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Short Communication

# Loudness in relation to iterated rippled noise

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## Abstract

This study examined the loudness of iterated rippled noises (IRNs) with different number of iterations under conditions of equal sound pressure. The scale values of loudness were obtained using a paired–comparison method. The results showed that the loudness of IRNs was not constant, even though the sound pressure level was equivalent. The loudness of IRNs increased with increasing iteration number. This indicated that repetitive components of sounds might affect their loudness.

## 1. Introduction

Changes in sound intensity are highly correlated with loudness changes, although the relationship is not perfect. Thus, changes in frequency, duration and bandwidth all affect the perceived loudness of a stimulus, even when the intensity is constant [1]. Previous studies have concluded that the loudness of a noise remains constant as the bandwidth of the noise increases up to the critical band. Thereafter, the loudness increases with increasing bandwidth under the same sound pressure conditions beyond the critical band [2–4]. However, the loudness of a sharply filtered noise increases as the effective duration of the autocorrelation function (ACF), $\tau_e$, increases, even when the bandwidth of the signal is within the critical band [5,6]. The $\tau_e$ represents repetitive components within the signal itself and increases as the filter bandwidth decreases.

Previous studies have indicated that the loudness increases as the bandwidth of bandpass filtered noise (BN) decreases, and have concluded that the $\tau_e$ of the ACF might have an effect [5,6]. However, the envelope and sound-pressure level (SPL) also vary as the bandwidth of the BN changes, as shown in Fig. 1. The variation of the envelope and SPL might therefore affect the loudness of the BN [7,8]. To eliminate such effects, iterated rippled noise (IRN) was used in the current study. IRN is produced by delaying a noise, adding it to the original, and iterating the delay-and-add process. The reciprocal of the delay determines the pitch, and the number of iterations determines the pitch strength [9]. Thus, the number of iterations determines the $\tau_e$ of

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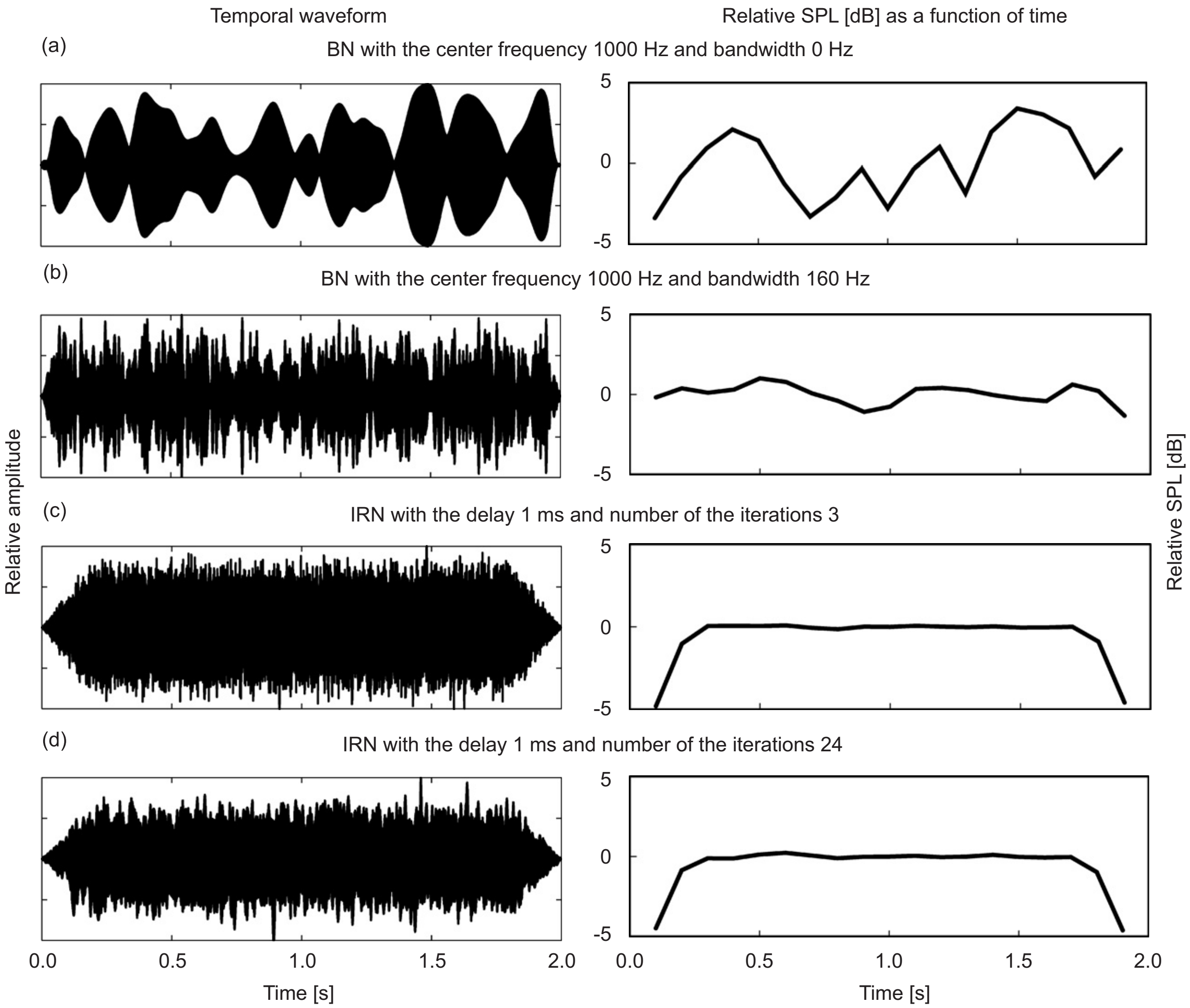

Fig. 1. Temporal waveforms and relative SPL as a function of time for the stimuli in a previous study [6] and the present study are shown in the left and right columns, respectively. The relative SPL was measured by the $\Phi(0)$ of ACF at an integration interval of 0.2 s.

the ACF. The envelope and SPL variation of the IRN are much smaller than those of the BN, as shown in Fig. 1. In the present study, the scale values of the loudness of IRNs with delays of 1, 2, 4 and 8 ms were obtained using a paired–comparison method.

## 2. Method

Ten subjects (aged 21–24 years) with normal hearing took part in each experimental session. Five of the subjects participated in all of the experimental sessions. The participants all had a normal audiological status and no history of neurological diseases. Informed consent was obtained from each subject after the nature of the study had been explained. The protocol was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology.

The IRN was produced by a delay-and-add algorithm applied to white noise. The number of iterations of the delay-and-add process was set at 3, 6, 12, 24 and 48. The delay was set at 1, 2, 4 and 8 ms, corresponding to a pitch of 1000, 500, 250 and 125 Hz. The auditory stimuli were binaurally presented using headphones (Sennheiser HD-650). All stimuli were fixed at the same SPL [65 dB(A)]. The SPL was calibrated by using a

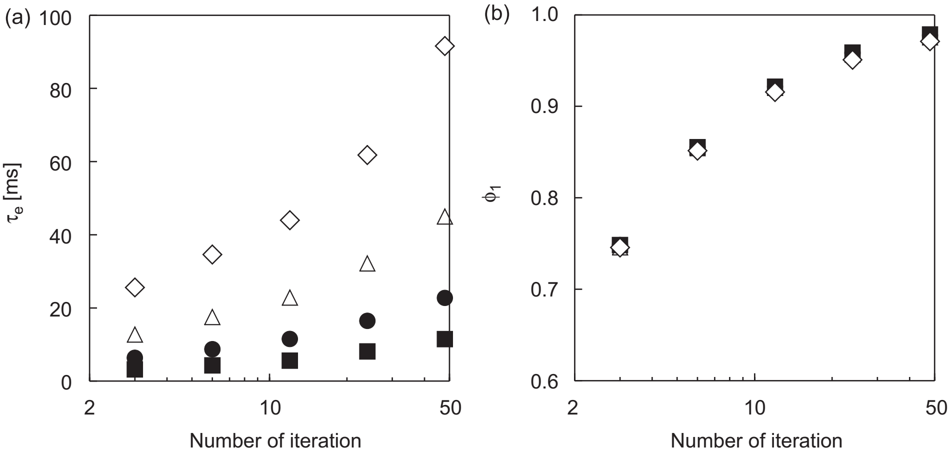

Fig. 2. The (a) $\tau_e$ and (b) $\phi_1$ of the stimuli used in the experiment as a function of the number of iterations with a delay of (■) 1, (●) 2, (△) 4 and (◇) 8 ms.

dummy head with 1/2 in. condenser-type microphones at both ears. The ACF provides the same information as the power spectral density of a signal. A normalized ACF as a function of time, $t$, can be expressed by

$$\phi(\tau) = \phi(\tau; t, T) = \frac{\Phi(\tau; t, T)}{[\Phi(0; t, T)\Phi(0; \tau + t, T)]^{1/2}}, \tag{1}$$

where

$$\Phi(\tau; t, T) = \frac{1}{2T}\int_{t-T}^{t+T} p(s)p(s+\tau)\,\mathrm{d}t, \tag{2}$$

in which $2T$ is the integral interval, $\tau$ is the time delay and $p$(s) is the signal as a function of time. The following can be determined from the ACF analysis: (1) the energy represented at zero delay, $\Phi(0)$; (2) the $\tau_e$, which is defined as the time delay at which the envelope of the normalized ACF becomes 0.1; (3) the amplitude of the first non-zero maximum peak at positive delay, $\phi_1$; and (4) the delay time $\tau_1$ [10,11]. The $\tau_1$ of IRN corresponds to the delay. The $\tau_e$ and $\phi_1$ increase as the number of iterations increases, and there is a certain degree of coherence between $\phi_1$ and $\tau_e$. Fig. 2 shows the $\tau_e$ and $\phi_1$ (calculated at the integration interval of 2.0 s) of the stimuli used in the experiment.

Loudness judgments were conducted by a paired–comparison method for each delay. Each subject compared all combinations of the pairs of IRNs with different iteration numbers, that is, 10 pairs ($N(N-1)/2$, $N = 5$) per session, and a total of 10 sessions were conducted for each subject. The pairs were interchanged and presented in random order. The stimulus duration used in the experiment was 2.0 s (including rise and fall ramps of 200 ms), the silent interval between the stimuli was 1.0 s and the interval between pairs was 4.0 s, which was the time allowed for the subjects to respond. The subjects were asked to determine which of the two sound signals was louder. The scale values of the loudness for each subject were calculated according to Case V of Thurstone's theory [12], and the model of Case V for all data was reconfirmed by a goodness-of-fit test [13]. The effects of the number of iterations on the scale value of loudness were statistically analyzed by a repeated-measure analysis of variance (ANOVA), with the number of iterations as a within subject factor, and the Greenhouse-Geisser correction being applied. A Bonferroni test was used for the subsequent *post hoc* tests.

## 3. Results

A one-way repeated-measure ANOVA revealed a significant main effect of the number of iterations on the scale value of loudness: [$F(4, 36) = 9.17$, $P<0.01$, $\varepsilon = 0.33$] for the delay of 1 ms [$F(4, 36) = 4.57$, $P<0.05$, $\varepsilon = 0.34$] for the delay of 2 ms, [$F(4, 36) = 17.21$, $P<0.001$, $\varepsilon = 0.40$] for the delay of 4 ms, and [$F(4, 36) = 24.03$, $P<0.001$, $\varepsilon = 0.31$] for the delay of 8 ms. The relationship between the scale value of

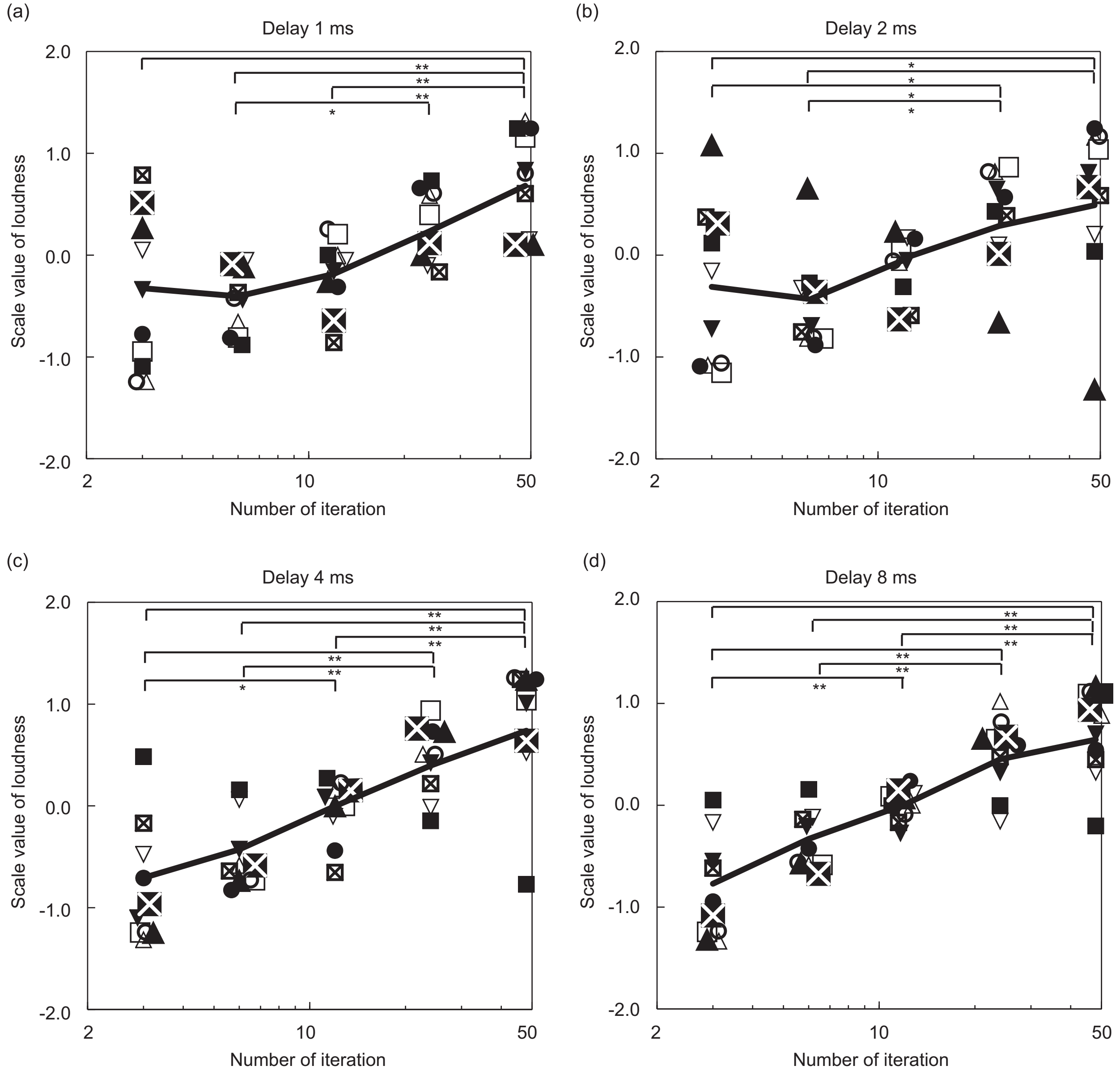

Fig. 3. Scale value of loudness as a function of the iteration number of IRN with a delay of (a) 1, (b) 2, (c) 4 and (d) 8 ms. Each symbol represents a subject. The line represents the mean scale value of 10 subjects. The asterisks indicate statistical significance (*$P<0.05$, **$P<0.01$; *post hoc* Bonferroni test).

loudness and the iteration number of IRN is shown in Fig. 3. When the delay was 1 or 2 ms, the averaged scale value of loudness was approximately the same when the number of iterations was less than 10; however, the averaged scale value of loudness increased as the number of iterations increased when the number of iterations was more than 10. When the delay was 4 or 8 ms, the averaged scale value of loudness increased as the number of iterations increased.

## 4. Discussion and conclusions

Previous research indicated that loudness increased as the $\tau_e$ of BN increased, although the envelope and SPL varied as the bandwidth changed [5,6]. In the current study, IRN was used to eliminate the effects of the envelope and SPL variation. Loudness was found to increase as the number of iterations of IRN increased (that is, the $\tau_e$ of IRN), as shown in Fig. 3. The $\tau_e$ represents the repetitive components of the source signals. This clearly indicated that loudness was influenced by the repetitive components of sounds.

The $\tau_e$ and $\phi_1$ increased as the number of iterations increased. The $\phi_1$ did not change as a function of the delay time of the IRN; however, the $\tau_e$ changed as a function of the delay time of the IRN, as shown in Fig. 2. Loudness, as a function of the number of iterations of the IRN, also changed according to the delay of the IRN, as shown in Fig. 3. Thus, the loudness did not increase as the number of iterations increased for lower numbers of iterations when the delay was 1 or 2 ms. This suggested that the $\tau_e$ had a greater influence on loudness than $\phi_1$.

The effect of an increase of loudness on IRN was not seen in a few of the subjects. This indicated that some of the subjects experienced a minor affect of the $\tau_e$ on loudness judgment. Thus, the effect of the $\tau_e$ on loudness judgment seemed to partially depend upon the individual. This was consistent with previous findings [6].

For a random signal, such as white noise, the $\tau_e$ is $\approx 0$. By contrast, for a periodic signal, such as a sine wave, the $\tau_e$ is $\infty$. The $\tau_e$ of sound sources, such as airplanes [14,15], trains, cars [16], motor bikes [17], flushing toilets [18] and vocalizations [19], were analyzed. The result clearly indicated that the $\tau_e$ varied according to the type of sound source. We therefore proposed that loudness changes with the $\tau_e$ of sound sources, even though the SPL remains the same. Factors extracted from the ACF, such as the $\tau_e$, could thus be useful criteria for evaluating environmental noise.

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