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Using a Virtual Reality Walking Simulator to Investigate Pedestrian Behavior

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Dear Editor Aaron Berard,

February 1, 2020

This letter accompanies the revision of "Using a virtual reality simulator to investigate pedestrian behavior " by Hyun Chae Chung, Soon Ho Kim, Jong Won Kim, Gyoojae Choi, MooYoung Choi, and Hui Li, for publication in the Journal of Visualized Experiments in the section Behavior. We first thank the reviewers for their careful reading, positive comments, and valuable suggestions. Please see the detailed responses provided with the manuscript. For convenience of the reviewers, we are submitting the revised manuscript with requested changes printed in red. The revised manuscript also reflects the formatting and style changes in compliance with the Submission Guidelines. An e-mail correspondence containing reprint permission from SAGE Publishing is also provided.

We hope the revised manuscript to be accepted for publication and appreciate your kind consideration.

Thank you for your consideration.

Sincerely,

Hyun Chae Chung, Ed.D.
Department of Sports Science
Professor at Kunsan National University

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TITLE:
Using a Virtual Reality Walking Simulator to Investigate Pedestrian Behavior

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KEYWORDS:
behavior, pedestrian, traffic safety, virtual reality, perception, action, ecological psychology

SUMMARY:
This protocol describes use of a walking simulator that serves as a safe and ecologically valid method to study pedestrian behavior in the presence of moving traffic.

ABSTRACT:
To cross a road successfully, individuals must coordinate their movements with moving vehicles. This paper describes use of a walking simulator in which people walk on a treadmill to intercept gaps between two moving vehicles in an immersive virtual environment. Virtual reality allows for a safe and ecologically varied investigation of gap crossing behavior. Manipulating the initial starting distance can further the understanding of a participant's speed regulation while approaching a gap. The speed profile may be assessed for various gap crossing variables, such as initial distance, vehicle size, and gap size. Each walking simulation results in a position/time series that can inform how velocity is adjusted differently depending on the gap characteristics. This methodology can be used by researchers investigating pedestrian behavior and behavioral dynamics while employing human participants in a safe and realistic setting.

INTRODUCTION:

Gap crossing, an interceptive behavior, requires moving oneself in relation to a gap between two moving vehicles[1–4]. Gap crossing involves perceiving oncoming vehicles and controlling movement in relation to moving traffic. This requires actions to be precisely coupled with perceived information. Many previous studies have examined perceptual judgment and gap-crossing behavior using artificial roads, roadside simulators, and screen projection virtual environments[5,6]. However, previous road-crossing literature has an incomplete understanding of this behavior, and the ecological validity of these studies has been questioned[7–9].

This protocol presents a research paradigm for studying gap crossing behavior in virtual reality, thus maximizing ecological validity. A walking simulator is used to examine the perception and actions of gap crossing behavior. The simulator provides a safe walking environment for participants, and the actual walking in the simulated environment allows researchers to fully capture the reciprocal relationship between perception and action. Individuals who actually cross a road are known to judge the time gap more accurately than those who only verbally decide to cross[10]. The virtual environment is ecologically valid and allows researchers to easily change task-related variables by altering the program's parameters.

In this study, a participant's initial starting location is manipulated to assess the velocity control while approaching the gap. This protocol allows the investigation of pedestrian locomotion control while intercepting a gap. Analyzing a participant's velocity changing over time allows a functional interpretation of velocity adjustments while he or she approaches a gap.

In addition, the spatial and temporal characteristics of intercepted objects specify how a person can move. In a gap crossing environment, changing of the gap size (inter-vehicle distances) and vehicle size should affect how a pedestrian's locomotion also changes. Accordingly, manipulating the gap characteristics will likely cause velocity adjustments in the participant's approaching behavior. Thus, manipulating gap characteristics (i.e., gap size and vehicle size) provides valuable information for understanding crossing behavior changes according to various gap characteristics. Thus, this study examines how children and young adults regulate their velocity when crossing gaps in various crossing environments. The speed regulation profile can be assessed for various gap crossing environments with different starting locations, inter-vehicle distances, and vehicle sizes.

PROTOCOL:

This experimental protocol involves human subjects. The procedure was approved by the Kunsan National University Research Board.

1. Preparation of equipment

NOTE: The equipment includes the following: a personal computer (PC, 3.3 GHz with 8 GM) with a mouse, keyboard, and monitor; Walking Simulator software installed on the desktop PC; a customized treadmill (width: 0.67 m, length: 1.26 m, height: 1.10 m) equipped with handrails, a belt, and a magnetic encoder with a USB cable; and an Oculus Rift virtual reality device (DK1, U.S., 1280 x 800 pixels). The equipment also includes a customized manual treadmill. The treadmill turns via the walking motions of the participants and does not use an internal motor.

1.1. Prepare sufficient space for the treadmill and a nearby desk for the PC. A photograph of the experimental setup is shown in **Figure 1A**.

1.2. Connect the equipment as shown in **Figure 2**.

1.2.1. Connect treadmill's magnetic encoder to the PC via a USB port.

1.2.2. Connect the treadmill to a power source.

1.2.3. Connect the headset to the PC via DVI/HDMI and USB ports.

2. Preparation of walking simulator configurations

2.1. Access the walking simulator directory on the PC and open the "Config" directory.

NOTE: Each configuration is saved as a text file in the "Config" directory with file names of "config001", "config002", etc. Here, 001, 002, etc. are the configuration numbers. Steps 2.2–2.8 describe how to create the configuration files so that they are readable by the simulator software. A schematic of a two-vehicle crossing situation showing customizable initial distances is shown in **Figure 3**. An example configuration file with proper formatting is shown in **Figure 4**. Section headings of the configuration file use square brackets (e.g., "[WALKER]").

2.2. Complete the section [WALKER] containing the parameter regarding the starting point of the participants.

2.2.1. Set the parameter "Distance", which indicates the starting distance of the participant from the starting point in meters (m).

2.3. Complete the section [CAR] containing parameters regarding the first vehicle.

2.3.1. Set the parameter "Type" (which indicates the type of vehicle) to "1" for sedan, "2" for bus, or "0" to remove the vehicle.

2.3.2. Set the parameter "Speed" (which indicates the vehicle speed) to the desired value in km/h.

2.3.3. Set the parameter "Distance" (which indicates initial distance of the vehicle from the crossing point) to the desired value in meters.

2.4. Complete the section [SECONDCAR] containing the parameters related to the second vehicle. Parameters are identical to those of [CAR].

NOTE: In two-vehicle studies, the gap is defined as the empty space between the two vehicles. The gap size, defined as the length of time during which the gap is along the participant's walking path, is a function of the "Distance", "Speed", and "Type" parameters of [CAR] and [SECONDCAR].

2.5. Complete the section [NEXTCAR] containing parameters related to additional vehicles. The parameters are identical to those of [CAR].

NOTE: This option can be used to investigate pedestrian behavior within continuous traffic flow. This option is not discussed in the representative results section.

2.6. Complete the section [ROAD], containing the parameter for lane selection. Set the parameter "lane" to "1" to use the lane closer to pedestrian's starting position, or "2" for the lane further away. [OBSTACLE] indicates the parameters that configure a vehicle traveling in the second lane at the same speed as the first vehicle.

NOTE: When using the closer lane as the primary lane, this option can be used to place additional vehicles on the farther lane going in the same direction. Hence, it can be used to study the impedance of the view of a vehicle by a parallel vehicle. This section has parameters "Type" and "Distance" with the same definitions described above. This option is not discussed in the representative results section. All results shown involve two vehicles driving in the lane closer to the pedestrian.

2.7. Complete the section [SAVE], which contains the parameter related to sampling frequency. Set the parameter "numberpersecond" to the desired value in Hz.

2.8. Save the configuration file and exit.

2.9. Repeat sections 2.2–2.8 for all desired configurations and prepare a separate sheet with the list of configurations (in a randomized order) to be used in the experiment.

2.10. Prepare three configuration files to be used in the practice trials.

NOTE: The first practice configuration should have no vehicles (i.e., all "Type" parameters set to "0"). The second and third practice configuration files should have vehicles. The third configuration should have lenient crossing conditions. The same configuration may be used for the second and third practice trials, depending on the experimental design.

3. Participation screening and preparation

3.1. Recruit participants with normal or corrected-to-normal vision.

NOTE: All participants should be free of any conditions that prevent normal walking. They should be free of any dizziness while walking, and they should not have any history of serious traffic accidents.

3.2. Ask the participant to sign a written, informed consent form before each experiment.

3.3. Prepare an audio recording with verbal instructions of the task and play the recording to the participant.

NOTE: The verbal instructions should narrate the basic procedure described below and give any specific prompts required by the experimental design.

3.4. Encourage the participant to ask any questions about the experiment.

3.5. Lead the participant to stand on the treadmill when ready.

3.6. Harness the stabilizing belt to the participant's waist. Instruct the participant to hold the handrails at all times during the experiment.

4. Running the practice trials

4.1. Instruct the participant to practice walking on the treadmill, with the belt on, while holding the handrails.

4.2. Begin the walking simulator program by double-clicking the executable simulator program once the participant is able to walk on the treadmill comfortably.

NOTE: The black and white cartoon crosswalk shown in **Figure 1B** is displayed between crossing trials. At this point, it should be shown on the PC screen.

4.3. Instruct the participant to wear the headset. Give assistance as needed. Check for both comfort and stability with respect to head turns.

4.4. Calibrate the headset so that the black and white cartoon crosswalk is properly aligned with participant's view.

NOTE: Sections 4.5–4.7 describe three practice trials, which are designed to gradually allow the participant to become accustomed to the simulator environment. If the participant fails any trial due to misunderstanding of the instructions, up to two more extra trials should be performed until the participant understands the instructions. Extra trials are not performed in cases of failure to cross for reasons other than misunderstanding the rules (e.g., if a collision occurs).

4.5. Begin the first practice trial.

NOTE: The first practice trial should be without any vehicles for the participant to become accustomed to walking in the virtual reality setting.

4.5.1. Inform the participant that the first practice trial will occur without any vehicles.

4.5.2. Enter the first practice trial's configuration number in the text box on the bottom of the screen.

4.5.3. Click the "Start" button at the bottom of the screen.

NOTE: The program should display the realistic setting depicted in **Figure 1C** on the screen.

4.5.4. Instruct the participant to look straight ahead.

4.5.5. Inform the participant to get ready when hearing "Ready" and to begin walking when hearing "Go". Give the verbal cues "Ready" and "Go".

4.6. Second practice trial

NOTE: The second practice trial should introduce the vehicles without walking. The direction of the virtual reality view shifts as the participant's head is turned.

4.6.1. Instruct the participant in this trial, at the verbal cue "Go", to look to the left and simultaneously take a small step forward, but not to walk forward any further. The participant should instead watch the vehicles pass by.

4.6.2. Type the second trial's configuration number into the text box and click "Start".

4.6.3. Give the verbal cues.

NOTE: The vehicles begin moving as the participant begins moving.

4.7. Third practice trial

NOTE: The third practice trial should be similar to the experimental configurations, but with lenient crossing conditions.

4.7.1. Inform the participant that 1) the third practice trial will involve two vehicles coming from the left side, and 2) he/she should attempt to cross the road between the two vehicles.

4.7.2. Enter the third practice trial number in the text box.

4.7.3. Click the "Start" button and begin the trial by providing the verbal cues.

5. Virtual walking experiment

5.1. Confirm that the participant understands the experimental task and is able to perform it.

5.2. When the participant is ready, type in the first configuration number from the randomized list on the text box and click “Start”.

5.3. Perform the simulation as done in the final practice trial.

NOTE: At the end of each crossing trial, the program displays “S”, “F”, or “C”, depending on whether the result is a successful crossing (i.e., the participant crosses to the other side of the street with no collisions), no crossing (participant does not cross to the other side), or a collision (participant has contact with a vehicle), respectively.

5.4. Record the result next to the configuration number on the experiment sheet.

5.5. Repeat for all configurations in the randomized list and complete the experiment.

6. Data export and analysis

6.1. Retrieve the data files for analysis. The walking simulator software saves each run as a spreadsheet file in the “Data” folder.

6.2. Analyze data with the preferred tools. The output data records the positions and velocities of the walker and the vehicles as a time series. Use this data to analyze participant movements and the dependence on traffic conditions.

REPRESENTATIVE RESULTS:

The walking simulator can be used to examine a pedestrian’s crossing behavior while manipulating the initial distance from curb to interception point and the gap characteristics (i.e., gap and vehicle sizes). The virtual environment method allows the manipulation of gap characteristics to understand how dynamically changing crossing environments affect children’s and young adults’ road-crossing behaviors.

A quantified velocity profile and crossing position within the gap used to compare the crossing behavior of various pedestrian groups. These representative results use data from 16 young adults (mean age = 22.75 years, SD = 2.56) and 16 children (mean age = 12.18 years, SD = 0.83). Generally, 12 year-old children undergo developmental changes in the ability to coordinate movements with moving objects[3,4,11–14], so varying the initial distance provided an opportunity to compare functional adjustment of approaching velocity in children vs. young adults. The participants were recruited via a university social media posting. Of the recruited participants, two young adults experienced motion sickness, in which the experiments were immediately stopped, and they were excluded from the study.

The success rate was 98.95% among children and 99.48% among young adults. Only successful trials were included in the analysis. To access the velocity data, a 3 x 2 x 2 x 4 (initial distance [near, intermediate, far]; gap size [3 s, 4 s]; vehicle size [car, bus]; time [3.5 s, 2.5 s, 1.5 s, 0.5 s]) repeated measures ANOVA was performed using initial distance, gap size, vehicle size, and time as within factor variables. Timing data was analyzed by performing a 3 x 2 x 2 (initial distance [near, intermediate, far]; gap size [3 s, 4 s]; vehicle size [car, bus]) repeated measures ANOVA with initial distance, gap size, and vehicle size as within factor variables. To estimate effect size, the partial eta squared (η^2_p) was used. For all pairwise post-hoc analyses, least square means were used.

Effects of initial distance

Tested first was the hypothesis that manipulation of the initial distance from the curb to interception point will affect the approach velocity of participants. The systematic change in initial distance affected both young adults' and children's velocity adjustments: $F(2, 30) = 29.62$, $p < 0.0001$, $\eta^2_p = .66$; and $F(2, 30) = 207.32$, $p < 0.0001$, $\eta^2_p = .93$, respectively.

For young adults, the initial distance and time interaction was significant: $F(6, 90) = 11.88$, $p < 0.0001$, $\eta^2_p = 0.44$. A simple effects test showed a significant effect of time for: near initial distance, $F(3, 45) = 140.34$, $p < 0.0001$, $\eta^2_p = 0.90$; intermediate initial distance, $F(3, 45) = 29.93$, $p < 0.0001$, $\eta^2_p = 0.67$; and far initial distance, $F(3, 45) = 184.46$, $p < 0.0001$, $\eta^2_p = 0.93$. It was found from the post-hoc analysis that young adults increased in speed throughout the approach ($p < 0.0001$). However, when the initial distance was short, participants slowed down ($p < 0.0001$) at the beginning of trials and sped up continuously. This represents the functional adjustment. The mean velocities during approach are plotted across age groups (**Figure 5**).

For children, initial distance and time interaction was also significant: $F(6, 90) = 53.51$, $p < 0.0001$, $\eta^2_p = 0.78$. This interaction effect was captured by the three-way interaction. The vehicle size, initial distance, and time interaction was significant: $F(6, 90) = 2.12$, $p < 0.05$, $\eta^2_p = 0.12$. The results indicate that children's velocity changes induced by the initial distance were affected by vehicle size.

Effects of vehicle size in children

Tested next was the hypothesis that manipulation of vehicle size will affect the velocity profiles and crossing time of children and young adults. It was found that in children, vehicle size affected the velocity profiles and crossing position induced by the initial distance.

In children, vehicle size, initial distance, and time interaction was significant: $F(6, 90) = 2.12$, $p < 0.05$, $\eta^2_p = 0.12$. Further analysis revealed that, between the cars, the initial distance x time interaction was significant, $F(6, 90) = 33.55$, $p < 0.0001$, $\eta^2_p = 0.69$. A simple effects test showed a significant effect of time for near initial distance, $F(3, 45) = 132.54$, $p < 0.0001$, $\eta^2_p = 0.90$; intermediate initial distance, $F(3, 45) = 173.83$, $p < 0.0001$, $\eta^2_p = 0.92$; and far initial distance, $F(3, 45) = 272.78$, $p < 0.0001$, $\eta^2_p = 0.95$. Post-hoc analysis showed that children sped up throughout the approach ($p < .0001$); however, when they crossed between the cars, they slowed down at the beginning of the approach for the near initial distance ($p < 0.0002$), However, when children crossed between the buses, the initial distance and time interaction was also significant: $F(6, 90) = 18.70$, $p < 0.0001$, $\eta^2_p = 0.55$. A simple effects test showed a significant effect of time for the near initial distance: $F(3, 45) = 124.41$, $p < 0.0001$, $\eta^2_p = 0.89$; intermediate initial distance, $F(3, 45) = 132.79$, $p < 0.0001$, $\eta^2_p = 0.90$; and far initial distance, $F(3, 45) = 331.16$, $p < 0.0001$, $\eta^2_p = 0.96$. Post-hoc analysis showed that when children crossed between the buses, their speeds neither increased nor decreased at the beginning of the approach for the near initial distance. The mean velocities during approach are plotted across age groups in **Figure 6**.

Evidently, vehicle size influenced children's crossing behavior as induced by initial distance. The children's crossing times deviated systematically from the gap center depending on the initial distance at which they crossed between the small vehicles. However, children did not deviate based on the initial distance when they crossed between the large vehicles.

The vehicle size also significantly affected the children's crossing position within the gap induced by initial distance. The vehicle size and initial distance interaction was significant: $F(2, 30) = 18.13$, $p < 0.0001$, $\eta^2_p = 0.55$. A simple effects test showed a significant effect of initial distance between cars, $F(2, 30) = 62.30$, $p < 0.0001$, $\eta^2_p = 0.81$, and between buses, $F(2, 30) = 6.15$, $p < 0.005$, $\eta^2_p = 0.30$. It was found that children's times of intercept increased significantly ($p < 0.0001$) as the initial distance increased from near to far initial distances. However, when crossing between buses, children's times of interception were not significantly different between near and intermediate initial distances. The mean crossing position during approach are plotted across age groups (**Figure 7**).

Interaction effects of vehicle size and gap size in children

Finally, the interaction effects of vehicle size and gap size in children were examined. The vehicle size and gap size interaction was significant: $F(1, 15) = 4.26$, $p < 0.05$, $\eta^2_p = 0.22$. A simple effects test showed a significant effect of gap size between the cars: $F(1, 15) = 7.42$, $p < .02$, $\eta^2_p = 0.33$; and between the buses, $F(1, 15) = 35.93$, $p < 0.001$, $\eta^2_p = 0.71$. Post-hoc analysis showed that when crossing between the cars, children crossed the gap significantly further ahead of the gap center in the 4 s gap than the 3 s gap ($p < 0.01$). When crossing between the buses, children also crossed the gap significantly earlier in the 4 s gap than the 3 s gap ($p < 0.0001$). Children crossed the gap further ahead of the gap center in the 4 s gap than the 3 s gap, regardless of vehicle presence.

FIGURE AND TABLE LEGENDS:

Figure 1: Images depicting the walking simulation experiment. (A) Photograph of a participant walking on the treadmill and an experimenter viewing the walking simulator program. **(B)** Image of the cartoon crosswalk displayed before the configuration is loaded. **(C)** Image of the realistic virtual environment in which the simulation takes place.

Figure 2: Experimental setup diagram. The components of the experimental setup and their connections are illustrated.

Figure 3: Configuration file example. Example of a properly formatted configuration text file for the simulation program.

Figure 4: Diagram of the crossing situation. Distance parameters that can be configured for each experiment are shown.

Figure 5: Velocity dependence on initial distance. Mean velocities for each initial distance in children and young adults (near, intermediate, and far defined as 3.5 m, 4.5 m, and 5.5 m from the interception point) as a function of time before reaching the interception point. The approaching velocity was averaged into 1 s intervals (-3.5 s, -2.5 s, -1.5 s, and -0.5 s), counting backwards from the interception point. Asterisks represent statistically significant inter-mean differences for initial distances at each timepoint. One asterisk represents one inter-mean difference, and two asterisks represent two or more inter-mean differences. Error bars indicate SD. This figure has been reprinted with permission from Chung et al.[15].

Figure 6: Children's velocity dependence on initial distance based on two different vehicle sizes. Children's mean velocity profiles before reaching the interception point for each initial distance are plotted for cars (top) and buses (bottom). The approach velocity was averaged into 1 s intervals, counting backwards from the interception point. Asterisks represent statistically significant inter-mean differences for initial distances at each timepoint. One asterisk represents one inter-mean difference, and two asterisks represent two or more inter-mean differences. Error bars indicate SD. This figure was reprinted with permission from Chung et al.[15].

Figure 7: Effect of vehicle size on children's TOI. The children group's mean TOI for each initial distance is shown as a function of vehicle size (car, bus). TOI refers to the temporal distance relative to the gap center, such that 0.2 s refers to 1.6 m when the vehicle speed is 30 km/h (8.3 m/s). Asterisks represent statistically significant inter-mean differences for vehicles at each initial distances. One asterisk represents one inter-mean difference, and two asterisks represent two or more inter-mean differences. Error bars indicate SD. This figure was reprinted with permission from Chung et al.[15].

Table 1: Interaction effects of vehicle size and gap size in children. The mean (SD) gap entry times are provided for vehicle size and gap size. The gap entry time is defined as the time the participant takes to enter the gap.

DISCUSSION:

Previous studies have used simulators with projected screens[16,17], but this protocol improves ecological validity via a fully immersive virtual view (i.e., 360 degrees). In addition, requiring participants to walk on a treadmill enables the examination of how children and young adults calibrate their actions to a changing environment. This experimental design's virtual scene changes simultaneously with participant motions, and the vehicles arrive at the pedestrian's crossing line at a specific point in time. This prevents participants from delaying their crossing times due to decisions or preparations to move. In this study, participants are already in motion when attempting to cross the road[6], so researchers can clearly access the control of locomotion while crossing.

Critical steps include properly setting the parameters to reflect the experimental design, stopping the experiment when motion sickness occurs, and performing the practice trials so that the participants are comfortable with the treadmill environment. A wide range of traffic flows beyond those discussed in the results is configurable with the current software. The software may also be easily extended to include a wider range of crossing situations (i.e., by adding more lanes or more vehicle types).

The protocol allows the investigation of how children and young adults regulate their locomotion according to dynamically changing environments. Specifically, systematically varying the initial starting location allows the examination of velocity adjustments in children and young adults. The protocol also permits the determination of whether changes in gap characteristics lead to specific velocity control patterns in interceptive actions. The results demonstrate that varying initial distances and gap characteristics is important for identifying systematic crossing behavior adaptations that reflect the perception/action type of control in crossing roads. The results indicate interaction effects of initial distance and vehicle size in children; specifically, their velocity adjustments while approaching the interception were affected by gap characteristics.

In contrast to previous findings on the weak effects of vehicle size on adults' crossing behaviors, this study found that children poorly adjusted their approach velocities according to the initial distance when facing a large vehicle from a close distance. The results suggest that the ability to finely tune motor movements using visual information in complex interception tasks is subject to developmental changes. However, future research should differentiate vehicle types and sizes by using various sizes of the same vehicle type. This setup would allow a more accurate answer for which visual information is used to control crossing actions in a dynamic environment.

Furthermore, manipulating gap size and vehicle size together did not answer to which properties of the dynamic gap environment directly influence movement modulation. The findings suggest that children underestimate a vehicle's arrival time and attempt to cross more quickly in front of large vehicles. Notably, children cross the gaps between buses earlier than expected in the 4 s gap. This may be due to a LV's closer distance in the 4 s gap. One limitation of this design is that the gap size's effects are confounded by the effects of a vehicle's outer edges. Future experimental designs may alter gap size without altering a vehicle's outer edges.

Compared to previous virtual reality research, this experiment's design offers a safe environment to investigate crossing behavior. However, the apparatus causes motion sickness in some participants. The literature on motion sickness reveals a relationship between motion sickness and postural control, so people who have poor balance control should be excluded[18–20]. Additionally, participants hold the handrails during walking, and this may interrupt a natural walking motion, which may be a limitation of the method. In sum, this study contributes to the understanding of children's road crossing behavior in relation to a gap's temporal and spatial characteristics.

ACKNOWLEDGMENTS:

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

Click here to access/download;Figure;fig1.png

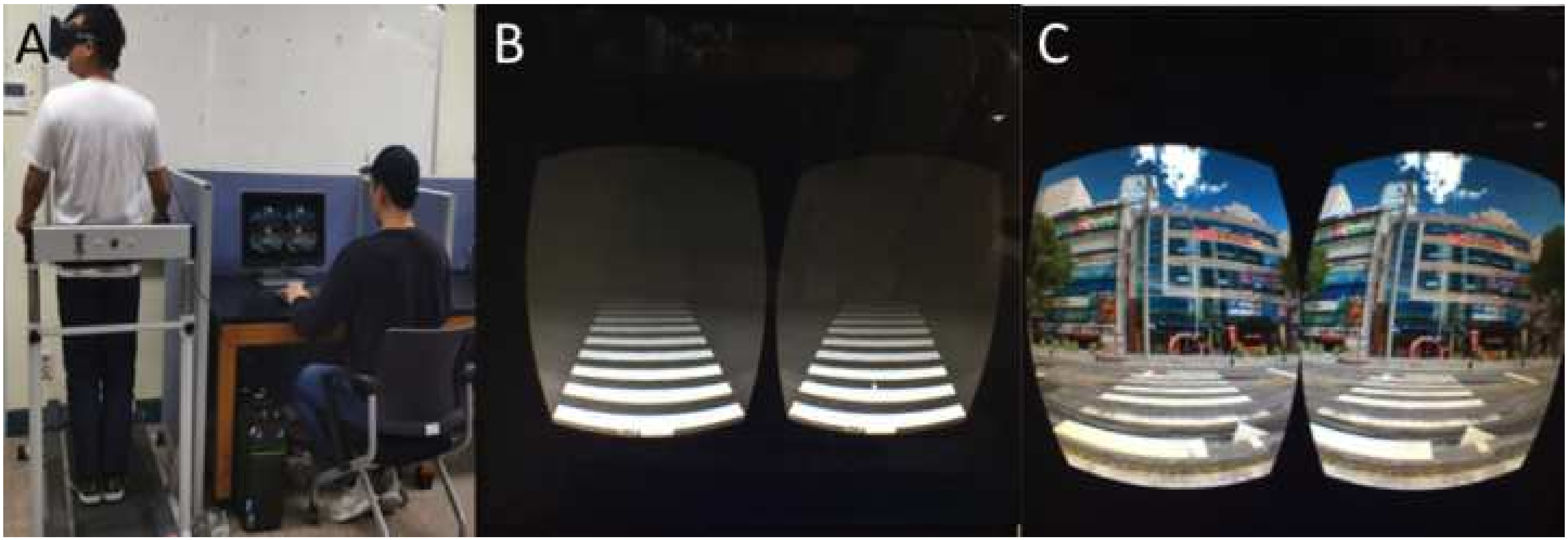

Figure 2

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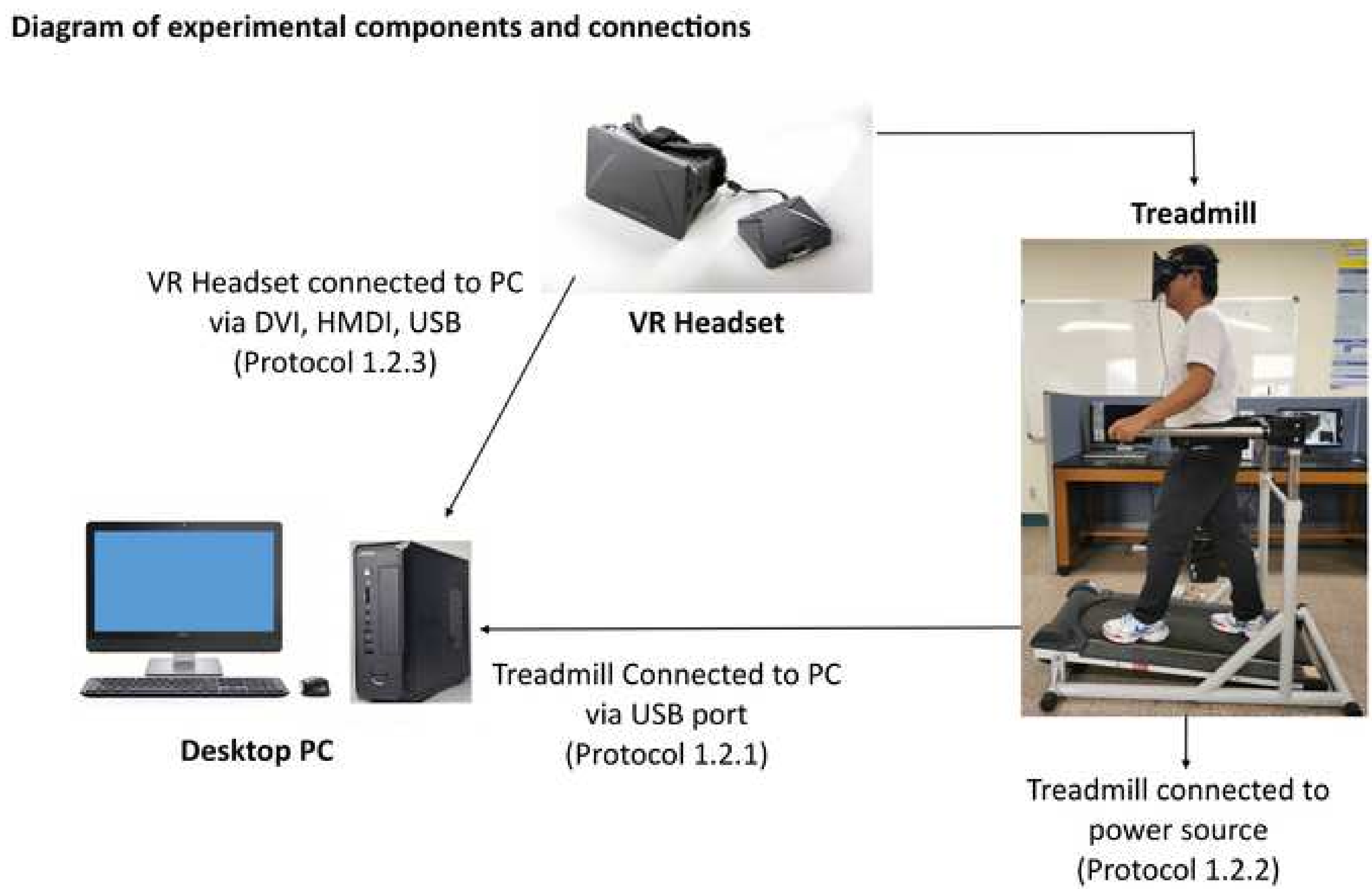

Figure 3 Click here to access/download;Figure;fig3.png

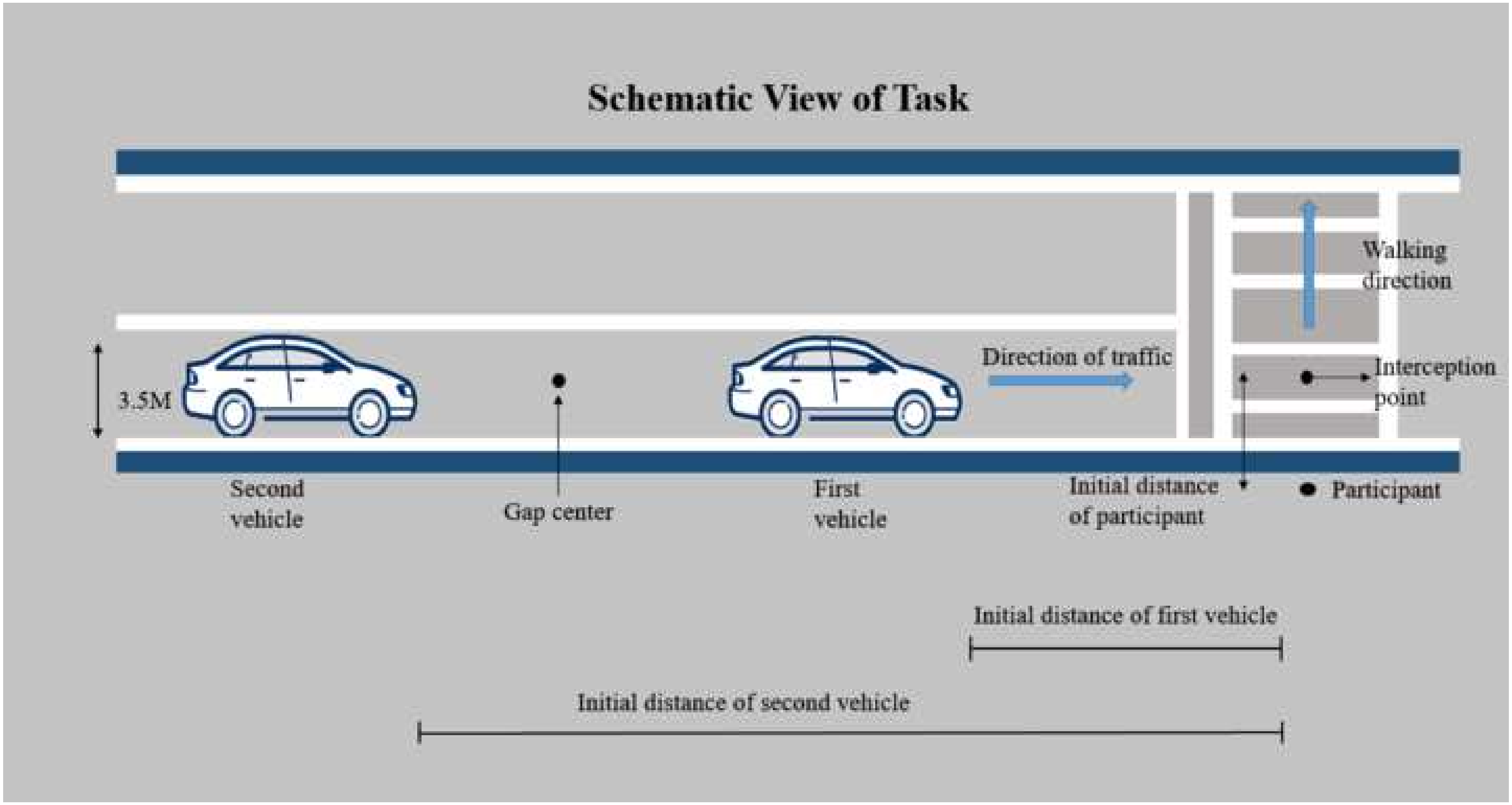

Figure 4

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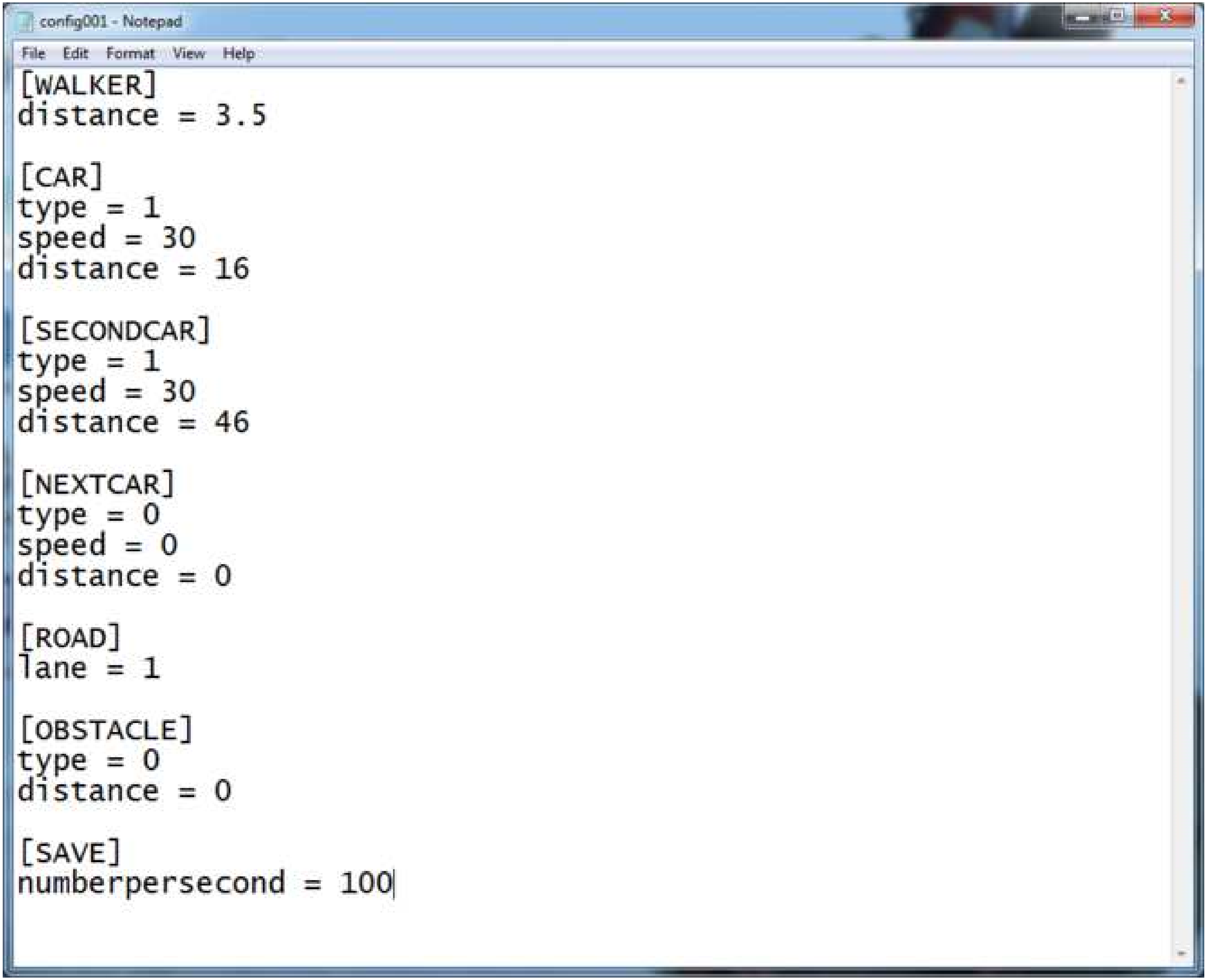

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File Edit Format View Help

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Figure 5

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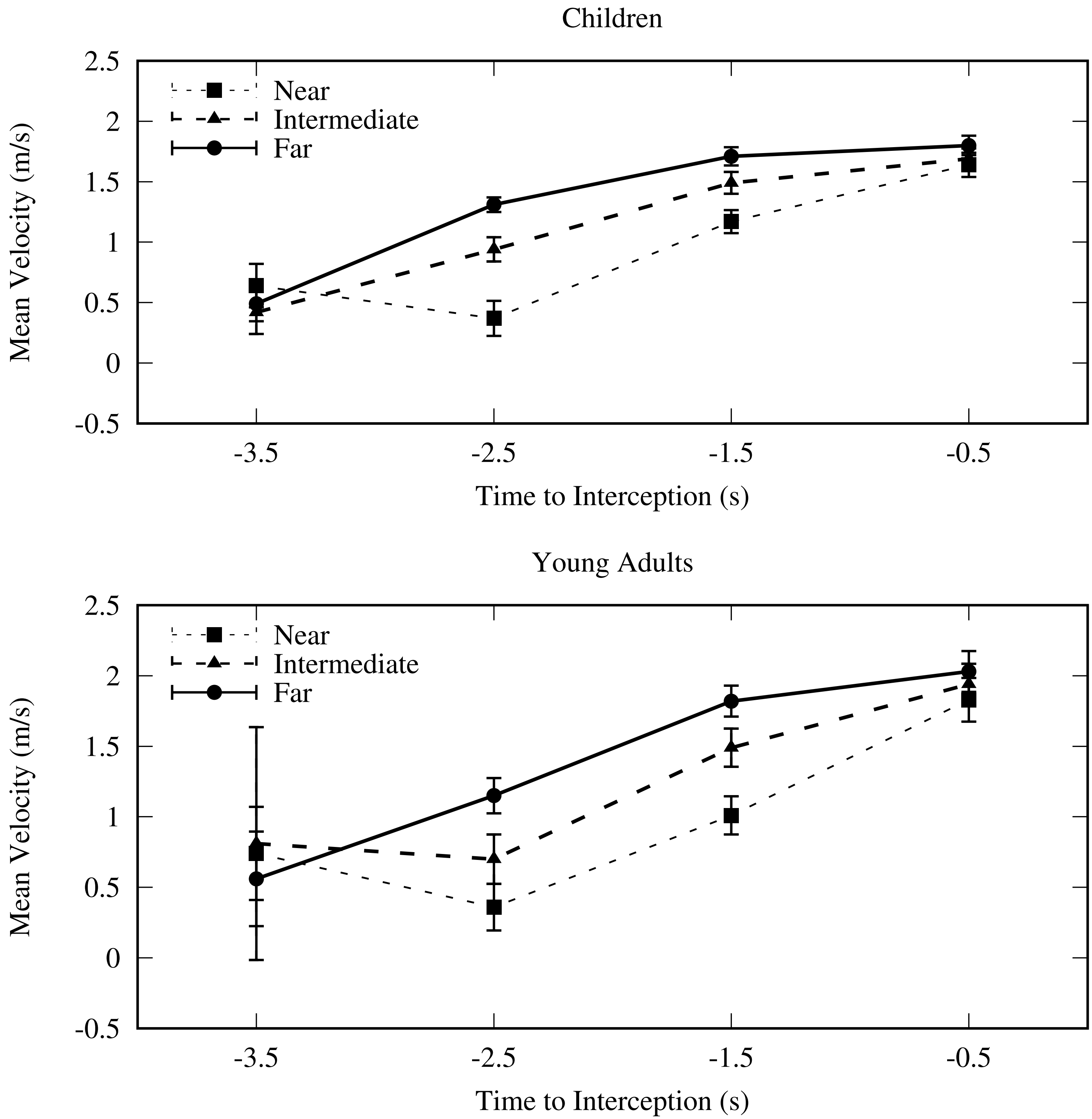

Figure 6

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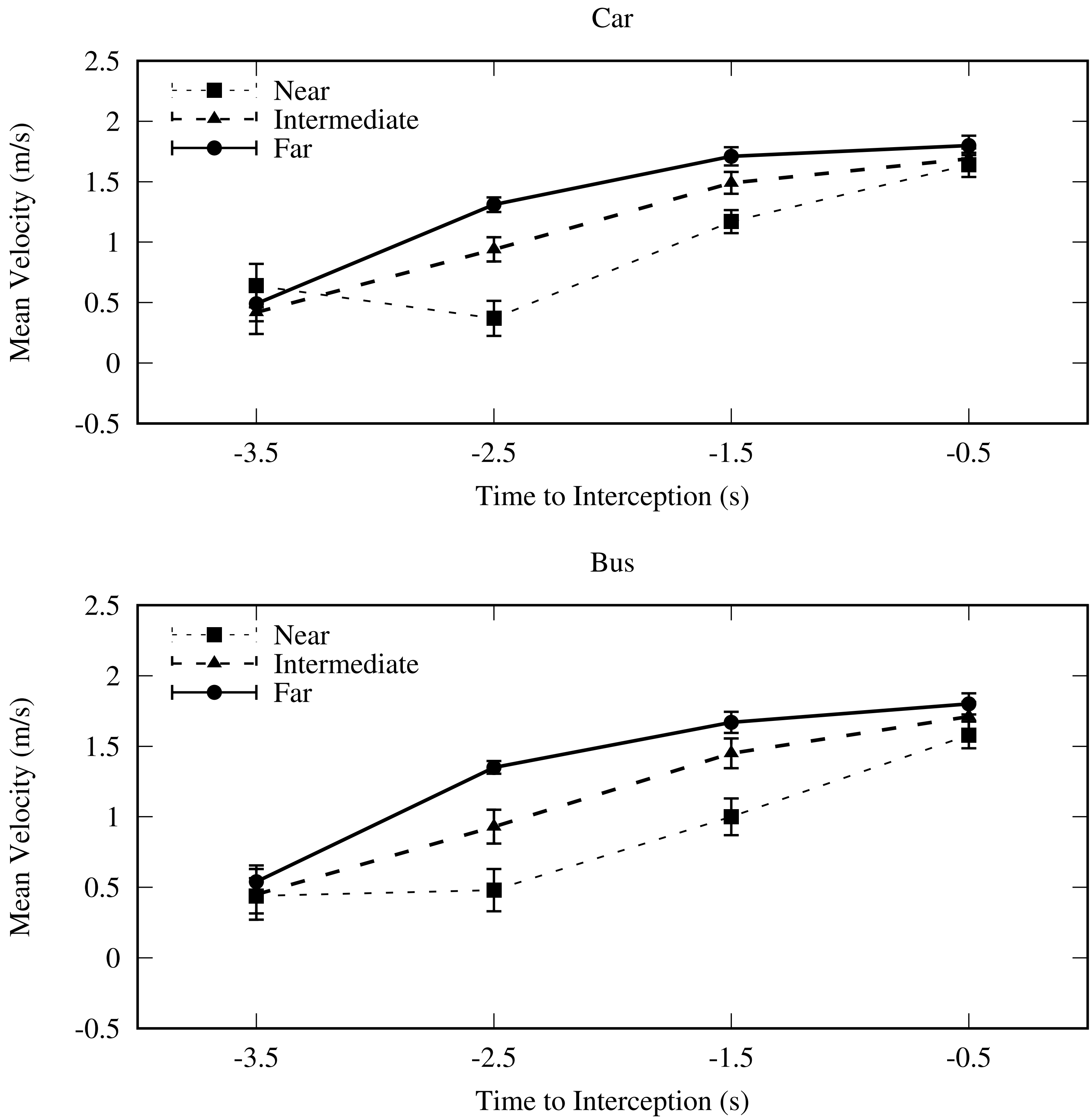

Figure 7

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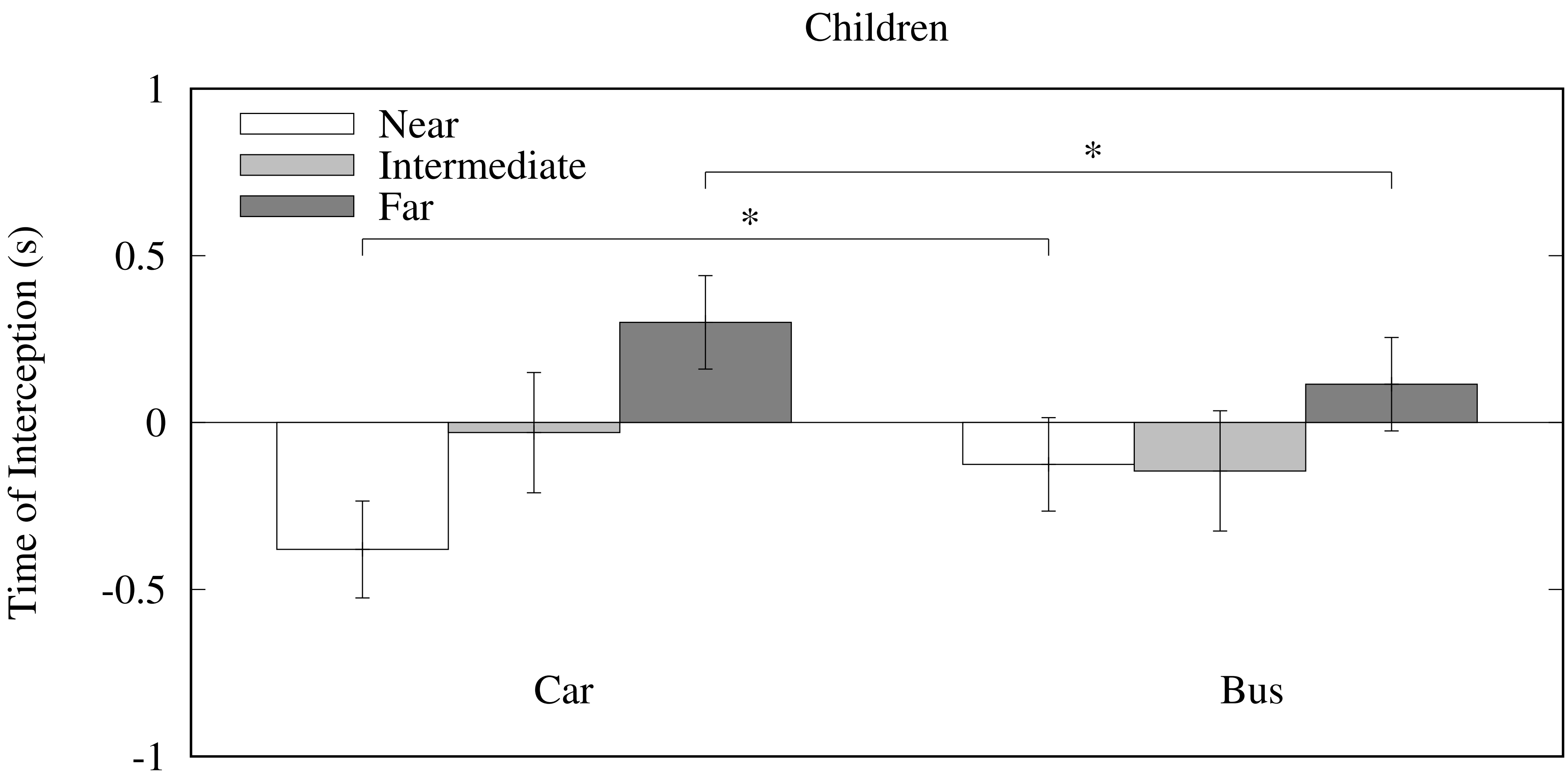

Table 1 Click here to access/download;Table;Table1.xlsx

Gap Entry Time (s)			
		Gap Size	
		3-s	4-s
		Mean (S.D.)	Mean (S.D.)
Vehicle Size	Car	3.75 (0.37)	3.57 (0.44)
	Bus	3.89 (0.25)	3.56 (0.32)

 Click here to access/download;Table of Materials;JoVE_Table_of_Materials.xlsx

Name of Material/Equipment	Company	Catalog Number	Comments/Description
Customized treadmill	Kunsan National University		Treadmill built for this study
Desktop PC	Multiple companies		Standard Desktop PC
Oculus Rift Development Kit	Oculus VR, LLC	DK1	Virtual reality headset
Walking Simulator Software	Kunsan National University		Software deloped for this experiment

Reviewer: 3	
Editorial comments: General: 1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.	According to the suggestion, we have reviewed the manuscript for grammatical and spelling errors.
2. JoVE cannot publish manuscripts containing commercial language. This includes trademark symbols (™), registered symbols (®), and company names before an instrument or reagent. Please limit the use of commercial language from your manuscript (including Figures; e.g. Figure 2) and use generic terms instead. All commercial products should be sufficiently referenced in the Table of Materials and Reagents. For example: Oculus Rift	In accordance with the comment, we have removed the commercial language and have replaced them with generic terms. In addition, we have updated the Table of Materials to include all equipment used in the study.
Protocol: 1. There is a 10 page limit for the Protocol, but there is a 2.75 page limit for filmable content. If revisions cause the highlighted portion to be more than 2.75 pages, please highlight 2.75 pages or less of the Protocol (including headers and spacing) that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol.	We have ensured that the highlighted portions of the Protocol do not exceed 2.75 pages.
2. For each protocol step/substep, please ensure you answer the "how" question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action. If revisions cause a step to have more than 2-3 actions and 4 sentences per step, please split into separate steps or substeps.	We have revised the protocol steps and we have made several revisions for clarity. (Please see red text in Pages 3 to 6.)

Specific Protocol steps: 1. Please provide a heading for section 1.	In accordance with the comment, we have added the following heading for section 1. Page 2 L94: 1. Preparation of Equipment
Figures: 1. Figure 5-8, Table 1: What statistical tests were used for the asterisks?	We analyzed position and velocity data using initial distance (near, intermediate, far) x gap size (3 s, 4 s) × vehicle size (car, bus) × time (3.5 s, 2.5 s, 1.5 s, 0.5 s) repeated measures ANOVA, with initial distance, gap size, vehicle size, and time as within-factor variables. The timing data were analyzed using initial distance (near, intermediate, far) × gap size (3 s, 4 s) × vehicle size (car, bus) repeated measures ANOVA, with initial distance, gap size, and vehicle size as within-factor variables. The partial eta squared (η_p^2) was used to estimate effect size. A least square mean was used for all pairwise post-hoc comparisons, and means were adjusted using a Bonferroni correction to decrease type I errors. We added the following text to the each figure caption to provide more information. Figure 3. In the figure, asterisks represent statistically significant inter-mean differences for initial distances at each time point. One asterisk represents one inter-mean difference, and two asterisks represent two or more inter-mean differences. Page 8 L321-328: We analyzed velocity data using initial distance (near, intermediate, far) x gap size (3 s, 4 s) × vehicle size (car, bus) × time (3.5 s, 2.5 s, 1.5 s, 0.5 s) repeated measures ANOVA, with initial distance, gap size, vehicle size, and time as within-factor variables. The timing data were

	analyzed using initial distance (near, intermediate, far) × gap size (3 s, 4 s) × vehicle size (car, bus) repeated measures ANOVA, with initial distance, gap size, and vehicle size as within-factor variables. The partial eta squared ($\eta^2{}_p$) was used to estimate effect size. A least square mean was used for all pairwise post-hoc comparisons.
2. Figure 5: Are both x-axes actually 'Time to Interception'? Please clarify.	Yes, it is time to interception. We apologize for the inconsistency. Figures 5 and 6 have been modified to include the correct x-axis labels.
Discussion: 1. Please revise the Discussion to explicitly cover the following in detail in 3–6 paragraphs with citations: a) Critical steps within the protocol b) Any modifications and troubleshooting of the technique c) The significance with respect to existing methods	As requested, the Discussion has been revised to explicitly cover the points mentioned. Page 11:L455-470 Previous studies used simulators with projected screens[16, 17], but our protocol improves ecological validity via a fully immersive virtual view (i.e. 360 degrees). In addition, having participants walk on a treadmill enabled us to examine how children and young adults calibrate their actions to a changing environment. This experimental design's virtual scene changes simultaneously with participants' motions, and the vehicles arrive at the pedestrian's crossing line at a specific time. This prevented participants from delaying their crossing times due to decisions or preparations to move—in this study, participants were already in motion when attempting to cross the road[6]. so that researcher can clearly access the control of locomotion while crossing. Critical steps in the protocol include properly setting the parameters to reflect the experimental design, stopping the experiment when motion sickness occurs, and performing the practice trials so that the participants are fully comfortable with the treadmill environment. A wide range of traffic flows beyond those discussed in the results is configurable with

	the current software. The software may also be easily extended to include a wider range of crossing situations, for example by adding more lanes or more vehicle types.
References: 1. Please do not abbreviate journal titles.	We have checked the References for journal title abbreviations.
Table of Materials: 1. Please ensure the Table of Materials has information on all materials and equipment used, especially those mentioned in the Protocol (e.g., the Walking Simulator software).	As requested, we have updated the Table of Materials to include all materials and equipment used, including the software.
Reviewers' comments: Reviewer #1: Thanks for the opportunity to review this manuscript. It's great to see continued improvement in VR technology being used to study pedestrian behavior and decisions, and these methods clearly extend the field in an incremental manner. I have several comments for the authors to consider.	Thank you for your valuable comments to improve our manuscript and your encouraging comments about the method. We have considered your comments and have revised the manuscript as follows.
1. I found some aspects of the protocol difficult to follow. Providing more details in the introduction concerning the goals of the research and the reason certain methodological features were adapted might help the reader understand specifics. Particular issues are listed below.	We have revised the introduction as shown below to provide a better understanding of the research goals. Page 2, Lines 77-86: In addition, the spatial and temporal characteristics of intercepted objects specify how actor can move. In the gap crossing environment, changing gap size (inter-vehicle distances) and vehicle size should

	affect how pedestrian affect their locomotion. […] Thus, this study investigated how children and young adults regulate their velocity when crossing roads in various crossing environments. The speed regulation profile may be assessed for various gap-crossing environments with differing starting locations, inter-vehicle distances, and vehicle sizes.
2. Why were only sedans and buses presented? I would think it would be easy to simulate other vehicles. Was there a particular reason for these two vehicles? Were they always of the same shape and color?	We presented sedans and buses to test how children and young adults respond differently to different vehicle sizes. Since we want to access how people control their actions for the different sized vehicles, we remained the shape and color of the vehicles throughout the experiment while deviating the size of the vehicles. However, our method can be applied to include other types of vehicles, such as motorcycles. This is left for a future study.
3. On line 138, the authors refer to "continuous traffic flow". Is there an option for non-continuous or irregular traffic? That seems important for various research questions.	There is currently no option for irregular traffic flow for more than 3 vehicles. However, the software can be further developed to include such scenarios. We thank the reviewer for the interesting suggestion.
4. Line 141-142. I see there were two lanes of traffic. Were they moving in the same direction or in opposite directions? Details on the lanes and directions seem important for readers to understand the protocol.	The lanes are moving in the same direction. The protocol has been updated to be more clear on this matter. Page 4, Lines 164-169: NOTE: When using the closer lane as the primary lane, this option can be used to place additional vehicles on the farther lane going in the same direction. Hence it can be used to study the

	impedance of the view of a vehicle by a parallel vehicle. This section has parameters "type" and "distance" with the same definitions as above. This option was not used in the Representative Results.
5. Participants were asked to hold the handrails at all times. This seems somewhat concerning to me, as it is an unnatural walking behavior and could alter behavior, speeds, judgments, and balance. Any thoughts? Perhaps this should be listed as a study limitation?	This is an excellent point and it may influence walking behavior. Following the suggestion, we have mentioned this point in the discussion section as a study limitation. Page 12 Lines 502-503: Additionally, the participants hold the handrails during walking, and this may interrupt the natural walking motion. This could be a limitation of the current methodology.
6. The practice trials seem logical to me, but I was confused by the "sets" of trials. We learn that two successful trials were required. Were there always only two trials? Or was a third trial run if the participant was unsuccessful (in other words, perhaps they were struck by a vehicle)?	Yes we have provided one more opportunity to cross if there was a misunderstanding of the protocol, for example, if participants crossed the road without seeing vehilcles, or does not strat on time or mechanical errors occurs. However, we did not provide extra trial when collisions with vehicles occurred. We did not provide more than third trails even if they were unsuccessful. The Protocol was revised to clarify this point. Page 6 L225-229 NOTE: 4.5-4.7 describe three sets of practice trials, which are designed to gradually allow the participant to become accustomed to the simulator environment. In each "set" the practice routine is repeated for a total of two trials. However, when the participant fails the trial due to a misunderstanding of the instructions, an extra trial is done for a total of three. Extra trials are not done in cases of failure to cross for reasons other than misunderstanding the rules, e.g. if a collision occurs.

7. I am a little confused about how the treadmill functioned. Normally treadmills move constantly. I assume that was not the case here - the treadmill began moving only when the pedestrian began walking? And how was speed manipulated by the pedestrian? Details on the engineering of the treadmill might be valuable, so we understand how pedestrians changed their walking speed, and how the treadmill responded to those changes.	We used a customized treadmill that moves forward by the frictional force exerted by the participants when walking. The treadmill does not move with an internal motor. The internal friction of the treadmill was kept minimal. The manuscript has been revised to include a more detailed description of the treadmill's mechanics. Page 3 L101-102: NOTE: The equipment includes a customized manual treadmill. The treadmill turns via the walking motions of the participants, and does not use an internal motor.
8. The representative results are great, but in the paragraph on lines 292-296, I was led to assume we would see results based on participant age - that is, we would see comparisons between different age groups. From what I can tell, however, the results are largely presented within age groups. Could we see comparisons across age groups, which of course is of greatest interest to developmental change, as the authors allude to in the paragraph on lines 292-296?	In the current manuscript, we present the velocity dependence on initial distance (Figure 5) of young adults and children groups. Because young adults clearly walk faster than children, we did not find it to be significant to compare their velocity profiles. The effects of vehicle size were more significant for the children group, so only the children group was shown (Figures 6, 7).
9. A major issue: unless I missed it somehow, we do not know the age groups studied. How old are the children in the representative results? This seems like absolutely critical information for scientific interpretation of the study.	The age of the groups studied is indeed critical information, and was left out by mistake. Details about the age of the participants were added in the results section.
10. I became very confused in understanding and interpreting the study results. The figures were hard to understand and the rationale for	In accordance with the comment, we have revised the Representative Results section for overall clarity. The hypotheses tested are stated more clearly. In addition, we shorted the

the comparisons unclear to me. Much more information might be provided to clarify the results and their interpretation.	exposition to be more clear and concise. We hope these modifications make the results sufficiently clear. (Please see Page 8 L312 – Page 10 L403).
11. On lines 309-311, it appears that participants who faced a wider (safer) gap actually crossed more quickly. This seems contrary to what I would expect. Am I interpreting it correctly?	Yes, this is correct. In our experimental setup, the LV in the 4-s gap begins closer to the interception point than the LV in the 3-s gap. Thus, this result reflects safe crossing behavior. However, we have removed these results from the manuscript to focus on reporting the vehicle size effects.
12. I like the focus on the car vs bus, and how pedestrians react to vehicles of different sizes. The authors might look up a very recent publication in Journal of Injury and Violence Research by Yu and colleagues that investigated this topic in China (via self-report, not in a virtual reality simulation).	Following the comment we have revised the Results section to focus on the effect of vehicle size and overall improve the clarity of the results. We thank the reviewer for the interesting reference.
13. There is mention of an article by Chung et al in the figure captions, but that reference does not appear in the references list.	We thank the reviewer for spotting the error. The article has been added to the References. Page 13 L558-560: [15] Chung, H. C., Choi, G., Azam, M. Effects of Initial Starting Distance and Gap Characteristics on Children’s and Young Adults’ Velocity Regulation When Intercepting Moving Gaps. *Human factors* (2019).

14. The issue of motion sickness arises in the final paragraph of the manuscript. This seems a very important topic for a methods paper and has implication for research ethics. I recommend adding considerably more information about the frequency and severity of these symptoms among study participants.	In accordance with this comment, we have added the following in the Results section. Page 8 L317-319: Of the recruited participants, two young adults experienced motion sickness during the experiment; the experiments were immediately stopped and they were excluded from the study.
15. Figure 2 makes it appear as if the treadmill is on an upward incline. Is this correct? If so, why? Or is the photograph misleading?	The treadmill is on a slight upward incline of about 10 degrees. This was done to make it easier for the participants to apply frictional force on the treadmill.
16. How does this methodology offer methodological advantages or improvements over VR pedestrian simulations that allow participants to walk in an empty room, such as those by Plumert/Kearney and colleagues at University of Iowa, and that by Morrongiello and colleagues at University of Guelph?	This methodology has the advantage of not being limited by the spatial constraints of the room. When using an empty room, the participant is limited by the boundaries. However, the treadmill method is limited in that it only allows walking in one direction. Therefore, we see free walking experiments as important as well, and such experiments are also done in our lab. However, that is beyond the scope of the current manuscript.
Reviewer #2: The manuscript is good, and I recommend it be published in JoVE.	
Reviewer #3: Manuscript Summary: The last sentence "This methodology can help ...interceptive action." is not clear and needs to be rephrased. It is important to clearly state the value of the work and potential beneficiaries.	In accordance with the comment, we have revised the last sentence of the Abstract to more clearly reflect the goals of the study. Page 2 L47-48: This methodology can be used by researchers

	of pedestrian behavior and behavioral dynamics to study with human participants in a safe and realistic setting.
Minor Concerns: The protocol itself is described clearly and with adequate detail. The most critical steps are highlighted and the results from the preliminary analysis show promise. On step 2.7 the use of the word "alternative lane" is ambiguous. The authors should clarify if they mean "opposing traffic lane" or something else.	In order to be more clear about that option in the protocol, we have added a Note as follows: Page 4 L164-169: NOTE: When using the closer lane as the primary lane, this option can be used to place additional vehicles on the farther lane going in the same direction. Hence it can be used to study the impedance of the view of a vehicle by a parallel vehicle. This section has parameters “type” and “distance” with the same definitions as above. This option was not used in the Representative Results.
Also the term "gap" should be clearly defined.	In accordance with the comment, definitions of the terms “gap” and “gap size” have been added to the Protocol section. Page 4 L146-149: NOTE: In two-vehicle studies, the gap is defined as the empty space between the two vehicles. The gap size, defined as the length of time during which the gap is along the participant’s walking path, is a function of the “distance”, “speed”, and “type” parameters of [CAR] and [SECONDCAR].

With respect to data analysis and in order to further strengthen the value of the work the reviewer recommends that all assumptions be stated clearly.	The Result section has overall been revised for better clarity. (Please see Pages 7-9)
Also, the authors should discuss when, where, how they recruited participants; how many subjects were involved in the experiments, if a process to eliminate participants was followed, what were the age ranges associated with "children" and with "young adults".v	The Representative Results Section has been revised to include these important details. Page 8, L313-322: These representative results use data from sixteen young adults (mean age = 22.75 yr., *SD* = 2.56) and sixteen children (mean age = 12.18 yr., *SD* = .83). Children undergo developmental changes in their ability to coordinate movements with moving objects[9–14], so varying the initial distance provided an opportunity to compare children's and young adults' functional adjustment of approaching velocity. The participants were recruited in a university social media posting. Of the recruited participants, two young adults experienced motion sickness during the experiment; the experiments were immediately stopped and they were excluded from the study. Across all participants, the success rate was 98.95% for children and 99.48% for young adults. We analyzed only the data from successful trials. Thank you for the helpful feedback to improve the quality of the paper.

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