



Prediction of optimal auditory signals using auditory evoked magnetic responses



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ABSTRACT

Birdsong is often used as an auditory signal for visually-challenged people in public spaces in Japan. However, more than 40% of visually-challenged people reported that such auditory signals were difficult to identify. We used auditory evoked magnetic field (AEF) responses in the human auditory cortex to uncover an auditory signal that was easy to identify. As an auditory signal, we focused on birdsong, which is currently used to inform passengers about the location of stairs in train stations in Japan. We presented birdsongs to participants in silent, noisy, reverberated, and interaural time-delay conditions. We analyzed the most prominent AEF response, N1m, and the correlation between the birdsong envelopes and the AEF. We found that the N1m amplitudes were maximal when the participants listened to the song of the Cuckoo and the above-mentioned correlation was maximal when the participants listened to the song of the Oriental Scops Owl. Thus, we believe the songs of the Cuckoo and Oriental Scops Owl to be candidates for optimal auditory signals.

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1. Introduction

Many different auditory signals are used to convey information in public spaces in Japan. These auditory signals can be classified into three groups according to their function: alarm signals, which give information about events involving human lives, attention signals, which give information about basic infrastructure, such as the locations of stairs, toilets, and ticket gates, and announcements, which convey information via speech.

Some signals serve as auditory cues for visually-challenged people in public spaces in Japan. The security guidelines for public transportation systems in Japan [1] recommend the use of sounds with a fundamental frequency between 100 and 2500 Hz and a broader frequency band. However, more than 40% of visually challenged people reported that such auditory signals were difficult to identify [2], even though these auditory signals were set according to guidelines based on previous psychophysical findings. Neurophysiological activity, such as electroencephalographic (EEG) and magnetoencephalographic (MEG) responses to auditory stimuli, can provide useful information about how sounds are processed in the human brain [3]. For instance, the amplitudes of the auditory-evoked N1 and N1m responses, which is observed

approximately 100 ms after sound onset, have been correlated with auditory basic elements of auditory perception, such as loudness [4–6], pitch salience [7–9], and localization performance [10,11]. Sounds that are louder, have a clearer pitch, or are highly localized, elicit a response with a larger amplitude. Additionally, the degree of correlation between an envelope of speech and the waveform of the response has been correlated with speech intelligibility, suggesting that activity in the human auditory cortex either directly corresponds to the envelopes of intelligible sounds or consistently reacts to changes in the envelope [12]. Thus, MEG responses may be useful in locating an auditory signal that is easy to identify.

As an auditory signal, we focused on birdsong, which is currently used to inform passengers about the location of stairs in train stations in Japan. Introducing birdsongs into public spaces has been found to increase the pleasantness of the associated soundscapes [13]. Among the natural sounds, birdsongs have been rated as the most effective and favorable sounds in terms of improvement of urban sound environments [14–16]. Thus, compared with other sounds, birdsongs seem less likely to damage sound environments in public spaces. We hypothesized that birdsongs that elicited auditory-evoked magnetic fields (AEFs) with larger amplitudes and/or those with a higher correlation between the response and the envelope of the birdsong would be perceived as louder, having a stronger pitch, or being clearer, that is, these would be the easiest to identify. Furthermore, we assessed subjective preference for

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birdsongs to confirm that the addition of birdsong stimuli did not damage sound environments in public spaces.

2. Methods

We analyzed 32 types of birdsong that had been recorded using a dummy-head microphone (KU100, Nuemann) at a sampling rate of 48 kHz and a sampling resolution of 24 bits. Eight birdsongs that most closely met the specifications indicated by the guidelines [1] were selected as candidate auditory signals. These were the songs of the Black Paradise Flycatcher (BP), Cuckoo (CC), Japanese Grosbeak (JG), Jay (JY), Jungle Nightjar (JN), Little Cuckoo (LC), Oriental Scops Owl (OS), and Ruddy Kingfisher (RK). The left and right hand side of Fig. 1 show the temporal waveform and spectrogram of the eight birdsongs used. The spectrogram was calculated with a time window of 20 ms and a time overlap of 15 ms.

It has been proposed that the qualitative aspects of a sound can be formulated using factors extracted from the autocorrelation function (ACF). The ACF factors of noise have previously been proposed to describe the sound quality [17–19]. The normalized ACF for the signals received at each ear from the microphones, $p(t)$, as a function of the running step, s , is defined by

$$\phi(\tau) = \phi(\tau, s, T) = \frac{\Phi(\tau; s, T)}{\sqrt{\Phi(0; s, T)\Phi(0; s + \tau, T)}}, \quad (1)$$

where

$$\Phi(\tau; s, T) = \frac{1}{2T} \int_{s-T}^{s+T} p'(t)p'(t + \tau)dt. \quad (2)$$

Here, $2T$ is the integration interval and $p'(t) = p(t) * s_e(t)$, where $s_e(t)$ is the ear sensitivity. For convenience, we selected $s_e(t)$ as the impulse response of an A-weighted network, which includes the transfer functions of the human outer and middle ear [17–19]. The ACF is normalized using the geometric mean of the energy at s and the energy at $s + \tau$ and should not be normalized by the energy at s alone; this ensures that the normalized ACF satisfies $0 \leq \phi(\tau) \leq 1$.

The first ACF factor is a geometrical mean of the sound energy arriving at the ear, $\Phi(0; s, T)$, which corresponds to the A-weighted equivalent sound pressure level (SPL), L_{Aeq} . L_{Aeq} is determined from the A-weighted $p(t)$ as a function of s and is calculated using

$$L_{Aeq}(s, T) = 10 \log \Phi(0; s, T). \quad (3)$$

The second and third ACF factors, τ_1 and ϕ_1 , are defined as the time delay and the amplitude of the first maximum peak, and are related to the perceived pitch and the pitch strength (i.e., the tonality) of the complex sounds [17,20]. Larger values of τ_1 and ϕ_1 mean that the noise has a lower and stronger pitch. The fourth ACF factor, τ_e , corresponds to effective duration and is defined by the delay time at which the envelope along the early decay of the normalized ACF becomes -10 dB [17,18]. τ_e represents a repetitive feature containing the sound source itself, and is related to the most highly preferred reverberation time (RT) and delay time of early reflections of sound fields [18]. The fifth ACF factor, $W_{\phi(0)}$, is defined as the width of the first decay and corresponds to the spectral centroid [18,19]. Larger values of $W_{\phi(0)}$ mean that the sound includes a higher proportion of lower frequency components. We calculated $\Phi(0)$, τ_1 , ϕ_1 , τ_e , and $W_{\phi(0)}$ as a function of time to examine the characteristics of birdsongs both quantitatively and qualitatively as shown in Fig. 2. The integration interval used was $2T = 100$ ms and the running step was $s = 10$ ms in all calculations. $\Phi(0)$ was calibrated by a sound calibrator (Type 4231, B&K).

Twelve participants (ten males) with normal hearing, no history of neurological disease, and ranging in age between 23 and 39 years (median age of 32.5 years) took part in Experiments 1 and 2. Eleven participants (ten males) with normal hearing, no history of neurological disease, and ranging in age between 23 and 39 years (median age of 34 years) took part in Experiments 3 and 4. The birdsong stimuli were presented binaurally through insert earphones with a duration of 500–1000 ms, as shown in Fig. 1. In Experiment 1, we tested which birdsong stimuli were the loudest and clearest in terms of pitch in the silent condition. The eight birdsong stimuli were presented at 60 dB SPL in the silent background condition. In Experiment 2, we assessed which birdsong stimuli were the loudest and clearest in pitch in the noisy condition. Accordingly, we presented the eight birdsong stimuli at 60 dB SPL in the noisy background condition. The noise condition was simulated based on the averaged SPL and spectral distribution of real subway stations [21] and presented at 58 dB SPL. To identify the birdsong stimuli that were loudest and clearest in pitch in the reverberant condition, we presented four birdsong stimuli (BP, CC, OS, and RK) at 60 dB SPL with RTs of 0.5 and 2.0 s in Experiment 3. These RTs were based on those in considering the actual underground stations [22]. We simulated the RTs of rooms with identical volumes but different absorptive materials using room acoustics software (ODEON, Odeon). The impulse responses obtained in the simulated rooms were convolved with the birdsong stimuli. To identify the birdsong stimuli that were easy to localize, we presented four birdsongs (BP, CC, OS, and RK) at 60 dB SPL with interaural time delays (ITD) of 0.0 and 0.7 ms in Experiment 4. ITDs were controlled via the shape of the sound envelope [11].

We recorded brain activities evoked by the sound stimuli using a 122-channel whole-head magnetometer (Neuromag-122™, Neuromag) in a magnetically shielded room [3]. To maintain a constant vigilance level, participants were instructed to ignore the stimuli and to concentrate on a self-selected silent movie that was projected on a screen in front of them. Magnetic data were sampled at 400 Hz after being bandpass-filtered between 0.03 and 100 Hz, and then averaged approximately 100 times. The averaged responses were digitally filtered between 1.0 and 30.0 Hz. The analysis time included the interval from 0.2 s prior to the onset of the stimulus to 0.7 s after stimulus onset. The pre-stimulus period (average of the 0.2 s prior to stimulus onset) was used as the baseline level. We obtained the root mean square (RMS) amplitudes from a subset of 18 channels over the left and right temporal areas. For each participant, we defined the maximum RMS amplitudes between 70 and 140 ms over the left and right hemispheres as the N1m amplitude. We then normalized the N1m amplitude using the averaged values for each participant. The RMS amplitudes were cross-correlated with the envelope of the birdsong stimuli, which were downsampled to 400 Hz. The envelopes of the birdsongs were calculated via the Hilbert transform. The temporal window was 0.5 s. The maximum values of the cross-correlation function in the delay range between 0 and 500 ms over the left and right hemispheres were defined as the maximum correlation coefficients between the birdsong stimuli and the AEFs.

We statistically analyzed the effects of the stimulus parameters (birdsongs and background noise) and hemisphere on the amplitudes of the N1m and the correlation coefficients using a repeated-measures analysis of variance (ANOVA) in Experiment 1 and 2. Additionally, the effects of the stimulus parameters (birdsongs and RT or ITD) and hemisphere on the amplitudes of the N1m and the correlation coefficients were statistically analyzed using an ANOVA in Experiments 3 and 4. Where appropriate, probabilities were adjusted using the Greenhouse-Geisser correction. Post-hoc comparisons were conducted using the Bonferroni method.

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