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Wheelchair Proxemics: interpersonal behaviour between pedestrians and power wheelchair drivers in real and virtual environments

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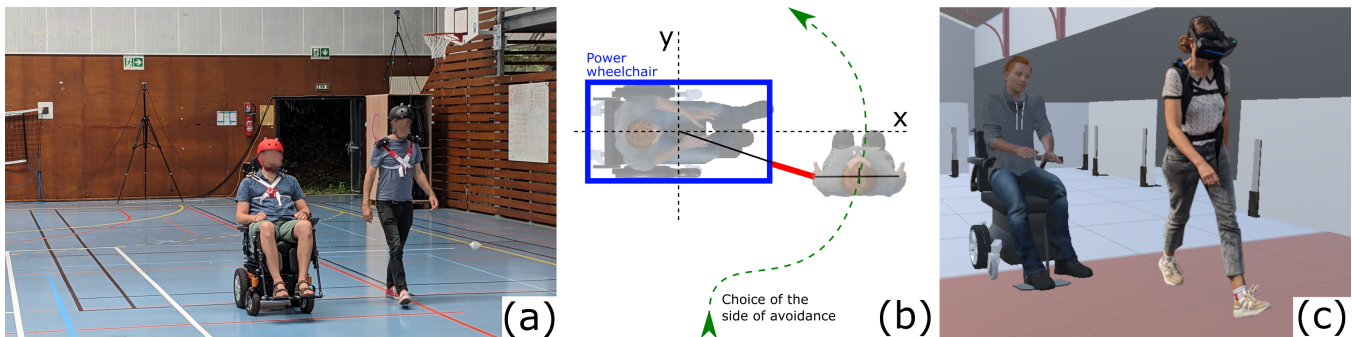


Figure 1: In this paper, we are interested in evaluating collision avoidance strategies (b) including speed, side of avoidance, and shape-to-shape distance between a pedestrian and a power wheelchair user to improve the design of power wheelchair navigation simulators. We designed 2 experiments where one of the 2 persons involved in the interaction was static and the other was moving to a given goal while avoiding the collision. We also aim to compare avoidance behavior in real (a) and virtual (c) conditions.

Abstract

Immersive environments provide opportunities to learn and transfer skills to real life. This opens up new areas of application, such as rehabilitation, where people with neurological disabilities can learn to drive a power wheelchair (PWC) through the development of immersive simulators. To expose these specific users to daily-life study interaction situations, it is important to ensure realistic interactions with the virtual humans that populate the simulated environment, as PWC users should learn to drive and navigate under everyday conditions. While non-verbal pedestrian-pedestrian interactions have been extensively studied, understanding pedestrian-PWC user interactions during locomotion is still an open research area. Our study aimed to investigate the regulation of interpersonal distance (i.e., proxemics) between a pedestrian and a PWC user in real and virtual

situations. We designed 2 experiments in which 1) participants had to reach a goal by walking (respectively driving a PWC) and avoid a static PWC confederate (respectively a standing confederate) and 2) participants had to walk to a goal and avoid a static confederate seated on a PWC in real and virtual conditions. Our results showed that interpersonal distances were significantly different whether the pedestrian avoided the PWC user or vice versa. We also showed an influence of the orientation of the person to be avoided. We discuss these findings with respect to pedestrian-pedestrian interactions, as well as their implications for the design of virtual humans interacting with PWC users for rehabilitation applications. In particular, we proposed a proof of concept by adapting existing microscopic crowd simulation algorithms to consider the specificity of pedestrian-PWC user interactions.

CCS Concepts

• **Applied computing** → **Life and medical sciences**; *Law, social and behavioral sciences*; • **Social and professional topics** → **People with disabilities**.

Keywords

Proxemics, VR, wheelchair users, social interactions, rehabilitation applications

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1 Introduction

When navigating everyday environments, such as the street, people often need to adapt their locomotion to the presence of obstacles and other people. While this is a simple task for any healthy young adult, it becomes a challenge with strong social implications for people with disabilities. For example, the lack of independence in mobility has been identified as a significant obstacle to social participation in activities such as employment for individuals with traumatic brain injury (TBI) [30]. In this context, our study focuses on the case of people with motor disabilities who are willing to use a power wheelchair (PWC). Previous studies conducted in real-world conditions have highlighted the benefits of using a PWC as it improves mobility and social participation while reducing the burden on caregivers [27]. However, one of the main barriers to autonomy remains access to mobility. Driving a PWC is a potential source of accidents and not everyone can benefit from such a device, especially people with visual or cognitive impairments. The risk of collision is one of the main problems reported, linked in particular to environmental factors (obstacles, road quality) and human factors (difficulties related to the disability or the behaviour of others) [22, 26], with major consequences for health and social participation [32, 51]. It is therefore essential to provide training for people with motor disabilities to enable them to drive a PWC. This will help to maintain their independent mobility and thus their autonomy. The main objective of our paper is to leverage immersive simulations of public areas to provide a new training tool for PWC users.

Virtual reality has already shown its potential to contribute to learning wheelchair driving on a simulator [6]. In particular, it offers a secure environment during the learning stage while improving driving performance. As highlighted by the survey of Arlati et al. [6], PWC maneuvering skills were improved at the end of the training, both in the simulator and in real-world tasks. The longer the participants trained, the more effective they were in their performance. However, to the best of our knowledge, none of the current studies have designed simulators using populated virtual environments. In addition, if we are to design virtual humans that respond appropriately to PWC users in these populated virtual environments, it is important to evaluate whether the interactions between pedestrians and PWC users are specific compared to the well-known pedestrian-pedestrian interactions. It is therefore essential that a simulator addresses these two fundamental aspects if the goal of the rehabilitation is to improve social navigation skills and social participation.

Our objective is then to contribute to the enhancement of current PWC immersive simulators by 1) expanding our knowledge of the interaction between pedestrians and PWC users, and 2) assessing the potential of VR to study and reproduce such interaction behaviors for future training applications.

The contributions of our paper are:

- The design of 2 user studies where 1) a pedestrian (resp. a PWC user) avoids a static PWC user (resp. a static pedestrian) and 2) where a pedestrian avoids a static PWC user in both real and VR environments.
- The characterization of collision avoidance behaviors between a pedestrian and a PWC user in comparison to pedestrian-pedestrian interactions.
- The evaluation of VR to reproduce pedestrian-PWC user interactions.
- The proposal of guidelines to improve the design of PWC simulators in the context of navigation in a populated environment by incorporating the specific rules of proximity when a pedestrian and a PWC user interact.
- A proof of concept to adapt an existing crowd simulation algorithm with these proxemics rules.

2 Related Work

2.1 Wheelchair driving simulators and rehabilitation

Previous work has focused on the design and assessment of wheelchair driving training simulators to help users in adapting their driving strategies to diverse environments [4, 17, 20, 24, 49]. They used different sensory modalities as detailed in the survey of Arlati et al. [6], namely visual feedback (screen or 3D) alone or coupled with auditory, vestibular and/or haptic feedback. VR has clearly shown its potential as a rehabilitation tool with a positive impact on motivation while allowing the development of new skills [46], especially regarding daily living tasks [16], including wheelchair driving. It also eliminates the risk of an accident to the driver or to their architectural and human environment that can occur when learning to drive in a real environment, specifically for drivers with cognitive impairments. The more realistic the environment, the greater the involvement of the patient, the greater the transfer of skills to real life [3, 42]. A high level of presence leads to the environment being perceived as a more engaging reality [31] than the surrounding real world because of the gamification, thus ensuring better learning outcomes. One of the main challenges then is to reproduce realistic virtual environments, especially in terms of social interactions.

We can also refer to other studies that have looked at the use of augmented reality (AR) devices to assist wheelchair users. Existing experimental systems often consider architectural aspects [1] and elements of the environment in order to provide visual cues on an obstacle avoidance path [13]. Interestingly, Chacon et al. [14] provides a driving assistance tool in AR, including aids for approaching a person. The principle is to add static or dynamic signifiers to the augmented reality environment to avoid pedestrians crossed by the wheelchair user. However, these tools are not perfect because they increase the cognitive load and do not take into account locomotor behaviour or the different strategies adopted when interacting with others, especially the potential specificities of proximity rules inherent in the asymmetry of the situation.

Those previous studies have therefore mainly focused on training users to avoid collisions with their environment without considering human interactions. In real life, however, people navigate in populated environments that can create challenging situations. These scenarios are currently not replicated in these simulators. The addition

of social navigation cues and the adaptation of virtual pedestrians' locomotion laws to account for the specificity of avoiding a PWC user are therefore essential to improve the realism of simulators and ensure skill transfer.

2.2 Pedestrian-PWC user interactions during locomotion

Enhancing the PWC driving experience relies on the modelling of social interactions encountered in a populated environment. However, while there are a lot of previous studies about pedestrian-pedestrian interactions and on pedestrian-robot locomotion, we can draw on a very few studies about pedestrian-PWC users, especially interested in designing smart wheelchairs. Zhang et al. [61] sought to gain a better understanding of the interactions between pedestrians and a wheelchair user, from the wheelchair user's perspective. To this end, they conducted semi-structured interviews [61]. Their findings highlighted that there are two distinct interaction loops in a crowd situation for wheelchair user: one between the user and their wheelchair and one between the user and the crowd. Their results showed that wheelchair users frequently encountered a lack of awareness and understanding from the pedestrians, which leads to feelings of being ignored and, can in turn, results in collisions. In a similar vein, Ali et al. [2] proposed to take into account the level of awareness of the pedestrian in order to determine whether the smart wheelchair should manage the collision avoidance maneuver.

We can then venture to draw a parallel with pedestrian-robot interactions, considering the analogy of the mode of movement between the wheelchair and the robot. Indeed, in such an interaction, some rules of priority emerge, where pedestrians prefer to let a passive robot (i.e. moving in a straight line at constant speed) pass first, even if they should go first [56]. Interestingly, the pedestrian's behavior is modified and is similar to that observed in pedestrian/pedestrian crossing situations when the robot behaves in a manner similar to the pedestrian [57]. However, it is important to note that Zhang et al. [60] showed that in a crowded situation where 28 pedestrians interacted with either a humanoid mobile robot or a smart wheelchair with a driver, pedestrians reported being more conservative and following social rules with the PWC user compared to the robot. Later, Neggers et al. [38] defined the differences in peripersonal space between pedestrians and humanoid or non-humanoid robots as a function of participants' feelings of discomfort. They determined an asymmetric ellipse between the front and back of the robot. Zouman et al. [62] developed a social locomotion model based on laboratory and real-world robot interactions to predict human path selection and walking trajectories in complex dynamic social scenes. However, it is not possible to extrapolate the conclusions of this model to a user driving a power wheelchair, which is indeed not a robot.

While these aspects of social navigation are essential for safe travel, there is still a lack of knowledge about pedestrian-PWC user interactions during locomotion. This makes it difficult to propose new simulators that consider these specific social interactions between a pedestrian and a PWC user that is neither a pedestrian nor a robot. To gain a more comprehensive understanding of the interactions between individuals during locomotion, the next section presents an overview of the works and approaches that have been

conducted when pedestrians interact with each other.

2.3 Pedestrian-pedestrian interactions during locomotion

Locomotion is mainly driven by vision [28, 43, 44, 58] and locomotor adaptations in pedestrian-pedestrian interactions are closely related to the risk of collision [19, 41]. This risk is limited to the physical contact between the pedestrians, but also encompasses social norms, namely proxemics, which imply the maintenance of an interpersonal distance during social interactions. During locomotion, the protective zone maintained around a pedestrian, i.e. the personal space, was shown to be elliptical and this fundamental variable is used by pedestrians to control their trajectory and avoid a collision [19]. Collision avoidance was shown to be solved by anticipation [19, 41], where pedestrians can adjust their speed or orientation [23, 40].

Several factors can affect pedestrian-pedestrian interactions and can be categorised as either situational or person-specific [29]. Regarding situational factors, previous studies have shown an effect of crossing order [29, 40], crossing angle [23], the presence of a spatial constraint [15], the orientation [5, 10], or the gaze behavior [35] of the person to avoid, as well as the number of people to avoid [11, 33]. Regarding person-specific factors, authors have shown that pedestrian-pedestrian interactions can be affected by age [45, 47], body size [10], emotion [9], sports experience [50], and impairments such as sports-related concussion [48]. We then assume that interactions between a pedestrian and a PWC, which can be characterized by an asymmetry between the users, should be influenced by individual and situational characteristics.

Moreover, these previous studies, have identified two main experimental approaches have been proposed for studying pedestrian-pedestrian interactions during locomotion and evaluating the influencing factors, as the studies rely on either real or virtual conditions. It is worth noting that significant efforts have been made to assess the validity of VR for studying human behavior. For example, authors of [34, 39] have evaluated the impact of locomotion technique on avoidance behavior. They found that visual information has a crucial role in this task, since even when moving with a joystick, participants avoid a virtual human in a very similar way as in real conditions [39]. While the authors demonstrated some quantitative differences with lower walking speed (when the participant is physically able to walk in VR) and increased clearance distance in VR [5, 8, 12, 18], they also showed a high relative validity of VR with a similar effect of influencing factors in real and virtual conditions. For example, it was shown that participants maintained a greater clearance distance when avoiding anthropometric than non-anthropometric obstacles [5, 36]. The orientation of the anthropometric obstacle also has a comparable effect in both environments, where participants maintained a larger clearance distance when passing in front of the obstacle rather than at their side [5].

3 Objectives

This literature review has shown that current PWC driving simulators, while relevant for patient training, do not integrate virtual humans into their environment, thus removing the social dimension

from the navigation task. Yet studies of pedestrian-pedestrian interactions have highlighted the importance of individual factors as well as the physical and behavioral characteristics of the obstacles we interact with on the locomotion strategies. In addition, virtual environments can also influence the interaction behavior compared to real conditions, mainly by introducing some quantitative changes while preserving the qualitative behavior in the interaction. We can then assume that the asymmetric nature of the PWC user/pedestrian interaction with respect to pedestrian-pedestrian interaction may induce specific behaviour during a collision avoidance task. Furthermore, it can then hypothesized that the use of VR might affect quantitatively the interaction metrics. In this study, we propose to examine the interaction between a static (resp. moving) PWC user and a moving (resp. static) pedestrian. Therefore, the objectives of this paper are twofold: 1) to characterize collision avoidance behaviour in terms of interpersonal distance regulation depending on situational (the orientation of the person to be avoided) and individual factors (the nature of the individual to be avoided i.e., pedestrian or PWC user) and the mode of locomotion (walking or using a PWC). 2) to compare the avoidance behaviour of pedestrian-PWC users in real and virtual conditions.

To meet these two objectives, we proposed two user studies. In the first study, participants were asked to walk or to drive to a goal while avoiding a static pedestrian or a static PWC user in real conditions. In the second study, participants were asked to walk to a goal while avoiding a static PWC user both in real and VR conditions. These two studies shared common methodology, including the participants, which we will describe in the next section before detailing each study individually.

4 Overall methodology

In this section, we are describing the methodology shared by the two users studies.

4.1 Participants

23 participants (8 males, 14 females, 1 non-binary, 35.6yo [21-62], 20 right-handed, shoulder width=46.7cm \pm 4.96) volunteered to our experiment. All participants had normal or corrected-to-normal vision and did not report any known disorders that could affect their locomotion. They were either students or professionals in computer science or health professional working in a rehabilitation center. Their experience with people with disabilities was 3.7/5 \pm 1.68 (5-point Likert scale from 0 = no experience to 5 = every day) and their experience with virtual reality was 1.6/5 \pm 1.31 (5-point Likert scale from 0 = no experience to 5 = every day).

4.2 Ethical aspects

Participants did not receive any compensation. Our study complied with the Declaration of Helsinki and was approved by our local ethical committee.

4.3 Procedure and Apparatus

The two studies consisted in a goal-directed locomotion task. The goal was located 10m away from the starting point and a static obstacle was situated in the middle of the path and had to be avoided. At the beginning of each study, participants were first informed of the task. They had the opportunity to ask any questions. Second, they

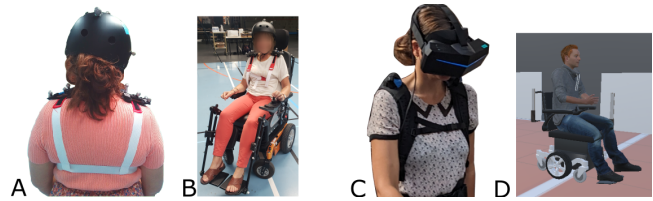


Figure 2: Using a Qualisys system, we tracked the participants' position over time based on 13 markers located on their shoulders and a helmet (A) and the PWC position with an extra set of 12 markers (B). Illustration of the VR apparatus (C) and the PWC agent (D).

signed an informed consent form. Third, after agreeing to participate in the study, participants were asked to complete a sociodemographic questionnaire (gender, age, hand dominance, height, weight, shoulder width, experience with people with disabilities, experience with virtual reality). Finally, they performed the user study in which they had to avoid the human obstacle. Participants were free to choose a side of avoidance and were instructed to walk at comfortable speed. When participants were moving using the PWC, the speed of the PWC was set at 1,8m.s⁻¹ which is the maximal speed permitted by the power wheelchair for this experiment. Participants were allowed to take breaks at any time between trials as fatigue was not a criterion considered in our study.

Both studies were conducted in a large gymnasium as illustrated in Figure 1, left. The gymnasium was equipped with a 12 cameras opto-electronic system (Qualisys, 100 Hz) that allowed us to record participants' motion in real conditions. The participants wore a harness with 2 clusters of passive markers and a helmet with a total of 13 markers as illustrated in Figure 2. The PWC used in this study was a B400 Ottobock which is a 4 wheels model. It was equipped with 12 markers, as shown in Figure 2, to record participant motion. In the 2 studies, a confederate played the role of the standing or seated human obstacle in real conditions. He was a 30 years old male (1.82m height, 0.43m shoulder width and 0.60m width with PWC, 1.43m depth with PWC). He was wearing a helmet with markers in order to control his position. In virtual conditions, we used his virtual counterpart, by choosing a visually faithful textured 3D model of himself with about the same measurements. The virtual avatar is illustrated on Figure 1.

In the virtual condition, participants wore a backpack (HP VR Backpack G2 running Unity 2021.3) and a virtual reality helmet with a wide field of view (Pimax 5k, FoV 120°) shown on Figure 2. Four cameras recorded their movements (SteamVR Base Station 2.0).

4.4 Analysis

To avoid considering the acceleration-deceleration phase at the start and the end of the locomotion path, we only focus our analysis on the 5 m wide central part. The position of the participants was filtered using a low-pass filter with a cut frequency of 1 Hz to remove natural medio-lateral oscillations due to stepping activity.

4.4.1 Dependent Variables Our dependent variables were the side of avoidance, the shape-to-shape interpersonal distance as well

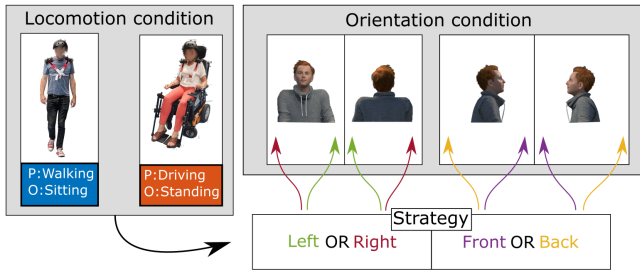


Figure 3: We manipulated the locomotion conditions ([participant driving, obstacle standing] and [participant walking, obstacle seated in a PWC]) and the orientation of the obstacle. We were interested in the strategy chosen by participants to avoid the obstacle, going either to the left/right or front/back of the obstacle as well as the shape-to-shape distance.

as the participants speed.

Side of avoidance was computed as the frequency of trials where participants passed either to the left, to the right, to the front or to the back of the static obstacle.

Shape-to-shape distance was computed using an approximation of the shape of the pedestrian and the shape of the PWC user, as described in Figure 1b. In contrast to what is typically employed in studies in pedestrian-pedestrian interactions, which involved computing distances from the middle of each body, we defined the wheelchair reference frame at its center, in order to account for the asymmetric shapes between the pedestrian and the PWC user. The wheelchair reference frame is then defined with the Y axis being in the antero-posterior direction of the pedestrian motion (from the starting position to the goal) and the X axis being in the medio-lateral direction of the pedestrian motion.

Let (x, y) be the position of the pedestrian in the wheelchair frame. We denote l_p the neck-shoulder width of the pedestrian. We then define (l_x, l_y) the coordinates of the centered rectangle around the wheelchair *i.e.* the half dimensions of the rectangle on the X and Y axis respectively (note that the values depends on the orientation of the interaction). Shape-to-shape distance s was then computed as $s = \sqrt{(x - l_p)^2 + y^2} - \sqrt{l_w^2 + \left(\frac{l_w}{\tan(\alpha)}\right)^2}$, with $\alpha = \text{atan}\left(\frac{y}{x}\right)$, $\alpha_w = \text{atan}\left(\frac{l_y}{l_x}\right)$ and $l_w = l_y$ when $\alpha \in [\alpha_w, \pi - \alpha_w] \cup [\pi + \alpha_w, 2\pi - \alpha_w]$, or $l_w = l_x$ otherwise. The red line in Figure 1b is a geometrical representation of the computed shape-to-shape distance.

Walking speed was computed as the first derivative of the horizontal position of the participant along time. It was then averaged on the 5 m central zone of the experiment.

4.4.2 Statistics Statistics were conducted using Jamovi and R softwares. The level of significance was set at $p < 0.05$. We assessed normality using a Kolmogorov-Smirnov test and homogeneity of variance using Levene test. We first evaluate whether participants had a specific strategy regarding the side of avoidance. The experimental condition has an influence on whether the participants have to avoid

the obstacle from right/left or front/back depending on whether the obstacle was facing the participant or was showing his profile. We then analysed those choices separately. We then conducted a binomial test to evaluate whether the frequencies observed for right/left or front/back were different from a random choice. To further evaluate whether there was an effect of the locomotion mode (Study 1) or the environmental condition (Study 2) on the side of avoidance, we ran a χ^2 test of association. To evaluate the effect of the environmental condition, *i.e.* Virtual (VE) or Real Environment (RE) and the side of avoidance (left/right/front/back) on shape-to-shape distance and walking speed, we conducted we conducted a linear mixed model fit by REML with R 4.2.3., with participants as random effect. Please note here that there were not the same number of trials per side of avoidance since this was part of participant strategy to avoid the obstacle. When the effects were significant, we conducted a Tukey post-hoc analysis.

5 Study 1: Collision avoidance between a PWC user and a pedestrian in real conditions

5.1 Objective and Hypotheses

The objective of this first study is to evaluate collision avoidance strategies between a PWC user and a pedestrian, when one of the persons to be avoided by the other is static. In this context, we formulated 2 hypotheses.

- **H1:** Interpersonal distances during pedestrian-PWC user interactions will be greater than those observed during pedestrian-pedestrian interactions.
- **H2:** The orientation of the human obstacle to be avoided, in relation with the asymmetric nature of the personal space as described by previous work [5], will affect interpersonal distances, both when interacting with a pedestrian or a PWC obstacle.

5.2 Design

Participants were asked to avoid a collision with a person while crossing a gymnasium as illustrated on Figure 3. We used a within-subjects design. The independent variables were the mode of locomotion, *i.e.*, walking (while the human obstacle was seated in a PWC) or driving a PWC (while the human obstacle was standing), and the orientation of the obstacle ($\theta \in \{0, 90, 180, 270\}$ degrees). Each participant completed 4 (orientations) \times 2 (mode of locomotion) \times 3 repetitions, resulting in 24 trials. Note here that we manipulated the orientation of the static individual but our analysis is focused on the actual side participants chose to avoid the static person, denoted "side of avoidance" with 4 levels (left/right/front/back). All the conditions were performed in a randomized order. Prior to each block, a training session was conducted during few minutes, without any obstacle, to familiarise participants with the locomotion modes. None of them being regular PWC users. The total duration of the experiment including instructions, questionnaires, training, experiments, breaks, and debriefing, was approximately one hour.

5.3 Results

Figure 4 illustrates the trajectories performed by participants during the experiment depending on the mode of travel : walking or driving

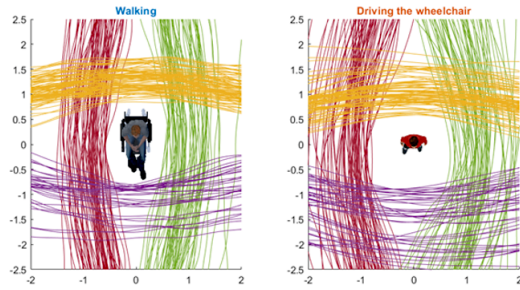


Figure 4: Trajectories in real condition for pedestrians in the reference frame of the PWC user (left) and PWC users in the reference frame of the pedestrian (right) in meters

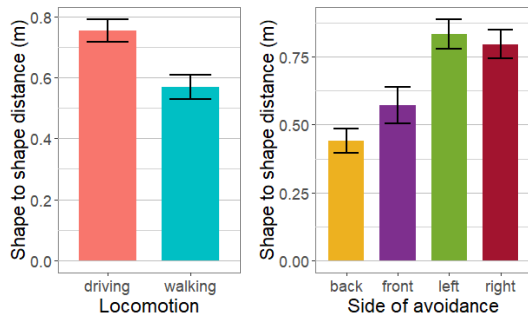


Figure 5: Study 1 : Main effect of the locomotion mode (left) and the side of avoidance (right) on the shape-to-shape distance. Errors bars represent the confidence intervals

a PWC and interacting respectively with a PWC confederate or a standing confederate.

5.3.1 Shape-to-shape distance There was a significant main effect of the mode of locomotion ($F(1,475)=144, p<0.001$) as well as an effect of the side of avoidance on the shape-to-shape distance ($F(3,476)=223, p<0.001$) as illustrated on Figure 5. The shape-to-shape distance was greater when driving than walking, and it was smaller when the participants passed to the back of the obstacle compared to the other sides. In addition, results showed an interaction effect of both the mode of locomotion and the side of avoidance on this shape-to-shape distance ($F(3,475)=102, p<0.001$, as illustrated in Figure 6. Especially, results showed that while the shape-to-shape distance was smaller to the back than the front while driving, it was bigger when walking. The detailed post-hoc analysis is reported in appendix.

5.3.2 Side of avoidance When walking, participants passed the PWC user obstacle as many times to the left ($N=59, 47.2\%$) as to the right ($N=66, 52.8\%$) ($p=0.592$). They also passed more to the back ($N=92, 73\%$) than to the front ($N=34, 27\%$) of the PWC user obstacle ($p<0.001$). Results showed the same conclusions when driving, where participants passed the standing user obstacle as many times to the left ($N=60, 46.8\%$) as to the right ($N=68, 53.2\%$) ($p=0.536$). They passed the standing user obstacle more to the back ($N=81, 65.3\%$)

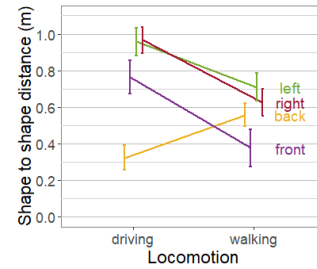


Figure 6: Study 1: Interaction effect between the locomotion mode and the side of avoidance on the shape-to-shape distance. Error bars represents the confidence intervals.

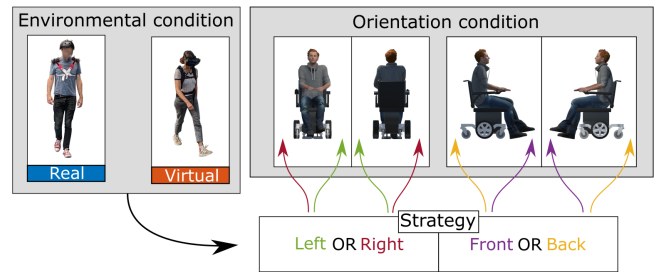


Figure 7: We manipulated the environmental conditions as well as the orientation of the PWC user. We were interested in the strategy chosen by participants to avoid the PWC user, going either to the left/right or front/back of the PWC, as well as the shape-to-shape distance and the walking speed.

than to the front ($N=43, 34.7\%$) ($p<0.001$). In addition, the locomotion mode did not affect the front-back strategy ($\chi^2(1)=1.74, p=0.188$) nor the left-right one ($\chi^2(1)=0.002, p=0.959$).

6 Study 2: Collision avoidance of a pedestrian avoiding a static PWC user in real and virtual conditions

6.1 Objective and Hypotheses

In this second study, our objective was to compare whether the avoidance behaviour of a pedestrian avoiding a static PWC user is preserved in virtual conditions, in comparison to real ones. Our hypothesis was the following:

- **H3:** as previously demonstrated for pedestrian-pedestrian interactions [5, 39], we expect that avoidance behaviours will be qualitatively preserved in VR but will show quantitative differences. In particular, we expect an increase in interpersonal distances and a decrease in locomotion speed.

6.2 Design

The same participants as in Study 1 came back to the lab for a second session. They were asked to avoid a collision with a virtual PWC user while walking in a virtual gymnasium as illustrated on Figure 7. We manipulated the orientation of the obstacle ($\theta \in \{0,90,180,270\}$ degrees), that was randomized for each participant. Each participants completed 4 (orientation) x 3 repetitions, resulting in 12 trials. Again,

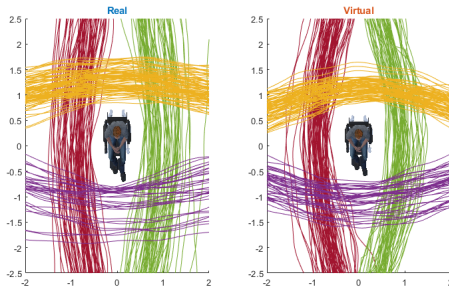


Figure 8: Pedestrians' trajectories in the reference frame of the PWC for real (left) and virtual (right) environments in meters.

note that we manipulated the orientation of the static person but we are then interested in the analysis of the actual side participants chose to avoid the static person, denoted "side of avoidance" with 4 levels (left/right/front/back). Prior to each block, a training session allowed participants to become familiar to the locomotion mode by walking in VR. In addition, we employed the Fast Motion Sickness Scale FMS [25] to assess participants' simulator sickness before and after the experiment. The experiment lasted about 30min including instructions, questionnaires, training, experiments, breaks, and debriefing. Participants were immersed in the VE for approximately 20 minutes.

For the statistical analysis, we considered the comparison between the results of experiment 1, when participants were walking and avoiding the PWC user in real conditions, and the results of experiment 2, where the participants performed the same task but in VR. Our independent variables were therefore the environmental conditions, i.e., virtual (VE) and real (RE) environments and the orientation of the obstacle

6.3 Results

Figure 8 illustrates the trajectories depending on the environment and the orientation of the PWC user. In the virtual conditions, participants did not experience cybersickness (Fast Motion Sickness Score=1.65/20).

6.3.1 Shape-to-shape distance There was a significant effect of the side of avoidance on the shape-to-shape distance ($F(3,477)=60.56$, $p<0.001$), as illustrated in Figure 9 left. Post hoc tests showed that participants maintained a smaller crossing distance when passing in front of the PWC user ($0.42 \pm 0.36m$), than when passing on the back ($0.54 \pm 0.36m$). This shape-to-shape distance was bigger when participants passed to the left than to the right of the PWC user (resp. $0.68 \pm 0.28m$ and $0.62 \pm 0.24m$). There was also a main effect of the environment (real or virtual) ($F(1,476)=5.1$, $p=0.024$) but no interaction between the environment and the side of avoidance ($F(3,476)=0.65$, $p=0.58$ on the shape-to-shape distance. The results of the post-hoc tests are reported in appendix.

6.3.2 Walking speed There was a main effect of the environment on walking speed ($F(1,476)=1570$, $p<0.001$) as illustrated in Figure 9 right: participants walked slower in VR (1.21 ± 0.14 m/s) than in real condition (1.52 ± 0.15 m/s). There was a significant main effect of the side of avoidance ($F(3,477)=3.40$, $p=0.018$) and a significant interaction between the environment and the side of

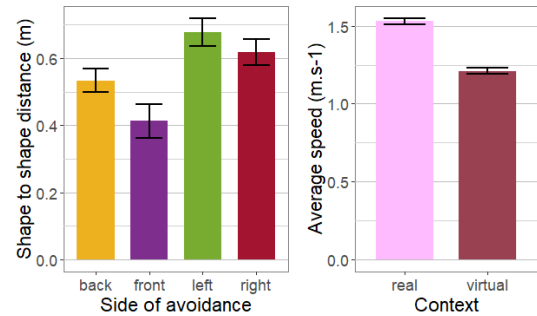


Figure 9: Study 2: Main effects of the side of avoidance on the shape-to-shape distance and of the Context on the walking speed

avoidance ($F(3,476)=4.26$, $p=0.006$). The results of the post-hoc tests are reported in appendix.

6.3.3 Side of avoidance In virtual conditions, participants passed the PWC as much to the right ($N=70,55.6\%$) as to the left ($N=56,44.4\%$) ($p=0.247$). They passed the PWC user more to the back ($N=82,64.6\%$) than to the front ($N=45,35.4\%$) ($p<0.001$). In addition there was no effect of the environmental condition (i.e., VR or Real) on those strategies both for left/right ($\chi^2(1)=0.192$, $p=0.661$) and front/back sides ($\chi^2(1)=2.10$, $p=0.147$).

7 Discussion

The general context of our study was the design of PWC simulators that would facilitate learning and training social navigation for patients. In particular, our experimentation aimed both to study interactions between a pedestrian and a static PWC user and to evaluate the ability of VR to enhance knowledge of such behaviors.

The first main result of our study is that the proxemics between walking and driving a PWC significantly differs in real conditions. Our findings validate **H1**: we observed that the interpersonal distances were statistically higher when the participants drive a PWC than when they walk.

The second main result is that in real conditions, while the strategies regarding the choice of avoidance side are consistent across walking and driving a PWC, the side of avoidance significantly affected the shape-to-shape distance. We therefore validate **H2**. Interestingly, there was an interaction effect with the mode of locomotion, where walking participants passed closer to the front of the PWC obstacle, and where driving participants passed closer to the back of the standing obstacle. Those results can be associated with a specific shape of the personal space, that can be described as an ellipse, rather than a circle, with a front/back asymmetry. In our study, considering a shape-to-shape distance, the personal space would leave more room for the back of a wheelchair user than for the front, and for the front of a pedestrian than for the back. Hayduk [21] proved back in 1981 that the 2-dimensional shape of personal space was not circular, but slightly larger in the front than in the back. Interestingly, they highlighted a reversible reduction of the interpersonal frontal distance when subjects turned their heads to one side providing experimental evidence of fluctuations in the shape of personal space. This larger distance maintained in the front vs. the back was also shown by Argelaguet et al. [5] when avoiding a static

standing human, either real or virtual. It is important to note that in their study, the side of avoidance was constrained. In our study, participants preferentially pass behind the PWC, with an asymmetrical shape-to-shape interpersonal distance between front and back. The difference between the 2 locomotion modes may be partly due to the position of the user in the wheelchair, with a centre of gravity that is more posterior to the body envelope because of the seated position and a different relative position of the head.

In addition, we observe that the distance to the sides is larger than in front or behind, which differs slightly from Argelaguet et al [5] but we did not use the same method to compute the interpersonal distance. We have considered the shape-to-shape distance, meaning that we identified the nearest points between the shape of the PWC and the one of the pedestrian. When seated on a wheelchair, it should be noted that the location of the head of the PWC user does not coincide with the wheelchair body that is used to compute the shape-to-shape distance. This raises the question of whether the head position is an important factor in regulating personal distance. Further experiments in a seated position on a simple chair would be of interest to distinguish the effect of the head position from that of being a wheelchair user. Finally, let's note that our participants chose in the same proportion to avoid the obstacle user towards their left or right sides. However, when the obstacle is shown in profile, they prefer to pass behind than in front of them such as previously shown in pedestrian/passive moving robots interaction [56]. It should also be noted that some of the participants were not used to driving a wheelchair in experiment 1 and that, despite a few minutes' familiarisation time before the experiments, this lack of experience may have influenced their avoidance behaviour. Future studies with expert PWC users should be considered in the near future.

Our last main result is that we observed a reduction in speed and an increase in shape-to-shape distance in VR compared to real conditions which is consistent with previous work [5, 8, 12, 18]. We emphasize that while the increase in shape-to-shape distance is statistically significant, the actual difference is only about 0.02 meters. In previous work by Argelaguet [5], this difference was measured at approximately 0.05 meters. While we cannot make direct quantitative comparisons with previous studies because our computation of interpersonal distance differs, and the clearance distance is affected by the shape of our wheelchair, such a small, clinically insignificant difference suggests that the concept of proxemics is minimally affected by the virtual environment. Consequently, virtual reality simulators can be considered effective learning tools for patients, as they provide an environment that closely mirrors real-world spatial interactions. We then validated **H3**.

Regarding the limitations of our study, we should note that our results should be treated with caution, given the relatively small number of participants with non-gender balanced participants and the fact that we had to exclude some trials due to tracking problems. For organisational reasons, the order of conditions was not counter-balanced, as this study was part of a summer school student project, which may have influenced the results. Finally, we did not include a condition where a PWC user avoids a virtual agent but this condition will be the subject of a forthcoming study.

Taken together, these results demonstrate the potential to enhance the virtual environments of wheelchair driving simulators by incorporating realistic locomotor interaction laws that can be integrated with existing crowd simulators such as [55]. In particular, we propose several guidelines for wheelchair simulator developers to populate virtual environments with virtual pedestrians performing realistic locomotor behavior:

- the shape-to-shape distances should be specifically tuned with respect to the side of avoidance, as previously described;
- the virtual pedestrian should preferentially walk behind the wheelchair user;
- the virtual pedestrian has the option of passing indifferently to the right or left of the wheelchair user.

Following these guidelines, we present in the last section a proof of concept demonstrating how these recommendations can be integrated into existing microscopic crowd simulator algorithms, i.e., considering the simulation at the individual level.

8 Application and Integration in microscopic crowd simulation

Microscopic crowd simulation involves simulating large groups of pedestrians by simulating the movements of individual agents within the crowd, as well as their interactions with other agents [55]. An agent of the simulated crowd, representing a pedestrian, is defined by a circle, with a position, a velocity, and a goal in a 2D environment. The principles of microscopic crowd simulation algorithms for predicting future collisions between agents have been summarized in four concepts [54, 55]: *Time to collision*, *Distance to collision*, *Time to closest approach* and *Distance to closest approach*. These metrics vary according to the relative position p_i of each interacting agent, as well as their relative velocity v_i , and the interaction distance $D = |p_i| - R_1 - R_2$ where R_1 and R_2 represent the radius of the circle of each interacting agent. Our proposal is to modify the shape of the circle representing a pedestrian into a more complex shape to better reflect specific agent proxemics parameters.

Definition of pedestrian-PWC user proxemics rules: The concept of representing agents with ellipses, defining the proxemics rules, has been previously proposed in the literature [7, 37, 59]. This representation allows a given agent to define its proxemics based on the agents' viewing direction relatively to the position of an other agent. While this representation is interesting for regular agents representing pedestrians, it does not specifically consider interactions where a PWC user is involved. In our case we require the proxemics computation to encompass the following findings of this paper:

- The left dimension of the ellipse is equal to the right one.
- Front, back and side (left and right) dimensions can be customized independently.

As shown in Figure 10, we define the proxemics of an agent i by an ellipse for which the center is offset in the forward direction of the agent. This allows centering the ellipse on the shape of the PWC instead of centering it on the head of the PWC agent. We define δ as the offset between the ellipse center and the agent position (i is its head position), a_i the main radius and b_i the secondary radius of the ellipse, respectively in the forward direction and in the lateral direction of the agent i . For the following, we consider the origin of the frame to be the center of the ellipse. In this frame, the agent

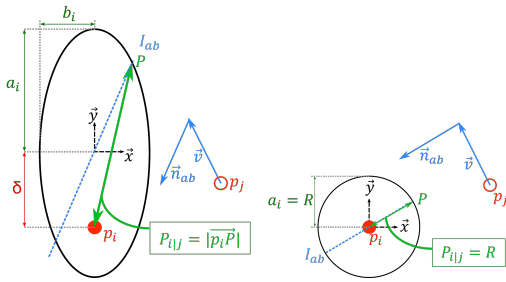


Figure 10: Comparison of proxemics based agent with radius based agent. left: Proxemics representation of a power wheelchair agent (PWCa) interacting with a pedestrian agent. a_i and b_i are the primary and secondary radii defining the proxemics ellipse of agent i . δ is the offset of the ellipse center. right: Proxemics representation for a radius based agent. In both case: v represents the relative velocity of the two agents. I_{ab} is the interaction line directed by n_{ab} the interaction vector. $P_{i|j}$ is the computed proxemics for the current interaction. The point P is the point on the proxemics shape of agent i that is the closest to the trajectory of the agent j .

position is $p_i = \begin{pmatrix} 0 \\ -\delta \end{pmatrix}$. We defined the interaction vector n_{ab} , for a relative velocity $v = \begin{pmatrix} v_x \\ v_y \end{pmatrix}$, such as $n_{ab} = \begin{pmatrix} -v_y b_i^2 \\ v_x a_i^2 \end{pmatrix}$. If $|v| = 0$ then $n_{ab} = p_j$. We defined the interaction line as the line directed by n_{ab} through the ellipse center. Therefore we set $m = \frac{n_{aby}}{n_{abx}}$. The interaction line crosses the proxemics ellipse in two points. To find those points, we have to solve the following system of equations:

$$\begin{cases} \frac{x^2}{a(v_i)^2} + \frac{y^2}{b(v_i)^2} = 1 & \text{Proxemics ellipse} \\ y = mx & \text{Interaction line} \end{cases}$$

The resolution gives $x = \pm \frac{\sqrt{-4AC}}{2A}$ and $y = mx$, where $A = a(v_i)^2 + b(v_i)^2 m^2$ and $C = b(v_i)^2 (-a(v_i)^2)$. We pick the solution according to which side the other agent is expected to cross the proxemics agent trajectory. Within the two solutions, the point P which verifies $\text{sign}(P_y) = \text{sign}(p_i p_j y - \frac{v_y}{v_x} * p_i p_j x)$ is the solution we need. Finally, the computed proxemics is the magnitude $P_{i|j} = |\vec{p}_i \vec{P}|$. The interaction distance can now be expressed as $D = |\vec{p}_i \vec{p}_j| - P_{i|j} - P_{j|i}$. Figure 10 illustrates the underlying geometry of the resolution.

Adaptation of existing crowd simulation algorithms We have adapted the crowd simulation library UMANS [54] to use the proxemics-based agent as defined in 8 instead a radius-based agents. We used the state-of-the-art standard crowd simulation algorithm ORCA[53] through the UMANS framework, modified with our implementation of the proxemics-based agents, to generate the trajectories shown in figure 11.

9 Conclusion and future works

We have demonstrated that there are specificities of proxemics during interactions between a pedestrian and a PWC user and that the locomotor behavior of a pedestrian in avoiding a PWC user in virtual reality is very close to that in real life, considering both the strategies to avoid the PWC user (avoidance side) and the regulation of interpersonal distance, especially with the same effect depending

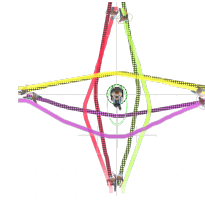


Figure 11: Synthetic trajectories of a simulated interaction between a pedestrian and a power wheelchair agent (PWCa) using ORCA[53] through UMANS[54] adapted with the proposed proxemics agents. The trajectories with grid over the color, resp. plain color, where generated with a radius-agent shown with the dotted circle, resp. a proxemics agent shown with the green ellipse

on the avoidance side. Speed is reported to be significantly slower in virtual reality than in the real world, as previously shown in the literature. The comparison with previous studies shows differences with situations of pedestrian-pedestrian or pedestrian-inanimate obstacle interaction, confirming the specificity of the interaction with a PWC user. To generalize those conclusions, future experiments should consider more complex and dynamic interactions, for example where a pedestrian and a PWC user cross each others.

We show here that it is possible to model these specific behaviours and integrate them into a crowd simulator to render realistic interaction behaviours for virtual agents. This opens up the possibility of using virtual reality to promote the rehabilitation of individuals with disabilities through social navigation. These environments must then be tested with regular power wheelchair users to justify their realism in terms of social navigation in the first instance [52]. Ultimately, clinical studies are required to assess the learning and rehabilitation effects of social cognition in these environments, as well as the ability to transfer skills into real life. Finally, these results present an opportunity to raise awareness of disability among the general population by embodying healthy individuals in PWC users who may face difficulties in social navigation in crowded environments.

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Appendix

Interesting p-values are highlighted. Green is for $p < 0.001$, blue is for $p < 0.01$ and red is for $p < 0.05$.

Post Hoc Tests study 1

Post Hoc tests for Shape-to-shape distance

Post Hoc Comparisons - side of obstacle view by participant at crossing

Comparison		Difference	SE	t	df	PTukey
side of obstacle view by participant at crossing	side of obstacle view by participant at crossing					
back	- front	0.0578	0.0192	3.01	479	0.014
back	- left	-0.1558	0.0159	-9.81	477	<.001
back	- right	-0.1098	0.0151	-7.27	477	<.001
front	- left	-0.2136	0.0197	-10.83	477	<.001
front	- right	-0.1676	0.0192	-8.72	478	<.001
left	- right	0.0460	0.0166	2.77	476	0.029

Post Hoc tests for walking speed

Post Hoc Comparisons - side of obstacle view by participant at crossing

Comparison		Difference	SE	t	df	PTukey
side of obstacle view by participant at crossing	side of obstacle view by participant at crossing					
back	- front	-0.0145	0.01258	-1.15	479	0.658
back	- left	0.0229	0.01040	2.20	477	0.123
back	- right	0.0112	0.00989	1.13	477	0.668
front	- left	0.0374	0.01292	2.89	477	0.021
front	- right	0.0257	0.01259	2.04	478	0.175
left	- right	-0.0117	0.01089	-1.08	476	0.706

Post Hoc Tests study 2

Post Hoc Comparisons - locomotion: walking/driving

Comparison		Difference	SE	t	df	PTukey
locomotion: walking/driving	locomotion: walking/driving					
driving	- walking	0.168	0.0141	12.0	475	<.001

Post Hoc Comparisons - side of obstacle view by participant at crossing

Comparison		Difference	SE	t	df	PTukey
side of obstacle view by participant at crossing	side of obstacle view by participant at crossing					
back	- front	-0.1664	0.0224	-7.442	477	<.001
back	- left	-0.3739	0.0183	-20.453	476	<.001
back	- right	-0.3925	0.0175	-22.425	475	<.001
front	- left	-0.2075	0.0228	-9.121	476	<.001
front	- right	-0.2261	0.0226	-10.018	476	<.001
left	- right	-0.0186	0.0192	-0.967	475	0.768

Post Hoc Comparisons - locomotion: walking/driving * side of obstacle view by participant at crossing

Comparison		Difference	SE	t	df	PTukey
locomotion: walking/driving	side of obstacle view by participant at crossing					
driving	back - driving	-0.4019	0.0296	-13.56	476	<.001
driving	back - driving	-0.5866	0.0260	-22.53	475	<.001
driving	back - driving	-0.6692	0.0250	-26.82	475	<.001
driving	back - walking	-0.1940	0.0230	-8.43	475	<.001
driving	back - walking	-0.1249	0.0321	-3.89	476	0.003
driving	back - walking	-0.3552	0.0260	-13.65	475	<.001
driving	back - walking	-0.3098	0.0251	-12.33	475	<.001
driving	front - driving	-0.1847	0.0305	-6.05	475	<.001
driving	front - driving	-0.2673	0.0301	-8.88	476	<.001
driving	front - walking	0.2771	0.0349	7.94	475	<.001
driving	front - walking	0.0467	0.0306	1.52	475	0.738
driving	front - walking	0.0922	0.0301	3.06	476	0.048
driving	left - driving	-0.0826	0.0271	-3.04	475	0.050
driving	left - walking	0.2314	0.0278	8.34	475	<.001
driving	left - walking	0.2768	0.0270	10.24	475	<.001
driving	right - walking	0.3595	0.0261	13.75	475	<.001
walking	back - driving	-0.2079	0.0288	-7.21	476	<.001
walking	back - driving	-0.3926	0.0253	-15.52	475	<.001
walking	back - driving	-0.4752	0.0243	-19.57	475	<.001
walking	back - walking	0.0692	0.0317	2.18	476	0.366
walking	back - walking	-0.1612	0.0253	-6.36	475	<.001
walking	back - walking	-0.1157	0.0244	-4.74	475	<.001
walking	front - driving	-0.4617	0.0331	-13.96	476	<.001
walking	front - driving	-0.5443	0.0326	-16.71	476	<.001
walking	front - walking	-0.2303	0.0331	-6.96	476	0.001
walking	front - walking	-0.1849	0.0327	-5.66	476	<.001
walking	left - driving	-0.3140	0.0270	-11.65	475	<.001
walking	left - walking	0.0455	0.0271	1.68	475	0.704