Can We Perceive Changes in Our Moving Speed? A Comparison between Directly and Indirectly Powering the Locomotion in Virtual Environments

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ABSTRACT

Many categories of the illusion of self-motion have been widely studied with the potential support of virtual reality. However, the effects of directly and indirectly powering the movement on the possibility of perceiving changes in moving speed and their relationship with sensory feedback on users' speed change perception have not been investigated before. In this paper, we present the results of our user study on the difference in perceiving changes in moving speed between two different movement techniques: "pedaling" and "throttling". We also explore the effects of different velocity gains, accelerations and speeds of airflow, and their interactions with the movement techniques on users' perception of speed changes in addition to user performance and perception. We built a bike simulator that supports both of the movement techniques and provides sensory feedback. In general, "pedaling" gave users more possibility to perceive changes in moving velocity than "throttling".

CCS CONCEPTS

• **Human-centered computing → User studies**; *User centered design*; • **Computing methodologies → Perception**; **Virtual reality**; • **Hardware →** Sensor applications and deployments;

KEYWORDS

Speed Perception, Bike Simulator, Virtual Reality, Locomotion

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1 INTRODUCTION

Virtual reality (VR) is playing an increasingly important role in providing artificial environments for studies which are hard or impossible to be conducted in the real world. VR has been used in a wide range of fields and multiple disciplines. Of particular interests are VR systems and studies comparing real world situations with VR simulations in terms of sensational and perceptual responses. The simulated environments are constructed and designed based on the knowledge about the real world and therefore sensory information is incorporated.

Traveling in any (larger) virtual environment requires the illusion of self-motion (vection) which has been vastly researched and investigated [6, 11]. A main category of illusory self-motion is linear vection (perception of translation), which can be produced when users move in a straight line along any three body axes in virtual environments, whereas they can move directly or indirectly in the real world. There are different simulation systems invented and developed to study different aspects and methods to elicit linear vection and to understand and investigate human perception on changes and mismatches in their moving speed between virtual and real environments. However, to the best of our knowledge, the effects and discrepancies between different moving techniques on perceiving changes in human moving speed are still unclear.

In this study, we compare two different moving techniques, namely directly and indirectly powering the movement, and investigate their contributions to the sense of perceiving changes in users' movement speed. We built a bike simulator which supports both moving techniques. Directly powering the movement is considered as pedaling a bike, whereas controlling the power of movement using hand-grip is regarded as indirectly. In addition, we examine the effects of different sensory factors and their relationships to the movement techniques. The system is built and incorporated with peripheral sensors, and an experiment is designed with multiple independent variables to support the investigation. Moreover, we also explore how participants perceive the changes in their moving speed.

This paper is structured as follows. Section 2 provides information about relevant related work and Section 3 presents our experimental design and procedure. The experimental results and discussion are presented in Sections 4 and 5, respectively. We give our conclusion on this study in Section 6.

2 RELATED WORK

Perception of speed has been studied widely with both of the above mentioned movement techniques. There are studies in which users were required to directly forcing their movement in virtual environments such as walking or pedaling a bike in virtual environments. Banton et al. [1] investigated how users perceived speed while walking. After conducting different experiments in which participants had to match their walking speed and optic-flow speed, they figured out that lamellar flow, which is eliminated by a limited view of field, is necessary for accurate speed perception. Durgin et al. [5] investigated speed perception for combinations of biomechanical self-motion and physical translation. They noticed that the factors had a reduced effect on visual speed. Nillson et al. [15] conducted two different within-subjects studies for walking in place in order to figure out the perceptual range of natural visual walking speed. They revealed that the size of field-of-view and the types of movement affected how users perceived virtual speed. Mohler et al. [14] showed that visual information might affect gait transition speed and preferred walking speed. There are efforts on how to distort users' walking speed without them noticing in redirected walking techniques [17, 20]. Lotechfeld et al. [12] investigated how to deceive user moving speed in virtual environments. They figured out that users could not notice the increase of 15.2% speed and the deception of both distance and speed is beneficial positively in some cases such as user performance and training.

Speed perception for indirectly powering the movement has been a popular topic with driving simulators. Brodsky [2] found that there was a stable effect of music tempo on estimates of simulated driving speed and perceived speed, whereas Ludwid [13] found that changes in visual representation could affect driving and locomotion speed. There was an evaluation of speed perception and effects including visual and vestibular cues on speed perception in driving experiments by Kemeny et al. [7].

Different bicycle simulators have been created by different research groups. Carraro et al. [3] created one of the first VR bike simulators. This system provided a VR environment with different features of sight, sound, and terrain. In addition, it was combined with a fan to provide some sort of multi-modal feedback. A complicated bicycle simulator was made by Shin et al. [10]. This simulator could provide users with the feeling of actual motion by visual display, controllers, and platforms integrated into the bike system. Sivak et al. [16] introduced a mechatronic rehabilitation system, called VRACK. This system could monitor users' kinetics and kinematics by pressure sensing handle-bars and pedals. Deligiannidis et al. [4] found that user performance could improve when the simulator was integrated with wind and tactile feedback, whereas Kulkarni et al [9] built an immersive virtual environment which could stimulate realistic wind perception while walking.

Although, there were widely research efforts on investigate vection, we cannot find any research on the difference between directly and indirectly powering the movement on the possibility of perceiving changes in moving speed and their relationship with sensory feedback on users' perception of changes in their moving speed. In this paper, we address those issues.

3 EXPERIMENT

3.1 Apparatus

The experiment was conducted in a laboratory environment on a personal computer with a head-mounted display (HMD) and a hybrid bicycle simulator. The computer is powered by an Intel Core i5 4460 3.20GHz with 8GB RAM and a NVIDIA GeForce 960GTX graphics card, and rendered the environmental scenes created with Unity3D. The HMD used in this study was a Dell Visor headset. This headset used inside-out tracking and had two liquid crystal displays with 1440 x 1440 resolution per eye, a 90 Hz refresh rate, and 105^{o} field of view.

The hybrid bike simulator was built from an electric bike, which supported both "pedaling" and "throttling" to control the bike movement, see Figure 1. For "throttling", the bike was powered by a 36V/350W adapter and the right throttle grip was used to control speed of the back flywheel. Users have to apply a force of about 39 N to rotate the throttle grip in order to reach a moving speed of 20 km/h. We integrated a speedometer device on the back of the bike and a magnet on the back flywheel. This device was made by using a Hall sensor and an Arduino Nano board. The moving speed of the bike was recorded by this device and sent to Unity3D through a serial port. In addition, we attached a fan to the system to simulate airflow. The fan consisted of a 12V/150W motor and three slender plastic blades. It was placed at 90 cm from the bike seat and participants could feel airflow from their hip to their head including their two arms. The fan speed was controlled by our scripts in Unity3D through an Arduino Uno board. In addition, our system also provided spatial sound through two Creative SBS A35 2.0 Desktop speakers which were installed in front of the bike.

3.2 Experiment Design

There were two different movement techniques in our experiment: directly ("pedaling") and indirectly ("throttling") powering the movement. These represented for two methods of operating and traveling with bicycles. We applied a multi-factorial 2x7x2x3 design based on two types of movement techniques, seven levels of velocity gain, two levels of acceleration, and three levels of airflow speed. We additionally analyzed three factors: velocity gain, acceleration, airflow speed.

The *velocity gain* was the scale of moving speed in regard to 20 km/h. After a pilot test, we chose in total seven gains for our study: 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, and 1.3. These gains were applied directly to change the base velocity at 20 km/h to a new velocity. So, the new velocity could be equal, lower, or higher than the base velocity.

The *acceleration* was a period of time for the moving speed to change from the base velocity to a new velocity. In this study, we used two different acceleration levels: 1 second (A1) and 3 seconds (A2).

The *airflow speed* was the level of wind speed the fan generated. There were three different levels of airflow speed in our experiment. The first type (F1) was that the airflow speed was maintained permanently at 20 km/h and not changed even when the moving speed was changed. The second type (F2) was that the airflow speed was always equal to the moving speed, whereas the last one (F3) was that the airflow speed was randomized between 14 km/h and 26 km/h.

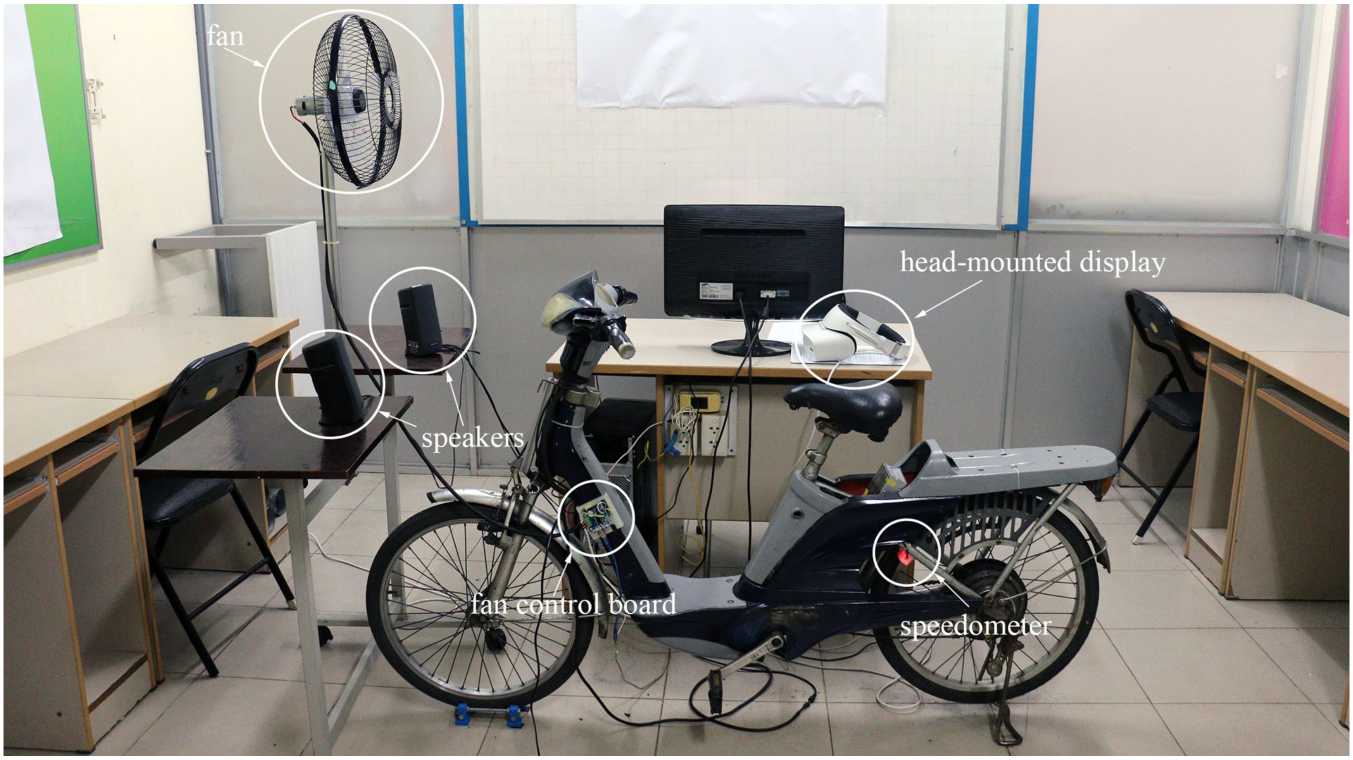


Figure 1: Experimental system.

Theses variables were considered as independent variables, whereas the movement techniques divided the whole experiment into two different blocks. In one block (B1), participants were required to move by pedaling. In contrast, they throttled for the movement in the other block (B2). The orders of velocity gains, accelerations, and airflow speeds were randomized, whereas the order of performing each movement technique was counter-balanced.

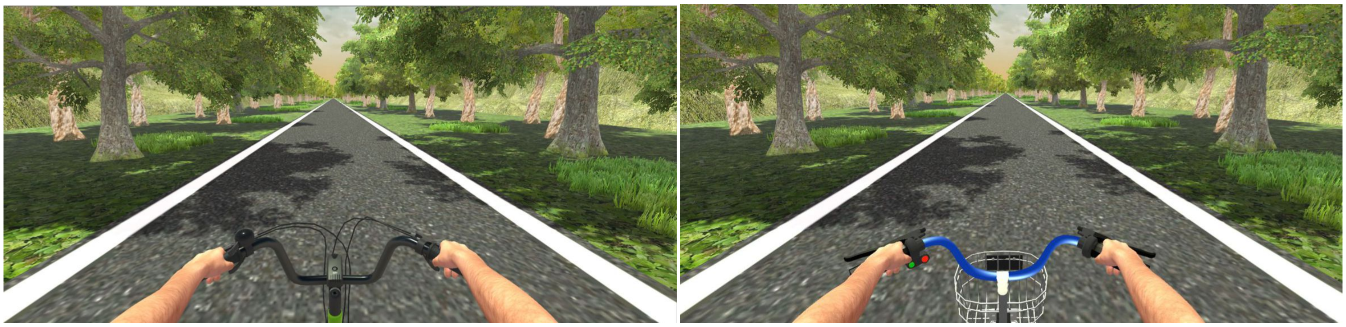
Each participant wore the HMD, rode the bike, and performed experimental trials. For each trial, they were required to keep the true velocity at around 20 km/h. Initially, the participant experienced her base velocity for three seconds (step 1). Her moving speed, then, was changed to a new velocity (step 2). After encountering the new velocity for three seconds (step 3), she was asked to decide whether the new velocity was lower, higher, or equal to her base velocity (Step 4). If she exactly perceived the change, a 'right' response was recorded. Otherwise, a 'wrong' response was saved. After making the decision, another turn was started and the participant was asked to do the same routine. The time she spent on decision was called decision time. Participants' movement speeds in the real world (real velocity) were also recorded during the experiment. For this, we considered the trial step in each trial as an additional independent variable.

There were 42 (7x2x3) combinations of 7 velocity gains, 2 acceleration levels, and 3 airflow speeds for each experiment block. Each participant was requested to accomplish three decisions for her perception of the new velocity for each combination. In total, she performed 126 (42x3) trials and selections in each block. The response, decision time, and real velocity were considered as dependent variables in our experiment.

3.3 Participants and Experiment Procedure

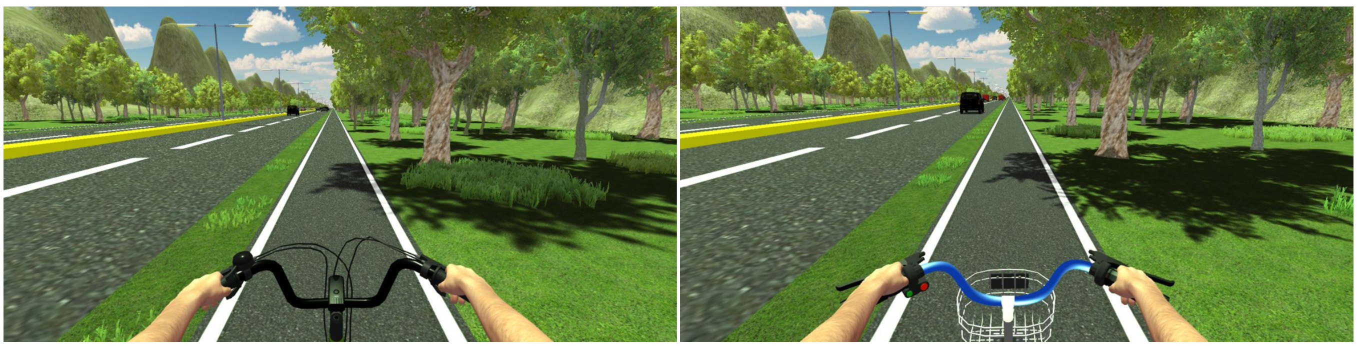
We recruited 40 volunteers (30 male, 9 female, and 1 other gender) who were students or officers to join our experiments. Their ages varied from 18 to 33 (M = 20.5, SD = 2.71). There were eight participants who frequently ride bikes, whereas twenty-two participants often travel by electric bikes or scooters, mopeds, or motorcycles. Twenty participants had experience with virtual reality and two of them had been exposed to a virtual ride before. All of the volunteers had normal or correct-to-normal vision, while no volunteers had problems with their vestibular system. Each participant was compensated for their participation.

The participants were randomly divided into two different groups. Volunteers in the first group performed block B1 first, then block B2. In contrast, the second group participants completed block B2 before block B1. When a participant arrived, she received an experiment information document. The participant was required to read the document carefully and decide whether to take part in the experiment. When she agreed to participate, she was provided with a consent form including agreements of her responsibilities on her response and a brief introduction form. She was requested to sign the consent form before starting the experiment. The design, procedure, and materials of the experiment were approved through a local ethics committee. After that, the volunteer was trained with two different training tasks for each type of movement techniques.



(a1) For "pedaling". **(a2) For "throttling".**

(a) Training scene.



(b1) For "pedaling". **(b2) For "throttling".**

(b) Experimental scene.

Figure 2: Training scene and experimental scene. Participants could see their arms and a traditional bike for "pedaling". In contrast, they could see their arms and a electric bike for "throttling" ". In addition, the experimental scene had additional objects which were moving or stationary in comparison with the training scene.

In each task, she saw her arm avatar and an bike model which could be a traditional bike for "pedaling" or an electric bike for "throttling" the movement in the training scenes, see Figure 2a. For the first a half of training session, participants were encouraged to experienced and be familiar with different moving velocities. In the second session, they were trained to keep their moving speed at 20km/h. After training, she had five minutes for taking a break before starting the blocks of experiment in experimental scenes, see Figure 2b and Figure 3.

Each participant was required to maintain her true velocity at around 20 km/h for the whole of each experiment block. For each block, an experiment trial started when she kept her true velocity continuously at 20 km/h for at least three seconds. Then, her movement velocity in the virtual environment changed to a new velocity in one or three seconds. After experiencing the new velocity for three seconds, she was asked to decide whether the new velocity was lower, equal, or higher than her base velocity. She was instructed to decide by moving a small white dot in her view to the selection button representing her perception, see Figure 4. After the selection, this trial was finished and the participant was requested to perform the same routine for other trials. After each trial, the volunteer could take a rest if she felt tired. In total, each block took about 30 minutes. After each experiment block, the participant filled three questionnaires and took a break. In this study, we used a Simulator Sickness Questionnaire (SSQ) [8], a Igroup Presence Questionnaire (IPQ) [18, 19], and a self-compiled questionnaire investigating how participant perceive about the experiment and the changes of their movement speed. The total time for each volunteer was about 105 minutes. She performed on average "pedaling" for 38 minutes (SD = 9.23) and "throttling" for 24 minutes (SD = 4.46). The procedure of our experiment is showed as in Table 1.

Table 1: Experiment procedure

Step	**Time** (min)
Instruction and informed consent	10
Experiment configuration	5
Training	10
Break	5
Experiment with the 1st block	30
Questionnaire	5
Break	5
Experiment with the 2nd block	30
Questionnaire	5

(a) with "pedaling". **(b) with "throttling".**

Figure 3: A participant was performing the experiment. She had to use her legs to pedal the bike (on the left). In contrast, the movement was indirectly powered when she throttle by using her right hand (on the right).

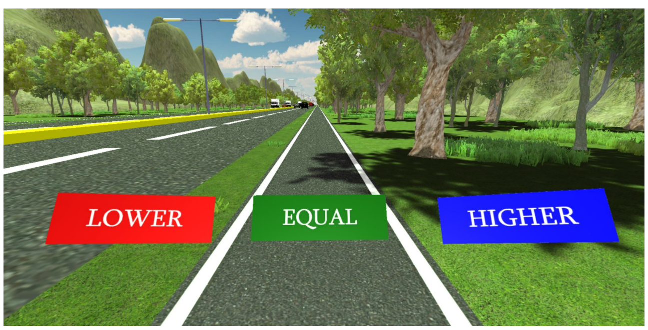


Figure 4: Selection options.

3.4 Hypotheses

This study is to investigate the difference between movement techniques on perceiving changes in movement speed. There were a few hypotheses made for our experiment. First, directly powering the movement would lead to better speed change perception than its counterpart. Second, users would perceive the changes in their moving speed better for one second acceleration than a for slower acceleration of three seconds. Third, airflow speeds were believed to provide the same possibility for perceiving changes in movement speed. Fourth, participants were required to keep their real velocity around 20 km/h. We expected that real velocity would not be significantly different between movement techniques during the experiment. Fifth, the HMD vibrated slightly when participants were pedaling, this would lead to a significant longer decision time for "pedaling". Sixth, the experimental system was carefully built and configured, therefore we assumed that the sense of presence and cyber-sickness would be the same for all movement techniques. To sum up, these are our hypotheses:

H1 Better speed change perception for "pedaling".

H2 Worse speed change perception for "throttling".

H3 No significant difference in real velocity for both movement techniques during the experiment.

H4 Longer decision time for "pedaling".

H5 Shorter decision time for "throttling".

H6 Better speed change perception for A1.

H7 Worse speed change perception for A2.

H8 No significant difference in speed change perception for airflow speeds.

H9 No significant difference in sense of presence for all the movement techniques.

H10 No significant difference in sense of cyber-sickness for all the movement techniques.

4 RESULTS

We used three different Generalized Linear Mixed Models provided by the GLIMMIX procedure in SAS® to analyze the results. In the first model, a binary distribution and a logit link were applied to participants' responses which were considered as a target variable and the fixed effects of the model were a full factorial interaction of movement techniques, velocity gains, acceleration levels, and airflow speeds. These fixed effects were also applied for the model analyzing decision time, whereas the fixed effects for real velocity were a full factorial interaction of all the independent variables. Real velocity and decision time were target variables for the second and third models. A normal distribution and a link were applied to these variables. Subjects and block order were applied as random effects in all of the models. Tukey-Kramer pair-wise comparison tests were conducted to figure out differences in the LS-means between the fixed effects ($\alpha = 0.05$). In this study, we only report one-way significant effects of the independent variables and two-way significant effects of the interactions between movement techniques and the other independent variables.

Table 2: Type III tests of one-way interaction for participants' response.

Effect	Chi-square	p-value
movement technique	$\chi^2(1, 39) = 4.92$	$p < .05$
velocity gain	$\chi2(6, 234) = 1304.44$	$p < .01$
acceleration level	$\chi2(1, 39) = 1.56$	$p = .22$
airflow speed	$\chi2(2, 78) = 275.33$	$p < .01$

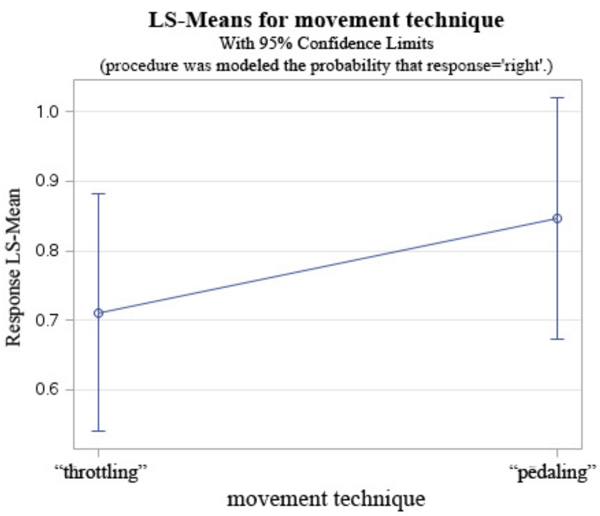


Figure 5: Estimated least squares means of response of movement techniques.

4.1 Response

The one-way interaction of the independent variables analysis showed that there were significant statistically effects of movement technique, velocity gain, and airflow speed on the response ($p < .05$), whereas acceleration level did not ($p > .05$), as shown in Table 2. We report the post-hoc test results of the significant effects as below.

Movement technique: The "right" response with "pedaling" (M = 0.7, SE = 0.02) was significantly more than that with "throttling" (M = 0.67, SE = 0.02), see Figure 5.

Velocity gain: The velocity gain of 0.7 (M = 0.92, SE = 0.01) had significantly more "right" response than the others. In contrast, the velocity gain of 0.9 (M = 0.33, SE = 0.02) and 1.1 (M = 0.34, SE = 0.02) has the fewest "right" responses. The experiment results showed that 60.76% and 61.6% of responses for the velocity gain of 0.9 and 1.1 were perceived to be equal to the velocity gain of 1. The "right" response for the other velocity gains are presented in descending order: 1.3 (M = 0.84, SE = 0.02), 1 (M = 0.78, SE = 0.02), 0.8 (M = 0.71, SE = 0.02), and 1.2 (M = 0.65, SE = 0.02).

Airflow speed: Experiencing the airflow speed F2 (M = 0.84, SE = 0.01) had significantly more "right" response than F1 (M = 0.58, SE = 0.02) and F3 (M = 0.59, SE = 0.02). In contrast, airflow F1 and F3 did not have significant difference in "right" response.

Table 3: Type III tests of two-way interactions for participants' response.

Effect	Chi-square	p-value
movement technique vs. velocity gain	$\chi^2(6, 234) = 22.4$	$p < .01$
movement technique vs. acceleration level	$\chi^2(1, 39) = 0.2$	$p = .65$
movement technique vs. air flow speed	$\chi^2(2, 78) = 3.13$	$p = .21$
velocity gain vs. acceleration level	$\chi2(6, 234) = 2.32$	$p = .89$
velocity gain vs. air flow level	$\chi2(12, 468) = 215.47$	$p < .01$
acceleration level vs. airflow speed	$\chi2(2, 78) = 0.69$	$p > .05$

Table 4: Type III tests of one way interaction for participants' real velocity.

Effect	Chi-square	p-value
movement technique	$\chi^2(1, 38) = 2317.91$	$p < .01$
velocity gain	$\chi^2(6, 240) = 38.38$	$p < .01$
acceleration level	$\chi^2(1, 40) = 58.91$	$p < .01$
airflow speed	$\chi^2(2, 80) = 2.23$	$p = .33$
trial step	$\chi^2(3, 120) = 1441.7$	$p < .01$

The analysis of the two-way interactions between the independent variables showed that there were statistically significant interactions between movement technique and velocity gain, and between velocity gain and airflow speed, whereas the other interactions were not significant ($p > .05$), as shown in Table 3.

Movement technique and velocity gain: Although, the interaction between movement technique and velocity gain was statistically significant, we did not observe any significant difference in "right" response between movement techniques for each velocity gain ($p > .05$).

Velocity gain and airflow speed: Airflow speed F2 had significantly more "right" response for both movement techniques than airflow speed F1 for velocity gains of 0.7, 0.8, 1.1, 1.2, and 1.3, and airflow speed F3 for velocity gains of 0.7, 0.8, 0.9, 1.2, and 1.3. In addition, there was significantly more "right" response for airflow speed F3 in velocity gains of 1.1 and 1.3 than that for airflow speed F1.

4.2 Real Velocity

The one-way interaction analysis showed that there were significant statistical effects of movement technique, velocity gain, acceleration level, and trial step on the real velocity ($p < .05$), whereas airflow speed did not ($p > .05$), as shown in Table 4. The post-hoc test results of the significant effects are reported as below.

Movement technique: The real velocity for "pedaling" (M = 19.53, SE = 0.03) was significantly lower than that for "throttling" (M = 19.91, SE = 0.03).

Table 5: Type III tests of two-way interactions for participants' real velocity.

Effect	Chi-square	p-value
movement technique vs. velocity gain	$\chi^2(6, 228) = 43.04$	$p < .01$
movement technique vs. acceleration level	$\chi^2(1, 38) = 34.04$	$p < .01$
movement technique vs. airflow speed	$\chi^2(2, 76) = 0.9$	$p = .64$
movement technique vs. trial step	$\chi^2(3, 114) = 892.52$	$p < .01$
velocity gain vs. acceleration level	$\chi^2(6, 240) = 8.03$	$p = .24$
velocity gain vs. airflow speed	$\chi^2(12, 480) = 21.86$	$p < .05$
velocity gain vs. trial step	$\chi^2(18, 720) = 30.39$	$p < .05$
acceleration level vs. airflow speed	$\chi^2(2, 80) = 3.68$	$p = .17$
acceleration level vs. trial step	$\chi^2(3, 120) = 26.8$	$p < .01$
airflow speed vs. trial step	$\chi^2(6, 240) = 0.89$	$p = .99$

Velocity gain: The velocity gain of 1.3 (M = 19.67, SE = 0.03) had significantly lower real velocity than the velocity gains of 0.8 (M = 19.73, SE = 0.03), 1 (M = 19.75, SE = 0.03), and 1.1 (M = 19.74, SE = 0.03). In addition, real velocity for the velocity gain of 1 had significantly higher than that for the velocity gain of 1.2 (M = 19.7, SE = 0.03).

Acceleration level: Acceleration level A1 (M = 19.75, SE = 0.03) had significantly higher real velocity than acceleration level A2 (M = 19.69, SE = 0.03).

Trial step: We observed that real velocity was not changed significantly when the virtual velocity was changing from base velocity (M = 19.84, SE = 0.03) to a new velocity. The real velocity for these trial steps were significantly higher than that of the other steps. The real velocity when participants made their response (M = 19.48, SE = 0.03) was the lowest.

The two-way analysis showed that the *movement technique* × *velocity gain*, *movement technique* × *acceleration level*, *movement technique* × *trial step*, *velocity gain* × *airflow speed*, *velocity gain* × *trial step*, and *acceleration level* × *trial step* interactions were statistically significant, whereas the other interactions were not significant ($p > .05$), as shown in Table 5.

Movement technique vs. velocity gain: Real velocity for "pedaling" was significantly lower than that for "throttling" in all of the velocity gains ($p < .01$).

Movement technique vs. acceleration level: For all of the acceleration levels, "throttling" had significantly higher real velocity than "pedaling" ($p < .01$).

Movement technique vs. trial step: At all of the trial steps, we observed that "throttling" had significantly higher real velocity than "pedaling" ($p < .01$).

Table 6: Type III tests of one way interaction for participants' decision time.

Effect	Chi-square	p-value
movement technique	$\chi^2(1, 38) = 57.31$	$p < .01$
velocity gain	$\chi^2(6, 240) = 93.42$	$p < .01$
acceleration level	$\chi^2(1, 40) = 6.37$	$p < .05$
airflow speed	$\chi^2(2, 80) = 5.59$	$p = .06$

Velocity gain vs. airflow speed: Although, the interaction between movement technique and airflow speed was statistically significant. We did not observe any significant difference in real velocity between airflow speeds for each velocity gain ($p > .05$).

Velocity gain vs. trial step: We observed that the real velocity for step 4 was significantly lower than that for the other trial steps. There was no significant difference in real velocity between step 1 and step 2 for all of velocity gains except for velocity gain of 1.3, and between step 1 and step 3 for velocity gains of 0.7, 0.8, and 0.9, and between step 2 and step 3 for velocity gain of 0.7 ($p > .05$).

Acceleration level vs. trial step: Real velocity in step 2 and step 3 for acceleration level A1 was significantly higher than those for acceleration level A2 ($p < .05$). In addition, real velocity was significantly changed between each step for each acceleration level ($p < .05$).

4.3 Decision Time

The result of one-way interaction analysis showed that there were statistically significant effects of movement technique, velocity gain and acceleration level on decision time ($p < .05$), whereas airflow speed did not ($p > .05$), as shown in Table 6. The post-hoc test results of the significant effects are reported as below.

Movement technique: Participants spent significantly less time on decision for "throttling" (M = 2.93, SE = 0.14) than for "pedaling" (M = 3.31, SE = 0.14).

Velocity gain: We observed that velocity gain of 0.7 (M = 2.89, SE = 0.15) took significantly less time for decision than that of 0.8 (M = 3.23, SE = 0.15), 0.9 (M = 3.45, SE = 0.15), 1 (M = 3.25, SE = 0.15), and 1.1 (M = 3.29, SE = 0.15). The velocity gains of 0.9, 1, 1.1, and 1.2 (M = 3.01, SE = 0.15) had significantly more time on decision than that of 1.3 (M = 2.71, SE = 0.15). In addition, we found that the velocity gain of 1.2 took significantly less time on decision than that of 0.9 and 1.1.

Acceleration level: There was significantly more decision time for acceleration level A1 (M = 3.18, SE = 0.14) than that for acceleration level A2 (M = 3.06, SE = 0.14).

The two-way analysis showed that the *movement technique* × *velocity gain* and *velocity gain* × *acceleration* interactions were statistically significant, whereas the other interactions were not significant ($p > .05$), as shown in Table 7.

Movement technique vs. velocity gain: For velocity gain of 0.7 and 0.8, we observed that there was a significant difference in decision time between "pedaling" and "throttling". "Throttling" had significantly less decision time in these velocity gains than "pedaling" ($p < .01$).

Table 7: Type III tests of two-way interactions for participants' decision time.

Effect	Chi-square	p-value
movement technique vs. velocity gain	$\chi^2(6, 228) = 26.64$	$p < .01$
movement technique vs. acceleration level	$\chi^2(1, 38) = 0.25$	$p = .62$
movement technique vs. airflow speed	$\chi^2(2, 76) = 0.67$	$p = .71$
velocity gain vs. acceleration level	$\chi^2(6, 240) = 12.96$	$p < .05$
velocity gain vs. airflow speed	$\chi^2(12, 480) = 18.02$	$p = .12$
acceleration level vs. airflow speed	$\chi^2(2, 80) = 1.6$	$p = .45$

Velocity gain vs. acceleration: Although, there was a significant interaction between velocity gain and acceleration. We did not observe any significant difference in decision time between acceleration levels in each velocity gain ($p > .05$).

4.4 Relation between dependent variables

We conducted Spearman's rank-order correlation tests in order to investigate the relationship between the dependent variables. The results showed that there was an association among them. The relationship between decision time and response (r_s = -.06, $p < .01$) was very weak negative linear. In addition, we also found that a very weak negative linear relationship between decision time and real velocity (r_s = -.16, p < .01). However, there was no association between response and real velocity (r_s = -.02, $p = .11$). Therefore, the correlation between response and decision time, and between decision time and real velocity was very weak.

4.5 Questionnaire

We analyzed the questionnaires' responses for all movement techniques using Friedman tests and Wilcoxon signed-rank tests as post-hoc tests for significant difference.

The analysis results of SSQ responses showed that participants felt different levels of fatigue ($\chi^2(1, 40) = 6.37$, $p < .05$) and sweating ($\chi^2(1, 40) = 21$, $p < .01$) between the movement techniques. The post-hoc tests showed that "throttling" made participant feel significantly less fatigue ($Z = -2.35$, $p < .01$) and sweating ($Z = -4.15$, $p < .01$) than "pedaling".

There was a significant difference in participants' response on IPQ between the two movement techniques. The volunteers felt that the virtual environment seemed as more like pictures when "pedaling" than when "throttling" ($Z = -2.01$, $p < .05$). In addition, when "throttling", participants paid significantly more attention to the real world than when "pedaling" ($Z = -2.11$, $p < .05$). There was no significant difference in responses for the other question on IPQ between the movement techniques.

Participants' feedback on our questionnaire showed that they felt they were moving when they performed our experiment. In addition, we found that with different visual cues in the experimental scenes, they mainly used trees and grounds along the moving road as reference points for perceiving the changes in their moving speed.

5 DISCUSSION

5.1 Hypotheses Evaluation

The results of our analysis showed that "pedaling" had significantly more "right" responses than "throttling". This supports both hypothesis **H1** (Better speed change perception for "pedaling") and hypothesis **H2** (Worse speed change perception for "throttling"). However, participants reported that the sense of pedaling on the bike system was lighter than on a bike in the real world. In addition, they found that it was harder to keep the movement speed around 20 km/h when "pedaling" than when "throttling". "Pedaling" made the participants feel the virtual environment more likely pictures because of the vibration of the HMD. However, participants paid more attention to the experimental environment when "pedaling". Moreover, the sense of proprioception for directly powering the movement was stronger than for indirectly. Thus, these contributed to the significant difference in "right" responses between "pedaling" and "throttling".

Participants maintained successfully their real velocity around 20 km/h when performing the experiment. However, the experiment analysis showed that there was a significant difference in real velocity between the two techniques. This does not support hypothesis **H3** (No significant difference in real velocity for both movement techniques during the experiment). However, real velocity for "throttling" was only higher from 0.37 km/h to 0.4 km/h than that for "pedaling". We believe that this discrepancy does not have a significant impact on perceiving changes in moving speed between the moving techniques.

The analysis results showed that "throttling" had significant lower decision time than "pedaling". This supports hypothesis **H4** (Longer decision time for "pedaling") and **H5** (Shorter decision time for "throttling"). Vibrations in the HMD when participant was pedaling and choosing their perception could make the decision time remarkably longer. Although, participants sometimes reported that it was difficult to choose the selection button representing their perception. This is believed to not have contributed to the difference in decision time between the movement techniques.

Although, participants reported that it was difficult to perceive the changes in moving speed when the velocity was changing for a longer period of time, our observations in the experiment showed that there was no significant difference in "right" response between acceleration levels. This does support both hypothesis **H6** (Better speed change perception for A1) and hypothesis **H7** (Worse speed change perception for A2).

From experiment analysis, we observed that there was a significant difference in "right" response between airflow speeds. This, therefore, does not support hypothesis **H8** (No significant difference in speed change perception for airflow speeds). We found that the airflow speed with the same speed of movement provided users more possibility to perceive changes in movement velocity than the others. In addition, if the airflow speed does not change while the movement speed changes, users cannot easily perceive the changes in their moving speed.

The volunteers did not perceive the same level of presence between "pedaling" and "throttling". In some degrees, they perceived the virtual environments neutrally as pictures when "pedaling" and still noticed slightly the real world when "throttling". This does not support hypothesis **H9** (No significant difference in sense of presence for all the movement techniques). However, we did not observe any significant difference between movement techniques in the other questions in the IPQ. It is believed that the difference might not significantly affect the discrepancy in perceiving changes in moving speed between the moving techniques and participants' performance in our experiment.

The analysis of participants' response for SSQ showed that people felt significantly more fatigue and sweating when "pedaling" than when "throttling". This does not support hypothesis **H10** (No significant difference in sense of cyber-sickness for all the powering techniques). For directly powering the movement, the volunteers had to generate the force for their movement. This could make them tired. However, this leads to a significantly more "right" response for "pedaling" than for "throttling".

5.2 Limitation

We had some limitations in our experiment. First, participants felt difficult to keep their real velocity around 20 km/h and spent significantly more time on "pedaling" than "throttling" because our bike system did not have a resistant system. So, the feeling of pedaling with our bike simulator might be slightly lighter than that of pedaling in the real world. However, we believe that more training time for "pedaling" could reduce this issue. In addition, the seat of the bike was not comfortable enough for participants to ride for a long period of time.

6 CONCLUSION

In this paper, we present our procedure and results of an experiment on perceiving changes in moving speed with two different movement techniques: directly ("pedaling") and indirectly ("throttling") powering the movement. In addition, we investigated the effects of acceleration level and airflow speed on users' speed perception, and the relationship in the association of real velocity, decision time, and users' response. The sense of presence and cyber-sickness was also studied for both of the movement techniques in our study. In general, the results showed that "pedaling" had a higher possibility to perceive the changes in moving speed correctly than "throttling".

The results of our study can provide knowledge on constructing different purpose simulators in virtual reality. In addition, they also contribute to our findings on speed perception. In the future, we schedule to investigate the sense of moving speed in different weather and environmental condition such as in cloudy or foggy environments.

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