Exploration of Sonification Feedback for People with Visual Impairment to Use Ski Simulator

YUSUKE MIURA, Waseda University, Japan
ERWIN WU, Tokyo Institute of Technology, Japan
MASAKI KURIBAYASHI, Waseda University, Japan
HIDEKI KOIKE, Tokyo Institute of Technology, Japan
SHIGEO MORISHIMA, Waseda Research Institute for Science and Engineering, Japan

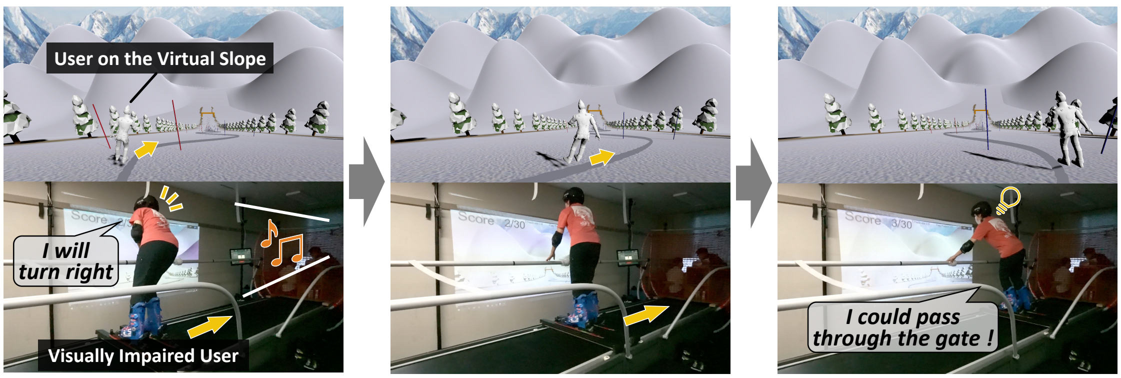

Fig. 1. Overview of our proposed system and experiment by a visually impaired person. The visually impaired person is passing through the gates placed on the virtual slope by our proposed sonification feedback.

Training opportunities for visually impaired (VI) skiers are limited because it is essential for them to have sighted people who guide them with their voices. This study investigates an auditory feedback system that enables ski training using a ski simulator for VI skiers alone. Based on the results of interviews with actual VI skiers and their guides, we designed the following three types of sounds: 1) a single sound (ATS: Advance Turn Sound) that conveys information about turns; 2) a continuous sound (CES: Continuous Error Sound) that is emitted according to the difference between the user's future position and the position he/she should progress to; and 3) a single sound (Gate-Passed Sound) which is emitted when a user passed through a gate. We conducted an evaluation experiment with four blind skiers and three sighted guides. Results showed that three out of four skiers performed better under the conditions in which ATS and gate-passed sound were emitted than the condition in which a human guide gave calls. The result suggests that a sonification-based method such as ATS is effective for ski training on the ski simulator for VI skiers.

CCS Concepts: • **Human-centered computing** → **Accessibility systems and tools**; **Virtual reality**.

Additional Key Words and Phrases: visual impairment, ski training, ski simulator, sonification

Manuscript submitted to ACM

ACM Reference Format:
Yusuke Miura, Erwin Wu, Masaki Kuribayashi, Hideki Koike, and Shigeo Morishima. 2023. Exploration of Sonification Feedback for People with Visual Impairment to Use Ski Simulator. In *Augmented Humans Conference (AHs '23), March 12–14, 2023, Glasgow, United Kingdom.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3582700.3582702

1 INTRODUCTION

People with visual impairment (PVI) enjoy a variety of sports (e.g., cycling, football, and shooting). However, PVI do not have access to exercise opportunities compared to sighted people [4, 21, 31], as most of the sports enjoyed by PVI require sighted guides to assist them (e.g., marathon, swimming, and skiing). Therefore many of them suffer from chronic physical inactivity [33]. In particular, ski training opportunities are very limited due to the lack of sighted guides who guide PVI with their voices. Also, constraints from seasonal and environmental issues reduce their opportunities for ski training. While recent research has explored systems that assist guides to efficiently convey directional cues to PVI in real-time [1, 9], there has been no research that enables PVI to train skiing without a sighted guide. Meanwhile, the indoor ski simulator (Figure 2) has been used for ski training. Users can train turns for skiing indoors all year round by sliding horizontally on the simulator by passing through the virtual gates displayed on the screen in front of them. However, it is difficult for PVI to use the ski simulator, as the ski simulation system is designed only for sighted people. Therefore, in this study, we explore the feedback which enables independent ski training for PVI with skiing experience using the ski simulator.

To design an effective feedback system in ski training for PVI, we conducted an interview with actual visually impaired (VI) skiers and their guides to investigate the specific calls guides gave. Through the interview, we revealed that guides determine the approximate area they want VI skiers to proceed based on the course conditions and the location of obstacles, and give calls such as "turn", "right" or "left" before the turn. Guides give these calls shortly before the turn so that the VI skiers can prepare for the turn. Guides also convey the depth of the turn (Figure 2) by the volume of these calls, and the length of the turn (Figure 2) by changing the duration of the calls.

Based on the interview, we propose a feedback system (Figure 1) composed of Advance Turn Sound (ATS), a single-tone sound that conveys information about the turn shortly before making it, and gate-passed sound, a sound that is emitted when a user passed through a gate. ATS is a sound that is designed based on the call that is actually used by guides. We varied the pitch and length of ATS to convey the depth and length of the turn and emitted the sound from the direction from which the turn should be made, using a stereo sound. In addition, ATS was emitted shortly before the turn to allow users to prepare for it. The gate-passed sound was constructed to enable users to verify whether they had passed a gate.

To evaluate the effectiveness of our feedback system, we conducted an experiment with four VI skiers and three guides. As a baseline feedback, we used a sound that rectifies the current error between the user and a trail that the user should be following, which was proposed by Parseihian *et al.* [26], and named it continuous error sound (CES). This feedback has been shown to help users maintain the proper trail and anticipate turns in driving tasks. In the experiment, we prepared four conditions: 1) **ATS condition**, in which ATS and gate-passed sound are emitted; 2) **CES condition**, in which CES and gate-passed sound are emitted; 3) **Mix condition**, in which ATS, CES, and gate-passed sound are emitted; 4) **Guide condition**, in which a human guide gives calls to participants. We defined the trail that users should follow based on the pre-collected skiing data from an experienced ski simulator user. We evaluated the user's performance by the number of gates passed and the mean distance to the virtual guide. As a result, three of the four participants passed through more gates in the ATS condition than in the Guide condition. In addition, the ATS

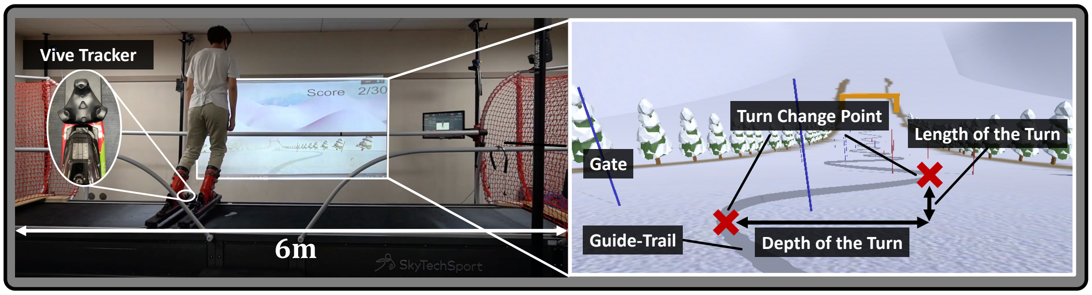

Fig. 2. Existing ski simulation system. The figure on the left is an overall view of the system. The ski simulator is approximately 6 meters in width. Two Vive Trackers are installed on the pair of ski boards to obtain the user's position. The figure on the right shows the user's view. Gates and a guide-trail are placed on the virtual slope. The turn change point, the depth, and the length of the turn are defined as shown in the right panel.

condition improved users' performance significantly, compared to the baseline CES condition. Furthermore, participants commented that they relied mainly on ATS in the Mix condition and not on CES. These results suggest that our proposed feedback system works significantly better than the baseline CES system and can allow the PVI to practice alone.

Our contribution to this paper can be summarized as follows:

(1) Development of a feedback system to enable independent ski training for PVI.
(2) An experiment to investigate what kind of feedback system is appropriate for ski training of PVI.
(3) Detailed quantitative and qualitative considerations from the results of the experiment.

2 RELATED WORK

2.1 Sports Assistance for People with Visual Impairment

In recent years, in the field of HCI (Human Computer Interaction), researchers have proposed systems that support sports played by PVI through various approaches, which can be divided into three types of purposes: 1) to expand the range of sports that can be played by PVI (e.g., exergame [23, 24], yoga [29], and badminton [15, 32]); 2) to enable PVI to play sports without supports of sighted guides (e.g., climbing [13, 30], running [8, 28], hiking [19], and kayaking [3, 16]; and 3) to reduce the burden on sighted guides (e.g., skiing [1, 9]). Particularly in VI skiing, Haladjian *et al.* [9] and Aggravi *et al.* [1] proposed systems using haptic feedback to facilitate communication between guides and VI skiers. However, these studies aimed at reducing the burden on sighted guides (3), meanwhile our main goal is to enable PVI to ski training without sighted guides (2).

2.2 Ski Training System

There are studies using auditory feedback to promote improvement in on-site skiing [5, 10]. For example, Hasegawa *et al.* [10] created a system that uses auditory feedback to present the user's center of gravity in real time, thereby inhibiting postural stooping. However, this study was conducted on only sighted people and no studies have been done to assist VI skiers.

In recent years, many studies have been conducted on the construction of effective ski training systems using indoor ski simulators. Aleshin *et al.* [2] proposed a system that projects a virtual slope on a front screen using a ski simulator and showed that ski simulators are effective for ski training for both beginners and professional athletes. In addition, research on effective visual feedback has been conducted using ski simulators in order to improve skiing for sighted people [25, 35], and research on time distortion in VR space has been conducted [22]. Furthermore, Hoffard *et al.* [12] investigated the effect of haptic feedback in addition to visual feedback on ski training on a ski simulator. Although such studies have been conducted to promote skiing improvement using ski simulators, all of the studies have been undertaken on sighted people, and no studies have been undertaken on PVI.

In light of this current situation, we use a ski simulator to create an environment in which PVI can ski train alone, anytime. Our purpose is to lower the barriers for them to participate in skiing and enable them to train skiing independently.

2.3 Non-visual Feedback for People with Visual Impairment

To enable PVI to play sports without the support of sighted people, it is necessary to use haptic or auditory feedback to convey the necessary information to play sports. Haptic feedback is often used as it allows users to hear the sounds of the surrounding environment. Rector *et al.* [28] investigated whether auditory or haptic feedback was effective for PVI when they ran on tracks. As a result, they found no significant difference between the two types of feedback, and the perception of vibration was difficult when users were holding an object (e.g., a cane or a guide dog). Also, there have been many studies on auditory feedback for PVI. Auditory feedback is usually provided through either text-to-speech (TTS) [6, 14, 18] or sonification [17, 20, 26]. Sonification was found to be the feedback that could effectively convey information about the quantity [20] and also induce a lower cognitive load compared to TTS [17]. Sonification methods that encode and convey information about distances and quantities as sound parameters have been used in many studies [7, 11, 27, 36]. In addition, one method for conveying direction through auditory feedback is using a stereo sound and a 3D sound [26, 34].

One approach to help PVI use ski simulators is to provide feedback to encourage them to follow a virtual guide who is skiing in front of them. There have been many studies using auditory feedback to help PVI follow a trail. For example, ProjectGuideLine [8] is a system that allows PVI to run along a trail by emitting a warning sound whenever a user deviates from the trail and keeps the user on the line. Compared to skiing, in running tasks, people usually follow a more straight trail, and they do not make frequent turns. Also, Parseihian *et al.* [26] showed that for trail following in a driving simulator, a continuous sound according to the difference between the user's future position and the position to be advanced is effective. In the driving task, on the other hand, the method of Parseihian *et al.* may be effective in skiing, since it requires dealing with a large number of turns. Therefore, in this study, we named the sound "Continuous Error Sound (CES)" and investigated its effectiveness as baseline feedback.

3 SYSTEM DESIGN AND IMPLEMENTATION

As described in Section 2, there are many studies that support sports for PVI, but none that support stand-alone ski training. Then, we propose a new sonification feedback system to enable the use of existing ski training systems [25], based on the methods of previous studies and interviews with VI skiers and their guides. As haptic feedback is not used in actual VI skiing, PVI are accustomed to audio-based interfaces in skiing. For this reason, in this study, we chose to use auditory feedback with speakers. In this section, we describe the specific system design and its detailed implementation.

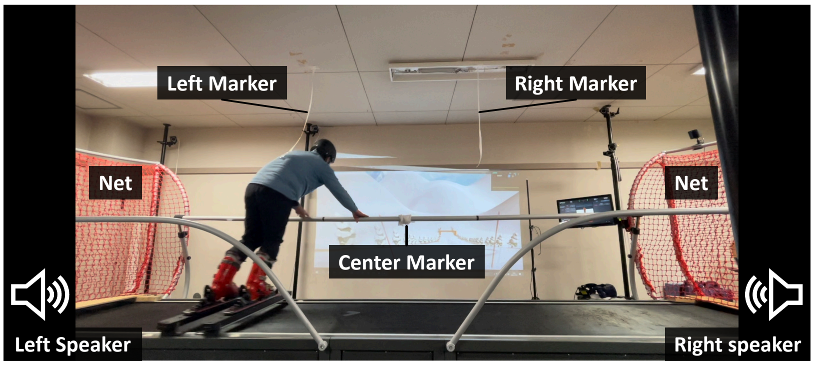

Fig. 3. Overall view of our system. Speakers and safety nets are placed on each side of the simulator. To prevent PVI from colliding with the nets on either side, we wrapped vinyl around the center of the handrail and hung markers from the ceiling to indicate the center position on the simulator.

3.1 Hardware

In this study, an indoor ski simulator (SkyTechSport Ski Simulator)[1] and a projector, two Vive Trackers were used to create a ski simulation system (Figure 2). The width of the ski simulator is approximately 6 m, the ski boards are placed parallel to each other with a fixed lateral distance on the simulator. When a user tilts the ski boards sideways, an external force is exerted to slide the skis in the tilt direction, allowing the user to move left and right on the simulator. Vive Trackers were attached to the tip of the ski boards of the ski simulator to detect the user's position. We also installed two speakers, one on each side of the simulator, to provide stereo auditory feedback to the user (Figure 3). We avoided using wireless headphones, as it may cause problems with delay. Furthermore, to prevent participants from colliding with the nets on either side, we wrapped vinyl around the center of the handrail and hung markers from the ceiling to indicate the center position on the simulator (Figure 3).

3.2 Creation of Virtual Slope

To train skiing in a virtual space, we created a virtual slope consisting of 30 gates and a *guide-trail* (Figure 2), a trail that passes every gate, using Unity [25]. In the simulator, the vertical velocity of a user, i.e., the velocity in the direction in which the slope descends, was set constant. Also, the horizontal position of the user on the virtual slope was determined by the user's actual position on the ski simulator, which was detected by the Vive Trackers. From the screen of the virtual slope projected on the projector, sighted people can grasp where the gates are, and practice turns by skiing in between the gates. To obtain a guide-trail, we first let an experienced skier who was accustomed to the simulator ski the route while passing all gates. Then we used the log of the ski of the experienced skier as a guide-trail.

3.3 Design of Proposed Auditory Feedback

3.3.1 Gate-Passed Sound. While sighted people can easily determine whether they passed through a gate, PVI cannot. For this reason, we constructed a gate-passed sound to inform users whether they had passed through the gate. This sound is essential for PVI to practice alone, and it is expected that this sound will improve their skiing skills. In addition, to improve user motivation, the pitch of the sound was made to be higher when users were able to consecutively pass

[1]https://www.skytechsport.com/ski-simulators-home

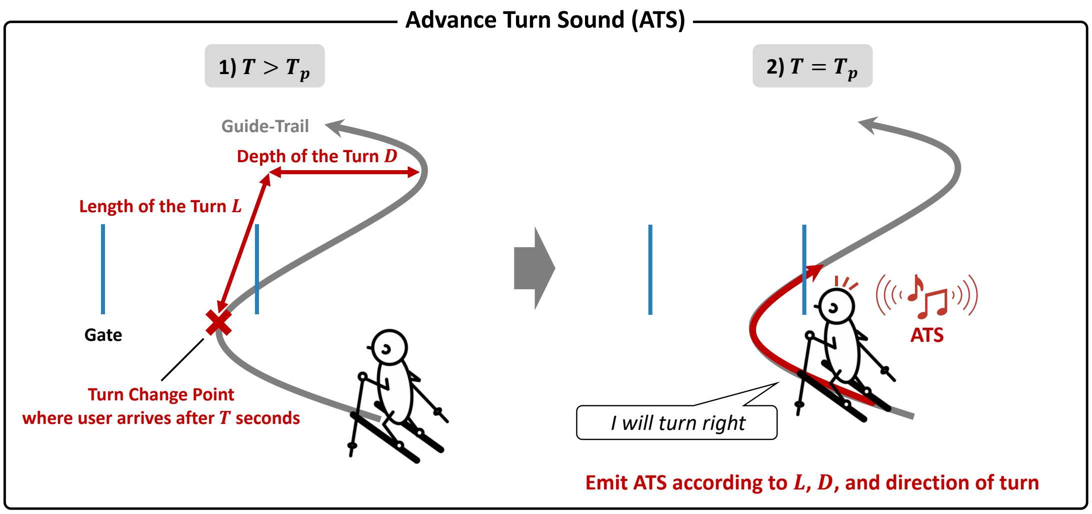

Fig. 4. Overview of Advanced Turn Sound (ATS). T represents the time it takes for a user to reach the turn change point, T_p is a constant value and ATS is emitted when $T = T_p$. In this study, $T_p = 0.74$ seconds.

the gates. In particular, we increased the pitch of the sound by a factor of 1.2, 1.4, 1.6, and so on when users were able to pass through the gate consecutively.

3.3.2 Advance Turn Sound (ATS). We created a single-tone sound (ATS) (Figure 4) that corresponds to the actual calls given by guides which are used to convey the length, depth, and timing of a turn. A turn is composed of the timing, the depth, the length, and the direction of the turn (Figure 2). Therefore, if all of the information is conveyed to VI skiers before the time when each turn should be made, it is expected that they will be able to pass through the gates. Note that at this time, guides allow VI skiers to prepare for the next turn by making the call shortly before when they actually need to make a turn. Therefore, we made ATS emit T_p seconds before the time when users should make the turn (the inflection point of the guide-trail). Although T_p is expected to vary from skier to skier, a constant value $T_p = 0.74[sec]$ was used in this study. In addition, actual guides convey information on the depth and length of turns by the volume and length of their calls, but these changes are highly dependent on the guides, and it takes time to get used to them. Thus, in this study, information about turns was replaced by sound pitch and length using a sonification method to promote intuitive understanding (Section 2.3). Specifically, the length of the sound was switched depending on whether the time until the next turn was 1.30 seconds or less, 2.22 seconds or less, or longer than 2.22 seconds. Also, to convey the depth of the turn, a low tone of 130.82 Hz was emitted for turns with a depth of 1.5m or greater, and a high tone of 261.63 Hz for turns with a depth of less than 1.5m. In addition, guides usually convey the direction of the turn by verbal feedback such as "right" or "left," but to reduce the cognitive load on users [17], we used a stereo sound to convey the direction of the turn by emitting a sound from the speaker in the direction in which the turn should be made.

4 EXPERIMENT

The aim of our experiment is to evaluate the effectiveness of our proposed feedback system. We recruited four VI participants (age: 50-72 (mean: 56.5) years, three males and one female) with skiing experience shown in Table 1 and three sighted participants (age: 46-56 (mean: 50.7) years, one male and two female) with guiding experience of VI skiers

Table 1. Data of VI participants in the experiment.

ID	Gender	Age	Eyesight	Years of disability	Years of skiing experience
P1	Male	50	Blind	44	7
P2	Male	72	Blind	65	32
P3	Female	51	Low vision	51	20
P4	Male	53	Blind	40	40

Table 2. Data of sighted participants in the experiment.

ID	Gender	Age	Guided participant	Years of guiding experience
G1	Female	50	P1, P2	15
G2	Male	46	P3	20
G3	Female	56	P4	30

shown in Table 2 (Figure 1). Each experiment took approximately three hours and each participant was compensated $65. This experiment was conducted after obtaining the review of the Research Ethics Committee of our institution.

4.1 Experimental Conditions

To investigate the effectiveness of our proposed method, we used the feedback proposed by Parseihian *et al.* [26] described in section 2.3 as a baseline and named it continuous error sound (CES). We also prepared a Mix condition in which both ATS and CES were emitted according to the user state.

Then, in this experiment, four conditions were prepared to verify the effectiveness of ATS, CES, and Mix:

(1) **Guide condition**: One human guide gives calls to a VI participant so that he/she can follow the virtual guide-trail projected on the screen in front of the ski simulator.
(2) **ATS condition**: ATS and gate-passed sound are emitted.
(3) **CES condition**: CES and gate-passed sound are emitted.
(4) **Mix condition**: ATS, CES, and gate-passed sound are emitted. ATS and CES are switched according to the user's position and the direction a user is currently traveling.

The following section describes specific implementations of CES and Mix conditions.

Continuous Error Sound (CES). We constructed a continuous sound for errors with the virtual guide, based on the sound proposed by Parseihian *et al.* (Figure 5) The sound's pitch and volume are according to the difference between the position in y seconds, which is predicted according to the user's current position and direction of travel, and the position that the user should actually be in y seconds later. Specifically, the larger the difference, the higher the sound pitch and the louder the sound volume. The specific implementation is as follows.

First, the angle of a difference θ [deg] between the direction a user is currently traveling and the direction to the position the user should reach in y seconds is calculated, as shown on the left of Figure 5 ($y = 0.74$). The sound frequency f[Hz] is then determined from the magnitude of θ based on the following Eq. 1 ($f_{max} = 1500Hz$, $f_{min} = 300Hz$).

$$f = f_{min} \cdot 2^{\frac{|\theta|}{90} \cdot \ln \frac{f_{max}}{f_{min}} \cdot \frac{1}{\ln 2}} \tag{1}$$

This reflects the fact that human perception of sound pitch is logarithmic. We also set the sound volume $V(-\infty \leq V \leq 80)$ [dB] to be $-\infty$ when θ is less than 10 degrees and to increase linearly with the absolute magnitude of θ (Eq. 2).

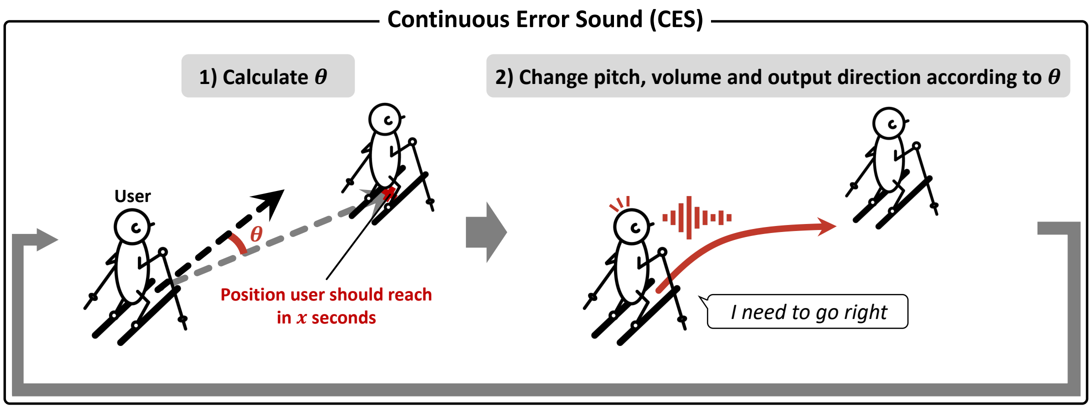

Fig. 5. Overview of the Continuous Error Sound (CES). First, the difference θ [deg] between the angle of the user's current direction of travel and the angle to reach the virtual guide that the user can reach after 0.74 seconds is calculated. Then, the pitch, volume, and output direction of the sound change according to the value of θ.

$$V(\theta) = \begin{cases} 80 & (90^\circ \leq |\theta|) \\ 80 + 20\log_{10}\frac{|\theta|-10}{80} & (10^\circ \leq |\theta| < 90^\circ) \\ -\infty & (|\theta| < 10^\circ) \end{cases} \quad (2)$$

In addition, in order to convey which direction a user needs to go from now on in relation to the current direction of travel, the sound was emitted from the direction in which the user should travel using a stereo sound. This allows a user to follow the virtual guide by proceeding in the direction in which the sound was emitted.

Combination of ATS and CES (Mix). The combination of ATS and CES (Mix) can allow the user to follow the guide-trail by using ATS to perform the turn and CES to correct users' deviation from the guide-trail. However, a simple combination will result in feedback with a higher cognitive load than necessary. Therefore, ATS and CES were switched according to the user's position and the direction the user was currently traveling, in order to convey information that should be conveyed to the user. The sound was switched according to the angle difference θ, which is an angle between the vector of the user's heading direction and the vector constructed by connecting the user and the virtual guide, and the horizontal distance between the user and the guide-trail d (Figure 6). Specifically, the system switched the feedback according to the values shown in Table 3. We determined that when $\theta > 20^\circ$, i.e., when the user had to correct the trail, then we emitted only CES. Otherwise, we judged that the user was on the trail and we emitted only ATS. As an exception, when $\theta \leq 60^\circ$ and $d \leq 1.4m$, we used both ATS and CES. This is because we assume the combination of both sounds will work well, as it will not take a long time for users to get back on the trail. We stopped emitting CES during ATS was being emitted to avoid a situation where ATS and CES were emitted at the same time.

4.2 Course Preparation

For this experiment, We prepared three courses, C0, C1, and C2, each consisting of 30 gates:

(1) **C0**: The time until the next gate ranges from 1.62 to 1.74 seconds, and the turn depth is randomly arranged to take values between 1.55 meters and 1.70 meters.

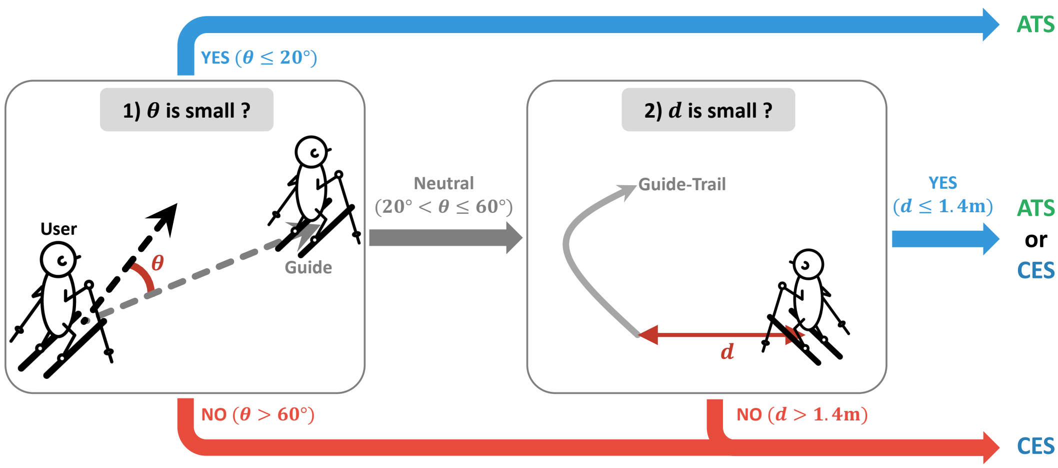

Fig. 6. Overview of the combination of ATS and CES (Mix). We switched the sound according to the difference in the angle of travel between the user and the virtual guide θ and the distance between the user and the virtual guide d.

Table 3. Relationship between user's state and emitted sound.

		Distance to Guide d	
		$d \leq 1.4$m	$d > 1.4$m
Difference of travel angle θ	$\theta \leq 20°$	ATS	ATS
	$20° < \theta \leq 60°$	ATS or CES	CES
	$\theta > 60°$	CES	CES

(2) **C1**: The time until the next gate is the same as in C0, and the turn depth is randomly arranged to take values between 1.96 meters and 2.17 meters.
(3) **C2**: The time until the next gate is the same as in C0, and the turn depth is randomly arranged to take values between 1.29 meters and 2.84 meters.

In addition, there were two locations on both courses that required two consecutive short turns in the middle of the course (the time until the next gate ranges from 0.78 to 0.90 seconds, and the turn depth ranges from 0.98 meters to 1.09 meters). We used randomly generated courses for our experiments according to the above constraints.

4.3 Procedure

Figure 7 shows the procedure of the experiment. The experiment was conducted in a combination of P1-G1, P2-G1, P3-G2, and P4-G3. While boarding the ski simulator, the participants wore helmets, protectors, and ski boots. The experiment was conducted according to the following procedure.

(1) We first conducted a pre-experiment interview asking them about their experience of skiing.
(2) Next, we explained what the ski simulator is and the contents of the experiment.
(3) Then, 30 minutes training session was given to familiarize the participants with the ski simulator and the feedback. In order to match the performance at the beginning of the practice session for each experimental

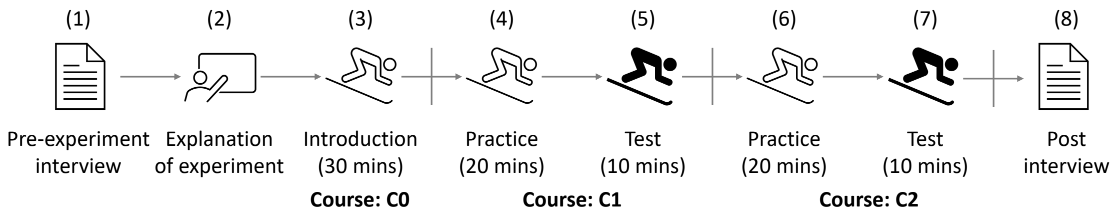

Fig. 7. Experimental procedure. In each practice and test phase, users performed the four conditions in random order.

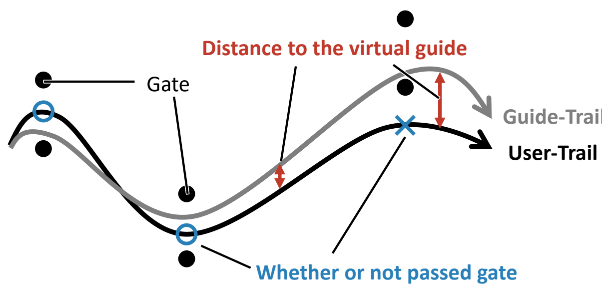

Fig. 8. Example of distance to the virtual guide and whether or not a user passed a gate.

condition, the participants practiced in each condition (ATS, CES, Mix, and Guide condition) until they passed 20 of the 30 gates on the C0.

(4) The participants practiced C1 four times for each of the four experimental conditions, making in total 16 practices.
(5) Two test runs (i.e., runs that were used to evaluate the user's performance) were made on C1 under the four conditions.
(6) The participants practiced C2 four times for each of the four experimental conditions, making in total 16 practices.
(7) Two test runs were made on C2 under the four conditions.
(8) After the measurement, post-questionnaires using a 7-point Likert scale and interviews were conducted with the participants regarding the experiment (Section 4.4.3).

During the experiment, the participants kept their hands on the handrail placed in front of the simulator until they understood the length of the width of the ski simulator for safety reasons. Also, to avoid learning effects, we randomized the order of experimental conditions (ATS, CES, Mix, and Guide condition).

4.4 Metrics

4.4.1 Number of gates passed. The number of gates passed through was defined as the "number of gates passed", and was calculated from the log of the user's position for each run (Figure 8).

4.4.2 Mean distance to the virtual guide. The average horizontal relative distance between a user and the guide-trail placed on the virtual slope was defined as the "mean distance to the virtual guide," and it was calculated from the user's positional information results for the virtual guide on each run (Figure 8).

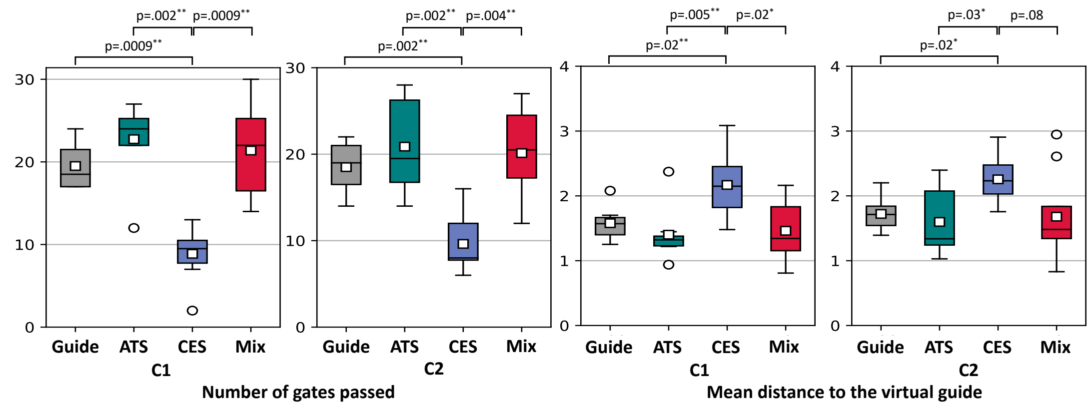

Fig. 9. Number of gates passed and mean distance to the virtual guide in each experimental condition. * and ** indicate the significance found at the levels of 0.05, and 0.01.

4.4.3 Subjective evaluation of the system. After the experiment, the participants were asked to complete a subjective evaluation questionnaire regarding each experimental condition. The participants were asked to respond to the questions in table 4 on a 7-point Likert scale (1: strongly disagree, 4: neutral, and 7: strongly agree). In addition, we interviewed the advantages, disadvantages, and suggestions for improvement of each condition.

5 RESULTS

In this section, we describe the results of the two quantitative evaluation metrics and the subjective evaluation described in section 4.4.

5.1 Quantitative Results

Figure 9 shows the results of the number of gates passed and the mean distance to the virtual guide in each condition and course. Comparison of each condition using the Mann-Whitney U-test (significance level: 5%) showed that the number of gates passed was significantly larger in the Guide, ATS, and Mix conditions than in the CES condition for C1 (p=0.0009, 0.002, 0.0009), and the same result was obtained for C2 (p=0.002, 0.002, 0.004). In C1, the mean distance to the virtual guide was significantly smaller in the Guide, ATS, and Mix conditions than in the CES condition (p=0.02, 0.005, 0.02). On the other hand, in C2, the mean distance from the virtual guide was significantly smaller in the Guide and ATS conditions than in the CES condition (p=0.02, 0.03), but there was no significant difference between the two conditions (p=0.08).

The quantitative evaluation results for each participant are shown in Figure 10 and Figure 11. The ATS condition resulted in an increase in the number of gates passed and a decrease in the mean distance to the virtual guide compared to the Guide condition for P1, P2, and P4, except for the mean distance to the virtual guide at C2 in P1. For all participants, the CES condition reduced the number of gates passed and increased the mean distance to the virtual guide in most cases compared to the other conditions. The results for the ATS and Mix conditions were almost identical for each participant.

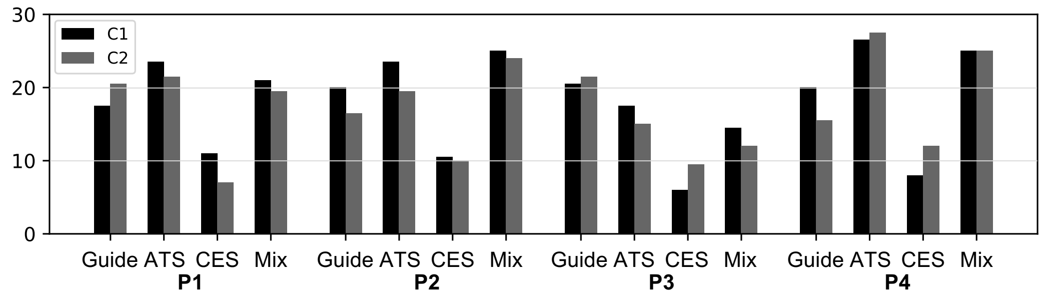

Fig. 10. Number of gates passed in each experimental condition per participant.

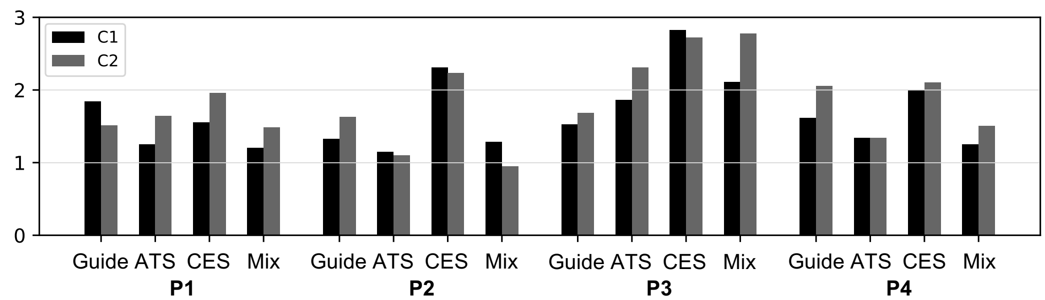

Fig. 11. Mean distance to the virtual guide in each experimental condition per participant.

5.2 Results of subjective evaluation of the system

The results of the questionnaire are shown in Table 4. For all questions, the CES condition was rated lower than the other conditions. Three out of the four participants answered that the Guide and ATS conditions were easier to understand than the Mix condition (Q2). However, responses to the other questions were similar for the Guide, ATS, and Mix conditions.

In the interview, all participants agreed that ski training using the ski simulator was enjoyable and that they would like to train using the simulator on a daily basis. In particular, all participants commented that the gate-passed sound increased their motivation: A1: *"When I heard the gate-passed sound, I knew that I was able to make a good turn and I enjoyed skiing. In that sense, I enjoyed the conditions other than the Guide condition because, in the Guide condition, I did not know whether I could pass the gate well or not."*[2] (P1)

Three of the four participants commented regarding the difference between the Guide condition and the other conditions, saying that the stereo-sound feedback was more intuitive and easier to understand than the verbal feedback of the guide. On the other hand, one participant provided the following negative feedback: A2: *"I usually rely on the voice prompts of guides when skiing, and I am used to that, hence the verbal feedback was easier to understand."* (P3)

All participants commented that ATS was helpful in understanding information about the next turn and preparing for it in advance. Three of the four participants also commented that the change in the length of ATS was easy to understand and helped them understand the time until the next turn. On the other hand, three participants found

[2]The reported comments are translated from the native language used where the study was conducted.

Table 4. Likert Items (1: strongly disagree, 4: Neutral, 7: strongly agree) and a summary of answers.

Question	Condition	P1	P2	P3	P4	Mean	SD	Median
Q1: I was able to ski with confidence.	Guide	6	5	7	5	5.75	0.83	5.5
	ATS	6	5	6	7	**6.00**	0.71	6
	CES	1	4	4	2	2.75	1.30	3
	Mix	4	5	6	7	5.50	1.12	5.5
Q2: Feedback was easy to understand.	Guide	6	7	7	5	**6.25**	0.83	6.5
	ATS	6	5	7	7	**6.25**	0.83	6.5
	CES	1	1	2	1	1.25	0.43	1
	Mix	5	1	5	7	4.50	2.18	5
Q3: I understood and was prepared for my next turn.	Guide	6	7	7	4	6.00	1.22	6.5
	ATS	6	5	7	7	**6.25**	0.83	6.5
	CES	1	2	4	3	2.50	1.12	2.5
	Mix	6	5	6	7	6.00	0.71	6
Q4: I was able to correct my course when I got off the trail.	Guide	1	7	7	4	**4.75**	2.49	5.5
	ATS	1	1	7	7	4.00	3.00	4
	CES	2	1	4	4	2.75	1.30	3
	Mix	3	1	6	7	4.25	2.38	4.5

the change in pitch of ATS difficult to understand: A3: *"I would prefer the difference in sound pitch to be clearer."* (P4) When we interviewed about the usefulness of ATS, the following comments were obtained: A4: *"When I was on the correct trail, I was able to ski correctly in rhythm by listening to the sound in combination with the gate-passed sound. Even when I deviated from the correct trail, I was able to get back on track by skiing in time with ATS"* (P4), and A5: *"When I deviated from the correct trail, I did not know how I was deviating from the trail, and it was difficult to correct my trail."* (P1) However, even though the turn should have been made 0.74 seconds after ATS was emitted, one participant started the turn to match ATS emitted, resulting in the following comment: A6: *"I could understand the meaning of ATS, but I could not wait for a little after the sound emission and made a turn. I think I will be able to do it with a little more practice and getting used to it."* (P3)

All participants also indicated that CES was of little use for tracking the virtual guide. Specifically, all participants commented that although they could see that CES indicated that they needed to make a course correction, they did not know how to move to make the correction: A7: *"I could see that I was off course by CES, but I did not know how to run to correct it."* (P2) On the other hand, the opinion that CES was useful for the gentle turn at the beginning of the course was obtained: A8: *"CES allowed me to pass the first gate."* (P1)

For the Mix condition, all participants commented that they relied only on ATS and not on CES: A9: *"I mostly listened to ATS and could not make use of CES in my decisions.* (P3), and A10: *"The presence of CES prevented me from concentrating on ATS. In fact, CES was a hindrance."* (P4)

6 DISCUSSION

Based on the results, in this section, we first discuss the effectiveness and limitations of ATS, CES, and Mix. Then, we discuss future prospects.

6.1 Effectiveness of ATS

No significant differences were observed between the ATS-based conditions (ATS and Mix conditions) and the Guide condition, regardless of the course or quantitative metric. On the other hand, for participants other than P3, the average number of gates passed increased and the average of the mean distance to the virtual guide decreased in the ATS condition compared to the Guide condition. All participants also commented that ATS was easy to understand and enabled them to understand the information about the next turn and prepare for it. These results suggest that sounds using a sonification method such as ATS are more effective at giving detailed instructions quickly and intuitively than verbal feedback given by human guides, similar to previous studies [17, 20].

Furthermore, P4 made the comment (A4) suggesting that only ATS could not correct the trail in the event of a deviation from the guide-trail, but listening to ATS in combination with gate-passed sound made it possible. Although gate-passed sound does not have a role in correcting the user's trail, users can indirectly know if they are responding correctly to ATS. Thus, during the practice phase, the users could have learned the movement corresponding to ATS from gate-passed sound, and finally, they became able to make subtle trail corrections depending on the presence or absence of gate-passed sound. These results suggest that the user may be able to perform as well as the guided feedback under the ATS condition after getting used to it.

6.2 Limitations and Effectiveness of CES

In the CES condition, the user's performance was significantly lower than in the other conditions. This is supported by a comment by P2 indicating that they were not able to determine how much they had to correct themselves using CES (A7). There are several reasons why CES did not work effectively.

The first possible reason is that the changes in pitch and volume of the sound were not clear. Also, we conveyed to them the information about the "angle to move", but the information did not directly tell them how they needed to move their bodies. Thus, there is room for exploration of what information and how users should be conveyed. We can make deeper considerations from the participants' observations. In a situation where CES is emitted, participants may need to make a turn, or they may need to shift slightly to fix their deviation while maintaining the direction of travel. However, participants instantly made turns in the direction of the sound emitted when they heard CES. In this way, it is difficult to respond appropriately to CES in the ski simulator because the practice in the ski simulator involves changing direction using the entire body, unlike changing direction via the steering wheel as in driving. On the other hand, for long and shallow turns which appeared at the beginning of the courses, all participants were able to follow the guide-trail accurately, and participants also commented that CES was useful at the beginning of the course (A8). Thus, CES may be effective in situations that do not require frequent turns and where the direction of travel can be easily changed. The experiment was conducted on two different courses, C1 and C2, but to confirm these considerations, it is necessary to conduct the experiment on other courses with different turn depths and lengths.

In conclusion, CES was not effective for three reasons: 1) the changes in pitch and volume of the sound were not clear, 2) it was not suited to the task of skiing on the ski simulator, and 3) it was not suited to the course used in the experiment. The effects of these factors need to be investigated in detail in the future.

6.3 Limitations and effectiveness of Combination of ATS and CES

No significant differences were found between the Mix and ATS conditions, regardless of the course or quantitative metrics. All participants indicated that they relied only on ATS, and not on CES at all (A9). In the interview (A10), the combination of ATS and CES did not work effectively, as some participants said that the combination of CES interfered with their concentration. These results are also supported by the discussion in Section 6.2.

6.4 Future Work

In this section, we first discuss proposed system improvements to enhance performance. Then, we discuss the problems of using our system in a real ski resort.

6.4.1 Proposed System Improvements. While ATS and the gate-passed sound were highly appreciated by the participants, there is room for improvement in these sounds. For example, the optimal time of emission of ATS can vary from user to user, as P3 was not accustomed to it (A6). Participants indicated that it was difficult to understand the change in the pitch of ATS (A3), therefore we hope to experiment with a more clear difference in the pitch of the sound to study if it improves user performance in the future. Furthermore, the effectiveness of ATS was shown in a course with frequent turns, but not in other courses. In the future, we would like to design an ATS that is optimal for each user by varying the parameters related to the time when ATS is emitted and the type and length of the sound and investigate the situation in which ATS is effective using various courses.

We can also consider the results of the subjective evaluation shown in Figure 4 for suggestions on how to improve the system. For Q1-Q3, the ATS condition has the highest mean value, but Q4 was inferior to the Mix condition and the Guide condition. In other words, the current ATS conditions did not provide enough information to correct the trail. However, we found that CES is not suited for this purpose, therefore we expect a higher performance by using other means to convey information about the user's errors. For example, although we currently only use the sonification method, the TTS method to correct user errors could be effective. This mirrors the "more right" or "more left" call for user trail correction that is used in real VI skiing and the user may be able to take advantage of both information by obtaining information about the turn and the error by different means.

In addition, there is room for improvement in the gate-passed sound. Results of the experiment suggest that the gate-passed sound has the effect of encouraging users to correct their course. However, currently, there is no information obtained when a user fails to pass through a gate, and even when a user does pass through a gate, the current sound does not convey where in the gate the user passed. Therefore, a possible future direction is not to simply provide feedback on whether or not the user has passed through the gate, but rather feedback on the user's degree of success or failure in each turn. For example, if the user fails to pass through a gate, feedback on how far away from the gate the user was at the time of passing through the gate is given, and if the user succeeds in passing through a gate, feedback on how far away from the inside of the gate the user passed through is given. In the future, we would like to explore further improvements to the gate-passed sound.

6.4.2 Applications in Ski Resorts. This study suggests that the effectiveness of ATS and CES varies depending on the frequency of turns. Therefore, when applying these sounds to the actual skiing of VI skiers, it is necessary to change between ATS and CES depending on the course that the skier is asked to ski. For example, it is possible to guide the user by mainly using ATS on courses where frequent turns are necessary, and using CES on courses where it is not. Therefore, it is necessary to explore the relationship between the frequency of turns and the effectiveness of ATS and CES in more detail in the future. In addition, in order for a VI person to actually ski alone, it is necessary for him or her to grasp the surrounding situation at the ski resort and to acquire information such as the user's position, posture, and speed. In the future, we would like to verify the effectiveness of ATS and CES in real-world situations, and to work on the detection of surrounding information and the acquisition of user information at ski resorts using computer vision technology.

7 CONCLUSION

In this study, we investigated auditory feedback that enables training using a ski simulator for VI skiers alone. Based on the results of the interview with actual VI skiers and their guides, ATS and gate-passed sound were designed. We conducted evaluation experiments with four VI skiers and three guides to verify the effectiveness of each feedback. For the baseline feedback, we used CES proposed by Parseihian [26] *et al.* and prepared ATS, CES, Mix (ATS and CES), and Guide condition. The results of the experiment showed that the ATS improved the performance of three of the four participants, compared to the Guide condition. This result indicates that the ATS enables VI skiers to understand the information about the next turn and to prepare for it, and suggests that ATS can be as effective as feedback given by human guides in giving instructions. On the other hand, the effectiveness of CES was not confirmed. There are three reasons for this: 1) the changes in pitch and volume of CES were not clear, 2) it was not suited to the task of skiing on the ski simulator, and 3) it was not suited to the course used in the experiment. In the future, we would like to verify how the effectiveness of CES and ATS changes when the required frequency of turns is low or when the user's range of movement is extended, and explore the possibility of skiing alone in a real environment for PVI.

ACKNOWLEDGMENTS

This work was supported by JST CREST Grant No. JPMJCR17A3 and JST-Mirai Program Grant No. JPMJMI19B2.

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