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Hype D-Live: XR Live Music System to Entertain Passengers for Anxiety Reduction in Autonomous Vehicles

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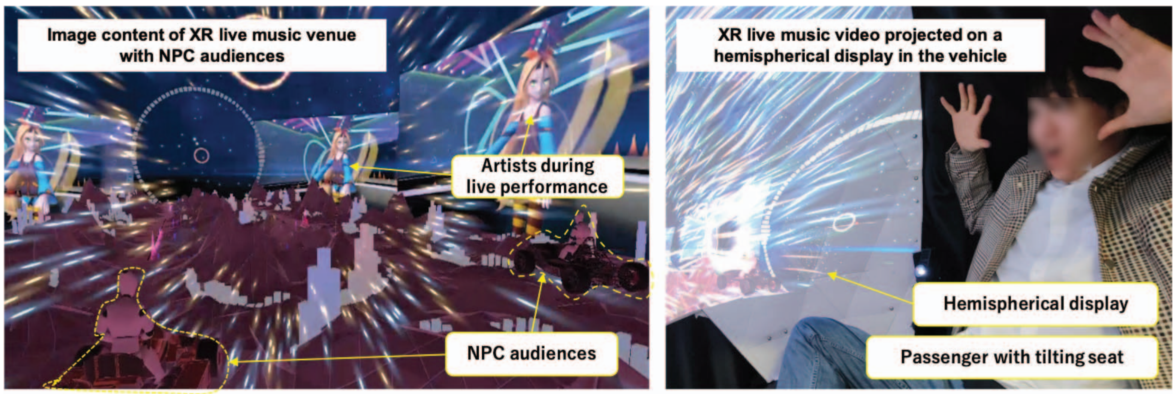

Figure 1: The left image shows the contents of XR live music system called "Hype D-Live". There are several virtual displays within the virtual environment, projecting the artist's performance with lighting effects to entertain the passenger. In addition, two Non-Player Characters (NPC) audiences are riding on a cart around the viewpoint, and appear to be experiencing the XR Live concert together with the passengers of the autonomous vehicle. The right image is the passenger sitting on a tiltable motion-platform seat inside the autonomous vehicle while watching live music. XR live music content is projected on an immersive hemispherical display to control visual, force, and vestibular stimuli generated from autonomous vehicles' behavior.

Abstract

Passengers in autonomous vehicles enjoy the comfort of being free from driving tasks, but they inevitably experience anxiety caused by autonomous vehicle stress (AVS). AVS encompasses vehicle behavior stress due to unpredictable acceleration, and external environmental stress due to potential collisions. Past research has explored approaches to improve passengers' comfort through behavior control and information presentation. However, methods that utilize stressful vehicle behavior in Extended Reality (XR) entertainment to distract from AVS-related anxiety are limited. Hence, the goal of this study was to maximize passenger comfort in automated vehicles. To achieve this goal, we implemented an XR entertainment system that utilizes vehicle behavior and evaluated its effect on reducing anxiety. In this study, we proposed "Hype D-Live", an XR live music system designed to reduce anxiety by providing multimodal visual, auditory, force, and vestibular stimuli using a hemispherical display and motion platform mounted on a vehicle. We developed system functions to adjust the force and vestibular senses according to the excitement level of the music and the direction of stressful acceleration and to reproduce moshing, a characteristic behavior at live music venues. However, we hypothesized that passengers might not fully enjoy the entertainment and could experience anxiety if the video content makes them aware of the external environment. Therefore, we conducted an experiment with a within-participant design, involving 24 participants (14 males and 10 females), comparing 3 types of video content for XR entertainment inside the autonomous vehicle: a real external environment, a virtual simulation of the external environment, and a virtual live music venue. The Wilcoxon signed rank test with the Bonferroni correction after the Friedman test revealed that, without the moshing function, the virtual live music venue video significantly enhanced enjoyment and reduced anxiety, compared to the real one.

Index Terms: Human-centered computing—Interaction paradigms—Virtual reality; Human-centered computing—HCI design and evaluation methods

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1 Introduction

With the progress of the Industry 4.0 [10], research on autonomous vehicles is flourishing [2, 19, 45, 47]. Autonomous vehicles aim to eliminate accidents caused by human error and lack of information confirmation and to realize smooth and safe road traffic by coordinating with road conditions and other vehicles [50]. In addition, comfort will be improved by freeing the driver from the need to drive [30]. In the future, as autonomous vehicles become more widespread and passengers have more free time in the car, they will increasingly enjoy entertainment in a comfortable environment [44]. Traditionally, drivers needed to constantly perceive information about their external environment, their vehicle's position and speed, and other information with their eyes in order to perform driving tasks. As a result, the entertainment that drivers could enjoy in the car was limited to auditory content, such as music and radio. However, with the advent of autonomous vehicles, drivers can be released from

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driving tasks and become mere passengers, enjoying not only auditory content but also entertainment that includes visual content. Furthermore, there will likely be more opportunities to enjoy new types of Extended Reality (XR) entertainment that take advantage of the movements of autonomous vehicles, such as Holoride [16] and COMS-VR [25].

On contrarily, anxiety due to autonomous vehicle stress (AVS) [40] is inevitable when passengers are enjoying entertainment content. AVS can be broadly classified into two types: vehicle behavior stress and external environmental stress. Vehicle behavior stress is caused by force and vestibular sensory stimulation due to unpredictable acceleration, deceleration, and route changes [37]. External environmental stress is caused by the possibility of close approaches or collisions with buildings, obstacles, moving pedestrians, or other vehicles in the vehicle's external environment [39]. Additionally, external environmental stress is caused by the perception of the external environment through vision or, if passengers cannot see outside, by predicting the external environment from force and vestibular stimuli based on vehicle behavior. AVS-related anxiety has the potential to interfere with the passenger's entertainment experience and reduce comfort during the ride.

In previous research, methods to reduce anxiety have been proposed, such as counteracting vestibular sensory stimulation in vehicle behavior control [4, 37] and informing passengers of vehicle behavior and the environment outside the vehicle by presenting information [18, 36]. These methods are mainly aimed at directly eliminating or reducing AVS, the causes of anxiety. However, there are still a few methods that utilize vehicle behavior, which is a cause of anxiety, to reduce anxiety by changing the perception of stress into entertainment and distracting passengers [27]. Therefore, the overall goal of this research is to increase passenger comfort, and two specific issues are addressed to achieve this goal. The first is the implementation of an XR entertainment system that utilizes stressful vehicle behavior. The second is to mitigate the anxiety that could occur during the entertainment experience in an autonomous vehicle.

In this paper, we designed "Hype D-Live", an entertainment system with audiovisual, force, and vestibular stimulation by means of a hemispherical display and motion platform mounted inside an autonomous (see venueFig. 1). This system for autonomous vehicles is an XR live music system that allows the passenger to move within a virtual live music venue according to the driving route. The stressful vehicle behavior was utilized as force and vestibular stimuli to generate a sense of presence and excitement. It was also hypothesized that even if the sensory stimulation caused by vehicle behavior can make passengers feel like an amusement park attraction, they may not be fully immersed in the entertainment and may feel anxious if the video of the content makes them aware of the real external environment. The results of the experimental evaluation under conditions where the visual part of the designed content was changed from real to virtual space suggested that the video of the virtual live music venue significantly enhanced enjoyment and reduced anxiety, compared to the video of the real external environment. The contribution of this research is to provide a new perspective on the use of XR technology to convert stressors into entertainment elements in order to reduce user anxiety and improve comfort.

2 Related Work

2.1 Anxiety from Autonomous Vehicle Stress

In considering the social acceptability of autonomous vehicles, it is essential to reduce the anxiety felt by passengers during autonomous driving and the main cause of this anxiety, Autonomous Vehicle Stress (AVS), in order to improve the comfort of the vehicle inside [26, 39, 40]. Various studies have proposed methods to reduce the AVS directory according to the stressors that cause it. In a study that classified stressors in autonomous vehicles using physiological indicators, the stressors were categorized into vehicle behavior and the external environment, which includes static and dynamic environments. Stressors caused by vehicle behavior include the behavior of the autonomous vehicle, such as acceleration, deceleration, and sudden changes in route due to abrupt changes in the planned path. Stressors from the static environment include approaching static external backgrounds, such as walls and obstacles, and potential collisions. Stressors due to the dynamic environment include approaching or potentially colliding with other dynamic external objects, such as pedestrians or vehicles.

One approach to reducing vehicle behavior stress is, for example, to present information about the behavior of the wheelchair robot [14]. Another approach is to use a motion platform mounted on an autonomous vehicle to control its own vehicle behavior, reducing the passenger's perceived acceleration. By varying the inclination of the motion platform, it is mechanically possible to reduce the forces that the passenger is subjected to [37, 38].

In addition, there are reduction techniques for static or dynamic external environmental stresses. Research on stressors arising from the static environment has investigated the stressors experienced by wheelchair passengers as they approach walls [28]. Previous research to mitigate this stressor has introduced the projection of information onto the dashboard in the forward and downward areas of the passenger's blind spot [36]. On the other hand, research on dynamic environments includes research on predicting collisions with pedestrians and other vehicles in blind spots in environments with poor visibility [41]. Prior research to mitigate this stressor has shown methods of presenting information, such as projecting path information when a wheelchair robot passes a pedestrian [49] and acquiring self-position and surrounding environment from sensors mounted on a vehicle and displaying it on a screen [18].

Many studies have shown the effectiveness of providing precise feedback on stressful vehicle behavior and the external environment to make passengers less likely to perceive anxiety or to understand the situation. However, if passengers are continually presented with information about potentially stressful situations, they may not be able to concentrate on the entertainment content. Therefore, unlike conventional anxiety reduction methods, this study proposes a method to transform anxiety into an enjoyable experience by utilizing force and acceleration stimuli that generate vehicle behavior stress and external environmental stress through prediction.

2.2 XR Entertainment in Autonomous Vehicles

Extensive research has been conducted on XR entertainment that can be experienced inside an autonomous vehicle. Holoride [16] allows users to experience virtual reality (VR) games by wearing a head-mounted display (HMD) inside an autonomous vehicle. It has been shown to avoid motion sickness by providing a strong sense of immersion through synchronizing VR images with vehicle behavior [15, 16]. However, this mechanism alone can only handle movement and speed in the direction of travel. In order to realize movements other than those in the driving direction, COMS-VR was developed with a motion platform installed inside the autonomous vehicle [24, 25]. It was shown to be effective in improving user enjoyment by expressing vibration and shaking differently from the driving route. On the other hand, there remained the issue of only being able to provide feedback through translational motion in the front-back direction. It was also shown that displaying video images at speeds faster than the vehicle's speed can enhance the sense of speed without causing discomfort to the passengers [35].

In summary, previous research has provided a wealth of knowledge, exploring XR entertainment combining force and vestibular stimulation in autonomous vehicles, as well as improving comfort in terms of passenger motion sickness and enjoyment. However, the relationship between entertainment content and methods of reducing anxiety related to AVS during the experience is relatively unexplored. Without reducing anxiety, full immersion in entertainment will be

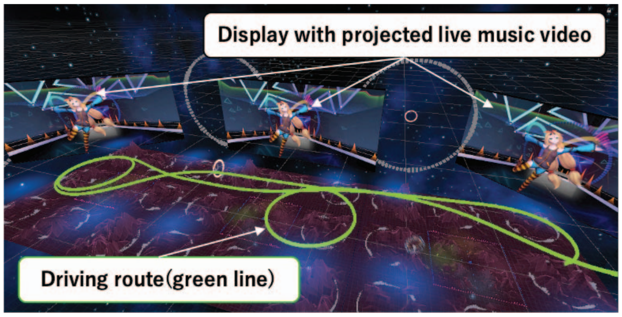

Figure 2: Multiple displays in the virtual live venue projected video of performances by the artist. A passenger can view the moving viewpoint images synchronized with the driving route.

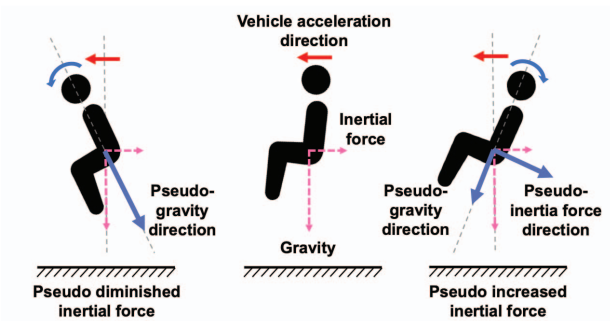

Figure 3: The change in inertia and gravity perceived by the passenger due to the tilt of the motion platform.

difficult and will be one of the major challenges to practical implementation. This study aims to extend the use of stressful vehicle behavior in all directions of motion by using a vehicle-mounted motion platform, thereby expanding the potential for new XR entertainment experiences with a focus on anxiety reduction.

3 XR Entertainment Content Design

3.1 Overview of Hype D-Live

Hype D-Live is an XR live music system that enables autonomous vehicles to navigate a virtual live music venue following a predetermined driving route. The schematic diagram of the system is presented below. Considering that vehicle behavior during autonomous driving can be an anxiety factor, the system aims to enhance passenger comfort by creating a sense of presence and excitement, stimulating the sense of force and vestibular sensation. The autonomous vehicle can calculate stress points in advance through onboard sensors and path-determination algorithms, allowing the vehicle to alleviate passenger anxiety by altering the entertainment content in real time. This system is specifically designed for autonomous driving because, with a human driver, the vehicle's behavior is determined by human perception, planning, and control, so it is impossible to predict in advance when acceleration changes and other anxiety-prone moments are likely to occur.

A passenger can sit on the onboard motion platform and experience realistic and immersive content on the hemispherical display inside the vehicle. Two functions were implemented to enhance passenger comfort: an acceleration adjustment function and a mosh function. The acceleration adjustment function in Fig. 3 modulates the stimulation to the force and vestibular senses generated by the vehicle behavior based on the intensity of the music. The mosh function in Fig. 4 creates mosh [34], a unique form of contact with

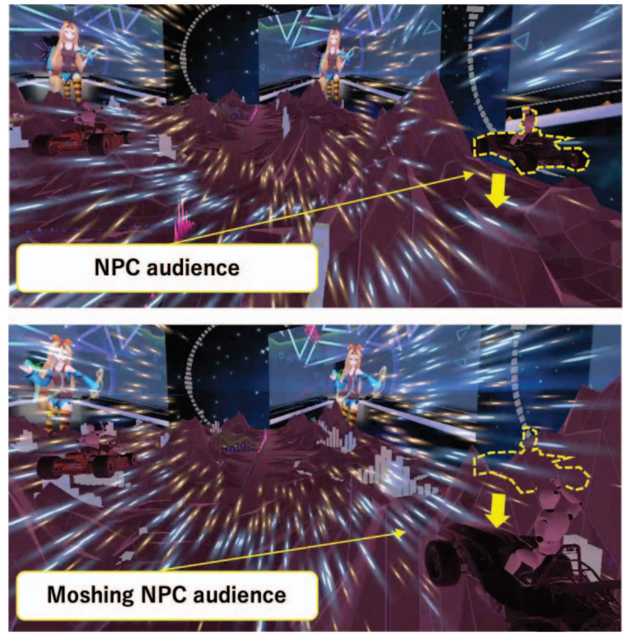

Figure 4: Before the mosh begins, the NPC audience is far away from the passenger, as shown in the yellow dotted line position in the image above. When mosh occurs, the NPC audience moves closer so that it hits the passenger's viewpoint, as shown in the image below.

the surrounding audience at live music concerts, using audience agents depending on the music's excitement level and the timing of changes in vehicle behavior.

The virtual live music venue created by this system is depicted in Fig. 2. The venue features six monitors showcasing the artist's performance, and the assets are arranged to provide colorful lighting and staging to match the music automatically. As passengers move around the venue following the driving route, they can view the display from various angles and perspectives, enjoying the performance at all times. In this system, Unity-Chan, provided by Unity Technologies Japan, was used as the artist by the Unity-Chan license terms [48]. Furthermore, we used a 2-minute edited version of Unity-Chan's song "UNITE IN THE SKY," connecting the intro to the outro after the first chorus, along with the corresponding dance choreography. The song's structure was analyzed by Songle [11].

3.2 Acceleration Adjustment Function

This function modulates the acceleration experienced by passengers by controlling the motion platform according to the intensity of musical excitement, shown in Fig. 3. The pseudo-inertial force is almost negligible when tilting forward, and the pseudo-inertial force is greater when leaning backward, and thus strong force and vestibular sensation stimuli are perceived. The motion platform can tilt in all directions, not just forward and backward. During exciting moments in the music, such as a chorus, the motion platform tilts in a direction that enhances the sensation of acceleration. Conversely, when the music is less exciting, the motion platform tilts in a direction that counteracts the perceived acceleration. By doing so, the system aims to deliver intense force and vestibular stimuli to the passenger when the music is most exhilarating, thereby heightening the overall experience. This design is inspired by the observation that many people enjoy amusement park rides and simulated VR roller coasters because the exposure to fluctuating forces and accelerations triggers fight-or-flight responses and the release of neurochemicals such as adrenaline and dopamine [33].

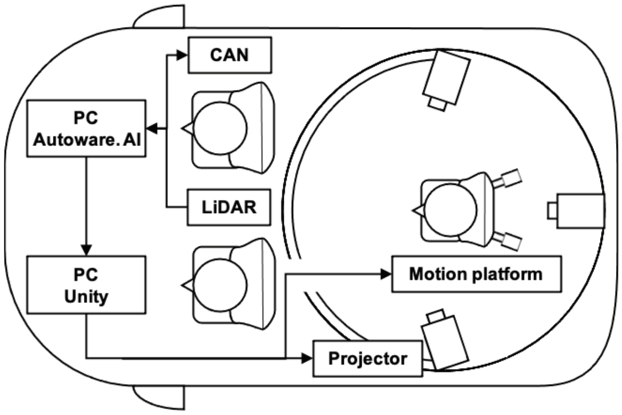

Figure 5: The system overview of our proposed system.

3.3 Mosh Function

Moshing is the energetic interaction among audience members when music becomes exciting at a live music venue [34]. This activity allows participants to share their excitement and foster a sense of unity. Fig. 4 depicts a moshing scene at an XR live concert. In this system, the passenger avatar and Non-player Character (NPC) audience members ride in vehicles, with moshing designed to occur upon collision. When moshing takes place, the motion platform's angle adjusts in the rebound's direction. Passengers perceive moshing through audiovisual feedback from the video images and the motion platform's effects on their sense of force and vestibular sensation. The moshing is timed to occur when the acceleration shifts from a straight-ahead direction to a curving direction as the autonomous vehicle moves. For instance, when turning right, the NPC audience is set to mosh from the left, and when turning left, the NPC audience is set to mosh from the right. This configuration enables the motion platform to slightly counteract the car's centrifugal force as it turns, and the impact generated by the seats gives the vehicle the sensation of an amusement park ride.

4 System Overview

Fig. 5 shows our system overview. Details of the hardware and software are described below.

4.1 Hardware Architectures

Fig. 6 illustrates the hardware components utilized in this system. The autonomous vehicle used in this study is based on the RoboCar Mini Van, an autonomous vehicle platform developed by ZMP Inc. Two rows of rear seats in the car have been removed to accommodate the installation of a motion platform and a hemispherical display. A pair of linear actuators (ASIN: B09B4SS6P3), manufactured by Koncy, are mounted on the back of the motion platform to facilitate seat movement. Each actuator features a 150 mm range, a maximum speed of 15 mm/s, and an 800 N load capacity. Additionally, a microcontroller board based on ATmega32u4 called Arduino Leonardo can be used to control the actuators.

Seated on the motion platform, passengers can view images on an immersive hemispherical display. The system employs a custom-made hemispherical display with an inner diameter of 1.24×10^3 mm, a height of 1.00×10^3 mm, and a depth of 6.20×10^2 mm to deliver highly immersive visuals. Three projectors are used to project videos covering the entire celestial sphere. Since the display is affixed to the motion platform, it tilts with the seat, preventing passengers from perceiving the seat's tilt. Furthermore, Bose Noise Cancelling Headphones 700, produced by Bose G.K., provide highly realistic and immersive auditory stimuli for the content by masking noises such as those generated by the autonomous vehicle's operation and the motion platform's movements.

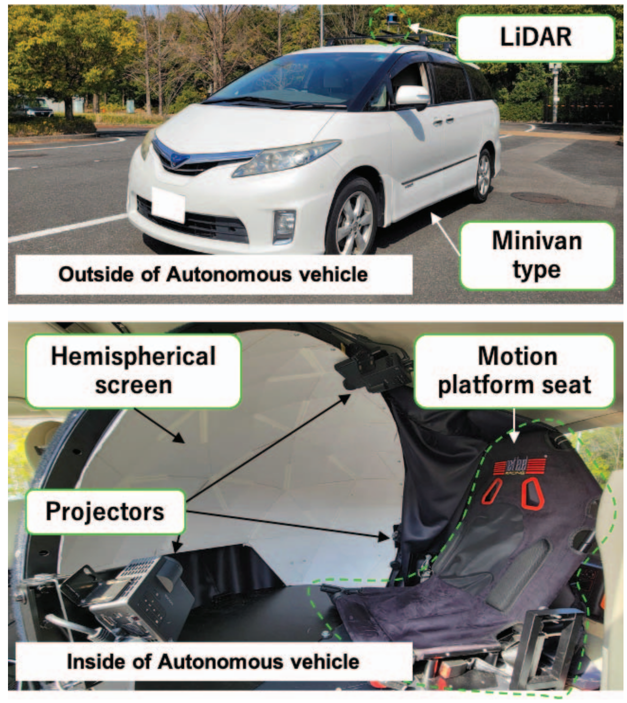

Figure 6: Exterior and interior view of the autonomous vehicle system used in the experiment.

4.2 Software Architectures

The autonomous driving system perceives the surrounding environment and vehicle position, plans a route based on the acquired information, and controls acceleration, braking, and steering to move the vehicle [7, 42]. The system uses Autoware.AI, an open-source driver control software, and each function of autonomous driving was built based on this software package [21]. In this system, LiDAR data is first utilized for map scanning to create a map of the surrounding area. The system then estimates its position by matching the LiDAR data with the created map. Based on the created map and self-position, a driving route is generated, and the autonomous vehicle follows this route. In addition, data related to vehicle behavior such as speed, acceleration, braking, and steering angle are acquired through the controller area network (CAN bus) and sent to the computer. Those vehicles' parameters can be controlled by sending operation signals to the CAN bus.

Additionally, LiDAR data and information about the vehicle's position, speed, and acceleration are sent to the game engine, Unity. Based on the information received by Unity, the virtual camera that captures the images to be shown to passengers is moved; the images generated within Unity are projected onto a screen via a projector. Then, through Unity, motion platform movement commands are sent at the timing preset by the information on the excitement of the music and the direction of acceleration.

5 Experiment

5.1 Hypothesis and Predictions

When humans drive, the driver can only enjoy auditory content, such as listening to music, because vision is used to operate the vehicle. With automated driving, the driver is freed from the driving

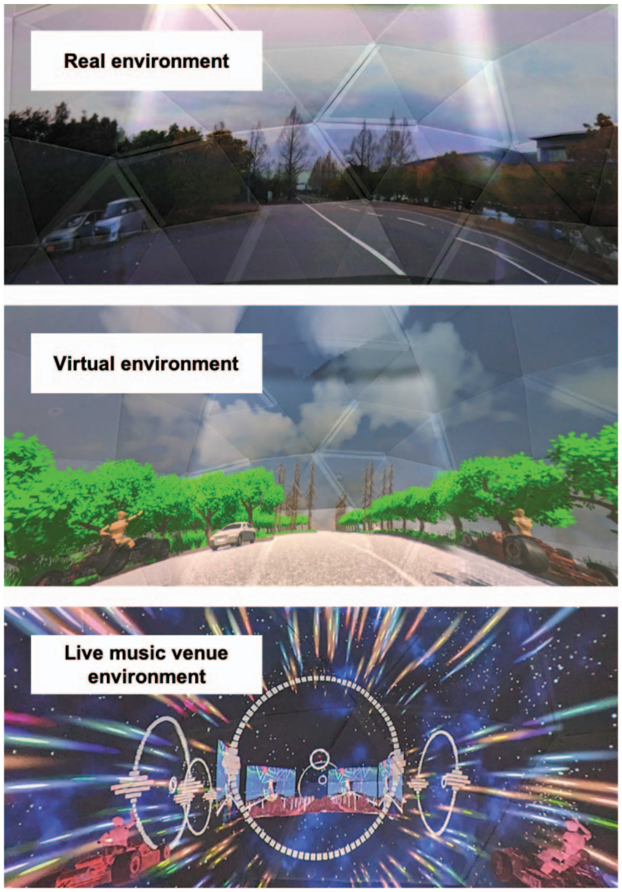

Figure 7: Image contents on the hemispherical screen used in each condition: the real environment at the top, the virtual environment at the middle, and the live venue environment at the bottom.

operation and can enjoy visual content as a passenger at the same time. On the other hand, if there is a sudden acceleration or route change while the passenger is enjoying the visual content, the passenger will experience anxiety as force and vestibular sensory stimulation, and furthermore, the passenger will feel another anxiety by predicting the external environment. Therefore, if passengers can perceive vehicle behavior as part of the entertainment content rather than stress, as in amusement park attractions, it would be possible to divert their attention without causing anxiety from vehicle behavior stress or external environment stress. However, the more information in the video content that also makes the passenger aware of the real external environment of the vehicle, the easier it will be for the passenger to predict the external environment. Then, we hypothesized that such a state would reduce the enjoyment of the experience and that passengers would become more conscious of sudden acceleration due to avoidance of objects in the external environment and imagination about possible collisions with objects, which may cause them to feel anxious [39]. Therefore, based on the following predictions, we conducted an experiment using the acceleration adjustment function in our proposed system:

Prediction 1-a (P1-a):
Reducing information about the external environment in the content to only entertainment increases passenger enjoyment.
Prediction 2-a (P2-a):
Reducing information about the external environment in the content to only entertainment reduces anxiety about vehicle behavior and the external environment.

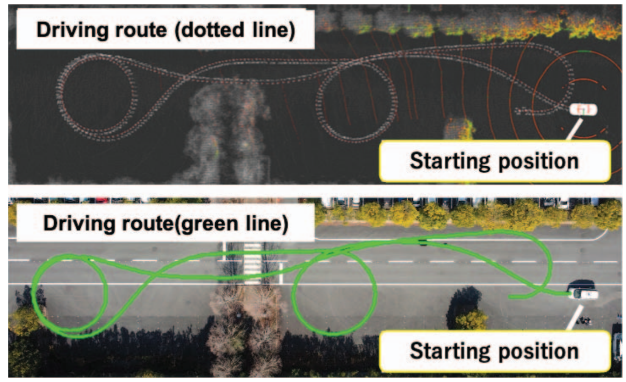

Figure 8: Top: Environment map and driving route created by Autoware.AI; Bottom: Environment and driving route at the test site.

Furthermore, we hypothesized that interaction with other NPC audiences, even in the same video content, would allow for more focus on the entertainment and divert attention away from anxiety because of a sense of unity with NPC audiences [1, 20]. Therefore, based on the following predictions, we conducted an experiment using the acceleration adjustment function and mosh function in our proposed system:

Prediction 1-b (P1-b):
The interaction with other NPC audiences increases passenger enjoyment.
Prediction 2-b (P2-b):
The interaction with other NPC audiences reduces anxiety about vehicle behavior and the external environment.

5.2 Conditions

This experiment was conducted in a within-participant design. The first condition experienced by participants to determine the criteria for responding to the questionnaire was the real environment condition (RC). To account for order effects, all participants experienced each condition in a different order in subsequent experiences. There were five conditions in all:
Real environment condition (RC):
A video of the real external environment captured by a camera in advance is played.
Virtual environment condition (VC):
A video of two NPC audiences running side-by-side in a simulated external environment is played.
Virtual environment with mosh condition (VMC):
A video of two NPC audiences running side-by-side and moshing in a simulated external environment is played.
Live music venue environment condition (LC):
A video of two NPC audiences running side-by-side in a virtual live music venue environment is played.
Live music venue environment with mosh condition (LMC):
A video of two NPC audiences running side-by-side and moshing in a virtual live music venue environment is played.

Fig. 7 shows the difference in video content under each condition. The VC and VMC simulate the real external environment with virtual objects, as an intermediate between the real external environment and the virtual entertainment environment. They have the same music, the same driving route, and the same driving speed. The speed of the autonomous vehicle was set to 8 km/h using the pure

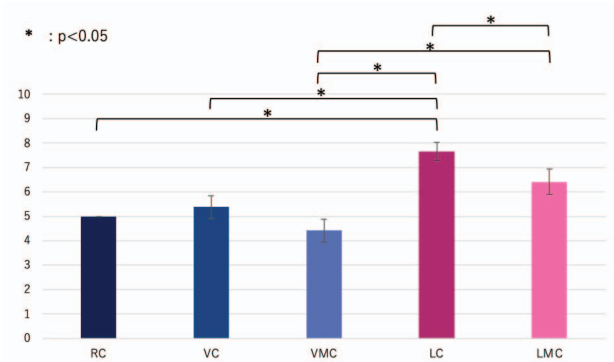

Figure 9: Average degree of enjoyment of the experience.

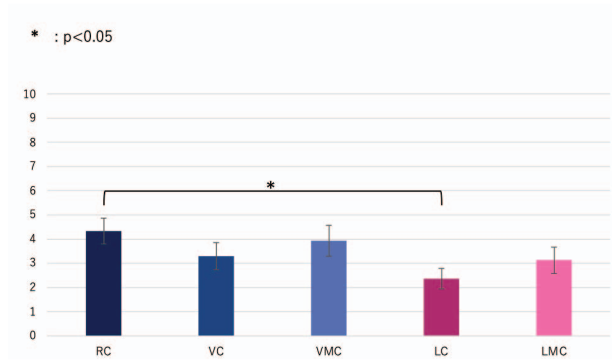

Figure 10: Average degree of anxiety about vehicle behavior.

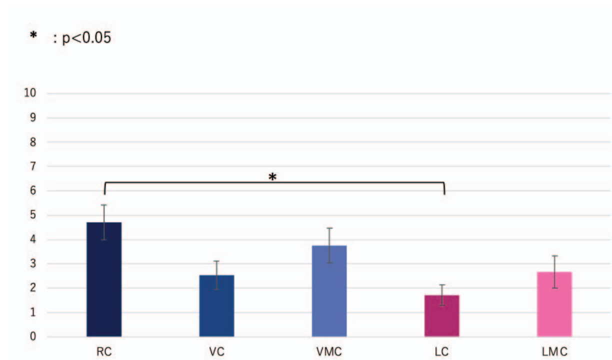

Figure 11: Average degree of anxiety about the external environment.

pursuit algorithm in Autoware.AI for safety issues. The algorithm is one of the typical algorithms for path following, which can determine the curvature from the self-position to the target position to enable automatic driving at the same speed in even different conditions.

The experiment was conducted at the Keihanna Open Innovation Center (KICK), with driving performed on the route shown in Fig. 8 under all conditions.

5.3 Participants

No specific language or nationality was required; 24 participants (14 males, 10 females, aged 18-54 years old (average=27.21, s.d.=7.72)) took part in this experiment. Recruitment of participants was conducted via e-mail to students of Nara Institute of Science and Technology. Among the participants, 12 had driven routinely or occasionally, 16 had used AR/VR a few times or frequently, and 2 had participated in an autonomous vehicle experiment.

5.4 Measurements

Participants were asked to complete a subjective questionnaire to measure their impressions during the experience in terms of enjoyment, fear, anxiety about vehicle behavior, and anxiety about the external environment. For each question, respondents were asked to answer on a scale of 0-to-10 (0: not at all, 10: very much). The questionnaire content is shown below. The questions regarding anxiety about vehicle behavior are Q2-a and Q2-b below, and the analysis is based on the average of these two questions.

- Q1: How did you feel about the enjoyment of the experience?
- Q2-a: Did you have anxiety about the vehicle moving forward?
- Q2-b: Did you have anxiety about the vehicle turning?
- Q3: Did you have anxiety about the external environment?

Additionally, this study included a questionnaire on the motion sickness induced by the system. The questionnaire used was the Simulator Sickness Questionnaire (SSQ) [22], with scores ranging from 0-to-3 (0: not at all, 3: very much). The SSQ consists of 16 items. Although some items overlap in each factor, it is composed of three factors: Nausea (seven items), Oculomotor (seven items), and Disorientation (seven items). Each factor is calculated by weighting the sum of the scores of the corresponding items of the questionnaire: 9.54 times the sum of the prime scores for Nausea, 7.58 times the sum of the prime scores for Oculomotor, and 13.92 times the sum of the prime scores for Disorientation. Additionally, the total score is calculated by 3.74 times the sum of all items. Questionnaires were administered before and after the start and end of the experiment, and scores were evaluated by subtracting the pre-experiment scores from the post-experiment scores.

5.5 Procedure

Before the experiment, participants were informed about the purpose and procedures of the experiment and then signed a consent form to agree to participate. This study was approved by the Ethics Committee of Nara Institute of Science and Technology with the review number 2022-I-36 and was conducted according to institutional ethical provisions.

First, participants entered an autonomous vehicle and fastened their seatbelts. They then put on headphones and used a tablet to complete the SSQ and a questionnaire about their experience with XR and automated driving. Following the completion of these preliminary questionnaires, the participants experienced the RC to familiarize themselves with autonomous driving, which served as a criterion for evaluating their overall experience. After this experience, participants were prompted to fill out a subsequent questionnaire to detail their impressions of the experience. The enjoyment of the experience was quantified by instructing participants to allocate a rating of ”5 points” on an 0-10 points scale. The ”5 points” were later employed as the evaluative benchmark for the subsequent enjoyment under four experimental conditions: VC, VMC, LC, and LMC. The other questionnaire items about anxiety were answered as the participants saw fit. After answering the impression questionnaire, participants experienced each condition and answered the questionnaire four more times. Upon completing the entire experience, participants were asked to answer the SSQ again and provide their impressions of the experience via oral interview.

6 Results

Fig. 9 shows the results for the mean of the scores for the enjoyment of the experience. Fig. 10 shows the results for the mean of the scores for anxiety about vehicle behavior, and Fig. 11 shows the results for the mean of the scores for anxiety about the external environment. They are the results of the evaluation questionnaire for the five conditions: real environment condition (RC), virtual environment condition (VC), virtual environment with mosh condition (VMC), live music venue environment condition (LC), and live music venue environment with mosh condition (LMC). The statistical analysis included a Friedman test for the five conditions and, if significant ($p < .05$), a Wilcoxon Signed Rank test with Bonferroni correction to identify which conditions were significantly different ($p < .05$). Based on the statistical analysis, we present the results for the predictions.

6.1 Verification of Prediction 1

Fig. 9 shows the mean values for each condition from the questionnaire results regarding the enjoyment of the experience. LC was significantly more enjoyable than RC ($p < .001$), VC ($p = .0034$), VMC ($p = .001$), and LMC ($p = .0033$). LMC was significantly more enjoyable than VMC ($p = .045$). No significant differences were found among the other conditions ($p > .05$), but VC showed a trend toward higher scores than RC and VMC. Based on these results, Prediction 1-a was supported, and Prediction 1-b was not supported.

6.2 Verification of Prediction 2

Fig. 10 shows the mean values from the results regarding anxiety about vehicle behavior. LC significantly reduced anxiety about vehicle behavior compared to RC ($p = .032$). No significant differences were found among the other conditions ($p > .05$), but LCs tended to score lower than VC, and VC tended to score lower than RCs. LC also showed a tendency to score lower than LMC and VC showed a tendency to score lower than VMC. Fig. 11 shows the mean values from the results regarding anxiety about the external environment. LC significantly reduced anxiety about the external environment compared to RC ($p = .024$). No significant differences were found among the other conditions ($p > .05$), but LC tended to score lower than VC, and VC tended to score lower than RC. LC also showed a tendency to score lower than LMC and VC showed a tendency to score lower than VMC. Based on these results, Prediction 2-a was supported, and Prediction 2-b was not supported.

6.3 Summary of Statistical Analysis

These analyses indicate that without the mosh feature, the video of the virtual live venue environment significantly enhances the enjoyment of the experience when compared to the video content of the real environment and the external environment simulated with virtual objects. For anxiety about vehicle behavior and the external environment, the video of the virtual live venue significantly reduced anxiety when compared to the video of the real environment. When the same video content was compared with and without the mosh function, the enjoyment of the experience was higher only in the video of the virtual live venue without the mosh function. There were no significant differences in other fears, vehicle behavior, or anxiety about the external environment.

6.4 SSQ Results

The mean pre-experimental scores were 12.32 for Nausea, 12.32 for Oculomotor, 16.82 for Disorientation, and 11.69 for total score. The mean post-experimental scores were 33.39 for Nausea, 24.95 for the Oculomotor, 35.38 for Disorientation, and 25.87 for the total score. The results indicated that the proposed system tended to produce less motion sickness.

6.5 Duration of Driving and Interval

For the pre-setup, the duration of each run of the experiment was just two minutes. The average duration of the interval for each condition was one minute 57.6 seconds. Participants responded to questionnaires and took breaks during these interval times.

7 Discussion

7.1 Implications

The main feature of this research is the use of XR technology to translate stressors inherent in vehicle behavior into entertainment elements, providing new perspectives on how stressors can be reduced or utilized in new ways to enhance the passenger experience. By transmuting moments of potentially stressful vehicle behavior into elements that enhance the excitement and immersion of entertainment, we revolutionize the paradigm of automobile travel itself. Further, the integration of a motion platform provides an environment for passengers to experience real-time stimuli based on vehicle movements. Collectively, these contributions present a fresh perspective on the use of XR in autonomous vehicles, serving as a springboard for further research and innovation in this field.

Through an experiment comparing a video of a real external environment with a video of an entertainment space, this study demonstrated that content that makes people more aware of reality increases the anxiety they feel. Conversely, it was shown that removing information from the content that makes people aware of reality makes the experience more enjoyable and reduces anxiety. Many of the participants commented that the images replicating the real external environment made them acutely aware that the car was actually driving, which made them feel anxious. In addition, in the virtual live music venue, they were not aware of driving and perceived it as if they were riding in an amusement park attraction. This result is supported by stress reduction due to cognitive changes [6, 43]. When an event or stimulus occurs, human emotions and behaviors are influenced by the beliefs and automatically generated thoughts that people have about this event, and therefore, the way we think and perceive this event determines whether the emotions generated are negative or positive [9]. Thus, even with exactly the same force and vestibular stimuli, as participants commented, the way the stimuli are perceived differs depending on the video, resulting in more enjoyment or more anxiety. Therefore, the results of this experiment showed that distracting passengers from their negative predictions and thoughts reduced their anxiety about the AVS.

We used content that was a virtual replica of actual real objects, but we believe that replacing real objects with other characters or objects as part of the entertainment content, rather than replicating their original appearance, will further expand the range of entertainment content design. For example, it would be intriguing if other autonomous vehicles could be displayed as avatars of spectators, and their proximity to the real vehicle could be represented as a close encounter or mosh with the avatar.

As for technical improvements, we consider it important to enhance the mosh function. In this system, the occurrence of a mosh was expressed by generating an impact on the motion platform or by producing the sound of a collision. However, several participants in the experiment commented that the sound of the collision was unpleasant and made them feel uneasy as if an accident had occurred in the environment outside the vehicle. Some participants also commented that the motion platform impacts were small and difficult to understand. Also, in this case, the NPC audience was designed to be hit unilaterally, but a more interactive mosh should be considered, where users can spontaneously initiate the mosh. Since content that allows users to participate proactively in a highly immersive environment is important for the spread of in-vehicle entertainment experiences [17], we believe that new interactive content with a sense of unity should be considered for the new XR Entertainment.

This research unveils the potential of XR technology as a tool to redefine the passenger experience in autonomous vehicles. Instead of viewing the journey as a mere transfer from point A to point B, we introduce the concept of the journey itself becoming a form of immersive entertainment. The application of XR in this context presents a multitude of new opportunities for entertainment, interaction, and engagement during transit.

7.2 Limitations

There are limitations to this study. First, in this experiment, a route combining straight, right, and left turns was used to simulate actual driving, but the driving route and speed were the same under all conditions. Therefore, although order effects were taken into account, it cannot be said that there is no effect on the experience due to fatigue or the accumulation of frustration and stress. It is also important to conduct a detailed analysis to take into account the long duration of driving and various driving routes and speeds in order to make the system work in a real traffic environment.

Second, the sensations felt by the participants were measured using only a subjective questionnaire. Objective data such as biometric data [8] could also be used to evaluate stress reduction. Biometric sensors can be utilized to detect changes in passengers' stress levels over time, enabling the provision of entertainment that effectively reduces stressors. In addition, the subjective evaluation did not use questionnaire items commonly used in the HCI research field, such as the NASA-TLX [13]. In this study, we also created our own questionnaire items based on previous studies on car-based VR entertainment that used their own questionnaire items [24]. The use of such standardized questionnaires in future studies is also important for comparison with the results of other studies. Furthermore, it is important to examine the effects of the video content and the mosh function on motion sickness in more detail by asking participants to rate their SSQ scores for each condition of the experiment.

Third, this experiment was conducted in a highly secure test site, which meant there were no dynamic external factors that makes passengers more stressed, such as pedestrians or other vehicles, present during the experiment.

Fourth, as a result of legal restrictions, the experimenter was seated in the driving seat in the front row of the autonomous vehicle. This caused the entertainment experience to be different from the actual automated driving experience on the road and may have provided participants with a sense of security regarding the safety of the vehicle's interior conditions. In the future, it is important to improve the system and evaluate the stress reduction using the Internet of Vehicle (IoV) [12], which can acquire and share information on traffic conditions and the vehicle in real-time, to provide entertainment when the vehicle is driven autonomously on actual roadways.

Fifth, although this experiment used a single piece of music and the motion platform moved at a pre-set speed, in order to provide higher quality entertainment, the music and motion platform speed should be freely changeable to suit passenger preferences. Allowing passengers to listen to their preferred music is important because it enhances their sense of social well-being [3, 5, 29] and reduces stress [32, 46] and motion sickness [23, 31].

Sixth, the gender of the participants in this experiment was 14 males and 10 females, with males accounting for about 58% of the total. Another limitation is that although the age range was 18 to 54 years old, the mean age was relatively low (27.21 years old) and the variance was large. In order to generalize the results of this experiment, it is important to conduct and analyze an experiment with more participants in more age groups.

Finally, the movement speed of the actuators built into the motion platform is fixed. Although participants in the experiments commented that the tilting of the seat made it feel like it was moving comfortably and smoothly and that it was like an amusement park ride, in order to maximize passenger comfort, the appropriate actuator movement speed and the magnitude of the impact generated need to be considered. Despite some limitations of this study, the developed system and its stress reduction results are noteworthy for researchers of autonomous vehicles and designers of entertainment in autonomous vehicles.

8 Conclusion

In this study, we proposed an XR live music system called "Hype D-Live" in order to improve passenger comfort in autonomous vehicles by using stressful force and vestibular sensory stimuli as part of the entertainment content to distract the passenger from their anxiety. For this system, we developed functions to project video content based on the driving route, change the size of the acceleration perceived by the passengers, and generate moshing with a motion platform installed in the autonomous vehicle. We then evaluated our system through an experimental study with human participants. The results showed that without the mosh function, the virtual live music venue video demonstrated a significant increase in enjoyment, and a significant decrease in anxiety about vehicle behavior and the external environment, compared to the real external environment video. In the virtual live venue video, the moshing function was shown to decrease enjoyment, and mosh had only a partial effect. Future improvements could make passengers more excited and united. The results of the experiment to reduce AVS-related anxiety are expected to contribute to the design of entertainment content in future autonomous vehicles. As future work, we are considering implementing a function to enable joint participation in XR music live performances with passengers of another autonomous vehicle in the surrounding area. This would be interesting to reduce anxiety through virtual moshing and other acts that improve the sense of unity with the actual human audience, rather than virtual agents.

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