2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

Development of a Platform for the Identification and Analysis of Simultaneous Localization of Static, Dynamic, and Instructional Sound Sources in Blind Soccer

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Abstract— **This study investigates the auditory-based spatial cognition critical for blind soccer, where players rely entirely on sound due to the absence of visual cues. Blind soccer is characterized by three distinct auditory signals: static sounds originating from fixed positions, dynamic sounds produced by the ball's movement, and instructional sounds conveyed by guides. Recognizing these sounds simultaneously is essential for effective gameplay. Our research focuses on understanding how blind soccer players recognize these specific sound sources. We conducted an evaluation using a virtual acoustic space system enhanced with stereophonic technology to test the localization abilities for one versus three types of sound sources. The findings indicate that players with visual impairments demonstrated superior localization skills for both static and dynamic sounds compared to sighted players, whether they had experience in blind soccer or not. Furthermore, the study reveals a prioritization in localizing the ball's sound and the guide's instructions among the three types of sounds. This underscores the specialized auditory perception skills developed by blind soccer players, offering insights into training methods and the design of auditory-based assistance systems.**

I. Introduction

In recent years, parasports have been recognized as an international sport. This is because of the improvement in their competitive nature and a growing social interest, reflecting a broader commitment to fostering an inclusive society that embraces individuals with disabilities. Among parasports, blind soccer, also known as blind football, stands out as a particularly distinctive and inclusive sport. Blind soccer is celebrated for its specialized design [1] and adaptations, which are thoughtfully tailored to accommodate the specific abilities and requirements of people who are visually impaired or blind [2][3].

Blind soccer is played by five players, including four outfield players and a goalkeeper. The game requires a unique ball with a bell inside, producing a distinctive shuffling sound when it rolls, aiding players in tracking its position [4]. Outfield players play while wearing an eye mask to ensure a level playing field, while goalkeepers are either sighted or low-vision players. International tournaments mandate that outfield players must undergo a medical examination prior to the tournament, with only those certified as completely blind eligible to play in these positions. Furthermore, each team benefits from the presence of a guide located behind the opposing team's goal, providing auditory cues and taps on the goalposts to help players orient themselves and indicate the location of the goal. Given the absence of visual cues, the players' capacity to navigate and understand their surroundings through sound becomes crucial [5]. Developing spatial awareness based on auditory information is thus a critical skill in blind soccer. The intricacies of this ability, however, remain largely unexplored.

Extensive research has been conducted on auditory capabilities of individuals with visual impairments [6][7][8][9][10][11]. Mental representations of auditory space have been found to be related to visual ones, as well as the impact of proficiency in auditory-based orientation [12][13][14]. In the context of blind soccer, specific investigations have assessed players' sound localization skills by employing speaker systems on soccer fields [15][16]. These studies have indicated that players with visual impairments, particularly those with considerable experience in the sport, exhibit superior abilities in localizing static sound sources compared to their sighted, inexperienced counterparts. However, this method requires considerable time and effort and the auditory function that can be evaluated is limited to the localization of a single stationary sound source.

To address the limitations of current methodologies in evaluating auditory spatial awareness, our laboratory, our laboratory has developed a virtual spatial acoustic system that can simply evaluate multiple types of sound sources [17]. Leveraging stereophonic technology, the system simulates the acoustics of a blind soccer pitch by simply putting on headphones. It can generate three distinct static sound sources within a virtual space: the noise of the soccer ball, vocal cues from players, and the sound produced by a guide tapping on the goalposts. Evaluations using this system revealed that blind soccer players possess superior localization abilities for all tested sound sources compared to sighted individuals without experience in the sport.

*Research supported by Waseda University, Tokyo, Japan.

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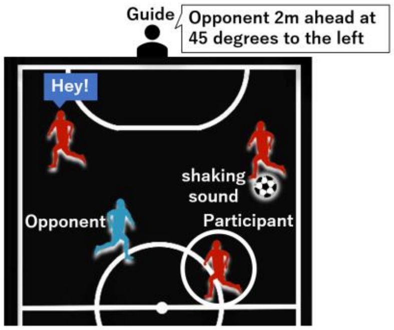

Fig.1 Representation of attack in blind soccer

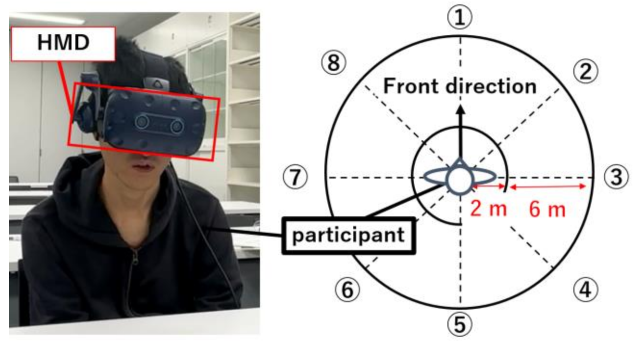

Fig. 2 Diagram of the constructed virtual space acoustic system

However, this initial assessment was constrained to static sound sources, such as a stationary ball, and did not encompass the localization of dynamic (e.g., a moving ball) or instructional (e.g., instructions from a teammate or guide) sound sources which are pivotal during actual gameplay.

Therefore, the objective of this research is to create a virtual reality (VR) framework designed for the assessment and comparative analysis of the capacity of blind soccer players, as well as individuals without visual impairments, to accurately identify the positions of various auditory signals that are integral to the game of blind soccer. This study aims to meticulously examine and illustrate the intricacies involved in the ability to pinpoint the origins of static, dynamic, and instructional auditory signals. Through the provision of a detailed and realistic visualization of an individual's proficiencies and limitations in spatial awareness and auditory spatial representation, the developed system seeks to offer valuable insights and strategies for enhancing training methodologies in parasports, especially blind soccer, where auditory perception plays a pivotal role.

II. METHOD

A. Cognitive model of three sound sources for ball non-possessors during attack

This section outlines a methodology to explore how blind soccer players recognize various sound sources during play, focusing on a scenario where a player without ball possession seeks to move into an open space to contribute to an attack. This example underscores the importance of discerning multiple sound cues in gameplay.

In the scenario depicted in Fig. 1, the player is required to discern three distinct sound sources characterized by varying cognitive attributes: (1) the auditory signal of a teammate vocally indicating the ball with a "Hey!," (2) the sound emanating from the moving ball, characterized by the distinctive [Shaka shaka], and (3) the verbal instructions provided by the guide, such as "Opponent 2 m ahead at 45° to the left." We also know from interviews with multiple blind soccer players that in blind soccer, when a teammate calls for the ball, the player says "Hey!" while stopping. In this study, we defined the sound source of a teammate from a fixed location as a static sound source, the sound of the ball as it moves as a dynamic sound source, and instructions from a guide, such as indicating an opponent's position, as an instructional sound source.

Through experiments designed to assess the ability of individuals to localize multiple sound sources simultaneously, our system clarifies the cognitive processes underlying sound perception in blind soccer players. This not only emphasizes the system's relevance in understanding the auditory spatial skills of athletes but also highlights its potential applicability in broader contexts, as a means of enhancing auditory spatial awareness beyond the realm of blind soccer.

B. Virtual space sound system

To replicate the actual game environment, improvements were made to the system of our previous study [17] so that the direction of the sound source does not change regardless of the head rotation. The virtual space acoustic system of the previous study uses Unity, which is a tool that can freely generate stereophonic sound in a virtual space [18]. This system employs the sound processing software Wwise for sound data manipulation, incorporating a head-related transfer function to produce realistic stereophonic audio effects [19][20]. In this test, as shown in Fig. 2, the participant faces direction ①, with sound sources positioned at intervals of 45° around the participant's central axis, spanning eight directions in total. The distances between the participant and the sound sources were established at 2 meters and 8 meters.

In conventional systems, the sound source moves together with the head angle, meaning that regardless of the direction faced by the participant, the angle between the head and the sound source remains constant. For example, if a sound is coming from the right and the head is tilted 90° to the right, the sound source moves at the same time and is heard from the right. This is in direct contradiction with real life game situations, where the perceived sound source location changes with respect to a player's head movement. Therefore, by using an inertial sensor built into the head-mounted display to acquire the head angle, we improved the system so that the direction of the sound source stays independent from head rotation. For example, if the sound source is at 8 m in the direction of ① in Fig. 2 (1), if the head is turned

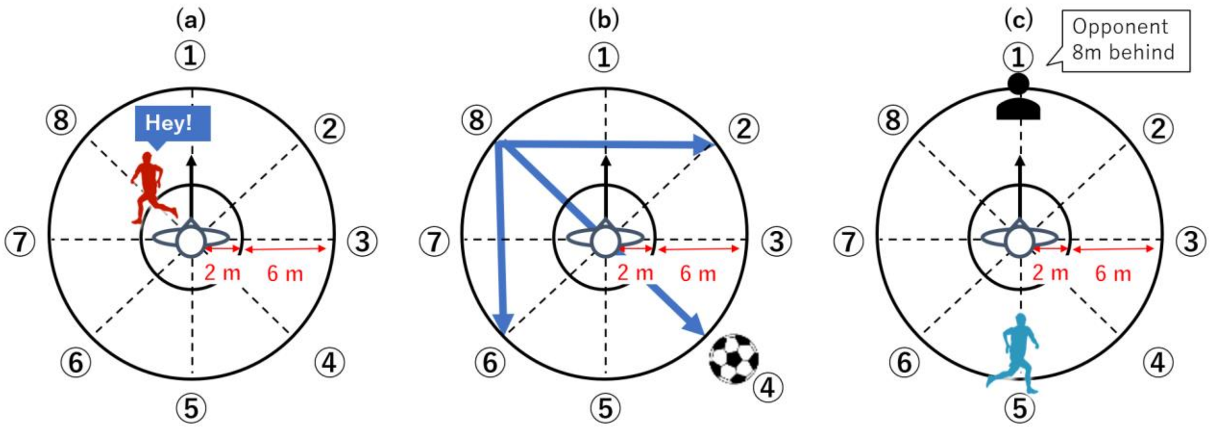

Fig. 3 Verification experiment setting: (a) hey sound source (static sound source); (b) ball sound source (dynamic sound source); (c) instruction from the guide (instructional sound source)

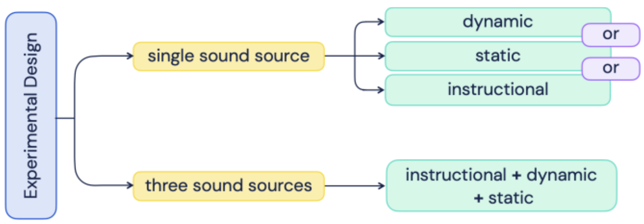

Fig. 4 Verification experiment sound source combination patterns

90° to the right, the sound volume heard from the left ear becomes louder than that from the right ear.

III. Experiment

Our objective was to assess the capacity of blind soccer players to identify and locate static, dynamic, and directed sound sources concurrently. To achieve this, we designed tests to gauge their recognition of various sound types. We utilized a single-source test to examine the localization ability for individual sound sources and a three-source test to assess the capability to localize multiple sound sources simultaneously. The single-source test included three variations based on the sound source type, while the three-source test involved a combination of three sound sources. In total, four patterns were tested (Fig.4), detailed in the subsequent sections.

A. Single-source test

We evaluated the differences in localization ability for each sound source: the "hey" sound source (stationary), the sound source of a moving ball (dynamic), and instructions from a guide (instructional). First, we discuss the stationary sound source. It is played randomly from 16 locations (2 distances in 8 directions), as shown in Fig. 3(a). Participants are required to verbally indicate the perceived location of the sound. This is repeated 48 times. For example, in Fig. 3(a), the correct answer would be "near ⑧."

For the dynamic sound source, as shown in Fig. 3(b), the ball moves from a starting point at one of the eight points located at 8 m to one of three available endpoints, also located at the 8m distance mark. If the starting point has an even number, the ending point also has an even number, and if it has an odd number, the ending point also has an odd number. For each trial, the ball is randomly shot along one of the available 24 trajectories (3 trajectories per start point, 8 start points). This is repeated 48 times. In the example, if the starting point of the ball is ⑧ and the ending point is ④, the correct answer is "from ⑧ to ④."

Lastly, we discuss the instructional sound source. Illustrated in Fig. 3(c), the guide's instructions, randomly indicate the location of an opponent at any of the 16 locations. For instance, in the setup shown in Fig. 3(c), if the guidance is "opponent at 8 m behind", the correct response would be "far ⑤" . Because the guide is located behind the goal, the guide sound source is always heard from 8 m toward ①, in front of the participant. Hence, the main difference between static and instructional sound sources is that unlike for the static source, participants must reconcile the sound source's location with the spatial information conveyed.

B. Three-source test

This test evaluates the ability of simultaneous localization to three sound sources. In this test, the participant responds to the location of each sound source when he/she hears a stationary sound source, a dynamic sound source, and an instructional sound source simultaneously. For example, "Hey is ② far, the ball is ①to ③, and guide is ⑧ near. This is repeated 48 times.

C. Procedure

At the beginning of this test, the participants were informed of the purpose, procedure, and methods of using the virtual space sound system. They were also informed about the possible risks during the experiment and were allowed to quit this study at any time for any reason. Signed consent documents were obtained from all participants before conducting the experiment.

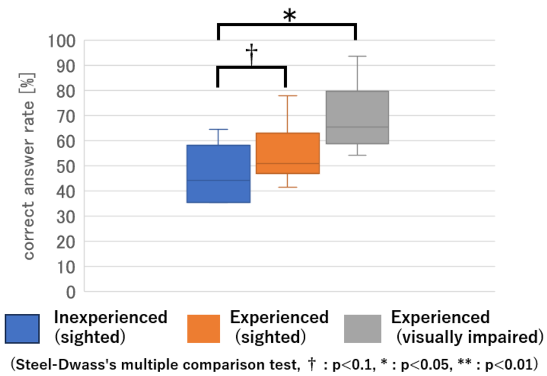

Fig. 5 Percentage of correct responses for static sources in single-source test

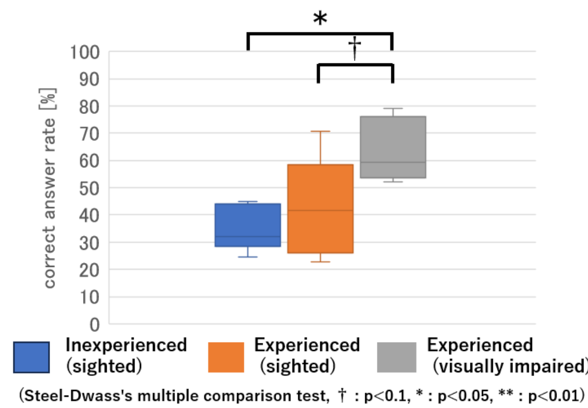

Fig. 6 Percentage of correct responses for dynamic sources in single-source test

Practice sessions were conducted to familiarize participants with sound source locations, distance perception, and response methods, with 5 minutes of practice for each test. The order of the four tests was randomized to prevent the order of the tests from influencing the results. Participants were divided into three categories: inexperienced (sighted), competitive (sighted), and competitive (visually impaired), to investigate the impact of blind soccer experience versus visual impairment on localization ability. This approach aimed to discern whether differences in localization skills were attributable to soccer experience or visual impairment, based on comparative performance across groups. For example, if results from inexperienced (sighted) players differ from both visually impaired and sighted competitive players, but those from competitive (visually impaired) and competitive (sighted) are the same, the difference can be attributed to the soccer experience. However, if competitive (visually impaired) differ from sighted players regardless of their experience, while inexperienced (sighted) and competitive (sighted) player are the same, this difference can be attributed to visual impairment. The study included 6 visually impaired competitors (1–22 years of experience), 6 sighted competitors (1–8 years of experience), and 6 inexperienced sighted individuals.

IV. Result and Discussion

A. Static sound sources

A comparison of the percentage of correct responses for each participant group for the static sound source for the single-source test is shown in Fig. 5. The average percentage of correct responses was 44.8% for inexperienced (sighted) participants, 51.6% for experienced (sighted) participants, and 65.2% for experienced (visually impaired) participants. The results of Steel–Dwass' multiple comparison test showed that the percentage of correct responses significant superiority in localization accuracy of experienced (visually impaired) participants over their inexperienced (sighted) counterparts, with a marginally significant improvement also observed for experienced (sighted) participants compared to the inexperienced group. Because of the difference between the inexperienced and the athletes, the ability to localize a static sound source is thought to be dependent on the game and blind soccer training. Therefore, the results suggest that localization ability to static sound sources is likely to improve with experience in blind soccer.

B. Dynamic sound sources

A comparison of the percentage of correct responses by participant group for the dynamic sound sources for the single-source test is shown in Fig. 6. The average percentage of correct responses was 32.4% for inexperienced (sighted) participants, 41.8% for experienced (sighted) participants, and 58.2% for experienced (visually impaired) participants. The results of Steel-Dwass' multiple comparison test showed that the percentage of correct responses was significantly higher for competitors (visually impaired) than for inexperienced (sighted) participants. In addition, the correct response rate was marginally significantly higher for the competitive (visually impaired) players compared to the competitive (sighted) players. The findings reveal that for dynamic sound sources, competitive (visually impaired) participants demonstrated distinct localization abilities compared to sighted players of any experience level, with no significant difference between inexperienced (sighted) and competitive (sighted) participants. This suggests that the skill to localize dynamic sounds is primarily influenced by visual impairment, rather than experience.

The superior ability of visually impaired individuals to localize dynamic sounds may stem from their routine reliance on auditory cues in daily activities, like navigating pedestrian crossings by listening for moving cars or pedestrians. In contrast, sighted individuals primarily depend on visual information for similar tasks [21]. The visually impaired's enhanced skill in localizing dynamic sounds is attributed to their more frequent reliance on auditory cues compared to sighted individuals. To test this hypothesis, future research should include inexperienced visually impaired participants to assess the influence of blind soccer on this ability.

C. Instructional Sound Source

The average percentage of correct responses for each participant group for the instructional sound source in the single-source test was 98.2% for inexperienced (sighted) participants, 97.7% for experienced (sighted) participants,

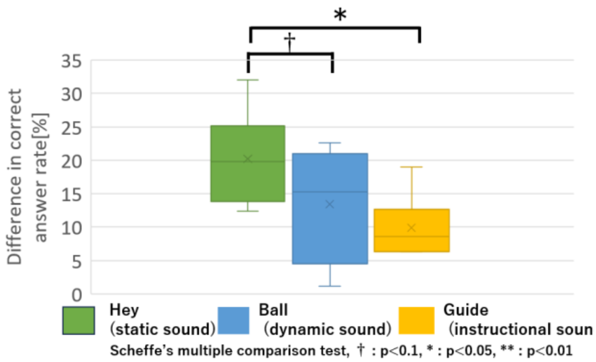

Fig. 7 Difference between the percentage of correct answers for each source in the single-source test and the three types of tests

and 98.0 for experienced (visually impaired) participants. The results of Steel-Dwass' multiple comparison test showed no difference in all participant groups. The similar ability of visually impaired and sighted individuals, as well as between blind soccer players and novices, to recognize and understand verbal instructions suggests that visual impairment does not impact the comprehension of vocal cues, explaining the lack of difference in this skill across groups.

D. Cognitive mechanisms of ability to simultaneously localize three sound sources

We explore players' cognitive processes when exposed to three simultaneous sound sources, aiming to determine which sound source is prioritized based on its localization. By comparing correct response rates between tests with a single sound source and those with three sound sources, we quantitatively assess the localization priority to identify sound sources that are less accurately localized in the presence of multiple auditory stimuli. The difference in the percentage of correct responses is expressed as follows:

Diff. in % error of correct responses = % of correct responses for the single-source test — % of correct responses for the three-source test (1)

A significant disparity in correct response rates reveals that sound source localization evident in the single-source test diminishes in the three-source test. This comparison highlights the prioritization of certain sound sources for localization, with specific differences illustrated in Fig. 7. The mean difference in the percentage of correct responses was 20.4% for the hey sound source, 12.8% for the ball sound source, and 9.6% for the guide sound source. Scheffe's multiple comparison test revealed a significantly higher correct response rate for the static "hey" sound source compared to the guide's instructions, and a marginally higher rate compared to the dynamic ball sound, with no significant difference between the ball and guide sounds. This suggests a player preference for prioritizing the recognition of dynamic and instructional sounds over static ones.

The prioritization of the guide's sound over static sources could stem from its utility in allowing players to discern their positional relationship with the goal and opponents, as the guide's voice consistently originates from behind the goal. The preference for the dynamic ball sound over static sources likely reflects its critical role in understanding the game's context. Consequently, blind soccer players seem to focus on localizing the guide and ball sounds to better comprehend the match's dynamics.

V. Limitations and Future Prospects

A. Limitation

In this study, six blind soccer players (sighted) and six blind soccer players (visually impaired) were tested. Although there were players with various levels of experience and background in blind soccer, no evaluations were based on these levels. Therefore, it is necessary to increase the number of participants with various levels of ability and to evaluate and identify the sound source localization ability according to the level of competition to develop a system that can be generalized to more people.

Additionally, as mentioned earlier, the participant pool did not include inexperienced, visually impaired, participants. In the future, we plan to further test the hypothesis suggested in this study by having them take part in the experiment.

B. Future prospects

The VR acoustic system developed in this study has two main features. First, each participant can quantitatively evaluate his or her strengths and weaknesses according to the type and number of sound sources. The system therefore offers the possibility to visualize individual's ability and weaknesses in sound space representation. The developed platform also allows clear identification of a person's sound source recognition prioritization through a quantitative evaluation based on the difference between the percentage of correct responses to one and three sound sources.

Using this feature, the sound source localization ability in blind soccer can be easily displayed in a radar chart, similarly to the one shown in Fig. 8 and Fig. 9. This radar chart shows the percentage of correct responses for each sound source in single- and three-source tests. All axes represent the percentage of correct responses. The lower part of the chart figure shows the sources that are preferentially localized. Fig. 8 shows the percentage of correct responses and the priority of sound source recognition for each sound source in the single- and three-source tests for a sighted competitor with a short competition history (1 year). Comparatively, Fig. 9 shows data from a former Japanese national team athlete (Paralympics). As depicted in this example, there is a significant difference in the percentage of correct responses for the three types of sound sources, notably when looking at ball identification results. This illustrates the developed platform's ability to give a clear picture of the abilities of players regardless of their experience and proficiency level. It also has the potential to reveal nuances in the evolution of these abilities when used continuously over time. The system also quantitatively shows the skills that need to be practiced to improve one's sound localization ability at other levels of competition. Thus, this system can be used not only for quantitative evaluation but also to provide guidelines for efficient training.

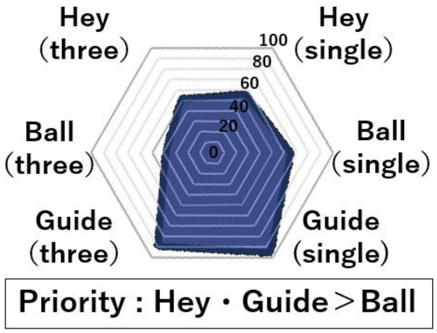

Fig. 8 Radar chart showing the percentage of correct answers for each sound source and and the priority order shown at the bottom on Athletes with a short competition history (1 year)

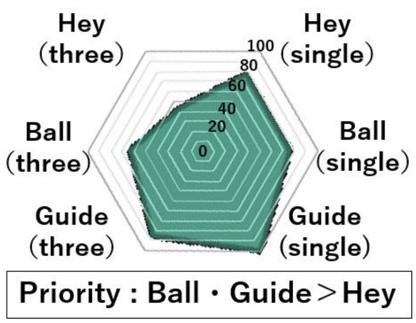

Fig. 9 Radar chart showing the percentage of correct answers for each sound source and the priority order shown at the bottom on Former national team athlete

VI. CONCLUSION

In this study, we developed a multiple sound source generation system that can freely generate multiple sound sources in a VR space. As a data acquisition test, we varied the type and number of sound sources and conducted tests with three groups of competitors (visually impaired and sighted) and inexperienced participants. We then conducted an assessment on the prioritization of sound source localization, along with an analysis of the strengths and weaknesses associated with each type of sound source and their quantity. This enabled quantitative evaluation of the ability of blind soccer players to localize multiple sound sources simultaneously. Although there were blind soccer players with various levels of experience and background, this study was not able to evaluate the performance of blind soccer players according to these levels. In the future, by increasing the number of participants with various levels of competition, we aim to develop a system that can be adapted to more people by evaluating and identifying the sound source localization ability according to their proficiency level.

ACKNOWLEDGMENT

This research was supported in part by the Green Computing Systems Research Organizations.

ETHICAL CONSIDERATIONS

The experiments conducted in this study were reviewed and approved by the Waseda University Ethics Committee (Approval No.2022-299).

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