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Measurement of Auditory Alleys in a Virtual Environment and Their Mathematical Models

Michiko Ohkura

Faculty of Engineering, Shibaura Institute of Technology, Saitama, Japan 330-8570

Yasuyuki Yanagida, Taro Maeda, and Susumu Tachi

Faculty of Engineering, University of Tokyo, Tokyo, Japan 113-8656

SUMMARY

The use of a virtual environmental display system enabled the construction of a psychophysical experimental system to measure subjectively straight lines running phenomenally parallel to the median plane, the parallel alley, and subjectively straight lines running phenomenally equidistant from the median plane, the equidistance alley, in binaural auditory space. Experiments were conducted using the constructed experimental system, to measure the parallel alley and the equidistance alley in binaural auditory space. The following results were confirmed: (1) The parallel alley and the equidistance alley in auditory space in a virtual environment are not always straight in the physical sense, and their forms depend on the distance from the median plane. (2) The parallel alley lies inside the equidistance alley. These tendencies are the same as those between the parallel alley and the equidistance alley in visual space and/or tactile space in the real world. Moreover, by employing sound intensity and binaural time differences as parameters, space perception models were constructed to explain the parallel alley and the equidistance alley in auditory space. Based on the results of the simulation performed using the models, it was confirmed that the models successfully explain the results obtained in psychophysical experiments performed using the virtual environmental display system. © 2000 Scripta Technica, Syst Comp Jpn, 31(4): 12–21, 2000

Key words: Auditory sensation; space perception; sound localization; virtual environment; neural network model.

1. Introduction

As the characteristics of space perception, the phenomena of subjectively straight lines such as Helmholtz's horopter, and the parallel alley and equidistance alley are well known in binocular visual space. Helmholtz's horopter is explained on the basis of the following phenomenon: Assuming that the x axis is the intersection of the horizontal plane at eye level and the median plane of the observer, and the y axis is the intersection of the same horizontal plane and the frontoparallel plane passing through both eyes of the observer (points L and R) as shown in Fig. 1, horizontal lines which appear to be parallel to the y axis (subjectively frontoparallel lines) are not always parallel in the physical sense [1]. It is known that the physical form of the perceived frontoparallel lines depends on the distance between the observer and the parallel lines on the x axis; that is, the form coincides with the physically parallel lines at a certain

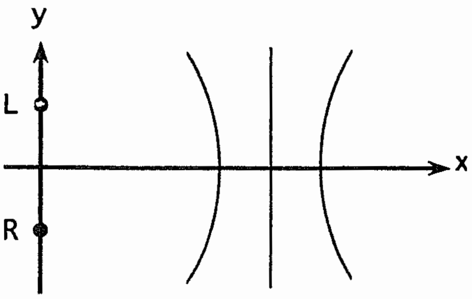

Fig. 1. Helmholtz's horopter.

distance, becomes concave when the observer is at nearer distances, and becomes convex at farther distances. On the other hand, the parallel alley and the equidistance alley represent the concept of subjectively parallel to the median plane. In Fig. 2, assuming that the x axis is the intersection of the horizontal plane at eye level and the median plane of the observer, and the y axis is the intersection of the same horizontal plane and the frontoparallel plane passing through both eyes of the observer (points L and R), a pair of lines p denotes the parallel alley and a pair of lines d denotes the equidistance alley. The parallel alley is a pair of perceived straight lines obtained when two rows of luminous points on the horizontal plane at eye level are arranged symmetrically to appear straight and parallel to the median plane. Physically, the two lines should be straight and parallel to each other, but in actuality they are not; their form depends on the distance from the median plane (the distance from the x axis). The equidistance alley is a pair of perceived straight lines obtained when two rows of luminous points on the horizontal plane at eye level are arranged symmetrically to appear straight and laterally equidistant from the median plane. Physically, the two lines should be straight and equidistant, but in actuality they are not; their form depends on the distance from the median plane [2]. The physical forms of these two types of subjectively straight lines have such a general tendency that the parallel alley lies inside the equidistance alley as shown in Fig. 2 [3]. Concerning the disagreement between these subjectively straight lines and physically straight lines, a similar phenomenon based on the sensation of upper limb movement has been observed for tactile space [4, 5].

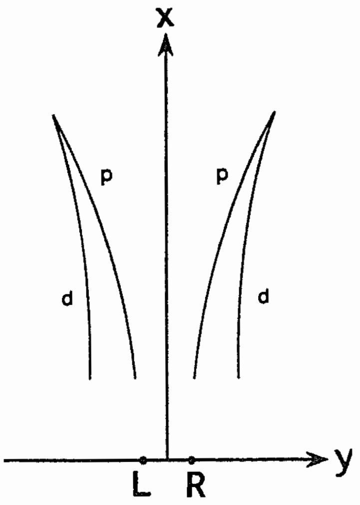

Fig. 2. Parallel and equidistance alley.

A basic experiment for sound localization with distance was conducted by the authors, and a similar phenomenon to that of Helmholtz's horopter was observed in binaural auditory space. That is, it was confirmed that the forms of the lines subjectively parallel to a frontoparallel plane are not always straight in the physical sense and depend on the distance between the sound source and the subject [6]. In this experiment, sound intensity and binaural time differences are considered to be very important cues for the subjects to judge the position of the sound sources. Thus, these two cues were employed as parameters to formulate a mathematical model for space perception to explain the auditory horopter, and the formulated model was examined by simulation. From the results, it was confirmed that the model successfully explained the distance dependency of the forms of the auditory horopter [7].

From the similarity of sensory modalities and the phenomenon of the auditory horopter, the phenomenon of the parallel alley and the equidistance alley in auditory space which is similar to those in visual space and tactile space is expected. However, no studies have been conducted to verify this. In order to measure the form of the subjectively parallel lines to the median plane in binaural auditory space, several sound sources should be located symmetrically with respect to the median plane as shown in Fig. 3, and the sound from each sound source should be outputted in order. However, such an experimental setup requires a large space, and the physical existence of nearer sound sources must occlude the sound from farther sound sources from reaching the ears of the subjects. These difficulties may prevent the performing of experiments for an auditory alley. Thus, the authors attempted to realize the psychophysical experimental system to measure the forms of a parallel alley and an equidistance alley in auditory space using a virtual environmental display system which was constructed for the study of sound distance perception [8, 9]. In this paper, the experimental setup, method, and obtained results are explained.

Moreover, the mathematical models to explain the parallel alley and the equidistance alley in auditory space were formulated in a similar manner to the space perception

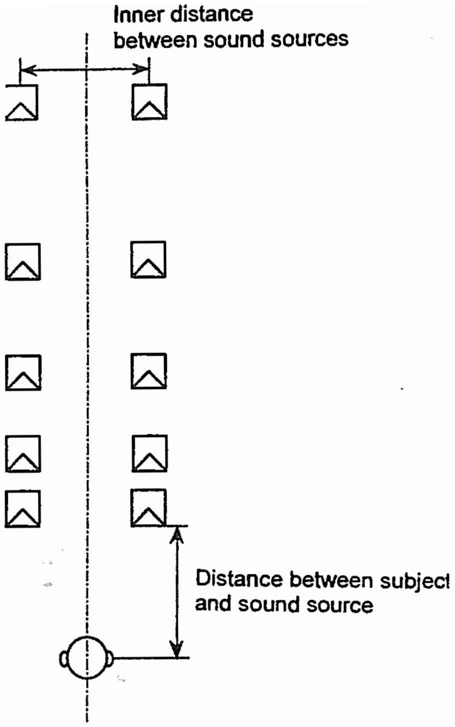

Fig. 3. Setup for experiments of auditory alley.

model for an auditory horopter. Based on the model, the results of the experiments conducted under the virtual environment were examined by simulation. This formulation of the auditory space perception model and the results of the simulation are also explained in this paper.

2. The Measurement of the Parallel Alley and the Equidistance Alley in Auditory Space

2.1. The system setup

The schematic of the virtual environmental display system used in this study is shown in Fig. 4. This system is the same as that used in the study to clarify the role of some cues for sound distance localization using a virtual environment [8, 9].

In order to construct the virtual environment, two computers (IRIS Indigo) were used to generate computer graphics images for both eyes based on the virtual environmental model. These images served as the visual signals for the subject through a calibrated see-through head-mounted display (STHMD) worn by the subject [10]. The STHMD, in which the virtual environment can be superimposed on the real environment by a beam splitter, can be calibrated to make the coordinates of the visual space for a virtual environment coincide with those of the visual space for a real environment by the superimposition. A calibration method was developed and applied to the visual parameters of the STHMD to eliminate errors caused by mechanical misalignments in the STHMD [11] and by individual differences between actual and designed location of pupils of eyes, which ensured the coincidence of the apparent distance in a virtual environment with that in the real environment [12]. Using one of the computers, auditory signals were synthesized, output through DSP, and input through headphones (Senheiser HD25SP) to both ears of the subject. The output rate was set at 48 kHz.

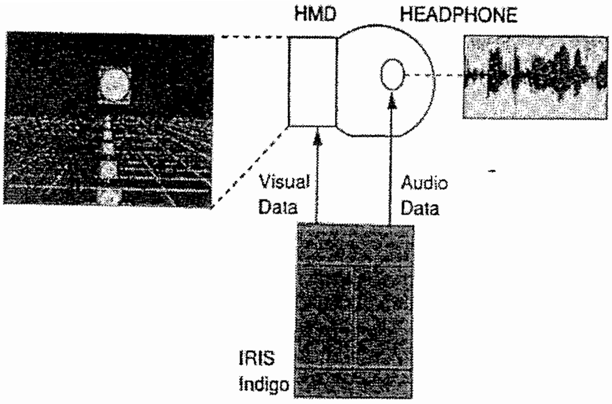

Fig. 4. Virtual environmental display system.

2.2. Experimental method

We designed the experiments to measure the parallel alley and the equidistance alley in auditory space using the method of constant stimuli. In this method, the stimulus with a 50% probability of appearance in the obtained psychometric function is considered as the subjective equivalence when the method of two categories is employed [13]. The schematics of the experimental systems used to measure the parallel alley and the equidistance alley are shown in Fig. 5. A pair of sound sources symmetrically positioned with respect to the median plane of the subject is called a "pair of sound sources" hereafter. Four virtual sound sources are assumed, which consist of a standard pair of sound sources and a comparison pair of sound sources; the latter pair with various inner distances is located nearer to the subject than the former pair.

As visual signals, the images of two sound sources symmetrically positioned with respect to the median plane on the horizontal plane at ear level of the subject are displayed as the images of the standard pair of sound sources. The auditory signal given to both ears of the subject

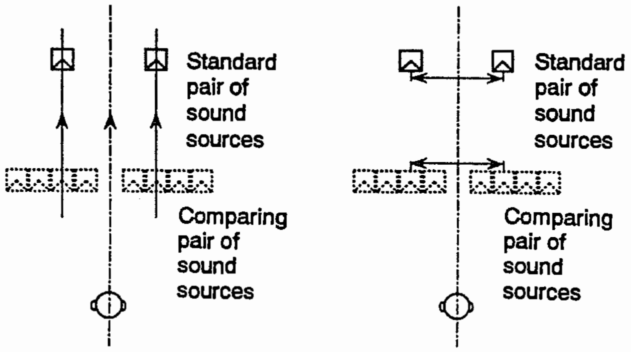

Fig. 5. Experimental system of parallel alley and equidistance alley.

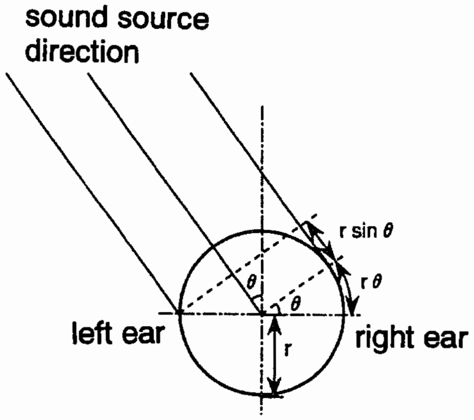

Fig. 6. Approximation of the difference between sound source and both ears.

is pseudorandom noise, and its intensity and binaural time differences are controlled as follows:

Consider the sound stimuli which reach both ears of the subject from a sound source located at the left side of the median plane in Fig. 3. For the sound stimuli which reach the left ear directly, the following notations are used:

P_l: The intensity of the sound stimuli which reach the left ear directly from the objective sound source

d: The distance between the objective sound source and the subject

P_0: The standard sound intensity

d_0: The distance between the subject and the sound source from which the sound stimuli directly reached the left ear has the standard sound intensity.

As P_l is inversely proportional to the distance from the sound source [14, 15], the intensity of the sound stimuli reaching the left ear of the subject is

$$P_l = \frac{d_0}{d} P_0 \tag{1}$$

On the other hand, the sound stimuli reach the right ear via the circumference of the head of the subject, as shown in Fig. 6. Therefore, the difference between the distance from the sound source to the right ear and the distance to the left ear (Δd) is approximated as follows, where the radius of the head of the subject is r [16]:

$$\Delta d = r\theta + r\sin\theta \tag{2}$$

The angle θ is obtained using the distance from the sound source (y) and the distance between the sound source and the median plane (x):

$$\theta = \arcsin(x/y) \tag{3}$$

Therefore, the intensity of the sound stimuli which reach the right ear (P_r) is given by

$$P_r = \frac{d_0}{d_0 + \Delta d} P_l \tag{4}$$

Also, the time difference between the sound stimuli which reach the right ear and those which reach the left ear (Δt) is given as follows, where r is 8.75 cm and the sound velocity (v) is 340 m/s:

$$\Delta t = \Delta d / v = 257(\theta + \sin\theta)\ [\mu\text{s}] \tag{5}$$

The examples of the sound intensity ratios and the time differences of both ears for various distances between the subject and the sound sources and for various inner distances between the sound sources are shown in Table 1, where the binaural time differences are represented as the numbers of shifts of data in 48 kHz, that is, 48,000 × Δt/1000.

Assuming the sound stimuli from the left sound source, the auditory signal given to the right ear of the subject is controlled to have a ratio and a binaural time difference with the signal given to the left ear, as shown in Table 1. Assuming the sound stimuli from the right sound source, the auditory signals with the opposite ratio and the opposite binaural time difference are given to both ears.

The head of the subject is fixed and visual parameters of STHMD are calibrated individually prior to conducting the experiments.

Each trial is carried out as follows:

(1) By assuming that the standard pair of virtual sound sources is located at a certain distance from both ears of the subject, parallel to the physical median plane, and

Table 1. Sound intensity ratios of sound source and time differences for various distances and inner distances between sound sources

Distance[m]	4.0				
Inner distance[m]	0.0	0.4	0.8	1.2	1.6
Sound intensity ratio	1.0	0.912	0.832	0.760	0.696
Time difference[♯ of shift]	0	1	2	4	5
Distance[m]	$4\sqrt{2}$				
Inner distance[m]	0.0	0.4	0.8	1.2	1.6
Sound intensity ratio	1.0	0.937	0.878	0.823	0.772
Time difference[♯ of shift]	0	1	2	3	3
Distance[m]	8.0				
Inner distance[m]	0.0	0.4	0.8	1.2	1.6
Sound intensity ratio	1.0	0.955	0.912	0.871	0.832
Time difference[♯ of shift]	0	1	1	2	2
Distance[m]	$8\sqrt{2}$				
Inner distance[m]	0.0	0.4	0.8	1.2	1.6
Sound intensity ratio	1.0	0.968	0.937	0.907	0.878
Time difference[♯ of shift]	0	0	1	1	2

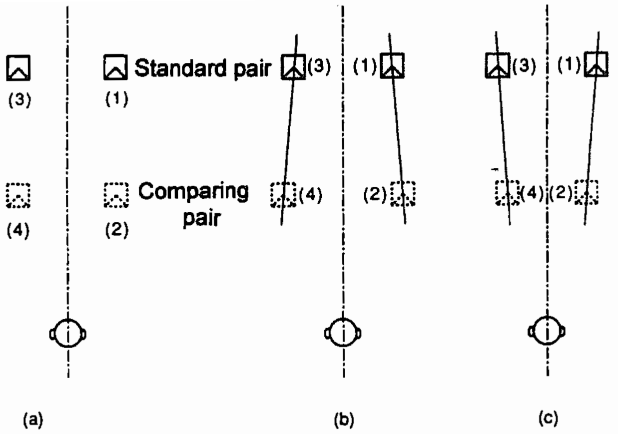

Fig. 7. Order of display and relations between two pairs of virtual sound sources in experiments of parallel alley.

symmetric with regard to the plane, the sound stimuli supposed from the right source of the standard pair of sound sources and the stimuli supposed from the left one are repeatedly given to the subject in order for a duration of 500 ms at 500-ms intervals. The subject is instructed to move a pair of visual markers of the virtual sound sources to the position where they are perceived by using a mouse in order to fix the subjective position of the standard pair of sound sources. Hereafter, the positions of the pair of visual markers are fixed so that the subject can confirm the position visually.

(2) Next, the sound stimuli assumed to originate from the standard pair and the comparison pair of sound sources are repeatedly given for a duration of 500 ms at 2500-ms intervals in order, and the subject is requested to input the result of his/her judgment using one of two mouse buttons. In the case of experiments for the parallel alley, the assumed order of the virtual sound sources of sound stimuli is the right standard sound source, the right comparison sound source, the left standard sound source, and the left comparison sound source, as shown in Fig. 7(a). The subject judges whether the relationship between the line connecting the former two sound sources and the line connecting the latter two sound sources is type (b) or type (c) shown in Fig. 7. On the other hand, in the case of experiments for the equidistance alley, the assumed order of the virtual sound sources of sound stimuli is the right standard sound source, the left standard sound source, the right comparison sound source, and the left comparison sound source, as shown in Fig. 8(a). The subject judges whether the inner distance of the latter two sound sources is narrower or wider than that of the former two sound sources, as shown in Figs. 8(b) and 8(c).

The distance between a pair of sound sources is defined as the distance between the midpoint of the line connecting both sound sources of the pair, which is the intersection of the line and the median plane, and the midpoint of the line connecting both ears of the subject. The assumed distance and inner distance of the standard pair of sound sources are $4\sqrt{2}$ m and 0.4 m, respectively. The assumed distance of the comparison pair of sound sources is set as $2\sqrt{2}$ m or 4 m, and their assumed inner distance is set as 0.0, 0.2, 0.4, 0.6, or 0.8 m.

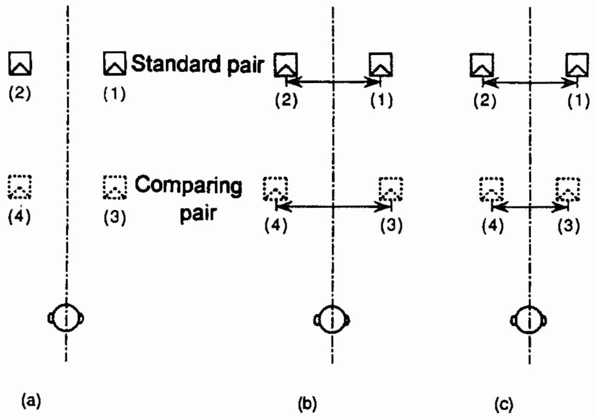

Fig. 8. Order of display and relations between two pairs of virtual sound sources in experiments of equidistance alley.

2.3. Experimental results and their analysis

In one trial run of the experiments, five different inner distances of the comparison pair of sound sources were assumed four times in random order with a certain distance assumed for the pair, and the relative position between the pair and the standard pair of sound sources or the width of the inner distance of the comparison pair was judged by the subject. Thus, the number of judgments for each trial was 20. For both the parallel alley and the equidistance alley, trials with two different assumed distances were conducted, that is, a set of experiments consisted of four trials. After confirming the phenomena by preparatory experiments, experiments for detailed data acquisition were conducted for three subjects.

As a result of each trial, psychometric functions were obtained, and probit analysis [17] was applied to estimate the equivalence of the inner distance of the comparison pair of sound sources, which was perceived to be parallel to or equidistant from the standard pair of sound sources. Examples of the results of the analysis are shown in Table 2. Figure 9 shows the results of the second example in the table with the position of the standard pair of sound sources, where open circles indicate the experimental results of the measurement of the parallel alley, solid circles indicate the experimental results of the measurement of the equidistance alley, and each central point indicates the estimated average of the distance of the comparison pair of sound sources from the median plane with standard deviation.

From the results of the analysis, the following general tendencies are observed:

(1) Both the parallel alley and the equidistance alley in auditory space have forms different from those of the physically parallel line to the median plane.

(2) The auditory parallel alley lies inside the auditory equidistance alley in physical space.

Thus, it was confirmed that the forms of the subjectively straight lines parallel to the median plane (parallel alley) and the subjectively straight lines equidistant from the median plane (equidistance alley) in binaural auditory space are not always parallel in the physical sense, and depend on the distance from the subject, and that the parallel alley lies inside the equidistance alley in auditory space. These tendencies are similar to those between the parallel alley and the equidistance alley in visual space or tactile space obtained in a real environment.

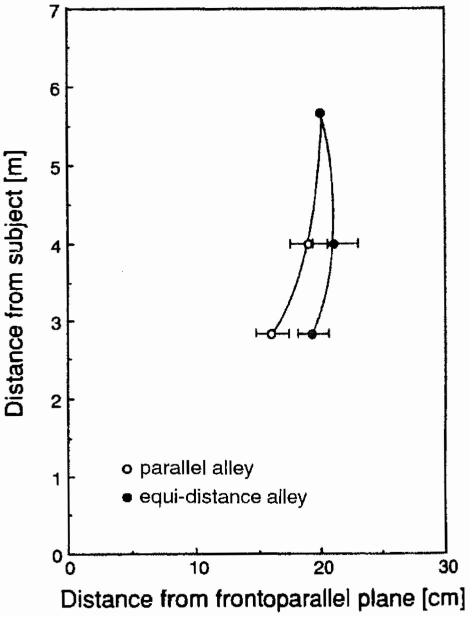

Fig. 9. Results of analysis.

3. Mathematical Model For Space Perception to Explain Auditory Alleys

3.1. Formulation of the mathematical model for space perception

We have constructed a neural network model called the ISLES (Independent Scalar Learning Element Summation) model using biological information and constraints,

Table 2. Subjective distance from frontoparallel plane [cm]

Example			1		2		3	
Alley(p:parallel,d:equidistance)			p	d	p	d	p	d
distance [m]	4	average	18.1	20.0	19.0	21.1	26.9	32.9
		standard deviation	2.7	2.2	1.6	1.8	3.3	3.9
	$2\sqrt{2}$	average	15.1	18.1	15.9	19.3	18.2	19.0
		standard deviation	2.9	2.7	1.4	1.2	3.1	1.6

and the model has successfully been used to explain the distance dependency of the forms of the horopter and alleys in visual space and in tactile space as a gap generated by the constraint of the learning process of space perception [18]. That is, in various types of space perception, invariant sensory information is set to be the standard function. Thus, the learning of the ISLES model, the neural network model with a scalar learning rule and with the constraint based on the physiological knowledge, has a limitation which produces a specific error between the model and the standard function. This error causes the distance dependency of the forms of horopters and alleys in perceptional space.

Moreover, it was confirmed that the distance dependency of the auditory horopter can be successfully explained by the ISLES model constructed using sound intensity and binaural time difference as parameters [7].

Therefore, an attempt is made to construct the ISLES model which explains auditory alleys using sound intensity and binaural time difference as parameters. That is, assuming the ISLES model is the model for space perception to generate auditory alleys, sound intensity and binaural time difference are considered to be the input signals for the model. Based on Ref. 19, sound intensity k is defined as the product of the sound intensity reaching the right ear I_A and the sound intensity reaching the left ear I_B,

$$k = I_A \cdot I_B \tag{6}$$

Then, the origin of a coordinate system in the physical space is set to be the midpoint of both ears, the x axis is set to be the line passing through both ears, and the y axis is set to be the horizontal line perpendicular to the x axis. The sound intensity k of a certain position (x, y) in the coordinate system is represented as follows:

$$\left(x^2 + y^2 + a^2\right)^2 = 4a^2x^2 + \frac{I_S^2}{k} \tag{7}$$

where I_S is the intensity of the sound source, and a is the distance from the origin to both ears [19]. Also, as for binaural time differences Δt, the following equation is obtained from the equation of phase difference described in Ref. 19:

$$\Delta t = \frac{\sqrt{(x+a)^2 + y^2} - \sqrt{(x-a)^2 + y^2}}{v} \tag{8}$$

where v is the sound velocity. The graph of Eq. (8) with a = 8 cm and v = 340 m/s is shown in Fig. 10. The line indicating the value of 20 in Fig. 10 is given by

$$\Delta t = 20\ \mu\text{s} \tag{9}$$

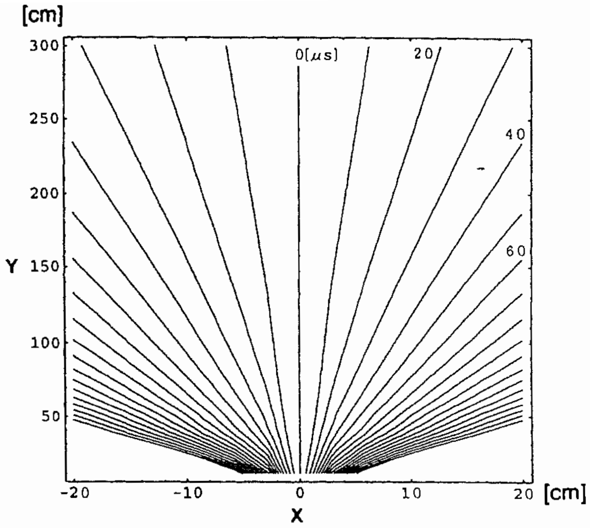

Fig. 10. Interaural time difference = constant.

which shows that the sound stimuli from the sound source located on the line reaches the left ear 20 μs after reaching the right ear.

In a perceptional signal system for auditory space, in the case of learning to perceive the parallel alley and the equidistance alley, the target for the learning (the plane parallel to and equidistant from the median plane) is physically described as

$$x = x_c \tag{10}$$

where x_c is a constant. On the target plane for the learning, the equations to render each of the three variables, Δt, x, and k, invariant may be considered as candidates for the standard functions, where the fourth variable y is excluded because of its apparent variability.

As the standard equation for the auditory parallel alley, the following equation is assumed on the analogy of the standard equation for an auditory horopter [7]:

$$H_p(k, \Delta t) = \Delta t + H_t(k) \tag{11}$$

where binaural time differences (Δt) are compensated additionally by the function of sound intensity (k), that is, Δt is considered invariant.

The ISLES model of Eq. (11) is assumed as follows:

$$\hat{H}_p(k, \Delta t) = \Delta t + \hat{H}_t(k) \tag{12}$$

The first term on the right-hand side, Δt, lies on the line parallel to the median plane described by k. The second term, $\hat{H}_t(k)$, is the scalar function obtained from the convergence of the learning process for the perception of parallel to the median plane.

$$\hat{H}_t(k) = \frac{\int_s \rho(\Delta t, k) H_p(k, \Delta t) ds}{\int_s \rho(\Delta t, k) ds} \tag{13}$$

where the learning area is s, and density distribution function of the learning points in the area is $\rho(\Delta t, k)$ [18]. Assuming the learning area for auditory space perception is from $x_{\min}$ to $x_{\max}$ in the direction of the distance from the median plane (x), and the distribution of learning points is uniform with regard to x, the following equation is obtained by the substitution of Eq. (11) in Eq. (13) and by representing Δt by x and k:

$$\hat{H}_t(k) = -\frac{\int_{x_{min}}^{x_{max}} \Delta t(x, k)\, dx}{x_{max} - x_{min}} \tag{14}$$

On the other hand, with regard to the standard function for the auditory equidistance alley $\hat{H}_d(k, \Delta t)$, "distance" should satisfy the additivity law so that x can be considered invariant as follows:

$$H_d(k, \Delta t) = H_u(k) + H_c(\Delta t) = x_c \tag{15}$$

Then, the ISLES model of Eq. (15) is assumed as follows:

$$\hat{H}_d(k, \Delta t) = \hat{H}_u(k) + \hat{H}_c(\Delta t) \tag{16}$$

With regard to the first and second terms on the right-hand side, the learning area in the acquiring process for distance perception from the median plane is assumed from $y_{\min}$ to $y_{\max}$ in the direction of the distance from the frontoparallel plane passing through both ears (y), and the distribution of learning points is assumed to be uniform with regard to y. Then, the following equations are obtained, similar to Eq. (14):

$$\hat{H}_u(k) = \frac{\int_{y_{min}}^{y_{max}} x(y, k)\, dy}{y_{max} - y_{min}} \tag{17}$$

$$\hat{H}_c(\Delta t) = \frac{\int_{y_{min}}^{y_{max}} x(y, \Delta t)\, dy}{y_{max} - y_{min}} \tag{18}$$

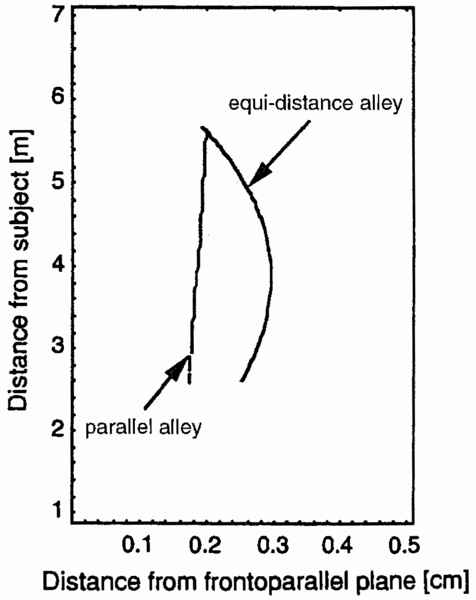

Fig. 11. An example of the results of simulation.

3.2. Examination of the experimental results

By executing Eqs. (14), (17), and (18) for various learning areas (areas for integration), the forms of Eq. (12) (parallel array) and Eq. (16) (equidistance alley) are examined by simulation. From the results, it was confirmed, as a general tendency independent of the learning area, that these forms have tendencies similar to the experimental results of auditory alleys using a virtual environment, that is, the forms of the parallel alley and the equidistance alley are not always parallel to the median plane in the physical sense and the parallel alley lies inside the equidistance alley.

Examples of the results of simulation for both curves through the standard pair of sound sources are shown in Fig. 11 ($x_{\min}$ = 0 mm, $x_{\max}$ = 300 mm for the parallel alley, and $y_{\min}$ = 1000 mm, $y_{\max}$ = 18,000 mm for the equidistance alley).

4. Conclusions

Using a virtual environmental display system, an experimental system to measure the parallel alley and the equidistance alley in auditory space is realized.

From the results of the experiments performed using the system, the following conclusions are drawn:

(1) The forms of the parallel alley and the equidistance alley in auditory space are not always straight in the

physical sense, and depend on the distance from the median plane.

(2) The auditory parallel alley lies inside the auditory equidistance alley.

These results show similar tendencies to those shown by the phenomena in binocular visual space and tactile space.

Employing sound intensity and binaural time differences as parameters, mathematical models were constructed to explain the parallel alley and the equidistance alley in binaural auditory space. From the results of the simulation, it was confirmed that the models successfully explain the results obtained from the psychophysical experiments using a virtual environmental system.

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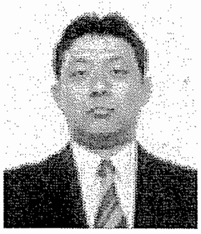
AUTHORS (from left to right)



Michiko Ohkura received her B.E. and M.S. degrees in mathematical engineering and instrumentation physics from the University of Tokyo in 1976 and 1978. She joined the Central Research Laboratory, Hitachi Ltd., in 1979. In 1986 she joined Dynax Corporation. She received her Ph.D. degree in advanced interdisciplinary studies from the University of Tokyo in 1995. In 1999 she joined the Faculty of Engineering, Shibaura Institute of Technology. Her research interests include human interface studies using auditory information and using virtual reality.

Yasuyuki Yanagida received his B.E. and M.S. degrees in mathematical engineering and instrumentation physics from the University of Tokyo in 1988 and 1990. He joined the Research Center of Advanced Science and Technology, University of Tokyo, in 1990 and moved to the Faculty of Engineering in 1997. His research interests include virtual reality systems.

Taro Maeda received his B.E. degree in mathematical engineering and instrumentation physics from the University of Tokyo in 1987. He joined the Mechanical Engineering Laboratory, Ministry of International Trade and Industry, in 1987. In 1992 he moved to the Research Center of Advanced Science and Technology, and to the Faculty of Engineering, University of Tokyo, in 1994. His research interests include neural network model and virtual reality.

Susumu Tachi received his B.E., M.S., and Ph.D. degrees in mathematical engineering and information physics from the University of Tokyo in 1968, 1970, and 1973. He joined the Faculty of Engineering of the University of Tokyo in 1973, and in 1975 moved to the Mechanical Engineering Laboratory, Ministry of International Trade and Industry, where he served as director of the Biorobotics Division. In 1989 he rejoined the University of Tokyo, and is currently a professor in the Department of Mathematical Engineering and Information Physics. From 1979 to 1980, he was a Japanese Government Award Senior Visiting Scientist at Massachusetts Institute of Technology (USA). His scientific achievements include intelligent mobile robot systems for the blind called Guide Dog Robot (1976 to 1983) and National Large Scale Project on Advanced Robotics, especially advanced human robot systems with a real-time sensation of presence known as Telexistence (Tele-Existence) (1983 to 1990). His present research covers Telexistence, Real-time Remote Robotics (R-Cubed), and Virtual Reality. He is a founding director of the Robotics Society of Japan, a Fellow of the Society of Instrument and Control Engineers, and president of the Virtual Reality Society of Japan. Since 1988, he has served as chairman of the IMEKO (International Measurement Confederation) Technical Committee 17 on Measurement in Robotics.