PAPER

Comparison of obstacle sense ability between the blind and the sighted: A basic psychophysical study for designs of acoustic assistive devices

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Abstract: The ability by which the blind can recognize objects around them solely by hearing is called “obstacle sense.” By analyzing and modeling the mechanism of this sense, the resultant model could be utilized in new concepts for blind mobility aids as well as training methods. In this paper, we first conducted a comparative experiment regarding coloration perception between the blind and the sighted. In the experiment, subjects are asked to answer whether two successive sounds with a different dip-to-dip interval are perceived to be same by means of two alternative forced choices. The results show no significant difference in discrimination between the two groups; the blind and the sighted. Next, “impressions” elicited by the sounds with various dip-to-dip intervals are analyzed on the two groups using the Semantic Differential Method (SDM). The results indicate that the sighted tend to focus mainly on the quantitatively represented changes such as pitch and loudness of the sounds, while the blind are inclined to focus not only on the quantitative sound change, but also on qualitative impressions in the sound changes. Since it is assumed that the qualitative impressions are related to distances of the obstacles from the blind, third, we carry out a comparative experiment regarding the obstacle-distance perception. The result indicates that the blind can more exactly answer the obstacle-distance than the sighted. From the results of the three experiments and past studies, we discuss whether the obstacle sense is formed in the peripheral process or in the central process of the auditory nervous system, and then we propose new concepts for blind mobility aids as well as the obstacle sense training method.

Keywords: Obstacle sense, Blind, Coloration, Ripple noise, DL, Semantic Differential Method

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1. INTRODUCTION

A large number of special education methods [1] and blind mobility aids [2–6] have been proposed to help the blind in walking and in carrying out other routine activities. Walking training is divided into two phases: “orientation” that is involved in awareness of one’s position in the environment; and “movement” that is involved in movement toward one’s direction [1]. Although the blind cannot use their visual sense, it is known that most of them can localize themselves in the environment by using “obstacle sense,” which is the ability that enables them to perceive objects solely by hearing [1,7–10]. It has been reported

that some auditory-enhanced blind people can detect an object’s existence, and also can estimate its distance, size and shape [11–14]. We have analyzed the auditory mechanism of the obstacle sense based on psychophysical experiments and acoustic signal processing methods in order to propose a new blind mobility aids. Our concept of the mobility aids is to positively utilize the obstacle sense, different from conventional mobility aids that rather prevent the blind from using their obstacle sense ability [2].

In this paper, first, we present an overview of previous studies on obstacle sense. This ability was introduced, by Diderot in 1749, as “amazing ability” of a blind to judge accurate distance of the object from him as well as to perceive the presence of object without visual information [15]. Many cases and theories related to this ability had been reported since the publication of his account. Hayes summarized these theories into three groups such as

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sensory, perceptual, and occult theories [16]. The sensory theories postulate a enhanced response of some organs of sense such as the sense of a face for pressure or temperature, of tympanic membranes in the ears for pressure, or of audition in the increased discrimination and analysis of the sound. The perceptual theories include the interpretation of sensory cues derived from the action of the air- or sound-waves on the skin or aural mechanisms. The occult theories explain this phenomenon is related to the action of vestigial organs in the skin and of the subconscious caused by magnetism, electricity, vibration of the ether or some their hypothetical substance. These hypotheses were organized on the basis of introspection by the blind as two theories; sense of the skin and of the auditory by Supa *et al.* [7].

Supa *et al.* also performed systematic studies of obstacle sense among the blind. They reported that the factor behind obstacle sense was not due to skin sensation, but resulted from auditory stimuli [7], in which the stimuli of the external ear were not important [8]. Cotzin *et al.* reached the assumption that auditory stimuli-induced obstacle sense was caused by sounds reflected from the obstacle [9]. Seki *et al.* particularly focused on “acoustic coloration,” which is caused by the interference between the direct sound and the reflected sound from the obstacle. They reported that the change in pitch resulting from the acoustic coloration is an essential factor in perceiving the distance from the subject to the object [10]. This interference makes sound nearly equal to comb-filtered direct sound. In a comb-filter, the dip-to-dip distance in frequency region is defined as the dip-frequency interval, which changes depending on the distance between the subject and the obstacle [18].

It also has been reported that comb-filtered sound produces pitches (sometimes referred to as repetition pitches) similar to residue pitches or missing fundamental pitches [19–25]. In particular, Yost *et al.* precisely investigated the characteristics of comb-filtered noise, and they referred the noise as ripple noise. It is reported that the ripple noise has a matched pitch equal to the reciprocal of the delay [20]. They reported that a transformation of the ripple noise spectrum based on a peripheral weighting function produces a consistent spectrum pattern as repetition pitch and pitch strength [19]. Ando showed that the perception of coloration in continuous sound fields results from the autocorrelation function of the signal in the short delay range of a weak sound [26]. Kates proposed a central auditory spectrum processing model for coloration perception in ripple noise [27]. Krumbholz investigated the salience pitch associated with a ripple noise when interaural time and level differences occur [28]. Although these results and assumptions only explain the common perception of a complex sound pitch, they cannot explain how this perception contributes to obstacle sense of the blind.

On the other hand, our approach is to investigate how the pitch perception of the ripple noise contributes to obstacle sense for both the blind and the sighted in order to clarify the auditory mechanism differences between the two. Furthermore, our goal is to construct a training method of the obstacle sense for the blind and also design a blind mobility aid that positively use the obstacle sense ability. If the blind are superior to the sighted in terms of pitch discrimination ability of ripple noise, they have an advantage to acquire the obstacle sense on a level of timbre discrimination that would be realized in the peripheral auditory system. In contrast, if the sighted have the same discrimination ability as the blind, it would be possible for them to acquire the obstacle sense only using auditory stimuli such as intensity, reflected sounds, coloration and other kinds of sound characteristics [9,10,14,17].

In this paper, we first conducted a comparative experiment regarding coloration perception between the blind and the sighted. In the experiment, subjects are asked to answer whether two successive sounds with a different dip-to-dip interval are perceived to be same by means of two alternative forced choices. The results show no significant difference in discrimination between the blind and the sighted. Next, “impressions” elicited by the sounds with various dip-to-dip intervals are analyzed on the two groups using the Semantic Differential Method (SDM). The results indicate that the sighted tend to focus mainly on the quantitatively represented changes such as pitch and loudness of the sounds, while the blind are inclined to focus not only on the quantitative sound change, but also on qualitative impressions in the sound changes. Since it is assumed that the qualitative impressions are related to distances of the obstacles from the blind, third, we carry out a comparative experiment regarding the obstacle-distance perception. The result indicates that the blind can more exactly answer the obstacle-distance than the sighted. From the results of the three experiments and past studies, we discuss whether the obstacle sense is formed in the peripheral process or in the central process of the auditory nervous system, and then we propose new concepts for blind mobility aids as well as the obstacle sense training method.

2. COLORATION

A timbre by coloration is caused by the interference between two surrounding sounds around a subject [29]. One is a surrounding sound directly transmitted to the subject’s ears, the other is a reflected sound from obstacles existing in the same surroundings. A time delay between the two sound waves at the subject’s ears forms a comb-like spectral pattern with dips. The frequency difference between the dips is a reciprocal of the time delay. Therefore, the coloration is an important information cue

Fig. 1 An example of spectrum patterns with periodical dips that cause acoustic coloration ($A = 1$, $T = 3$ ms).

for identifying the distance from the obstacle to the subject [18]. A spectral amplitude of a synthesized sound wave consisting of direct and reflected sound wave $|H(f)|$ is expressed by:

$$|H(f)| = \sqrt{1 + A^2 + 2A \cos 2\pi fT} \quad (1)$$

where f , A , and T stand for frequency, reflectivity coefficient of obstacle, and arrival-time interval between the direct and reflected sound, respectively. Figure 1 is an example of visual representation for (1).

Here, the dip-to-dip interval in the spectrum is defined as the dip-frequency interval Δf_d , the relation between Δf_d and the distance from obstacle d is:

$$d = \frac{c}{2\Delta f_d} \quad (2)$$

where c stands for sound velocity. The relationship between the obstacle distance from an arbitrary position and dip-frequency intervals is shown in Fig. 2. In the experiments described below, we especially focus on the discrimination threshold of Δf_d and acoustic impressions regarding the change in Δf_d .

(1) is the same equation as the frequency response of the comb-filter. Thus, sound waves caused by the coloration can be generated by applying a comb-filter to a signal. In the real world, the blind can recognize the coloration by listening to the surrounding noise. Thus, we use the comb-filtered noise, which is known as ripple noise [19,20,24]. It has been reported that the ripple noise has a matched pitch equal to the inverse of the time delay, and produces pitches (sometimes referred to repetition pitches) similar to residue pitches or missing fundamental pitches [20,25].

3. DISCRIMINATION EXPERIMENT FOR THE CHANGE OF DIP-FREQUENCY INTERVAL

3.1. Subjects

Six congenital visually impaired people aged 23–34 years old participated in the following experiments. Two of them are congenitally blind, the other four are acquired blind. Acquired blind subjects congenitally had visual

Fig. 2 Dip-frequency interval change in relation to the distance between the obstacle and the observation point.

Fig. 3 Experimental protocol for discrimination of spectrum with different Δf_d . Sound 1 (f_d) varies in the range of 50, 60, 100, 200, 300, 400, 500, 600 and 1,000 Hz, while Sound 2 changes in the range of $0, \pm 0.1, \pm 0.2, \pm 1, \pm 2, \pm 5, \pm 10, \pm 20, \pm 50$ Hz around Sound 1.

disorders such as amblyopia and had been depended on as well as visual information before getting totally blind in midstream. Of the six, four are totally blind, while two can only recognize the existence of light stimuli. Four are males and two are females. As the sighted control group, four males and two females aged 23–42 years old participated in the experiment. All of the subjects have normal hearing; within normal limits (-20 dB HL) as defined by pure-tone audiometry. In addition, experimenter explains the contents of the experiment to subjects and all subjects agree to participation.

3.2. Methods

Before the experiment starts, we asked the subjects to put on headphones and adjust the sound to a comfortable level. Then, two successive sounds are presented at the time sequence as shown in Fig. 3. Sound 1 of Δf_d varies in the frequency range of 50, 60, 100, 200, 300, 400, 500, 600 and 1,000 Hz, while Sound 2 varies $0, \pm 0.1, \pm 0.2, \pm 1, \pm 2, \pm 5, \pm 10, \pm 20, \pm 50$ Hz around Sound 1. These sounds are comb-filtered white noises (frequency range: 20 Hz ~ 20 kHz). Sounds like white noise are ordinarily existing in the real acoustic environment and these sounds result in lower localization errors than sinusoidal sounds [30]. The experiment is performed based on a two-alternative forced choice task, and the subjects are asked to answer whether the two sounds are same or not by inputting 0 or 1 via a keyboard. In addition, the subjects are asked to inform their mistyping so that typing errors are corrected by the experimenter and are asked to close their eyes in experiment for concentrating on the series of stimuli.

Fig. 4 Discrimination results of dip-frequency interval (Δf_d) changes as a function of Δf_d . The top graph shows the data in the case of an increase in dip-frequency interval; the bottom graph shows those in the case of a decrease. The results show very few differences between the blind and the sighted.

The experiment is composed of 20 sets for training and 200 sets for actual tests. In actual tests, set of Δf_d in sound 1 consists of above-mentioned nine and randomly-selected one frequency range (total: 10 sets). Series of randomly-selected one stimuli are firstly presented but count out from the result. Whereas, sound 2 varied 0 (4 times), $\pm 0.1, \dots, \pm 50$ Hz around sound 1 (total: 20 sets).

The difference limen is defined as over 75% in the accuracy ratio for each set of Sound 1 and Sound 2, and determined by linear approximation.

3.3. Results

Figure 4 shows the result of the Δf_d discrimination test represented by DL (difference limen) between the blind and the sighted. The top graph shows the result in the case of a Δf_d increase around the frequency of Sound 1; the bottom graph shows the result in the case of a Δf_d decrease. These graphs show there is little difference in Δf_d change discrimination between the blind and the sighted. In addition, the discrimination difference between the increase and the decrease of the dip-frequency interval is properly observed over 600 Hz in the dip-frequency interval of Sound 1.

Figure 5 shows the perceivable distance ratio between the corresponding distance change to difference limen for the dip-frequency interval and the distance from the obstacle by blind subject group; the result of sighted group is almost same. The perceivable corresponding distance

Fig. 5 Differentiable distance ratio between the corresponding distance change to difference limen for dip-frequency interval of the blind and the distance from the obstacle. The continuous line plots the case of a dip-frequency interval increase; the dotted line plots the case of a decrease.

ratios to the DL of increasing and decreasing dip-frequency intervals are $0.960 \sim 0.984$ (Mean: 0.978, S.D.: 0.00858) and $1.013 \sim 1.037$ (Mean: 1.027, S.D.: 0.00896), respectively in the blind, and $0.966 \sim 0.990$ (Mean: 0.977, S.D.: 0.0104) and $1.014 \sim 1.053$ (Mean: 1.027, S.D.: 0.0113) in the sighted.

3.4. Discussion

The results shown in Fig. 4 suggest there is little difference between the blind and the sighted in difference limen for dip-frequency difference interval. Bross and Borenstein reported almost the same hearing-threshold levels for the blind as for the sighted [31]. Starlinger and Niemeyer found there is no significant difference in perception of loudness and frequency changes between the sighted and the blind [32]. Benedett and Loeb also found no significant difference in basic auditory sensitivity between the two groups [34]. Thus, it is ascertained that there is no significant difference in peripheral auditory function regarding the dip frequency discrimination between the blind and the sighted. In addition, the superiority of the blind in obstacle sense is mainly caused not by sensory compensation, but by perceptual compensation, which is influenced by continuous auditory training [12,33–35]. Therefore, it is likely that auditory obstacle sense likewise results from sensitization not of the peripheral nervous system but of the central nervous system.

Figure 4 shows that the discrimination difference between the case of the increase and the decrease in the dip-frequency interval is observed over 600 Hz, especially 1,000 Hz, in the dip-frequency interval of Sound 1. This is because, as Bilsen and Ritsma point out, pitch sensation degrades rapidly for two sound intervals at shorter than

1.25 ms, or longer than 20 ms [25]. The 20 ms in time delay means approximately 600 Hz in dip-frequency interval.

Figure 5 shows that the perceivable distance ratio to the dip-frequency interval is almost constant. This indicates that an instantaneous $\pm 3\%$ change in the dip-frequency interval may give subjects a sensation of objects moving. However, the impression of tone coloration may not be the same between the blind and the sighted. Thus subjects other than the auditory-enhanced blind need to train to recognize obstacles by means of auditory stimuli.

4. IMPRESSION ANALYSIS OF TIMBRE CHANGE ACCOMPANIED BY OBSTACLE DISTANCE CHANGE

The preceding section shows that the blind and the sighted are the same in difference limen with regard to a change in the dip-frequency interval. However, the blind can practically recognize the direction of loudspeakers [35] and the existence of surrounding obstacles [36] more acutely than the sighted. This superiority results not from the peripheral sensation process, but from the central perception process of timbre change. This process of perception emerges as a psychological impression. Therefore, it is hypothesized that subjective impressions regarding timbre change among the blind differs from that among the sighted. The acoustic factors of the obstacle sense may be determined by a difference of impression between the two groups. In this section, we carry out an impression analysis among the blind and the sighted using the Semantic Differential Method (SD method).

4.1. Subjects

Six congenital visually impaired people aged 22–33 years old participated in the experiment. Five are congenitally blind, the other is acquired blind. Acquired blind subjects congenitally had visual disorders such as amblyopia and had been depended on as well as visual information before getting totally blind in midstream. Five are totally blind, the other can only recognize the existence of light stimuli. Four are males and two are females. As the sighted control group, two males and four females aged 23–42 years old participated. Sighted subjects forced to be blindfolded during this experiment. All of the subjects have normal hearing; within normal limits (-20 dB HL) as defined by pure-tone audiometry. In addition, experimenter explains the contents of the experiment to subjects and all subjects agree to participation.

4.2. Method

As shown in the experimental setup in Fig. 6, the obstacle (a wooden board measuring $50 \times 70 \times 0.24$ cm) is placed 8.0 m away from the loudspeaker (TANOI system800) in a semianechoic chamber (size: $6.0 \times 6.0 \times$

Fig. 6 Experimental setup of the impression analysis of timbre change.

6.0 m, background noise level: 30 dB). Two markers are positioned at Points A and B (A is nearer to the loudspeaker than B) between the loudspeaker and the obstacle to inform the subject of the starting and stopping positions. The combinations used for Points A and B are 6 m–3 m, 3 m–0.3 m and 6 m–0.3 m. According to the findings of a series of studies, approximately 3 m from the obstacle is defined as the position of “first perception,” while approximately 0.3 m is defined as “final appraisal” [7,9]. This experiment is designed to investigate the impression change when a listener approaches these two positions.

The experimental procedure is as follows: First, a subject is placed at Point A, facing the obstacle. Second, white noise is played over the loudspeaker (volume: hearing level + 30 dB). Third, the subject is asked to walk to Point B. The subject then evaluates the impression of timbre change by the adjective scales as shown in Table 4 on a scale of -3 to 3 ; scale 0 should not be rated as “little as possible.” These adjective scale sets A-B mean $-$ to $+$ direction, e.g. “deep” corner means minus side, while “metallic” means plus side in the case of “deep-metallic.” The authors picked these adjective scales in reference to Namba’s study [37,38]. The order of combination of Points A and B is randomized for each subject. Subjects are allowed to walk back and forth toward the obstacle and to listen to the sound as they like: the average of task-elapsed time was approximately one minute. The experiment consists of 1 set for training and 2 sets in each condition (totally 6 sets) for the actual tests.

The evaluation results are processed by factor analysis based on the SDM. On the assumption of a dependence among factors for each other, either a maximum-likelihood method or a Promax rotation are applied for factor-extraction and rotation, respectively. After finishing their tasks, the subjects are asked to describe their feelings as to the sound impression change and evaluation criteria.

Fig. 7 Semantic profiles for blind and sighted groups.

Table 1 Eigenvalues of factor analysis.

Factors	Eigenvalue (Sighted)	Eigenvalue (Blind)
1	4.652	6.455
2	2.775	2.932
3	1.811	1.106
4	1.139	0.887
5	0.777	0.513

4.3. Result

The mean semantic profiles for blind and sighted groups in three conditions shown in Fig. 7 indicated that the evaluation tendency of the blind were similar to that of the sighted with the exception items such as “calm-shrill” and “harmonic-d discordant.”

The corresponding eigenvalues to the number of factors are shown in Table 1. The number of factors with an eigenvalue greater than 1, are 4 in the sighted and 3 in the blind. However, because a great deal of researches for timbre impression discuss cases with 3 factors [38–40], similarly we also discuss cases of 3 factors.

The factor-pattern matrix and factor-correlation matrix of the sighted are shown in Tables 2 and 3, respectively. Cronbach’s α for the scales in this group equals to 0.7052.

Adjective scales that are highly related to Factor 1 are “weak-strong,” “powerful-unsatisfactory,” “annoying-quiet” and “harmonic-d discordant.” Thus, this factor can be interpreted as the factor of “powerful” factor that is quantitatively represented. Factor 2 shows high loadings for “matte-mellow,” “clear-thick” and “beautiful-ugly.” This factor can be called the factor of “cleanness.” The third-factor-related adjective scales are: “calm-shrill,” “dark-bright,” “gentle-hard,” “deep-metallic,” and “distinct-dull.” This factor can be termed the “metallic” factor.

Table 2 Factor-structure matrix (sighted group).

Adjective scale	Factor		
	1	2	3
weak-strong	<u>−0.916</u>	0.017	0.243
powerful-unsatisfactory	<u>0.856</u>	−0.293	−0.066
annoying-quiet	<u>0.822</u>	−0.068	−0.238
harmonic-d discordant	<u>−0.522</u>	−0.138	0.365
matte-mellow	0.156	<u>0.986</u>	−0.058
clear-thick	−0.162	<u>0.779</u>	0.151
beautiful-ugly	−0.221	<u>0.777</u>	−0.169
clam-shrill	0.038	0.393	<u>0.738</u>
dark-bright	0.360	0.039	<u>−0.728</u>
gentle-hard	−0.440	−0.111	<u>0.663</u>
deep-metallic	−0.205	−0.278	<u>0.658</u>
distinct-dull	0.475	−0.203	<u>−0.523</u>
rich-poor	0.176	0.051	−0.019
Proportion of variance explained [%]	38.053	23.216	13.406

Table 3 Factor-correlation matrix (sighted group).

Factor	1	2	3
1	1.000	−0.023	−0.094
2	−0.023	1.000	0.001
3	−0.094	0.001	1.000

These tendencies are the same as in many studies such as Sone’s and Namba’s [38,39].

The factor-pattern matrix and factor-correlation matrix of the blind are shown in Tables 4 and 5, respectively. Cronbach’s α for the scales in this group equals to 0.7075.

Adjective scales that are highly related to Factor 1 are “deep-metallic,” “calm-shrill,” “dark-bright,” “weak-strong,” “powerful-unsatisfactory,” “annoying-quiet” and “beautiful-ugly.” This factor can be termed the factor of “sound timber” that can be only qualitatively represented. Furthermore, it includes the main related scales of all factors in the sighted group: “weak-strong,” “powerful-satisfactory” and “annoying-quiet” corresponds to Factor 1 of the sighted, “beautiful-ugly” corresponds to Factor 2 of the sighted and “deep-metallic,” “calm-shrill” and “dark-bright” corresponds to Factor 3 of the sighted. Factor 2 shows high loadings for “rich-poor,” “matte-mellow” and “harmonic-d discordant.” This factor can be interpreted as sound’s “harmonic” factor because a sound’s harmonics change in the case of the high sound’s coherence. The third-factor-related adjective scales are: “gentle-hard” and “distinct-dull.” This factor can be termed the “intelligibility” factor. The results indicate that the sighted tend to focus mainly on the quantitatively represented changes such as pitch and loudness of the sounds, while the blind are inclined to focus not only on the

Table 4 Factor-pattern matrix (blind group).

Adjective scale	Factor		
	1	2	3
deep-metallic	<u>0.846</u>	0.059	0.137
calm-shrill	<u>0.791</u>	0.027	0.213
dark-bright	<u>0.785</u>	−0.389	0.182
weak-strong	<u>0.780</u>	0.027	0.532
powerful-unsatisfactory	<u>−0.769</u>	−0.140	−0.466
annoying-quiet	<u>−0.760</u>	−0.352	−0.331
beautiful-ugly	<u>0.652</u>	0.579	−0.019
rich-poor	−0.148	<u>0.908</u>	−0.183
matte-mellow	0.065	<u>−0.897</u>	−0.096
harmonic-discordant	0.234	<u>0.699</u>	0.217
gentle-hard	0.345	0.256	<u>0.872</u>
distinct-dull	−0.435	−0.023	<u>−0.703</u>
clear-thick	−0.055	−0.049	0.344
Proportion of variance explained [%]	49.656	22.552	8.506

Table 5 Factor-correlation matrix (blind group).

Factor	1	2	3
1	1.000	−0.030	0.065
2	−0.030	1.000	0.044
3	0.065	0.044	1.000

quantitative sound change, but also on qualitative impressions in the sound changes.

4.4. Discussion

For both the sighted and the blind group, the extracted factors are the same and are different from the conventional studies such as [38,41]. The blind may be different in terms of what kind of sound characteristics they focused upon.

Factors 2 and 3 in the blind group are termed the factors of harmonics and intelligibility. In this experiment, white noise as a stimuli resulted in the generation of ripple noise due to the interference of direct sound and reflected sound from an obstacle. Increasing the dip-to-dip interval in the frequency response of ripple noise corresponding to the approaching obstacle raises the harmonic tonal pitch referred to as “repetition pitch” [19]. Thus, the reason for the extraction of a harmonics factor is that the blind focused on the repetition pitch of coloration, which is related to obstacle distance.

However, the extraction of the intelligibility factor may be caused by the less ambiguous presence of obstacle as the subject approaches the obstacle. Approximately 3 m from the obstacle is defined as the position of “first perception,” while approximately 0.3 m is “final appraisal.” The former and latter positions are the points for starting to perceive the existence of an obstacle and for predicting contact with the obstacle when approaching it, respectively [7,9].

In addition, Kate applied the perception of coloration in filtered Gaussian noise to the central spectrum model [27]. Kate reported that maximum sensitivity occurs for delays at 2 ms: the obstacle-to-subject distance at about 0.3 m: the position of final appraisal. Bilsen reported an experiment using an analog noise generator with a tape-loop delay device to realize comb-filters and got a similar result [25]. They also indicated that pitch sensation degrades for two sound intervals longer than 20 ms: the position of first perception. In other words, one of the main reasons the blind can perceive it is dangerous to approach nearer to an obstacle is because coloration is at its highest sensitivity at final appraisal. Thus, the factor of intelligibility is related to the impression of obstacle unambiguity as determined by a change in timbre of coloration.

As a result, the following factors are obtained in the experiment; factors of “power,” “cleanness” and “metallic” among the sighted, and factors of “sound timber,” “harmonics” and “intelligibility” among the blind. Thus, the sighted tend to focus mainly on the quantitatively represented changes such as pitch and loudness of the sounds, while the blind are inclined to focus not only on the quantitative sound change, but also on qualitative impressions in the sound changes.

Abe *et al.* carried out a factor analysis for the perception of environmental sounds with adjective scales of feeling associated with sound and information of sound such as spatial characteristics, as well as adjectives describing sound quality [42]. They obtained the factors of not only cleanness, brightness (almost synonymous with metallic), and quantity (almost synonymous with potency), but also factors related to localization information, sound-source information, and the importance of existence and memory. Some investigators found a better ability among the blind for localization in the horizontal plain of signals and obstacles [11,12,35]. Our study did not employ these adjective scales for the spatial information of sounds, but factors of localization information and sound-source information could be highly related to the sound impression that concerns obstacle sense by the blind. Since it is assumed that the qualitative impressions are related to distances of the obstacles from the blind, we carry out a comparative experiment regarding the obstacle-distance perception.

5. EXPERIMENT OF AUDITORY DISTANCE PERCEPTION

The preceding section discusses matters what plays the main role in the process of obstacle sense: peripheral nerves, or the central nervous system. In this section, we tried to observe the reflection of the central process to the obstacle sense by carrying out an experiment regarding distance perception in the blind and the sighted. The

purpose of this section is to ascertain that the blind can more exactly answer the obstacle-distance than the sighted because the blind have more cues for recognition of there surroundings than the sighted.

5.1. Subject

Four congenital visually impaired males aged 23–33 years old participated in the experiment. Three are totally blind, and one can only recognize the existence of light stimuli. One male and four females aged 18–23 years old participated as the sighted control group. All of the subjects have normal hearing; within normal limits (-20 dB HL) as defined by pure-tone audiometry. Before starting the experiment, all of the subjects put on an eye mask and wear an ear muff to shut out visual and auditory information. In addition, experimenter explains the contents of the experiment to subjects and all subjects agree to participation.

5.2. Experimental Setup

The experimental arrangement is shown in Fig. 6, apart from the fact that the markers are removed and a thick blanket is laid over the floor between the loudspeakers and the obstacle to prevent the subjects from hearing their own footsteps. The obstacle is a $50\text{ cm} \times 70\text{ cm} \times 24\text{ mm}$ (width $\times$ height $\times$ thickness) wooden board that is placed to the front of the subject at the same height as the center height of the subject's head and the obstacle. Subject stood at the center of the chamber or started to walk from the center in each trial. The distance of the obstacle from the subject was variable. Subjects could set the sound intensity of the loudspeaker at a comfortable level ($45 \sim 60$ dB SPL) at the beginning of the experiment.

5.3. Method

Before starting each trial, an experimenter moves the obstacle to default position; at a distance of 1 m, 2 m, 4 m, or 6 m from the obstacle. First, a white noise (frequency range: $20\text{ Hz} \sim 20\text{ kHz}$) is generated from the loudspeaker, and then the subject takes an ear muff off and try to walk to the half distance as far as the default position. For example, the subject tries to move to 2.0 m from the obstacle when an experimenter asks the subject to start moving, when the default position is 4.0 m from the obstacle. At that time, the subject are allowed to move back and forth while walking, but not allowed to produce sounds such as footsteps and vocal utterances. Then, the experimenter checks his arrival distance from the obstacle and requests the subject to wear an ear muff again. Before going on to the next trial, obstacle distance is changed by the experimenter.

The experiment was composed of 2 sets for training and 24 sets for actual test.

Fig. 8 Results of arrival distance from the obstacle. Marks for the blind and the sighted groups are plotted at ± 0.05 m points from the setup of the experimental configured distance transverse to each other to facilitate visualization. The dotted line represents the goal distance between the subject and the obstacle.

Fig. 9 Ratio of arrival and goal distance in relation to the goal distance from the obstacle. Marks for the blind and the sighted groups are plotted at ± 0.05 m points from the setup of the experimental configured distance transverse to each other to facilitate visualization. The dotted line represents the goal distance between the subject and the obstacle.

5.4. Result and Discussion

The arrival distances from the obstacle for the blind and the sighted groups are shown in Fig. 8. The sighted group localized a further distance than the goal distance when the goal distance was within and equal to 1.0 m, while it achieved a nearer distance when the goal distance was more than and equal to 2.0 m. The blind group localized a generally further distance than the goal distance. In addition, a remarkable variability in distance localization was observed in the sighted group, especially within and equals to 1.0 m of the goal distance.

Figure 9 shows the ratio of arrival and goal distance in relation to initial distance from the obstacle. The blind group localized a position whose ratio from the goal distance remained constant.

The result of arrival time for a subject reaching the required position as illustrated by Fig. 10 shows that the blind took less time to localize than the sighted.

Fig. 10 Arrival time of subject's reaching the required position for the blind and the sighted groups.

Localized distance for the sighted group as shown in Figs. 8 and 9 are almost the same as that for the sighted group, as reported by Rosenblum [43]. The tendency for a decrease in the distance ratio as against an increase the goal distance among the sighted is due to the inconsistency of relying on which of two localization cues (acoustical or somatosensory) for the obstacle. However, the blind localized less variably in the distance ratio as shown in Fig. 9 because they consistently depended on one acoustical cue: coloration caused by ripple noise. They stopped a little bit further than the goal distance. This phenomenon might be caused by a habitually conscious act to avoid danger.

6. GENERAL DISCUSSION

The results of the first two experiments as mentioned at sections 3 and 4 show that there is no significant difference in the peripheral nervous system between the sighted and the blind, but that there are differences in the central process such as obstacle localization using acoustic cues. This central process results from the training of the spatial hearing because of the long-time complete deprivation of visual sense. Rauschecker found that binocularly deprived cats improve their auditory localization, and that their anterior ectosylvian visual areas are taken over by auditory inputs: auditory spatial tuning in the visual cortex is observed [44]. Lessard *et al.* reports that blind people with residual peripheral vision localize sounds less accurately than both the sighted and the total blind [45]. Thus, the development of auditory obstacle perception might be dependant on the complete deprivation of eyesight.

We now specifically discuss the role of the central process in the obstacle sense. It has been reported that higher activity in the striate and prestriate cortical areas is observed with the activation of the lateral cortex among the blind than among blindfolded sighted in auditory tasks [46–48]. Some investigators found that early blind people can localize azimuth with equal or higher accuracy, while they can localize elevation less accurate than the sighted [49,50]. Zwiers *et al.* successively stated that auditory localization for elevation needs optimal calibration to

elevation-related spectral pinna cues, while azimuth localization can be calibrated without vision information [50]. Lewald *et al.* reported the posterior parietal cortex is specifically involved in azimuthal angles of sound and is a part of the “where” stream in the cortical processing of auditory information [51]. In our second experiment, an “intelligibility” factor was extracted from the blind group, which was caused by the following process after perceiving a timbre change. Thus, this factor is probably related to the visual and posterior parietal as well as auditory cortices.

The blind localize more constant in the distance ratio of obstacle and subject, and take a shorter time than the sighted, as shown in Figs. 9 and 10. This differences also probably results from more effective interactions among the auditory, visual and posterior parietal cortices. Hausfeld suggests that an improvement in echo perception by the sighted occurs after the first few trials in recognizing simple shapes and material difference of obstacles [52]. Thus, the generation of an efficient central interaction is developed by all in an effective condition for auditory localization training, such as complete deprivation of eyesight at most, or even under a similar condition when temporally without visual information. These training conditions are effectively realized by conventional acoustic virtual reality systems such as [53,54]. Thus, if acoustic virtual reality systems can present virtual acoustical obstacles to the blind, this system will also present the newly realistic sensation to the sighted. In addition, our result indicates that the sighted would potentially perceive obstacles aurally like the blind. If the sighted train the auditory obstacle perception over long period without visual information, they can probably obtain as useful obstacle sense as the blind.

Zwiers *et al.* found that the early blind localize elevation less accurately than the sighted [50], while there are a number of blind mobility aids that acoustically support obstacle detection in the horizontal plane ([2,3,5], *et al.*). Support for obstacle detection in the frontal plane relies on tactile devices such as white canes or canes equipped with sensors [55], and these mainly help the blind to perceive obstacle on the ground. However, these devices face a difficulty when trying to detect obstacles not directly on the ground at a height somewhere between knee- and chest-height. Thus, future blind mobility aids can contribute to improving the quality of life by enabling the blind to perceive obstacles even in the frontal plain with utilizing the obstacle sense positively as well as without preventing auditory obstacle perception. When this concept reflects to blind mobility aid, blinds who are either well or not well in obstacle sense can use it effectively. Although the way to assist the obstacle sense actively remains unknown only in our study, we will propose the better model of the blind mobility aid based on our findings in addition to the other studies especially Zwiers' results.

7. CONCLUSION

Three experiments related to obstacle sense by the blind were carried out in order to clarify its perceptual process. The result for the discrimination ability in various coloration changes implied the same discrimination ability between blind and sighted groups. Thus, there was little difference in the peripheral auditory system between them, such as perception differences of various dip-frequency intervals in coloration.

In the second experiment of sound impression change while approaching to an object on a flat surface, the extracted factors were different between the blind and the sighted. This result suggested that the blind could detect the obstacle by perceiving the quality changes of sound impressions. It means that the obstacle sense would be performed in the central auditory system.

In the third experiment, the experiment of auditory distance perception of obstacle is carried out for observing the reflection of the central process to spacial perception. The results indicated the blinds' superiority in central process: more accurate in the localized distance and shorter-time in the distance localization than the sighted. These results implied that the training of obstacle sense would be possible for the untrained acquired or just-acquired blind as well as the sighted. In addition, we discussed that the central process among the blind resulted from more effective interactions among the auditory, visual and posterior parietal cortices.

Finally, from the results of the three experiments and past studies, we discussed new concepts for blind mobility aids as well as the obstacle sense training method.

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