SONIFICATION-BASED STEERING ASSISTANCE FOR CURVE DRIVING: EVALUATIONS IN VIRTUAL AND REAL-WORLD ENVIRONMENTS

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ABSTRACT

Maintaining stable steering is essential for safe and comfortable driving, and reducing corrective steering is a key factor in achieving this stability. In our previous study, we proposed a method that facilitates the recognition of the correct steering angle by mapping a musical scale to the steering angle in real-time. However, prior experiments were limited to short and simple curves, and its effectiveness in a full driving course within a virtual environment and in real-world driving remained unclear. In this study, we develop and evaluate two prototype systems to assess the effectiveness of our method in both virtual and real-world environments. One system is implemented in a full driving course within a virtual environment using a driving simulation game, while the other is applied in a real-world environment using an actual vehicle. We hypothesize that using the proposed method for driving practice will reduce corrective steering compared to conventional steering. Experimental results in the virtual environment showed that our method significantly reduced corrective steering compared to normal steering. Furthermore, our findings suggest that its effect persisted to some extent even after the auditory feedback was removed. Additionally, experimental results from a driving training program in a real-world environment indicated that our method was effective for some users, suggesting that effectiveness may vary across users.

1. INTRODUCTION

Accidents, including crashes involving novice and young drivers, are a prevalent concern [1, 2]. Several factors contribute to accidents, including attention lapses, misinterpretation of visual information, inappropriate speed relative to conditions, inadequate hazard recognition, and difficulty performing emergency maneuvers at high speeds. Novice drivers need to understand their skill level, improve their driving abilities, and assess accident risks in various hazardous situations [3].

There are several important skills in safe driving. Nakagawa et al. [4] conducted a survey and found that 23% of the 2,000 respondents reported that they were not confident in their driving skills, and 52% of them reported that steering on curves is a difficult driving skill. These results suggest that less skilled drivers often struggle with steering on curves.

Experience plays a crucial role in learning to drive on curves, as drivers develop an understanding of the timing and magnitude of steering adjustments through visual perception and proprioception. Poor steering control can lead to excessive steering or overcorrection after a turn, reducing driving stability. Stability is an important factor in driving [5]. Our project aims to develop a system that enables drivers to maintain stable steering while navigating curves.

In our previous study, we proposed a method that facilitates the recognition of the correct steering angle by generating a real-time musical scale corresponding to the steering angle [6]. In addition, we demonstrated that our method reduced corrective steering compared to normal driving on short courses with simple curves. However, our previous tests were limited to short, simple curves, and we have not yet examined the effectiveness of our method in a full driving course within a virtual environment or in real-world driving.

In this study, we develop and evaluate two prototype systems to assess the effectiveness of our method in a full driving course within a virtual environment and in real-world driving. One system is implemented in a full driving course within a virtual environment using a driving simulation game, while the other is applied in a real-world environment using an actual vehicle. We hypothesize that using the proposed method for driving practice will reduce corrective steering compared to conventional steering. To test this hypothesis, we evaluate its effectiveness in both virtual and real-world environments.

The contributions of this study are as follows:

- We extended prior research by implementing our sonification-based steering assistance in a full driving course within a virtual environment using a driving simulation game and demonstrated that it significantly reduces corrective steering compared to conventional steering.
- We developed and integrated our method into a real-world driving training program using an actual vehicle and identified individual differences in its effectiveness, suggesting the need for further adaptation.

2. RELATED WORK

2.1. Multimodal Driving Assistance System

Existing research on multimodal driving assistance has demonstrated the potential of auditory and visual feedback in enhancing driving performance.

For example, Sodnik et al.[7] compared auditory and visual interfaces in a driving simulator and found that the auditory interface not only improved driving skills and reduced perceived workload but was also rated as more satisfying. Similarly, Onimaru et al.[8] developed a system that used interaural sound pressure differences to convey the vehicle's lateral position. When combined with visual cues, this approach enhanced driving performance without increasing cognitive load.

Graham et al.[9] evaluated various types of voice warnings and found that they prompted faster driver responses than conventional alerts, emphasizing the importance of optimizing urgency and clarity. Similarly, Bian et al.[10] showed that appropriately timed and detailed voice navigation improved driving efficiency, stability, and comfort, suggesting that voice guidance can reduce cognitive load and enhance safety.

Beyond auditory feedback, Dmitrenko et al. [11] proposed a system that utilized multiple scents to convey driving-related information, aiming to reduce driver distraction. They utilized scents such as lavender, peppermint, and lemon to convey messages such as "Slow down," "Short inter-vehicle distance," and "Lane departure." The results showed that olfactory notifications were less distracting and more pleasant than visual notifications, leading to improved driving performance.

While these studies show that auditory feedback can support driving, most focus on discrete alerts or navigation instructions. In contrast, our method provides continuous auditory feedback based on steering angle, helping drivers make fine motor adjustments during curve driving.

2.2. Sonification to Guide

Numerous studies have explored the use of sound to guide behavior.

Van den Berghe et al. [12] proposed a system that provides music and noise feedback during running to reduce tibial shock. Their results showed that real-time audio feedback effectively reduced running impact. Lorenzoni et al. [13] proposed a system to improve deadlift technique, where music played correctly for proper movements and discordant sounds indicated improper ones. Experimental results showed that the system was comparable to feedback from an experienced trainer, allowing users to intuitively adjust their form.

Walker et al. [14] suggested the "Audio Abacus," an application for visually impaired individuals that allows them to understand numerical values through a musical scale. They demonstrated that users could determine the digits of a phonetized number with little practice.

Our study builds upon these findings by applying sonification to driving assistance. Specifically, we propose a system that maps steering angles to a musical scale to assist curve driving. By using our system, we expect that users will be able to recognize how much they need to turn the steering wheel based on auditory cues.

3. IMPLEMENTATION OF TWO TYPES OF PROTOTYPE SYSTEMS

To verify the usefulness of the proposed method on a full driving course within a virtual environment and in real-world driving, we implemented prototype systems in both settings. In this section, we describe the implementation details of each prototype system.

3.1. Prototype System in a Full Driving Course within a Virtual Environment

We chose Assetto Corsa as the driving simulation game because it allows developers to access driving data in real time using a shared memory library [15] and supports user-installed custom courses. The data acquisition module transmitted the collected data to our system via UDP communication. Our system receives the data in real time and plays the musical scale sound.

When the driver turns the steering wheel, the system generates a sine wave sound corresponding to the steering angle. The notes are evenly distributed: a "C" plays when the absolute angle reaches 5 degrees, and a "C" one octave higher is played at 95 degrees. Based on preliminary testing, we found that continuously playing the "C" note when the steering wheel was straight caused discomfort. To address this issue, the system does not produce sound when the absolute steering angle is below 5 degrees, preventing unnecessary auditory fatigue on straight roads (see Figure 1).

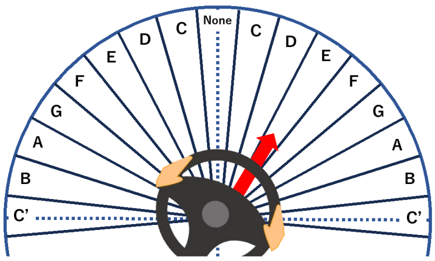

Figure 1: The mapping between the steering angle and generated sound.

The prototype system setup in the full driving course within a virtual environment is shown in Figure 2. A large display was positioned at an optimal viewing angle. We used Fanatecs ClubSport Wheel Base V2.5 as the steering controller, Fanatecs Podium Lenkrad Classic 2 as the steering wheel, Fanatecs ClubSport Pedals V3 as the pedals, and Next Level Racings NLR-S010 as the driving seat.

3.2. Prototype System in a Real-World Environment

To evaluate the effectiveness of our method in real-world driving, we implemented the prototype system in an actual vehicle. Figure 3 presents the system architecture.

The data acquisition module collects driving data from the vehicle via UDP communication in real time and transmits it to the information receiving module. The sound generation module receives this information and plays corresponding sounds through a speaker. Unlike the full driving course in the virtual environment, where the steering angle can be directly obtained from the simulation software, the real-world setting requires

Figure 2: The prototype system setup in a full driving course within a virtual environment.

acquiring the steering angle from the vehicles internal system. This adds complexity to the system implementation. Furthermore, real-world driving differs from the virtual environment in several ways. In an actual vehicle, the steering wheel has physical weight and mechanical play, and the driver also experiences road vibrations, all of which can influence steering behavior.

The prototype system was installed in a test vehicle driven on a designated test course to evaluate its real-world applicability. Based on preliminary testing, the pitch range was adjusted to span from 5 to 90 degrees, with the highest note at 85 degrees. This adjustment was made to ensure that the feedback was effective in real-world driving conditions.

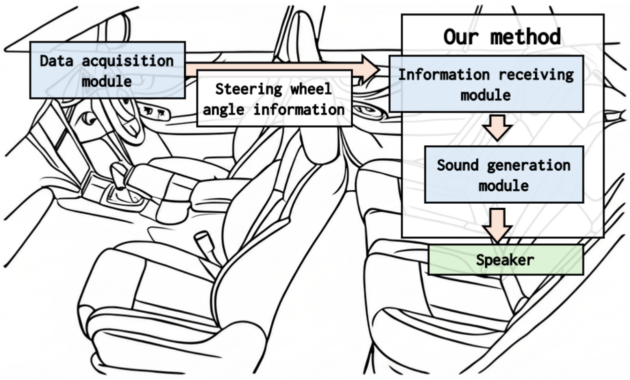

Figure 3: The system architecture of the prototype in a real-world environment.

4. EXPERIMENT 1: EVALUATING STEERING ASSISTANCE IN A VIRTUAL ENVIRONMENT

4.1. Overview

To evaluate the effectiveness of the proposed method on courses with multiple curves, we conducted an experiment using a racing simulation game. We hypothesize that driving practice using the proposed method on a full driving course with compound curves will reduce steering corrections, as drivers will associate pitch changes with steering angles. Additionally, we examine whether the effect persists after removing auditory feedback.

To test our hypothesis, we compared the following two conditions:

- **Proposed method:** Driving practice is conducted using a steering wheel that generates auditory feedback based on the steering angle.
- **Baseline method:** Driving practice is conducted using a standard steering wheel without auditory feedback.

4.2. Experimental Settings

We divided the participants into two groups, one being the baseline group and the other being the group using the proposed method, considering its inherent capabilities. The driving course used in the experiment (see Figure 4) was a reproduction of a course with complex curves in a car company. The total length of the course was 1800 m. The vehicle model represented a sedan-type production car. In this figure,

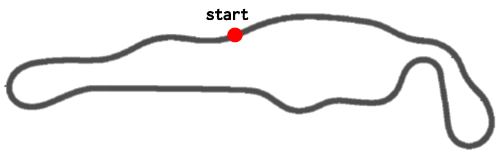

Figure 4: Course used in both experiments.

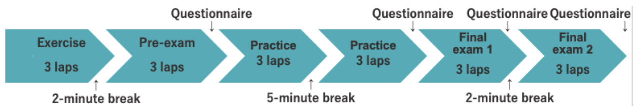

Figure 5: The flow of the experiment using a racing simulation game.

The experimental flow was as follows (see Figure 5):

- **Exercise phase (3 laps):** In this phase, all participants were free to try three laps with the normal, non-sounding steering wheel. If a participant feels sick when using the system, he/she can quit this experiment.
- **Pre-exam phase (3 laps):** In this phase, we instruct participants that this phase is to check their abilities. They drive three laps with a normal, non-sounding steering wheel.
- **Practice phase (6 laps):** Driving practice in the steering wheel mode for each group. The group using our system is asked to drive with a steering wheel that plays the notes of the musical scale. The baseline group is asked to drive with a normal, non-sounding steering wheel.
- **Final exam 1 (3 laps):** In this phase, we asked participants to drive using their group's method to measure the growth of the participants in the experiment. We instruct participants that this phase is to check their abilities.
- **Final exam 2 (3 laps):** In this phase, the development of the experimental participants is measured by asking all participants to drive with the normal, non-sounding steering wheel. We also instruct participants that this phase is to check their abilities.

Participants in the experiment using a racing simulation game were 26 undergraduate and graduate students (20 males and six females) who had never used a driving simulator. All participants held a valid driver's license. The duration of the experiment was approximately 60 minutes per subject, from instruction to the end of the experiment.

4.3. Results

One participant was excluded from the analysis due to incomplete or inaccurate driving data. As a result, there were 13 participants in the proposed method group and 12 participants in the baseline group. A statistical comparison of pre-exam steering corrections showed no significant difference between the proposed method group and the baseline group. This result suggests that the baseline and proposed method groups had no significant difference in initial driving proficiency.

To assess steering stability, a key factor in effective curve driving, we analyzed the number of steering corrections. A steering correction was defined as a change in the sign of the differential of the steering wheel angular velocity. Additionally, minor steering corrections of less than 3 degrees were excluded from the analysis, as they were considered negligible in terms of driving skill.

We hypothesized that driving practice with the proposed method on a full driving course with compound curves would reduce the number of steering corrections, as drivers would become more aware of their steering behavior through auditory feedback. To test this, we analyzed data across five experimental phases. The first lap of each phase was excluded to account for potential adaptation effects, and the average of the second and third laps was used for analysis.

The reduction rate of steering corrections (RC) for each participant in each curve was calculated using Equation (1):

$$RC(p_i, \text{curve}_j) = \frac{SC_{\text{final}}(p_i, \text{curve}_j)}{SC_{\text{pre}}(p_i, \text{curve}_j)} \quad (1)$$

Figure 6 compares the reduction ratio of steering corrections between the Pre-exam and Final exam 1 phases using a box-and-whisker plot. The figure indicates that participants in the proposed method group achieved a greater reduction in steering corrections compared to the baseline group. An independent samples t-test revealed that the number of steering corrections was significantly lower in the proposed method group compared to the baseline group ($p < 0.05$).

The questionnaire included a 5-point Likert scale question regarding the ease of driving, where 1 represented "not easy to drive" and 5 represented "easy to drive" (see Fig. 8). The results show that participants in the proposed method group tended to report a higher sense of ease in both Final exam 1 and Final exam 2 compared to those in the baseline group.

In the free-response section, positive comments included: "I would like to use the proposed system when I want to drive with an awareness of steering correction on my own," and "I felt that even just hearing the musical scale while turning the steering wheel increased my awareness of steering corrections."

Conversely, some participants expressed concerns such as: "If I rely too much on the sound, I might make a mistake, so I think it would be better if the system didn't rely solely on sound," and "It would be easier to use if the correct sound were presented in advance."

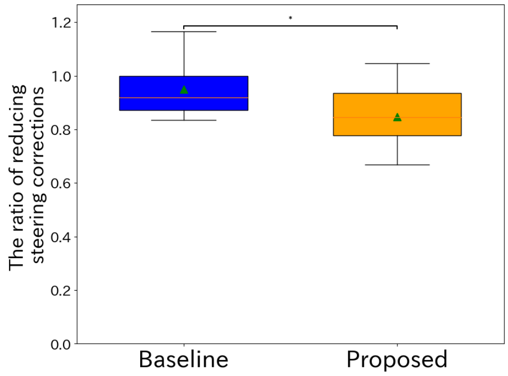

Figure 6: Reduction ratio of steering corrections between the pre-exam and final exam 1.

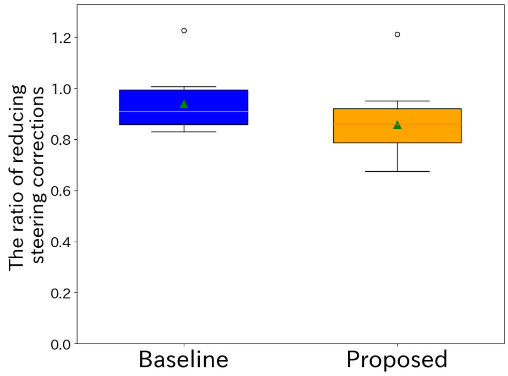

Figure 7: Reduction ratio of steering corrections between the pre-exam and final exam 2.

Figures 9 and 10 show the percentage of participants in each group who reported paying attention to various aspects during Final exam 1 and Final exam 2, respectively. The categories included steering angle (handle), vehicle speed, course, and others.

In Final exam 1, participants in the proposed method group most frequently reported focusing on the steering angle, while participants in the baseline group more often reported focusing on the course layout. However, in Final exam 2, the distribution of attention was similar across both groups, suggesting that the differences observed during feedback presentation diminished once auditory feedback was removed.

4.4. Discussion

4.4.1. Effectiveness of the Proposed Method

The analysis of steering corrections demonstrated that participants using the proposed method showed significantly fewer steering corrections compared to the baseline group. This suggests that the auditory feedback made drivers more aware of their steering operations, allowing them to recognize and suppress unnecessary adjustments. These findings support the effectiveness of the proposed method in promoting smoother and more stable driving on a full driving course with complex curves in a virtual environment.

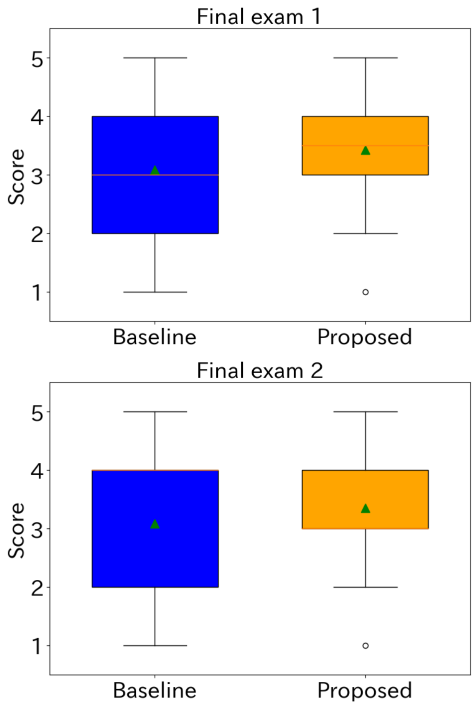

Figure 8: Self-reported ease of driving (1: not easy to drive, 5: easy to drive).

To analyze the driving behavior, we calculated the average angular velocity of the steering wheel and calculated the reduction rate of the average angular velocity in each group between Pre-exam phase and Final exam 1 (see Figure 11). This result showed that the group using the proposed system showed a significant decrease in the angular velocity of the steering wheel from the Pre-exam to the Final exam 1 compared to the baseline group. Therefore, it can be said that the steering wheel operation became more gradual when the proposed system was used, and driving skills improved. This is thought to be due to the fact that the driver tried to operate the steering wheel with awareness of the changes in the sound, as a sound was heard in conjunction with the steering wheel maneuvers.

However, some limitations were also identified. Several participants reported that they found it difficult to rely solely on auditory feedback, particularly when curve entry speed varied. In such cases, the pitch of the sound could lead to confusion, as the same steering angle might require different inputs depending on vehicle speed. This indicates a need to improve the system by either reducing overreliance on sound cues or adapting the pitch mapping to incorporate vehicle speed dynamically.

4.4.2. Effects of Removing Auditory Feedback

As shown in Figure 7, steering corrections tended to decrease even in the phase without auditory feedback after participants had practiced with the proposed method. Although the difference was not statistically significant, this result suggests a possible transfer effect. Participants may have internalized the pitch-angle relationship and retained it as a mental reference when steering.

This interpretation is supported by post-experiment comments. One participant noted that they recalled the approximate steering angle and curve shape by remembering how the tone had sounded during prior trials. In other words, the auditory feedback may have served as a short-term cognitive anchor for steering strategies, even after the sound was no longer present.

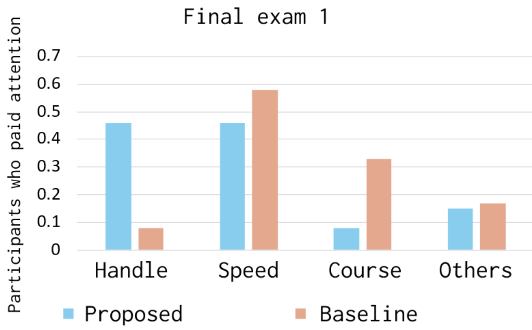

Figure 9: Percentage of participants who paid attention to each driving aspect in Final exam 1.

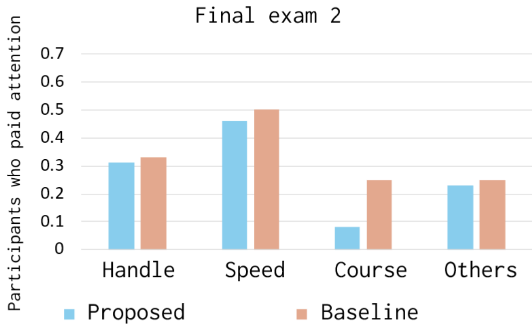

Figure 10: Percentage of participants who paid attention to each driving aspect in Final exam 2.

Furthermore, the ease-of-driving ratings (Figure 8) indicate that participants in the proposed method group reported higher subjective comfort in both Final exam 1 (with sound) and Final exam 2 (without sound), compared to the baseline group. This reinforces the hypothesis that auditory feedback may have a residual cognitive effect, potentially improving steering awareness and confidence.

To ensure long-term effectiveness, future work should explore the optimal frequency and duration of practice using the proposed method. Additionally, it may be valuable to investigate whether these effects persist over days or weeks of non-use.

5. EXPERIMENT 2: EVALUATING STEERING ASSISTANCE IN A REAL-WORLD ENVIRONMENT

5.1. Overview

While the previous experiment demonstrated the effectiveness of the proposed method in a virtual environment, it is ultimately intended for use in real-world driving. Therefore, this experiment was designed to evaluate whether the proposed method is effective when applied in an actual vehicle.

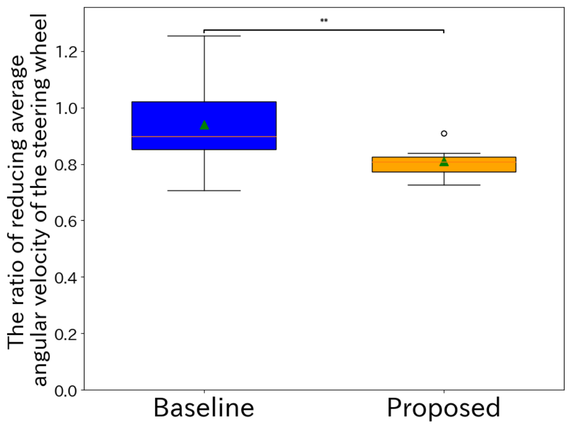

Figure 11: Reduction ratio of the average angular velocity of steering wheel between the pre-exam and final exam 1.

We hypothesize that the number of steering corrections will decrease when the proposed method is used during real-world driving practice. To evaluate this, we conducted a comparative experiment between the following two methods:

- **Proposed method:** Driving practice with a steering wheel that generates auditory feedback based on the steering angle.
- **Instructor-guided method:** Driving practice with real-time verbal guidance from an instructor seated in the passenger seat. This is a standard training method regularly conducted within the automobile company to prepare for driving tests and experiments.

5.2. Experimental Settings

The course used in this experiment was the same real-world test track that the virtual course in Experiment 1 was modeled after (see Figure 4). The experiment was conducted as part of a 50 km/h speed-maintenance training session in fourth gear (manual transmission mode) using an SUV-type production vehicle provided by the automobile company.

Ten employees who regularly drive participated in the experiment. They were evenly divided into two groups: one group used the proposed method, while the other received real-time instruction from an instructor riding in the passenger seat.

The experiment followed the procedure shown in Figure 12:

- **Exercise phase (1 lap):** All participants completed one familiarization lap using a standard steering wheel without auditory feedback. Participants were allowed to withdraw from the experiment if they experienced discomfort.
- **Pre-exam phase (5 laps):** To assess baseline driving skills, all participants drove five laps using a standard steering wheel, without any instructor guidance.
- **Practice phase (5 laps):** Each group practiced driving using their assigned method either the proposed method or instructor guidance.
- **Final exam phase (5 laps):** To evaluate the effects of each method, both groups drove five laps under the same conditions as the pre-exam phase without auditory feedback or instructor guidance.

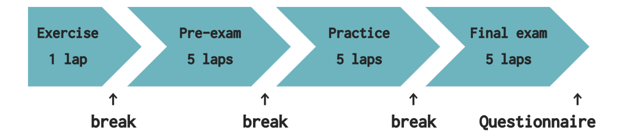

Figure 12: Experimental procedure in the real-world environment.

Participants were instructed to take breaks between phases and were guided to and from the test course to ensure safety and reduce fatigue.

5.3. Results

A statistical comparison of pre-exam steering corrections showed no significant difference between the proposed method group and the instructor-guided group. This result suggests that both groups had comparable initial driving proficiency.

To evaluate steering stability, the number of steering corrections was analyzed in the same manner as in section 4.3. In this experiment, all laps within each phase were included in the analysis, as it was assumed that participants were already familiar with the course after entering from the rest area.

Figure 13 shows a box-and-whisker plot comparing the percentage reduction in the number of steering corrections from the pre-exam to the final exam. The plot reveals no statistically significant difference in the reduction rate between the two groups.

The post-experiment questionnaire revealed mixed feedback. Participants in the proposed method group reported that the auditory feedback helped convey steering-related information (e.g., correction magnitude and steering speed) and served as a cue for adjusting accelerator input. Some noted that the pitch changes provided intuitive guidance during the early phase of curve driving.

However, several participants also mentioned challenges. Specifically, the inability to hear engine sounds made it difficult to maintain speed, and some drivers needed time to get accustomed to the system. In the instructor-guided group, participants appreciated the immediacy and specificity of verbal instructions, but some reported decreased focus on driving due to the added cognitive load from ongoing conversation.

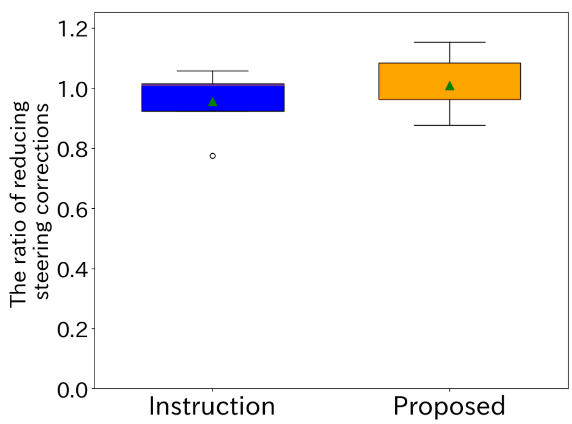

Figure 13: Reduction ratio of steering corrections between the pre-exam and the final exam.

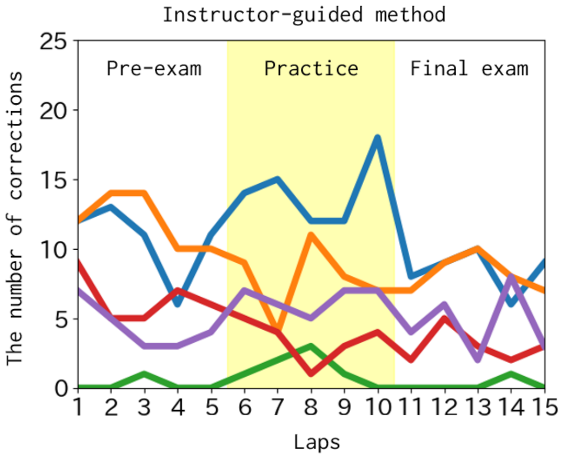

Figure 14: Number of steering corrections per lap for each participant in the instructor-guided method.

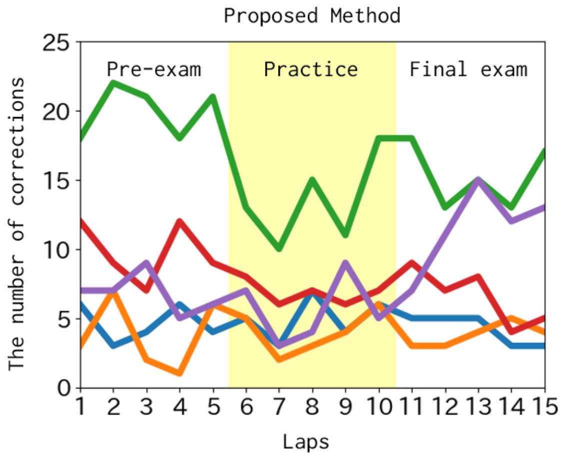

Figure 15: Number of steering corrections per lap for each participant in the proposed method.

5.4. Discussion

The results suggest that the proposed method has the potential to reduce steering corrections in real-world driving, with an effect comparable to traditional instructor-guided practice. A notable advantage of the proposed system is its ability to provide non-intrusive, real-time feedback via sound, which may alleviate the psychological pressure often associated with direct observation and verbal instruction. This aligns with participants' subjective feedback indicating that they felt more comfortable focusing on driving without external interference.

Figures 14 and 15 show the number of steering corrections per lap for each participant in both conditions. Each colored line represents the number of corrections per lap for a single participant. These figures illustrate how steering behavior changed during the practice phase.

In the instructor-guided group (see Figure 14), the number of steering corrections increased for several participants during practice. One possible explanation is that being directly observed and instructed by an instructor may have introduced psychological pressure, disrupting some participants steering control.

In contrast, in the proposed method group (see Figure 15), many participants showed a gradual decrease in steering corrections over time. This suggests that the auditory feedback provided a less intrusive and more self-directed learning environment, which may have helped participants maintain focus and improve their control.

To further explore when and where the proposed method was most effective, Figures 16 and 17 visualize steering angle data across driving distance. Red circles indicate instances of steering correction, with the diameter corresponding to correction magnitude. The figures suggest that the proposed method was particularly effective during sharp curve entry and in sequences of tight hairpin turns, where corrective inputs are typically frequent.

However, the system may not be suitable for all drivers, particularly those who rely heavily on auditory cues such as engine noise. Some participants noted difficulty in maintaining vehicle speed due to the masking of familiar sounds, and required time to adjust to the new auditory modality. These observations highlight the need to consider individual driving styles and sensory preferences when designing such feedback systems.

6. CONCLUSION

To support drivers in achieving stable steering during curve driving, we proposed a sonification-based method that maps the steering angle to musical scales and provides real-time auditory feedback. We implemented two prototype systems: one in a full driving course within a virtual environment using a racing simulation game, and the other in a real-world setting using an actual vehicle.

In the virtual environment experiment, the proposed method significantly reduced steering corrections compared to conventional steering, and subjective feedback suggested that the auditory cues enhanced drivers' awareness of their steering behavior. Furthermore, improvements in steering persisted to some extent even after the feedback was removed.

In the real-world experiment, the proposed method showed comparable effects to traditional instructor-guided practice in reducing steering corrections. The results also suggested that auditory feedback may reduce psychological pressure during practice by offering less intrusive guidance. However, feedback from participants indicated that the method may not be suitable for all drivers, particularly those who rely on engine sounds or are sensitive to changes in auditory environments.

Overall, the results demonstrate that the proposed method is a promising approach to support steering practice in both virtual and real-world environments.

Future work includes refining the auditory feedback to account for individual differences, such as adjusting pitch mapping based on driving speed, and exploring the effectiveness of listening to expert driving as auditory priming before practice.

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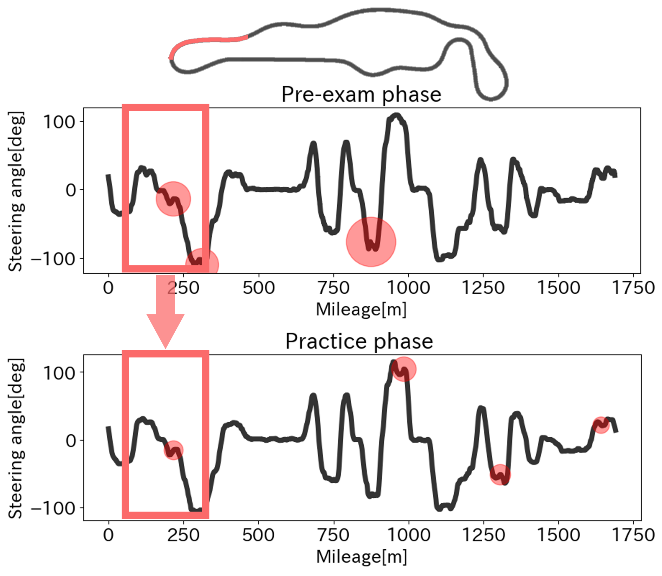

Figure 16: Example of reduced steering corrections during sharp curve entry.

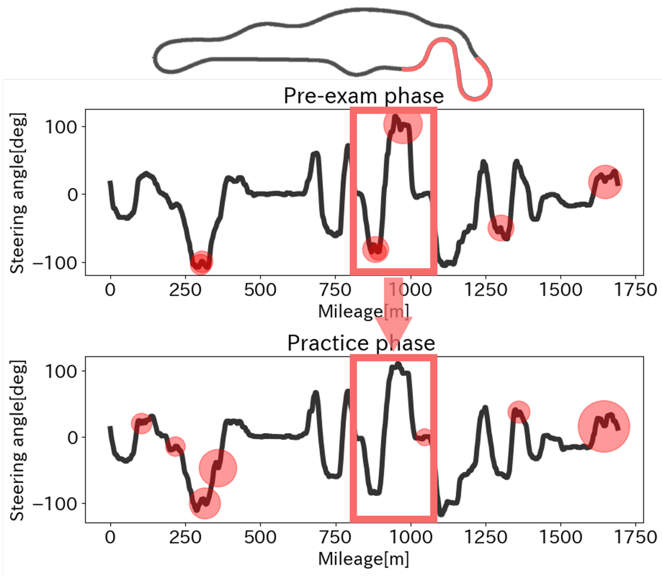

Figure 17: Example of reduced steering corrections in a series of tight hairpin turns.

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