INVITED REVIEW

Optimization of auditory guide signals in public spaces on the basis of sound localization abilities in humans

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Abstract: In Japan, auditory guide signals are installed in public spaces mainly for the purpose of guiding visually impaired pedestrians. The acoustic signal is emitted from a loudspeaker installed at a destination such as a ticket gate, a stairway, and a restroom. Then, the pedestrians move in accordance with spatial information obtained from the signal. As the auditory guide signal is targeted at pedestrians, not only static sound localization cues but also dynamic sound localization cues are effective. In addition, unlike other applications such as sound field reproduction, precise sound image localization is not necessarily required and it is important to grasp a rough sound source position in this application. Furthermore, the degradation of sound localization accuracy owing to background noise and reverberation sound cannot be ignored in public spaces. Considering the above factors, the research on the optimization of auditory guide signals based on sound localization tests with human listeners so far carried out by the authors and their colleagues will be introduced in this review.

Keywords: Visually impaired persons, Head movement, Localization in daily situations

PACS number: 43.66.Qp, 43.55.Hy [doi:10.1250/ast.41.121]

1. INTRODUCTION

In Japan, auditory guide signals are installed in public spaces mainly for the purpose of guiding visually impaired pedestrians. The auditory guide signal is emitted from a loudspeaker installed at a destination such as a ticket gate, a stairway, and a restroom, and the pedestrians can use spatial information from the signal to decide a moving direction. Spatial information is often transmitted linguistically by speech, but in this review, only auditory guide signals without linguistic information are targeted.

The points where an auditory guide signal differs from other applications of sound localization are as follows.

- (1) Localization target: What is really needed is the localization of the sound source (loudspeaker) position in the real world, not the localization of the sound image position in one's mind. Ideally, the two positions coincide with each other, but the former is more essential for moving in the correct direction.
- (2) Required accuracy: Fine precision of localization, such as the minimum audible angle, is not required. On the other hand, front-back and left-right local-

ization errors should be avoided to prevent serious accidents such as falling onto a railway track.

- (3) User's state: It is necessary to assume that the users may listen to the auditory guide signal while walking. For this reason, dynamic localization cues are effective as well as static localization cues.
- (4) Use in public spaces: In public spaces, reverberation sound and background noise often disturb the listening and localization of an auditory guide signal. At the same time, it is also necessary to pay attention so that the signal does not increase noisiness and annoyance in the area.

Considering the above points, the research on the optimization of auditory guide signals based on sound localization tests with human listeners so far carried out by the authors and their colleagues are introduced in this review.

The contents of this review are as follows. Section 2 focuses on the dynamic localization cues generated by head movement mentioned in point (3) and describes the following two themes: whether or not people spontaneously move their heads during sound localization (Sect. 2.1), and the required temporal characteristics of the signal to utilize the head movement (Sect. 2.2). Section 3 focuses on the effect of disturbing sounds on

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the performance of signals mentioned in point (4), and describes the following two themes: the effects of disturbing sounds on the localization accuracy of signals actually used in public spaces (Sect. 3.1), and the interaction between the temporal characteristics of a signal and the decrease in localization accuracy owing to reverberation sounds (Sect. 3.2). Section 4 summarizes the optimization of signals based on the research introduced here.

2. EFFECTS OF HEAD MOVEMENT

Head movement during sound localization generates dynamic cues, and utilization of the cues significantly decreases the front-back localization error [1–5]. The front-back judgment based on the hypothesis by Wallach, that is, the judgment from the relative relationship between the temporal change of interaural differences and the rotation direction of the head, is effective even if the rotation angle is small. Furthermore, it is also effective when the signal is low-pass noise, which can only provide the interaural time difference.

As described above, accurate front-back judgement is critical for an auditory guide signal. In public spaces, a spectral cue, which is a cue of front-back judgment, is often not provided to users of an auditory guide signal because of masking by disturbing sounds and the narrow frequency range of the loudspeaker. It may be necessary to remove the high-frequency components of the signal to reduce its noisiness and annoyance. Furthermore, left-right judgment on the basis of interaural differences is robust against reverberation sound and background noise (see Sect. 3). Therefore, the dynamic cue generated by head movement is extremely important in the design of auditory guide signals.

2.1. Spontaneous Head Movement

Thurlow *et al.* [6] investigated types of head movement during sound localization, and reported that left-right rotation movements of the head, which provide the Wallach cue, were most commonly found. However, in their experiment, the instruction inferred the benefit of head movement during sound localization, so the listeners participated in the experiment with awareness of head movement. Here, one question arises. Can we premise that the users who are naive about sound localization spontaneously move their head during sound localization?

To clarify this question, we conducted experiments as follows [7]. A narrow-band noise from 150 to 500 Hz was radiated from one of twenty-four loudspeakers located every 15° in the horizontal plane. The noise continued until the listener indicated that judging the direction of the noise had finished by pressing a button. The listeners were not informed about head movements at all, and listened to the stimulus only once without any training.

Table 1 Conditions of four experiments conducted by Nojima *et al.* [7].

Condition	Experiment			
	1	2	3	4
Vision before stimulus presentation	No	Yes	No	Yes
Vision during stimulus presentation	No	No	No	Yes
Assumption of traveling	No	No	Yes	No

The listeners were university students with standard vision. Visual information of the loudspeaker arrangement was controlled with a blindfold. Table 1 shows the experimental conditions. The condition “vision before stimulus presentation” indicates whether or not the loudspeaker arrangement was visible to the listeners before the stimulus was presented. The condition “vision during stimulus presentation” indicates whether or not the loudspeaker arrangement was visible to the listeners during the presentation of the stimulus and the listener’s response. The condition “assumption of traveling” indicates whether or not the experimenter made the listeners assume that they traveled toward the perceived direction of the sound image. Sixty-eight, thirty-two, thirty-five, and thirty-six listeners participated in experiments 1, 2, 3, and 4, respectively.

The head movements of the listeners were recorded and analyzed in three dimensions by a motion capture system. The authors judged that a listener moved his/her head when the angle of rotation exceeded the minimum audible angle for each direction from which the noise was radiated. Figure 1 shows the occurrence rate of head movement in each experiment. The rates in experiments 1, 2, and 3 (around 20–30%) are significantly lower than that in experiment 4 (around 70%). Thus, although spontaneous head movements occur during sound localization, they do not always occur.

Fig. 1 Occurrence rate of head movement [7].

As shown in Table 1, the difference in the experimental conditions between experiments 1, 2, and 3 and experiment 4 is related to the vision during stimulus presentation. Namely, the arrangement of loudspeakers was visible to the subject during stimulus presentation and the subjects' response in experiment 4, but not in experiment 1, 2, or 3. The vision before stimulus presentation was unlikely to increase the occurrence rate in experiment 4, considering that the occurrence rate in experiment 2 was not significantly different from that in experiment 1. The occurrence rate depends on whether or not the loudspeaker arrangement was visible to the subject during stimulus presentation. When it is visible to the subject, the rate is high and vice versa. Furthermore, some of the subjects in experiment 4 reported that they tried to visually confirm which loudspeaker radiated the stimulus. From these findings, it can be inferred that listeners do not spontaneously move their heads very often to localize a sound image, but they do in order to identify which sound source radiates an acoustic signal.

2.2. Head Movement and Temporal Characteristics of a Signal

A reasonable stimulus duration is necessary to be able to utilize the dynamic cues generated by head movement. Vliegen and Opstal [8] found that it takes at least 200–300 ms for listeners to move their heads after hearing an acoustic signal. On the other hand, the results of Thurlow and Mergener [9], Perrett and Noble [3], and Iwaya *et al.* [5] demonstrated that at least 500 ms is required for listeners to utilize dynamic cues. Thurlow and Mergener stated that a duration of approximately 2 s is necessary to allow the effect of head movement but no significant difference appeared for durations longer than 1 s. Therefore, a stimulus duration of around 1–2 s can be considered as the minimum duration to utilize dynamic cues.

In the above basic studies, continuous noise with a certain duration was used. In this case, the temporal change of the interaural differences due to head movement is continuous while the stimulus is being presented. If this continuity is not a necessary condition for Wallach's cue to be effective, the signal can have intermittent temporal characteristics. This allows greater opportunities for auditory guide signal design.

To clarify whether or not Wallach's cue is still effective for sound localization of intermittent sound, we conducted the following experiments [10]. Figure 2 shows the temporal pattern of intermittent noise used in the experiments. The intermittent noises consisted of two short continuous noises with a duration of 200 ms and an interval between them. A continuous noise with a duration equal to the total duration of the intermittent noises was also used

Fig. 2 Temporal pattern of intermittent noise [10]. The total duration of a stimulus is $2T_1 + T_2$.

Fig. 3 Rates of correct judgment of source direction for continuous (C) and intermittent (I) noise [10].

as a test stimulus. Both noises were made from a narrow-band noise from 150 to 500 Hz.

The listener's task was to identify the sound source from twenty-four loudspeakers located every 15° in the horizontal plane. The experiments were conducted with the head of the listener both fixed and not fixed. For the condition of not fixing the head, the listeners were instructed to face the direction of the sound image by rotating their heads. The light of the test chamber was turned off during the presentation of the stimulus and the listener's response.

Figure 3 shows the rates of correct judgment of the source direction for each condition. The labels C and I indicate continuous and intermittent noises, respectively, and the numbers indicate the total duration of the noise. For example, C-200 represents continuous noise lasting 200 ms and I-1600 represents intermittent noise consisting of two 200 ms continuous noises with an interval of 1,200 ms between them. A listener's perceived direction was considered correct if it was within $\pm 22.5^\circ$ of the source loudspeaker, because the ability to distinguish eight directions can be assumed as practically affordable accuracy for guiding visually impaired persons to their destination.

First of all, under the condition of not fixing the head, the rates for I-800 and I-1600 were almost perfect as well as those for C-800 and C-1600. This means that the benefit of head movement for sound source localization remains

even if intermittent sound is used. However, the rates for I-800 and I-1600 did not exceed that of C-200 when the listener's head was fixed. In other words, even if the listener can obtain the same interaural difference twice, that information is not effective for sound source localization. These results indicate that, in sound source localization, it is important to obtain different interaural differences multiple times by head movement.

3. LOCALIZATION IN DAILY SOUND ENVIRONMENT

In the daily sound environment, there are multiple sound sources, and sounds with various intensity arrive from various directions. This tendency is further strengthened by sounds reflected from the boundary surface in rooms. The performance of an auditory guide signal in such an environment depends on how much the localization cues included in the direct sound from the sound source of the signal are disturbed by other sounds.

The sounds that disturb sound localization of the auditory guide signal are divided into reverberation sounds that originate with the signal and background noise composed of other sounds. Regarding the effects of background noise on sound localization, it was reported that the accuracy of sound localization decreased as the signal-to-noise ratio (SNR) decreased [11–13]. Furthermore, Good and Gilkey [11] and Abouchacra *et al.* [12] pointed out that the accuracy of front-back judgment was more degraded by background noise than that of left-right judgement.

Meanwhile, regarding the effects of reverberation sounds, Hartmann [14] reported that the accuracy of sound localization decreased with decreasing the ratio of the direct sound to reverberation sounds (DRR). The effects of background noise can be explained by masking in general, but in the case of reverberation sound, the mechanism becomes complicated because of the precedence effect or the law of the first wavefront. Specifically, it is known that not only DRR but also the arrival direction of early reflections [15] and the temporal pattern of the signal affect the sound localization [16,17].

Furthermore, reverberation sounds more severely degrade the interaural level difference (ILD) than the interaural time difference (ITD) [18]. This might also be the case when the disturbing sound is uncorrelated background noise, considering that ITD is obtained by the cross-correlation of binaural signals. This implies that low-frequency components will be more robust against reverberation sounds than high-frequency components if they are compared under the same SNR or DRR, which corresponds to the dominance of low-frequency ITD in the sound localization reported by Wightman and Kistler [19].

3.1. Effects of Background Noise and Reverberation Sounds on the Auditory Guide Signals Actually Used in Public Spaces

In Japan, a triangular wave with a sharp rise and gentle time decay (*ping-pong sound*) and artificial sounds simulating various birds singing are widely used as auditory guide signals. The authors examined the localization performances of these sounds in noisy and reverberant sound fields by carrying out listening tests [20].

In the first experiment, a total of fifteen loudspeakers were located in the horizontal plane to radiate the signal and disturbing sounds. Five steady-state and wideband noise samples, which were uncorrelated with each other, were presented from five of the loudspeakers at the same time. The A-weighted equivalent continuous sound pressure level (L_{Aeq}) of the noises was 60 dB at the listening position. The *ping-pong sound* was used as the test signal. Figure 4 shows the temporal pattern and spectrogram of the test signal. The first half of the signal was a 770 Hz triangle wave and the second half was a 660 Hz triangle wave. The presentation levels of the test signal were 55, 65, 75, and 85 dB in the A-weighted maximum of the binaural sound pressure level (BSPL) [21]. The test signal was presented from one of thirteen directions, which were spatially balanced in the front, back, left and right directions. Eleven listeners with normal hearing participated in the first experiment. The listeners were asked to indicate the perceived direction on a circle displayed on a PC monitor with a pointing device after a signal was presented. Lights in the experimental room were switched off and only the light from the PC monitor was present in the experimental room. During the listening tests, the listener's head was fixed.

Figure 5 shows the rates of correct judgment of the source direction and the rates of front-back reversal for each presentation level. A listener's perceived direction

Fig. 4 Temporal pattern and spectrogram of the *ping-pong sound*.

Fig. 5 Rates of correct judgment of source direction (open bars) and rates of front-back reversal (filled bars) for the *ping-pong sound* in noise [20].

was considered correct if it was within $\pm 22.5^\circ$ of the source loudspeaker. The rates of correct judgment increased with increasing presentation level, in other words, increasing SNR, and the trend was opposite for the rates of front-back reversal. Note that almost all localization errors were due to front-back reversal. This result coincides with those of Good and Gilkey [11] and Abouchacra *et al.* [12].

The setup and procedure for the second experiment were almost identical to those used in the first experiment, but the disturbing sound was altered to reverberation sounds. The reverberation sounds were uncorrelated and the first reflection was delayed by 5 or 160 ms from the direct sound. The delay of 160 ms was used to produce a sound image split. Four levels of DRR were used. The DRRs were controlled by using two reverberation times (1 and 4 s) and two reverberation strengths relative to the direct sound. See Ref. [20] for the details of the reverberation sounds. The *ping-pong sound* and artificial sparrow singing were used as the test signals. Figure 6 shows the temporal pattern and spectrogram of artificial sparrow singing. Compared with the *ping-pong sound*, the temporal fluctuation was large and quick, and it contained many

Fig. 6 As Fig. 4, but for artificial sparrow singing.

Fig. 7 Rates of correct judgment of source direction (upper panel) and rates of front-back reversal (lower panel) for *ping-pong sound* (open bars) and artificial sparrow singing (filled bars) under reverberation [20].

high-frequency components. The presentation level for the *ping-pong sound* was 65 dB in BSPL (A-weighted), and that for artificial sparrow singing was set to have the same perceived loudness. Twelve listeners with normal hearing participated in the second experiment.

Figure 7 shows the rates of correct judgment of the source direction and the rates of front-back reversal for the sound fields with a 5 ms initial reverberation delay, as an example. The rates of correct judgment under the condition without reverberation were around 90% for both signals. However, under reverberant conditions, the rates for artificial sparrow singing significantly decreased and were strongly affected by the reverberation strength, while those for the *ping-pong sound* remained around 80% regardless of the conditions. For the *ping-pong sound*, almost all localization errors were due to front-back reversal even under the reverberant conditions. On the other hand, for artificial sparrow singing, although the major error was front-back reversal, some left-right reversals were also found. These results clearly demonstrated that the temporal pattern of the signal affects the sound localization in reverberant sound fields.

3.2. Sound Source Localization of Intermittent Noise in Reverberant Sound Fields

The previous studies revealed that physical characteristics of the signal such as onset time and duration, and those of reflections such as direction, amplitude, and delay time affect the accuracy of sound localization. On the other

Fig. 8 Schematic of the stimulus used by Sato *et al.* [22]. Solid lines represent short continuous noises, and shaded areas represent reverberation sounds of the noises.

hand, our previous study introduced in Sect. 2.2 showed that the benefit of head movement for sound source localization remains even if intermittent sound is used. The intermittent sound can be expected to have higher DRR at the onset of sound, which is important in sound localization, than the continuous sound.

Sato *et al.* [22] investigated the localization accuracy of intermittent sounds in a reverberant sound field. Figure 8 shows a schematic time pattern of the stimulus. The stimulus was reverberated intermittent noises consisting of three short continuous noises and two intervals. T_1 and T_2 were the durations of the continuous noises and the intervals, respectively. The total duration, that is $3T_1 + 2T_2$, was constant at 1,600 ms, while T_1 was set at 50, 200, 400, and 500 ms. Therefore, T_2 for each T_1 was 725, 500, 200, and 50 ms, respectively. The short continuous noise was narrow-band white noise from 150 to 500 Hz. An uncorrelated reverberation sound field was used. The reverberation time was 4 s in the frequency range of the stimulus. The direct sound was emitted from one of seven loudspeakers in the horizontal plane, while uncorrelated reverberation sounds were emitted with 5 ms delay relative to the direct sound. The peak amplitude of the reverberation sound relative to the direct sound was set at -25 dB. The presentation level for the stimulus was 65 dB in BSPL (A-weighted). Two university students with standard vision participated in the localization test. They were blindfolded upon entering and exiting the test chamber. Furthermore, thin felt fabric was installed to hide the loudspeaker arrangement from the listener. The listener's head was not fixed. The listeners were instructed to face to the direction of the perceived sound image.

Figure 9 shows the rates of correct judgment of the source direction for each listener. A listener's perceived direction was considered correct if it was within $\pm 22.5^\circ$ of the source loudspeaker. The time pattern of the stimulus was expressed using a format such as 50(725)50(725)50, which corresponds to $T_1 = 50$ ms and $T_2 = 725$ ms. Although there were individual differences, especially for

Fig. 9 Rates of correct judgment of source direction for each stimulus and listener [22].

stimulus (c), the rate usually decreased with decreasing T_2 . This indicated that the rate was proportional to DRR at the onset of each short continuous noise and decreased with decreasing T_2 . If the listeners could obtain the interaural differences at the onsets intermittently, they could localize the stimulus with the help of head movement.

Figure 10 shows ITD for each time pattern of the stimuli in the case that the direct sound was presented from the right side. The ITDs were measured using a KEMAR dummy head facing the front direction, and were obtained for each time window, which was shifted in 1 ms steps. The duration of the time window was constant at 100 ms. A dashed line represents ITD for a steady state and not reverberated noise with the same frequency characteristics as the stimuli. For 50(725)50(725)50, the peaks of ITD at all of the onsets of short continuous noise were almost equal to those for a steady state and not reverberated noise. Meanwhile, for other time patterns, the second and third peaks decreased and blurred with decreasing T_2 . The blurred peaks of ITD would prevent the listener from obtaining different ITDs multiple times by head movement and would decrease the rates of correct judgment. Also, if we consider this in reverse, the peak height of ITD can be used as an indicator to optimize the time patterns of auditory guide signals.

4. CONCLUSION

Previous studies and our studies revealed that it is very important to reduce the front-back reversal by head movement in the localization of auditory guide signals. Unfortunately, however, our study [7] demonstrated that people do not always move their heads spontaneously during sound localization. Although our experiments were conducted with sighted listeners, in another experiment [23] where visually impaired participants actually walked with an auditory guide signal, most participants also judged

Fig. 10 ITD for the stimuli used by Sato *et al.* [22] in the case that the direct sound was presented from the right side.

the direction of the signal without moving their head. Therefore, it is necessary to educate users of auditory guide signals on the importance of head movement in sound source localization.

Concerning the optimization of auditory guide signals, the following can be suggested from the studies introduced in this review.

Regarding frequency characteristics, an auditory guide signal should include a component of a low-frequency band to provide ITD. This is because ITD is more robust against disturbing sound than other localization cues and is important in the dynamic cues generated by head movement. Our study [10] demonstrated that narrow-band white

noise from 150 to 500 Hz can achieve almost perfect sound source localization. Needless to say, it would be better if the signal includes high-frequency components, which provide the spectral cue for front-back discrimination.

Regarding temporal characteristics, a certain duration of the signal is required to utilize the dynamic cues generated by head movement. On the basis of our study [10], the minimum duration is around 800 ms. However, the same study showed that the temporal characteristics of the signal do not have to be continuous, and intermittent sounds can also achieve almost perfect sound source localization. Furthermore, another study carried out by the authors [22] showed that intermittent sounds are robust against the disturbance of reverberation sounds.

ACKNOWLEDGMENT

We express our gratitude to everyone who cooperated in the studies introduced here. This work was partially supported by JSPS KAKENHI Grant Numbers 1730019, 21300214, and 25282182.

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