produced a smaller loudness difference than tones. We found that differences in subjective duration were smaller for noise than for tones. By contrast, Stecker and Hafter (2000) reported no statistical difference in the loudness of noise with ramped or damped envelopes. Our results are consistent with those of Patterson and Irino (1998), but there is no obvious explanation for the difference between these stimulus carrier types in their subjective durations or loudness.

The matching experiment also demonstrates that the reason damped sounds are judged to be shorter than ramped sounds is due to an underestimation of the duration of the damped sound rather than an overestimation of the duration of the ramped sound. This result agrees with a recent finding by Grassi and Darwin (in press). They found that ramped sounds with durations between 250 and 1000 ms were about 30 percent longer than damped sounds for a number of stimuli: 1.0-kHz tones, a complex tone, and a vowel. This finding agrees favorably with our results for 200 ms, the longest duration we tested. Grassi and Darwin's (2001) results also show a trend for the ramped–damped difference to decrease as duration increases.

IV. EXPERIMENT 3: DURATION DISCRIMINATION AS A FUNCTION OF DURATION

Experiments 1 and 2 demonstrate that ramped sounds are perceived to be longer than damped sounds of the same physical duration. This prompted us to wonder whether the subjective difference in duration would be reflected in a difference in the just-noticeable difference (jnd) for duration. That is, would the damped stimuli, which are perceived to be shorter in duration, have a smaller jnd for duration in absolute terms than the ramped stimuli and/or the rectangular stimuli? This might be predicted on the basis of the fact that the jnd for duration is typically 10% of the duration of the stimulus for long duration stimuli (Abel, 1972).

To date, the only discrimination measurements for stimuli with asymmetric modulator shapes (Akeroyd and Patterson, 1995, 1997) have measured discrimination for gross changes in envelope shape (e.g., discrimination of ramped from damped).

A. Subjects

Four young adults with hearing within normal limits between 0.25 and 8.0 kHz participated. Subjects were paid for their participation.

B. Stimulus

A broadband noise was used to avoid spectral cues. The noise was generated using the same method as described in experiment 1. The noise level was 80 dB SPL (peak).

C. Procedure

Subjects listened individually in a sound-treated room through an earphone. A 3-AFC adaptive procedure that targeted 70.7% correct was used (Levitt, 1971). Two of the three intervals contained the standard duration (T) that was

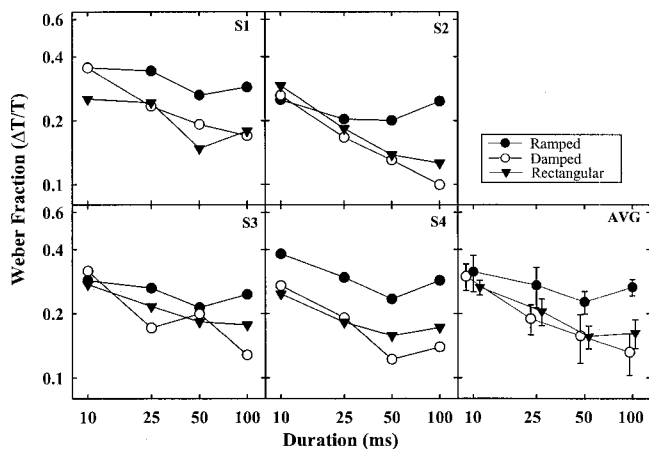


FIG. 7. Duration discrimination for ramped noise (closed circles), damped noise (open circles), and rectangular-gated noise (triangles) as a function of duration. Data are for four listeners (S1, S2, S3, and S4) and for the group (AVG). The abscissa values for the average condition were adjusted slightly for ease of viewing.

fixed within each block of 80 trials. The remaining interval of the 3-AFC task contained the standard duration plus an increment in duration ($T + \Delta T$).² The position (one, two, or three) of the interval containing the increment was assigned randomly. The listeners' task was to select the interval thought to contain the increment by pushing a button corresponding to that interval. Correct-answer feedback was given following each trial.

After two consecutive correct responses, the duration of the increment was decreased. Each incorrect response resulted in an increase in the duration of the increment. Based on pilot data, the starting duration for the increment for a block of trials was set about a factor of 4 above the expected threshold. For the first two reversals, the duration of the increment changed by a factor of 2. For subsequent reversals, the duration of the increment was changed by a factor of the square root of 2. For each block of 80 trials, threshold was calculated based on the average of reversals in duration that occurred within that block. Average thresholds for each listener were based on the mean threshold for five blocks of trials.

D. Results

Figure 7 illustrates just-noticeable differences in duration as a function of duration for the four listeners as well as the average group data. All subjects show the same pattern of results. Notably, the Weber fractions for duration for rectangular and damped noise are nearly identical when evaluated for the same physical duration. By contrast, the Weber fractions are larger by about a factor of 2 for ramped noise for durations between 25 and 100 ms. An examination of data from Abel's (1972) experiment that presumably used rectangular-gated tones and noise bands shows results nearly identical to our results for rectangular-gated noise and damped noise. The Wilcoxon signed-ranks test showed that Weber fractions for duration for stimuli with ramped envelopes are statistically significantly different than those with rectangular ($z = 6.29$; $p < 0.000\,000\,5$) or damped ($z = 5.98$; $p < 0.000\,000\,5$) envelopes. The Weber fractions for

rectangular-gated noise and damped noise were not significantly different ($z = 0.566$; $p = 0.571$).

E. Discussion

These data suggest that there is not close coupling between subjective duration and duration discrimination. The perceived duration of noise with ramped and rectangular envelopes is judged to be longer than that of noise with damped envelopes. By contrast, Weber fractions are larger for noise with ramped envelopes than for noise with damped or rectangular envelopes.

V. GENERAL DISCUSSION

Damped sounds are perceived to be shorter than ramped sounds of the same duration. We found this result using two methods: ME and duration matching. The average data from the duration-matching experiment summarize the main effects from these studies. Duration matches between ramped and damped tones show that damped tones have to be a fairly constant factor of about 2.0 times the duration of a ramped sinusoid to produce a match (Fig. 5). When ramped and damped broadband noises are matched (Fig. 4), damped noise differs from ramped noise by a fairly constant factor of 1.5, a smaller effect than is observed for tones. Figure 3, which illustrates matches between ramped and rectangular-gated tones and damped and rectangular-gated tones, shows that the size of the effect is attributed to the damped sinusoid. That is, the rectangular-gated sinusoid and the ramped sinusoid are roughly equal for all durations. By contrast, the damped sinusoid differs from the rectangular-gated sinusoid by about a factor of 4.0 for short durations and this factor diminishes with duration until it reaches a factor of 1.5 for the longest duration examined (200 ms). Figure 2, which illustrates the corresponding matches for a noise carrier, shows the same finding but with a smaller effect. Namely, the ramped–damped difference is due to the damped noise differing from the rectangular-gated noise and ramped noise.

Two explanations come to mind to explain the finding that damped sounds are perceived to be shorter than ramped and rectangular-gated sounds. First, listeners may perceive the damped sound as sound source and its echo (Stecker and Hafter, 2000). The echo may not be considered as a part of the sound when judging its duration, or, as Stecker and Hafter report, its loudness. An alternative explanation for the difference in perceived duration for sounds with ramped and damped envelopes may be related to the asymmetrical nature of the temporal window. The temporal window has a gradual slope for times before its center than for times after its center, which accounts for the main features of forward and backward masking (Moore *et al.*, 1988). For modeling judgments of subjective duration, the temporal masking pattern for a stimulus, which includes segments of forward and backward masking, has proved important. Fastl (1977) found subjective duration grows at a slower rate than physical duration for rectangular-gated noise and that this difference can be accounted for by the temporal masking patterns for these sounds. The subjective duration for a given stimulus was determined by observing the times where the temporal masking pattern dropped to a critical value close to detection

threshold in quiet. These critical times mark the beginning and end of a stimulus for calculating subjective duration, and forward masking plays a large role in explaining discrepancies between physical duration and subjective duration for the rectangular-gated noise bands used in Fastl's (1977) study. Applied to sounds with ramped and damped envelopes, the abrupt offset of sounds with ramped envelopes would result in more forward masking than for sounds with damped envelopes. If this forward masking represents a persistence of perception, as assumed by Fastl (1977), the difference in perceived duration between ramped and damped sounds is qualitatively consistent with the asymmetrical shape of the temporal window that causes this forward masking.

The observed pattern of duration discrimination is difficult to explain based on the results for the subjective duration experiments. Noise with rectangular envelopes is judged to be about equal in duration with sounds with ramped envelopes, but the ramped condition produces much poorer discrimination performance than the rectangular condition. Noise with damped envelopes is perceived to be shorter than noise with rectangular or ramped envelopes, but discrimination performance is nearly identical for damped and rectangular noises. These results suggest that subjective duration and duration discrimination are not related for these stimuli.

The abrupt onset and offset of a stimulus might provide the decision processor a possible cue for duration discrimination. Abrupt changes in stimulus level would result in synchronous neural firing when these changes occur. From this, one would predict that rectangular envelopes would result in better duration discrimination than either ramped or damped envelopes. Given that damped envelopes yielded performance comparable to those of rectangular envelopes (rather than ramped and damped being roughly equal and poorer than rectangular), an explanation for the duration discrimination results remains a puzzle.

This difference in duration discrimination for noise with ramped and damped envelopes is in contrast to the result for intensity discrimination for 1.0-kHz tones (Schlauch *et al.*, 1998), where a difference was not observed. This finding may be due to peak amplitude of the waveform dominating the response for intensity discrimination for tones.

VI. CONCLUSIONS

- (1) Sounds with damped envelopes are perceived to be shorter in duration than sounds with ramped envelopes. This is true for ME and duration-matching tasks.
- (2) The difference in subjective duration between sounds with ramped envelopes and sounds with damped envelopes is larger for 1.0-kHz tones than for noise.
- (3) Sounds with ramped envelopes have larger Weber fractions for duration than sounds with damped envelopes for identical durations for durations between 25 and 100 ms. This finding is not consistent with differences in perceived duration.

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¹The lines drawn between two adjacent data points for these interpolations make minimal assumptions about the overall shape of the function representing subjective duration as a function of duration. This would not be the case if we used the linear regression fitted to the entire data set. A consequence of this procedure is that variability in the average judgments for each datum is more likely to affect the interpolated values than a regression analysis involving the entire data set.

²The increment in duration was not appended directly to the standard. Instead, the total duration of the increment and standard ($T + \Delta T$) was calculated and this new value of T was used to generate the stimulus using Eq. (1).

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