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# DURATION SENSATION OF THE SIMULATED ENVIRONMENTAL NOISE IN RELATION TO ITS AUTO-CORRELATION FUNCTION

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This is the report of an investigation into the sensation of the duration of environmental noise simulated by mixing a pure tone (1 kHz) with white noise. In paired-comparison tests five subjects judged whether simulated-environmental-noise stimuli were longer or shorter than a standard pure-tone stimulus with the same sound pressure level and rise–fall time. In experiment 1, the attenuation level ($\phi_m$) of the envelope of the normalized autocorrelation function (ACF), i.e., the repetition of similar features in the stimulus, was varied by changing the relative amplitude of the pure tone and white-noise components. Results show that the sensation of duration of the white-noise stimulus with a small value of $\phi_m$ is significantly ($p < 0{\cdot}05$) longer than a pure-tone stimulus with a higher value of $\phi_m$. Results of experiment 2 showed that the duration of pure-tone stimuli with lower frequencies as presented by the $\tau_1$ extracted from the ACF are perceived as being longer ($p < 0{\cdot}01$) than those of pure-tone stimuli with higher frequencies.



## 1. INTRODUCTION

The human experience of the time duration of a sound signal has been studied from various points of view. Gyuau [1] found that estimates of time depend on many variables, such as the number, type, and intensity of sound stimuli presented and the subject's expectations, levels of attention, and interest. Woodrow [2] described his data in terms of "Vierordt's law": that shorter time intervals are overestimated and longer intervals are underestimated. He also described an indifferent range in which intervals are neither overestimated nor underestimated. Frankenhaeuser [3] presented clicks as acoustical stimuli, at various intervals from 13 to 72 s and sequenced at various speeds, and found that estimates of duration increased with the speed at which the clicks were sequenced. Fraisse [4] found that an interval during which signals are presented at 5/s is estimated to be longer than an interval in which they are presented at 10/s. Michon [5] described the variation of subjective duration with the type and amount of activity in which the subjects are engaged. Austin and Marilyn [6] used auditory clicks at frequencies between 0 and 10/s and found that the magnitude of the frequency effect was a monotonically decreasing function of duration. Vorn [7] found that the apparent durations increase with the rate of information transmission and that when the subject has to behave actively, i.e., by translating the stimuli into binary choices, the experienced duration decreases with the number of processed bits. Ando [8] found that time passes more quickly when it is filled with noise than when it is silent and explained this to an internal clock inhibited by noise. Zakay *et al.* [9] found that subjective estimates of time were a decreasing function of task difficulty, and that estimates of the durations of "empty" intervals were longer than those of the "filled" intervals. Subjects produced the longest estimates of duration when the external tempo was fastest and produced shorter estimates when the external tempo were. Pastor and Artieda [10] stated that the internal clock can be imagined to be an oscillating circuit, with a single pacemaker neuron or a group of pacemaker neurons, that generates rhythmical electromagnetic activity the brain uses in the temporal analysis of information. Ando and Ando [11] found that the subjective duration of music with a slow tempo is longer than that of music with a fast tempo.

Given this background, we thought that the effect of the environmental noise on the sensation of duration should be studied. In the work reported in this paper, environmental noise was simulated by mixing a pure tone and white noise (such a mixture is perceived to be similar to the noise of an aircraft landing). Environmental noise simulated this way can be easily characterized in terms of the ratio of the two sound pressure levels (SPLs) and the frequency of the pure tone.

This study is an investigation of the way that the sensation of duration of simulated environmental noise depends on certain factors extracted from the ACF of that noise ($\Phi_0$: energy of sound stimulus; $\tau_1$: period of the first peak; $\phi_m$: amplitude of peaks, "at the *m*th peaks where" $m = 1, 2, 3, \dots$). Two experiments were conducted with two parameters: $\phi_m$ in experiment 1 and $\tau_1$ in experiment 2. The $\phi_m$ was varied by changing the ratio of sound pressure levels (SPLs) of the pure tone and the white noise, and $\tau_1$ was varied by changing the frequency of the pure tone.

## 2. STIMULI AND SUBJECT

### 2.1. STIMULI

In experiment 1, values for the peak amplitudes ($\phi_m$) of the ACF envelope were extracted by analyzing the short-term moving ACF of each of five stimuli (5 s each) over a constant integration interval of $2T = 2$ s, as shown in Figure 1. The stimuli were recorded in a soundproof chamber through an A-weighted filter. Note that the changes of the value of $2T$ have no effect on $\phi_m$ in this investigation. Such values of $\phi_m$ are extracted as constant (see Appendix A). This means the envelope of ACF on a logarithmic scale is almost parallel to the horizontal axis ($\phi_m = 0$ dB line for pure tones). For white noise, however, the values of $\phi_m$ is not parallel to the zero level. Values were measured for an 80 dB(A) pure tone: $\phi_m = 0{\cdot}00$ dB; an 80 dB(A) pure tone plus 59 dB(A) white noise: $\phi_m = -0{\cdot}06$ dB; an 80 dB(A) pure tone plus 64 dB(A) white noise: $\phi_m = -0{\cdot}23$ dB; an 80 dB(A) pure tone plus 69 dB(A) white noise: $\phi_m = -0{\cdot}64$ dB; and for 80 dB(A) white noise alone (see Table 1).

For the same set of stimuli the calculated peak amplitudes of the ACF envelopes were, respectively, 0·00, − 0·08, − 0·25 and − 0·75 dB (these values were calculated as described in Appendix A). The values of $\phi(\tau)$ given by equation (3) in Appendix A, were, respectively, 0·99, 0·97 and 0·92 for three mixed stimuli in which $\phi_m = 10\log_{10}\phi(\tau)$. The measured and calculated values of $\phi_m$ for the first four of these stimuli (i.e., excluding the value for white-noise stimulus) are plotted in Figure A1 of the appendix and can be seen to be very close to a straight line.

In experiment 2, six pure tone stimuli with different values of $\tau_1$ were extracted from the ACF (0·125, 0·25, 0·5, 1·0, 2·0 and 4·0 kHz frequencies) and used in a paired-comparison test.

The rise and fall times of all stimuli in both experiments were 1 ms. The times were defined as the time taken to reach − 3 dB different from the steady level.

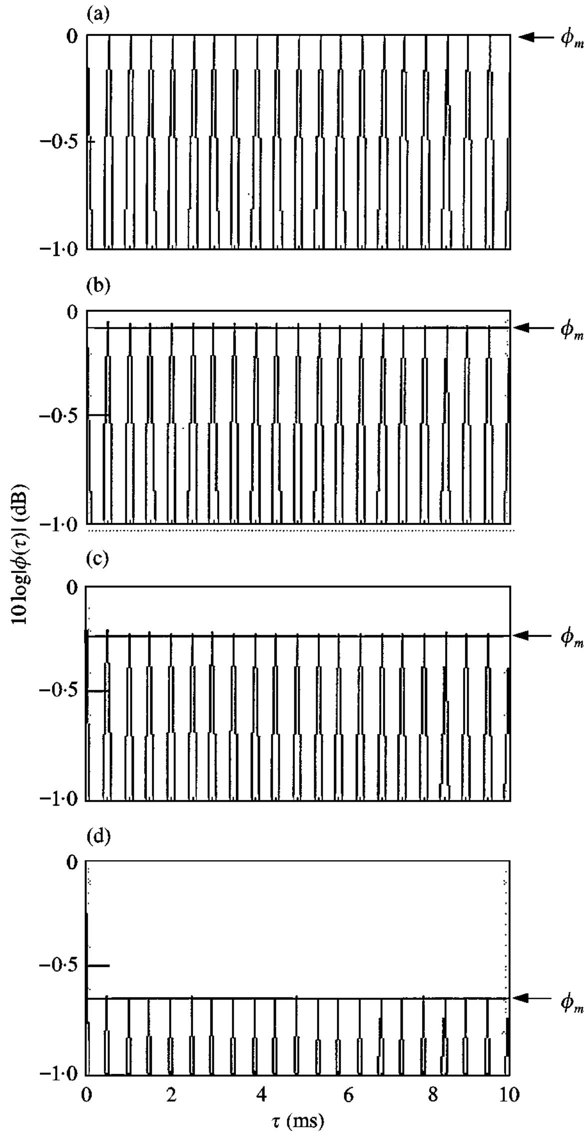


Figure 1. Measured $\phi_m$ ($m = 1, 2, 3, \dots$) of the ACF envelope for four sound stimuli. (a) pure tone ($P$) (1 kHz, 80 dB(A)), $\phi_m = 0{\cdot}00$ dB; (b) pure tone plus 59 dB(A) white noise ($PW_1$), $\phi_m = -0{\cdot}06$ dB; (c) pure tone plus 64 dB(A) white noise ($PW_2$), $\phi_m = -0{\cdot}23$ dB; (d) pure tone plus 69 dB(A) white noise ($PW_3$), $\phi_m = -0{\cdot}64$ dB. Note that the measured ACF of white noise was obtained, where $\phi(0) = 1$ and $10 \log \phi(\tau) < -10$ dB, $\tau > 0$.

### 2.2. SUBJECTS

The subjects of both experiments were five male students in the laboratory (KF, MI, NS, OK and YS). All of them have good hearing and were between 22 and 25 years old.

## 3. PROCEDURE

### 3.1. SUBJECTIVE RESPONSE

The subjects were seated in the soundproof chamber on a chair in front of two loudspeakers aligned vertically with their centers 15 cm apart. One loudspeaker

TABLE 1

*Measured and calculated values of the peak amplitudes* ($\phi_m$) *of the envelope of* ACF *for five stimuli*

| Stimulus | Measured values of $10 \log |\phi_m|$ (dB) | Calculated values of $10 \log |\phi_m|$ (dB) |
|---|---|---|
| P: 80 dB(A) pure tone | 0·00 | 0·00 |
| PW1: 80 dB(A) pure tone Plus white noise 59 dB(A) | − 0·06 | − 0·08 |
| PW2: 80 dB(A) pure tone Plus white noise 64 dB(A) | − 0·23 | − 0·25 |
| PW3: 80 dB(A) pure tone Plus white noise 69 dB(A) | − 0·64 | − 0·75 |
| W: 80 d(BA) white noise | ( < − 10·00) | − ∞ |

*Note*: The values in the parentheses are estimated.

provided the pure tone and the other provided the white noise. The distance between the center of the subject's head (central point) and the front of the loudspeakers was 74 ( ± 1) cm.

A constant standard stimulus (pure tone, 150 ms) was used for experiment 1, which consisted of two tests (first test and second test). Most of the test stimuli in the first test were slightly longer than the standard stimulus and most of those in the second test were slightly shorter than the standard stimulus. The subjects were asked to judge whether the duration of the second of a pair of stimuli (the test stimuli) was longer than or shorter than the first standard stimulus [12]. In the first test of experiment 1, and throughout experiment 2, subjects were told to push the button only when the second stimulus seemed longer than the standard. In the second test of experiment 1, subjects were told to push the button only when the second stimulus seemed shorter than the standard. Each subject went through five sessions with five different test stimuli for each test in experiment 1 and through six sessions with six standard stimuli in experiment 2.

### 3.2. STIMULUS PRESENTATION

The first (standard) stimulus in experiment 1 was a pure tone (1 kHz) with a duration of 150 ms and a SPL of 80 dB(A). Ten sets of stimuli with a 10 ms step size in the range from 140 to 230 ms were used in each session of the first test. Ten sets of stimuli changing from 70 to 160 ms (with the same step size) were presented in each session of the second test. The five stimuli in each set had five different $\phi_m$ values for their ACF envelopes. The SPL of all stimuli was kept at a constant 80 dB(A). In the paired-comparison test, the second stimuli were presented in random order. Each pair was presented 20 times. The intra- and inter-pair (response time) gaps, respectively, were 1 and 3 s.

In experiment 2, six pure-tone stimuli with different frequencies (as measured by $\tau_1$) but with a constant duration of 150 ms were presented as the standard stimulus. Ten white-noise test stimuli with a 10 ms step size durations in the range from 140 to 230 ms were presented. The procedure was otherwise the same as in experiment 1.

## 4. RESULTS

### 4.1. EXPERIMENT 1

Cumulative frequencies of the correct judgement of duration for the five subjects were obtained by the effect of five different stimuli as a parameter of different values of $\phi_m$s in the ACF, as shown in Figures 2 and 3. In the first and second test, values of correct judgements are obtained as durations cross the 25, 50 and 75% line for the stimuli of $P$, $PW_1$, $PW_2$, $PW_3$, and $W$, respectively, in Table 2. A significant difference ($p < 0{\cdot}05$) was found between results for the five test stimuli of both tests for each 25, 50 and 75% crossing lines.

Taking the results (●) for the pure tone in Figures 2 and 3 as a judged reference, the other four of the results ( + , □, △ and ○) show a significant ($p < 0{\cdot}01$) deviation in the judgement of durations. The deviations of duration from the result of the judged reference (pure tone) for the first and second tests are shown in Figures 4 and 5 respectively. Only exception ($p = 0{\cdot}069$) is found for the graph " + " on the 75% line in the first test.

### 4.2. EXPERIMENT 2

Cumulative frequencies of the correct judgements are obtained as duration (same five subjects) by the effect of six different frequencies (controlled by $\tau_1$) of a pure tone. The pure-tone stimuli with a constant duration (150 ms) were presented at first for comparison with a second white-noise stimulus (see Figure 6). Correct judgements of duration obtained for the above six stimuli cross the 25% correct lines are found at 153·5, 157·0, 160·0, 164·5, 170·0 and 175·0 ms; the 50% line at 162·0, 165·5, 172·0, 177·8, 184·0 and 188·0 ms; and the 75% line at 172·8, 178·0, 182·0, 190·0, 197·0 and 204·5 ms respectively. Differences among the durations judgement of the six stimuli were found to be significantly ($p < 0{\cdot}01$) different for each line (25, 50 and 75%).

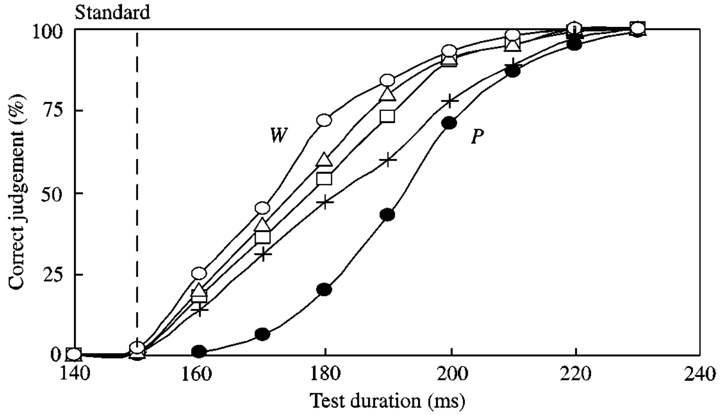


Figure 2. Cumulative frequencies of correct judgements indicate the 25, 50 and 75% lines of durations for five stimuli: (●)($P$), $\phi_m = 0{\cdot}00$ dB; +($PW_1$), $\phi_m = -0{\cdot}06$ dB; (□)($PW_2$), $\phi_m = -0{\cdot}23$ dB; (△)($PW_3$), $\phi_m = -0{\cdot}64$ dB; (○)($W$), white noise 80 dB(A). (-----), The physical duration of the standard stimulus was 150 ms. Results of the first test: judging whether the duration of test stimuli was longer than that of the standard stimulus.

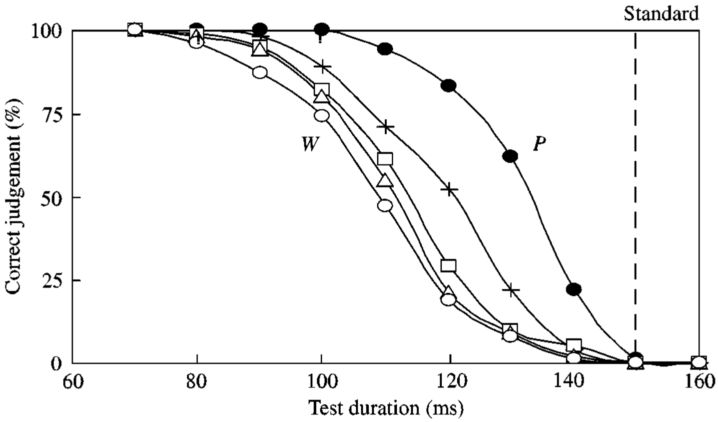


Figure 3. Cumulative frequencies of correct judgements indicate the 25, 50 and 75% lines of durations for five stimuli: (●)(P), $\phi_m = 0{\cdot}00$ dB; (+)($PW_1$), $\phi_m = -0{\cdot}06$ dB; (□)($PW_2$), $\phi_m = -0{\cdot}23$ dB; (△)($PW_3$), $\phi_m = -0{\cdot}64$ dB; (○)($W$), white noise 80 dB(A). (----), The physical duration of the standard stimulus was 150 ms. Results of the second test: judging whether the duration of test stimuli was shorter than that of the standard stimulus.

TABLE 2

*Values of judged durations obtained by the paired-comparison test (Experiment 1) with respect to five auditory stimuli (see Figures 2 and 3)*

| Lines of percentage (%) of judgement | $P$ (Pure tone) | $PW_1$ | $PW_2$ | $PW_3$ | $W$ (White noise) |
|---|---|---|---|---|---|
| | | *First test* | | | |
| 25 line | 182·5 | 167·0 | 164·0 | 162·5 | 160·0 |
| 50 line | 193·0 | 182·5 | 177·5 | 175·0 | 172·0 |
| 75 line | 202·0 | 198·0 | 191·0 | 187·0 | 182·0 |
| | | *Second test* | | | |
| 25 line | 139·0 | 129·0 | 122·0 | 118·5 | 117·5 |
| 50 line | 134·5 | 121·5 | 115·0 | 112·0 | 109·5 |
| 75 line | 125·0 | 108·0 | 104·0 | 102·0 | 99·0 |

*Note*: $p < 0{\cdot}05$.

## 5. DISCUSSION

### 5.1. EXPERIMENT 1

In both tests, all five test stimuli produced different results when subjects compared them with the one standard stimulus. The results indicate a tendency for lower attenuation levels ($\phi_m$) of the envelope of the ACF for the test stimuli to produce a longer judgement of duration for both tests (see Figures 2 and 3). A lower $\phi_m$, however, produces a shorter difference from the physical standard stimulus (150 ms; dotted lines in Figures 2 and 3) in the first test and an inversely longer distance in the second test. This is because of the nature of the judgements in the two tests: whether longer judgement for the longer test stimuli in the first test, and shorter judgement for the shorter test stimuli in the second test. Shorter durations on the graph (horizontal axes) thus indicate a longer judgement of duration in

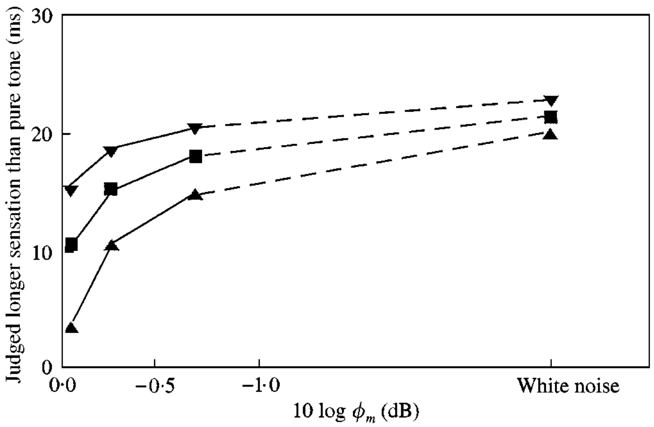


Figure 4. Longer deviations of the judged durations for four stimuli (including white noise) than the judged reference of pure tone in the first test of experiment 1. (▼), 25%; (●), 50%; (▲), 75% line of correctly judged.

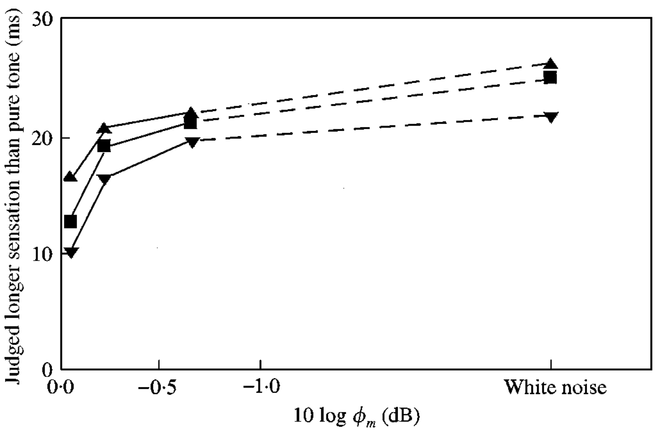


Figure 5. Longer deviations of the judged durations for four stimuli (including white noise) than the judged reference of pure tone in the second test of experiment 1. (▼), 25%; (●), 50%; (▲), 75% line of correctly judged.

comparison with the judged reference pure tone (*P*: in Figures 2 and 3). The lines of 25 and 75% correctly judged appear to be roughly the inverse of each other as judged to be longer, as graphed in Figures 4 and 5. In Figures 4 and 5, data for white noise (the $\phi_m$ cannot be graphed exactly) can be explained as a continuation of data for the other three values of $\phi_m$. It is clear, however, that the envelope of ACF may be an indicator of the judged duration. So the effects of the $\phi_m$ of the envelope of an ACF for sound stimulus was found to have a significant effect on the human sensation of duration.

### 5.2. EXPERIMENT 2

In Figure 6, the results with a shorter duration indicate that the first stimulus is judged to be shorter (higher frequency pure tone) and the second stimulus is judged as longer (white noise) in the presented pair. Judging the second stimulus as longer makes the correct response (according to instructions) plotted on the graph and appears to be of shorter

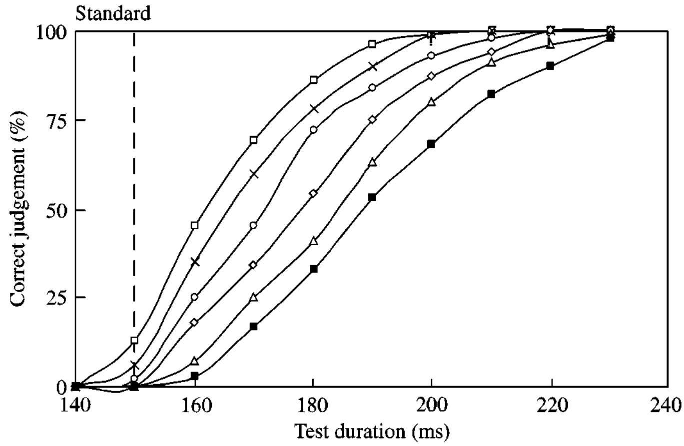


Figure 6. Cumulative frequencies of correct judgements indicate the 25, 50 and 75% lines of duration for six stimuli: (■), 0·125 kHz; (△), 0·25 kHz; (◇), 0·5 kHz; (○), 1·0 kHz; (×), 2·0 kHz; (□), 4·0 kHz. (- - - -), Physical duration of the standard stimulus (150 ms).

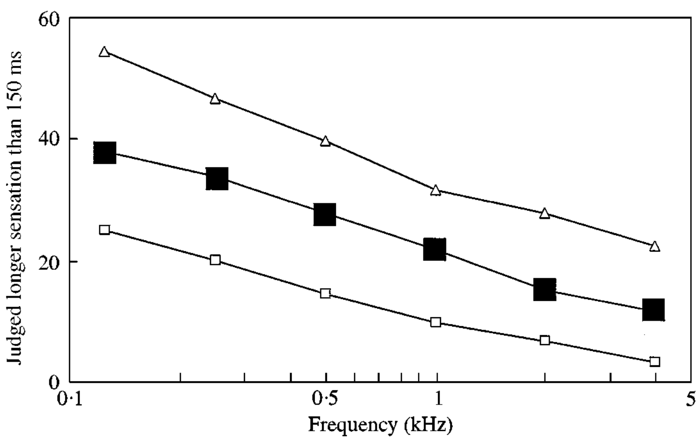


Figure 7. Durations are judged to be longer for the lower frequencies of pure tone than higher frequencies as standard stimuli (150 ms), when comparison stimuli are the white noise. (□), 25%; (■), 50%; (△), 75% lines of correct judgement.

duration. This means that the judged duration is longer for a pure tone with a lower frequency (see Figure 7). Frequency was thus found to have an effect on the human sensation of duration in that pure tones with higher frequencies were judged to be shorter than pure tones with lower frequencies when their durations were compared with the duration of a white-noise test stimulus.

Thus, one can compare the values of judged durations for the effects of different values of $\phi_m$ and $\tau_1$, with the judged duration of a pure tone (1 kHz) and white noise in Figures 4, 5, and 7. Considering the 50% line (■) of a pure tone was compared with the white noise, then higher $\phi_m$ (see Figures 4 and 5) and longer $\tau_1$ (see Figure 7) indicate shorter and longer durations respectively.

This result is supported by previous findings as cited in the introduction: that the rate of external information affects the experience of duration, if the frequency is considered as information. That is, time duration seems to pass more rapidly when one hears pure-tones with higher frequencies. This is why an interval occupied by a higher frequency tone seems shorter than an interval of the same length occupied by a lower frequency tone. That a pure tone passes more rapidly and the sensation is shorter can be explained if one supposes that frequency is the unit used by the counting mechanism in the brain's internal clock.

## 6. CONCLUSIONS

From the significant results of the study one can conclude the following.

1. The sensation of the duration of a white-noise stimulus is judged to be longer than that of pure-tone stimuli (1 kHz) with the same sound pressure level, that actually have the same duration.

2. The sensation of the duration of mixed stimuli (pure tone and white noise) with higher values of attenuation level ($\phi_m$) of the envelope of ACF are judged as shorter.

3. The sensation of the duration of pure-tone stimuli with lower frequencies ($\tau_1$) are judged longer than those of pure-tone stimuli with higher frequencies (shorter $\tau_1$).

## ACKNOWLEDGMENTS

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## APPENDIX A

The procedure for the calculation of the peak amplitudes of the ACF envelope $\phi_m$ ($m = 1, 2, 3, \ldots$) shown in Figure 1 is described here. The ACF of the sound stimuli $\Phi_p(\tau)$

can be defined as

$$\Phi_p(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} p(t)\,p(t+\tau)\,\mathrm{d}t. \tag{A1}$$

where $\tau$ is the delay time.

In this study, the sound stimulus was $p(t) = s(t) + An(t)$, where $s(t)$ is the pure tone, $n(t)$ is the white noise being incoherent with $s(t)$ and coefficient $A$ is the relative amplitude of $n(t)$–$s(t)$. Here, sound energies of $s(t)$ and $n(t)$ should be equal so as to have a relation: $\Phi_s(0) = \Phi_n(0)$. The integration interval $2T$ was 2·0 s. For such a mixed stimulus, the normalized amplitude of the $m$th peak $\phi_m$ is given in the form

$$\Phi(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} [s(t)s(t+\tau) + a^2 n(t)n(t+\tau)]\,\mathrm{d}t,$$

$$= \Phi_s(\tau) + a^2\,\Phi_n(\tau). \tag{A2}$$

The normalized ACF $\phi(\tau)$ becomes

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)} = \frac{\Phi_s(\tau) + A^2\Phi_n(\tau)}{\Phi_s(0) + A^2\Phi_n(0)} \quad = \frac{\phi_s(\tau) + A^2\phi_n(\tau)}{1 + A^2}.$$

Here $\phi_s(\tau) = \Phi_s(\tau)/\Phi_s(0)$ and $\phi_n(\tau) = \Phi_n(\tau)/\Phi_n(0)$.

When $s(t) = \sin \omega t$ and $n(t)$ is the white noise,

$$\phi(\tau) = \frac{\cos \omega\tau + A^2\delta(\tau)}{1 + A^2}, \tag{A3}$$

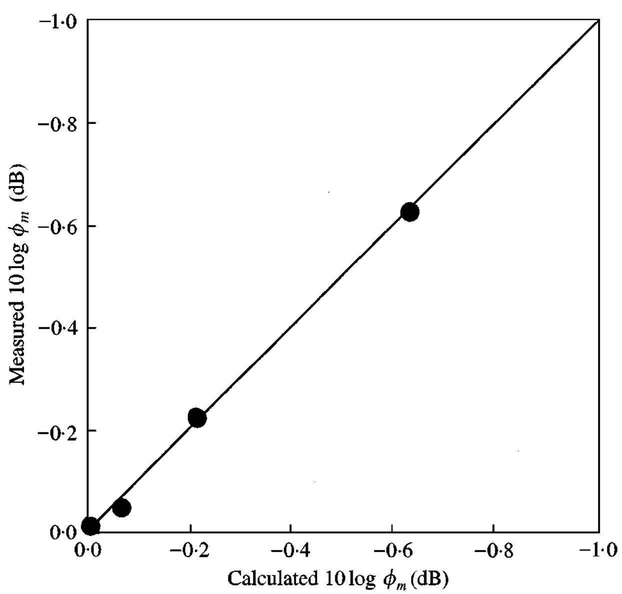


Figure A1. The horizontal and vertical axes are, respectively, the calculated and measured $\phi_m$ for the envelope of the ACF for four stimuli.

where $\delta(\tau)$ is the Dirac delta function. Thus, $\phi_{(0)} = 1$.

$$\phi_m = 10 \log_{10} \frac{1}{1 + A^2}, \quad m = 1, 2, 3, \ldots . \tag{A4}$$

Measured and calculated values of $\phi_m$ for four of the stimuli used in this study are listed in Table 1 and shown in Figure A1.