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Original Article

Audiospatial cognitive ability of visually impaired athletes in static and dynamic spatial cognitive tasks

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Abstract. [Purpose] This study compares the orientation sense of sighted and visually impaired participants to provide basic research on the audiospatial cognitive ability of visually impaired athletes. [Subjects and Methods] Subjects included nine blind athletes and seven sighted subjects wearing eyeshades during static and dynamic tasks. In the static spatial cognitive task, a coin was dropped towards the right, center, or left of the subject, and the task consisted of identifying the location of the coin. In the dynamic spatial cognitive task, performed with the participant walking, an auditory stimulus was provided. In both spatial cognitive tasks, the independent variables consisted of the "blind athlete" and "sight" groups, as well as three directions; a one-way analysis of variance was performed with the mean error angle as a dependent variable using IBM SPSS Statistics. [Results] The error angles found in the rightward and leftward directions during the static task showed no significant differences, but in the dynamic task, the sight group showed a markedly greater error in the left side, indicating a right-and-left asymmetry in spatial cognition. [Conclusion] Our results suggest a highly developed skill of instantly determining the spatial orientation of auditory information in dynamic situations in blind athletes.
Key words: Audiospatial cognitive, Visually impaired athletes, Spatial cognitive

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INTRODUCTION

Goalball and blind soccer are official Paralympic events, sports conceived to allow the visually impaired to participate, as the competitions are carried out with a ball that has a bell sound while participants wear eyeshades. Since all visual information is completely blocked, the players need to have a high level of spatial cognitive ability in order to instantly determine not only their own position in space, but also the movements of their teammates and opponents, as well as the ball's position, and also to carry out attacks and blocks. Spatial cognition is achieved by reproducing three-dimensional coordinate axes in vivo through integration of multiple sensory inputs; all routine body movements, such as walking, are predictively controlled on the basis of the in vivo three-dimensional coordinates[1)]. Normally, in sighted subjects, visual perception is a highly important source of information for motion and postural control; as movements are performed, visual and auditory perception work in a complementary manner. However, previous studies[2)] have shown that when such movements are performed in the absence of visual perception, a control system different from the above is at work.

In particular, in the absence of visual perception, sound source localization (sense of orientation), which is the ability to identify the direction of and the distance to the sound source, is considered important; sound source localization is defined as

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a sensation resulting from the time of arrival of the sound emitted from the sound source (time difference) and its intensity at arrival (intensity difference), as well as the phase difference[3]. In addition, comparisons between sighted individuals and visually impaired subjects showed no significant difference in terms of the reaction to sound from the centerward direction; however, for sounds from long distances and from lateral sides, reaction times associated with discriminative ability have been reported to be faster in visually impaired subjects[4]. In particular, discriminative ability has been reported to be even higher and reaction times have been reported to be even faster in athletes who practiced sports, such as blind soccer players[5]. However, these previous studies were conducted under static conditions. Moreover, in sport for the visually impaired, blind athletes who move themselves during playing aspect moving line of the ball which inside a bell. In addition, in situations involving movements, the spatial perception of sounds is measured on the basis of sound source localization (horizontal and vertical direction) and distance perception; the ability to localize the sound source while performing movements is considered important, as is the ability to do so while determining the relative positional relationship between oneself and the sound source, as well as information on one's own location in space[6]. Thus, in sport situations in general, there is a difference between the spatial perception of sounds in dynamic and static situations.

However, in sports for the blind, this fact has not yet led to the establishment of training or assessment methods that are based on systems aimed at processing sensory and locomotor information in relation to space in the absence of visual perception. While training aimed at enhancing physical function, such as muscle strength, is essential for sports for the visually impaired, utmost importance must be given to training aimed at enhancing perceptual and spatial cognitive abilities, including auditory perception. The development of training methods on the basis of scientific evidence and assessments aimed at improving performance may potentially lead to further improvements in performance and competitiveness in sports for the visually impaired. In particularly, there is a difference between congenitally blind athletes and athletes with acquired blindness, regarding their different spatial cognitive abilities. Therefore, this study provides basic research on the audiospatial cognitive ability of visually impaired athletes, to compare the sense of orientation in sighted subjects and visually impaired athletes during static and dynamic spatial cognitive tasks, in order to determine the properties of visually impaired athletes' audiospatial cognitive ability under static and dynamic conditions.

SUBJECTS AND METHODS

This study was approved by the ethical review board of Waseda University (proposal number: 2014-198), and the ethical committee of the National Rehabilitation Center for Persons with Disabilities. The researcher described the research purposes, methods, risks, and potential impact of the research to each subject before obtaining written informed consent for participation in the study. If participants, due to their visual impairment, could not write by themselves, an amanuensis wrote and signed on their behalf, as outlined in the ethics statement.

The recruitment of participants was carried out at the National Rehabilitation Center for Persons with Disabilities, and was open to the general public. The participants consisted of a group of blind athletes (BA group), composed of subjects who had been certified as visually impaired, and who gave their consent to participate in this study; the participants consisted of six men and three women (age: 29.9 ± 8.3 years, 20–44 years), and the characteristics of their visual impairment are as shown in Table 1. In terms of sports history after becoming visually impaired, the average number of years playing goalball was 1.8 ± 5. 6 years. For three of the participants, the average number of years playing blind soccer was 1 year. The sighted subjects' group (ST group) consisted of four men and three women (age: 27.4 ± 4.3 years, 22–33 years). Both subjects were students in this center and they had also used a gymnasium before this study.

In the static spatial cognitive task, a coin was dropped towards the right, center, or left of the subject, and the task consisted of identifying the location of the coin after it stopped moving. Three 1.5 m high stands, used for dropping the coin, were placed at 1.5 m intervals at the left, center, and right of the participants. The participants were instructed to wear an eyeshade, to stand at a line located 1 m anterior to the stands designed for dropping the coin, and to determine the sound source. After the dropped coin was completely stationary, the participants were instructed to move to a point that they thought to be the location of the coin, and to point a finger to the floor. If the coin hit the participant or the measuring instruments (on the vertical side, 1.0 m from the participant), the measurement was canceled and repeated. The measurer recorded the location pointed to by the participant as well as the coin's actual location; the process was performed nine times successively, with a random sequence of stand locations. After a measurement was complete, the location of the coin and the location pointed to by the participant were transformed into coordinates, and the error angle was calculated. The error angle equals the difference between the angle formed by "a straight line connecting the starting position (the determined location of the sound source) and the point where the coin stopped," and "a straight line connecting the starting position and the pointed location (Error angle= $\tan^{-1}\frac{y_c}{x_c} - \tan^{-1}\frac{y_f}{x_f}$)" (Fig. 1). In addition, the error angles for the rightward direction, the center, and the leftward direction were calculated.

The dynamic spatial cognitive task was carried out in a gymnasium (depth: 26 m, width: 15 m, height: 6 m), where a goalball court was used for the range of measurements. A reference walking path was set as follows: 3 m in a straight line from the start (point A_0), then from point A_0 to point A_1 (4.2 m from point A_0, at an angle of 37° towards the right), A_1 to A_2 (1 m from point A_1, at an angle of 90° towards the left), A_3 to A_4 (3 m from point A_3, at an angle of 45° towards the right), and

Table 1. Characteristics of disorders in the BA group

Type of disorder (n)	Visual field disturbance	5
	Visual impairment	6
Severity of the disorder (n)	Level 1	2
	Level 2	5
	Level 4	1
	Level 6	1
Diagnosis (n)	Retinitis pigmentosa	3
	Optic canal injury	1
	Retinal detachment	2
	Behcet's disease	1
	Leber's disease	1
	Others	1
Age at diagnosis (n)	Congenital	2
	Acquired	7
	In their teens	5
	In their 20s	1
	In their 30s	1
History of the disability (n)	Less than 5 years	2
	5 years or more but less than 9 years	4
	10 to 20 years	2
	More than 30 years	1

Type of disorder includes multiple responses.

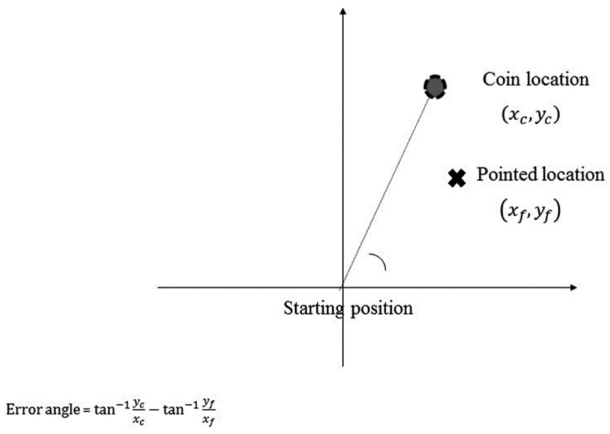


Fig. 1. Calculation method of the error angle in the static spatial cognitive task (example)

A_4 to A_5 (4.3 m from point A_4, at an angle of 60° towards the left). As an audio stimulus (Multipass, DKH, Japan), a buzzer was placed in the rightward and leftward directions and at the center; six video cameras were also installed. The participants were instructed to wear eyeshades to block visual information pertaining to the reference walking path, and they were guided to the start line. Later, they were instructed to confirm the sound of the buzzer, and were given the following standardized instructions: "You will hear sounds from various directions; please move towards the direction from which you heard the buzzer." The sound of the buzzer was set to 500 Hz for 300 ms, and the direction of the sound of the buzzer was set up in advance on the reference walking path. When either of the participant's feet passed a limiting point on the reference walking path, the measurer pressed the buzzer to instruct the participant to change directions. Because sound source localization can be affected by walking speed, all participants were instructed to practice walking at a normal speed before the actual experiment; this speed was considered the reference speed, and the tasks were performed using a metronome. The measurements were performed twice; when a participant walked past the sideline of the court, or when they walked past the limiting points on the reference path, the measurement was canceled and repeated. After the measurements, the points through which the participant had actually passed were converted into X and Y coordinate data by using a video camera. The error angle was calculated on the basis of the coordinates of the location of the buzzer and that of each point on the reference path. The error angle equals the difference between the angle formed by the line connecting the passing point at the point location that needed to be calculated and the passing point at the point immediately before the latter, and the line connecting the location of the buzzer leading to the point to be calculated and the passing point at the point immediately before the latter (error angle:

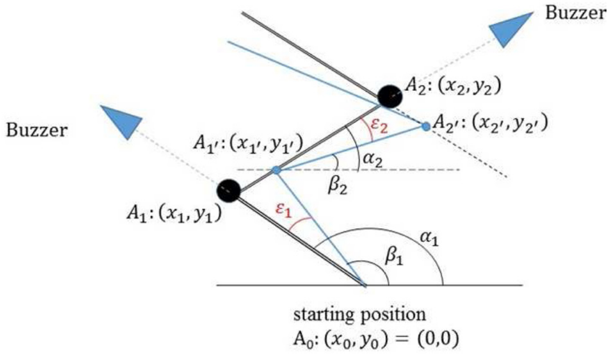
$$\varepsilon_n = \tan^{-1}\frac{y_n - y_{n-1}}{x_n - x_{n-1}} - \tan^{-1}\frac{y_{n'} - y_{n-1}}{x_{n'} - x_{n-1}}(y_{n-1} \leqq y_{(n-1)'}),\quad \varepsilon_n = \tan^{-1}\frac{y_n - y_{(n-1)'}}{x_n - x_{(n-1)'}} - \tan^{-1}\frac{y_{n'} - y_{(n-1)'}}{x_{n'} - x_{(n-1)'}}(y_{n-1} > y_{(n-1)'})$$

) (Fig. 2).

In addition, the mean of the values found for the right, middle, and left direction was calculated. In the static and dynamic spatial cognitive tasks, the independent variables consisted of the BA group and ST group (participant groups), as well as three directions (right, center, and left) (directionality); a Mann-Whitney test of variance was carried out by using the mean value of the error angle as the dependent variable. Three directions (right, center, and left) were compared in each group (the BA group and the ST group); a one-way analysis of variance (ANOVA) was carried out by using the mean value of the error angle as the dependent variable. The software used for statistical analyses was IBM SPSS Statistics for Windows version 22.

RESULTS

In the static spatial cognitive task, aimed at examining whether differences in error angle occurred depending on the participant group or the direction of the sound, an analysis of the error angle as a dependent variable was performed. The error angles were: Average: 9.0 (SD:4.4)° for the BA group and 9.0 (6.6)° for the ST group, respectively in the right direction; 6.5 (4.7)° and 6.1 (3.8)° in the centerward direction; and 8.1 (6.8)° and 9.5 (3.4)° in the leftward direction

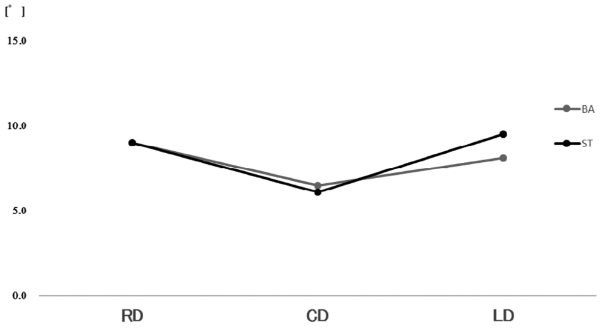


A_n: correct point, $A_{n'}$: actual point, ε_n: error angle

$$\varepsilon_1 = \alpha_1 - \beta_1 = \tan^{-1}\frac{y_1 - y_0}{x_1 - x_0} - \tan^{-1}\frac{y_{1'} - y_0}{x_{1'} - x_0}$$

$$\varepsilon_2 = \alpha_2 - \beta_2 = \tan^{-1}\frac{y_2 - y_{1'}}{x_2 - x_{1'}} - \tan^{-1}\frac{y_{2'} - y_{1'}}{x_{2'} - x_{1'}}$$

Fig. 2. Calculation method of the error angle in the dynamic spatial cognitive task (example)

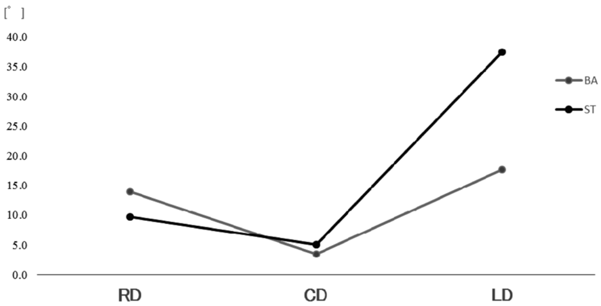


Group (°)*	RD	CD	LD	Multiple comparison
BA (n=9)*	9.0±4.4	6.5±4.7	8.1±6.8	RD>CD, LD>CD
ST (n=7)	9.0±6.6	6.1±3.8	9.5±3.4	

Fig. 3. Comparison based on the directionality of error angles in a static spatial cognitive task
EA: Error angle; RD: Rightward direction; CD: Centerward direction; LD: Leftward direction
*p<0.05

(Fig. 3). No statistical significant difference was found between the BA and ST groups (p>0.05. The mean errors in the rightward and centerward, leftward and centerward direction were BA (p<0.05). No statistical significance was found between in ST groups (p>0.05).

Similarly, in the dynamic spatial cognitive task, The mean errors in the rightward direction were BA: 13.9 (4.4)°, and ST: 9.7 (5.4)°, respectively; in the centerward direction, 3.4 (3.6)° and 5.0 (2.3)°; and in the leftward direction, 17.7 (13.5)° and 37.4 (23.3)° (Fig. 4). There was a significant difference between the BA and ST groups in the leftward direction, with the mean error in the leftward direction being smaller in the BA group (p<0.05). Meanwhile, comparisons of the three directions showed significant differences in both the BA and the ST groups (p<0.05). There were significant differences between the centerward and rightward and between the centerward and leftward directions in the BA group (p<0.05). There were also significant differences between the centerward and leftward and between the rightward and leftward directions in the ST group (p<0.05). In both the BA and the ST group, the largest error value was found in the leftward direction.



Group (°)*	RD	CD	LD	Multiple comparison
BA (n=9)*	13.9±4.4	3.4±3.6	17.7±13.5	RD>CD, LD>CD
ST (n=7)*	9.7±5.4	5.0±2.3	37.5±23.3	LD>CD, LD>RD

Fig. 4. Comparison based on the directionality of error angles in a dynamic spatial cognitive task
EA: Error angle; RD: Rightward direction; CD: Centerward direction; LD: Leftward direction
*p<0.05

DISCUSSION

This study shows no significant differences between cognitive angles in three directions for a group of blind athletes (BA) and a sighted participant group (ST) in static cognitive tasks. However, in dynamic cognitive tasks, a comparison between the BA and the ST groups showed a significant difference in the leftward direction. In addition, a comparison between the three directions showed that in both the BA and ST group, the error was significantly larger in the leftward direction compared to the rightward and centerward directions.

The error was overall smaller in the BA group than in the ST group. Previous studies comparing the sound source localization ability of visually impaired and sighted subjects have reported that auditory discrimination ability and localization ability, as well as reaction times in auditory discrimination, were superior in visually impaired subjects[7–11]. Similarly, in studies using functional magnetic resonance imaging and electroencephalography, the reaction zones and waveforms found at the time of a task consisting of localizing auditory stimuli have been reported to be different in the two groups[12]. In regard to accuracy according to the directionality of the sound, our study shows that the perception error was greater at both lateral sides compared to the center; this supports the findings of previous studies[5]. In addition, the subjects in this study play goalball, for which lateral movement localization is especially important, and we find thus significant differences between the BA and ST groups regarding the lateral sides.

Conventionally, in sighted subjects who perform postural control under conditions of predominance of sight, the differences in terms of the processing of visual and auditory information are that visual perception deals with spatial information, whereas auditory perception deals primarily with temporal information[13]. In addition, auditory information often consists of transient information, and the circumstances might make it impossible to get the same information twice. A more instantaneous and appropriate judgment is believed to be necessary in regard to auditory information. In the dynamic perception task in our study, which required the participants' instantaneous understanding of their own location and that of the buzzer, the error was significantly higher at both sides than at the center in sighted subjects as well as in visually impaired subjects; in the same manner, this tendency is likely to occur more markedly in dynamic situations. In this study, the difference between the static task and the dynamic task was that in the static task, the subjects heard the sound of the dropping coin while standing at one location. In the dynamic task, in contrast, they were walking, which means they had to recognize their own location in space when hearing the buzzer for only 300 ms, and immediately decide to move to the correct direction. The time they had to recognize the sound in the dynamic task was thus shorter than in the static task, showing that the dynamic task is more complicated than the static task and requires a different ability.

In addition, binaural balance is deemed to be important for the identification of the spatial location of the sound source, including spatial perception through auditory perception, the determination of the distance from the sound source, and the direction of the sound source; reasonably accurate estimation of the direction of the sound source is considered possible if binaural hearing is functional and well balanced. This study does not elucidate the relationship between right-and-left balance in binaural hearing and the accuracy of spatial perception; however, as shown in Figs 3 and 4, the presentation of a left-right symmetrical V-shaped curve might be important for the accuracy of spatial perception in sound source localization under any condition, in a static or dynamic environment.

This study has several limitations. The participants in both groups consisted of students who attended the facility where the measurements were conducted. In the BA group, there may have been a bias in regard to the level of visual impairment, and in regards to whether the visual impairment was congenital or acquired. In addition, this was not the first time that the measurements were conducted in the environment and space mentioned in this study. Nonetheless, the findings of our study indicate the need to conduct an evaluation of functional properties in static and dynamic environments, as well as an evaluation of binaural functional ability, in order to allow for adequate spatial perception. Further, our study does not include an analysis of the mechanisms behind the characteristics of the tendency towards deviation, which specifically occurs in the absence of visual perception, or of the influence of auditory localization aftereffects; those issues may need to be further examined. Appropriate evaluations determining the characteristics of athletes' spatial cognition may need to be established, and more effective training methods may need to be developed.

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