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Interacting with a virtual cyclist in Mixed reality affects pedestrian walking

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Abstract

When walking in shared traffic spaces, the nearby presence and movement of other pedestrians and cyclists can prompt individuals to make speed and path adjustments to avoid potential collisions. The study of such collision avoidance strategies in virtual settings allows for the controlled scaling of environmental complexity that are present in a real situation, while ensuring pedestrians safety. Our pilot study in this work makes an early effort towards understanding the influence of cyclist movements on human walking using mixed reality (MR). On this account, the collision avoidance behavior of pedestrians crossing the path of a moving virtual cyclist avatar was examined. This was done by analyzing the temporal and spatial characteristics of the participants walking trajectory using the speed profiles and Post Encroachment Time (PET) metric. The early results from our pilot study demonstrates that mixed reality cyclist experiments can be used to study pedestrian-cyclist interactions. Furthermore, for all interactions that were noted in the study, a significant proportion of participants decided to cross the virtual cyclist, while others preferring to give the right of way. We also discuss our current findings, insights and implications of studying pedestrian behaviours using virtual cyclists.

CCS Concepts

• ***Computing methodologies*** → *Collision detection;* • ***Augmented Reality*** → *Motion Influences;* • ***Mixed Reality*** → *User Study;*

1. Introduction

Walking is by far the most environmental friendly and healthy mode of everyday transport. Further, walking also contains a strong social component, e.g short distance journeys on foot help to socialise with fellow walkers and to explore the surrounding environment. However, the choice of the actual walking route within a given outdoor space is highly dependent on the perceived level of safety ([PCS19], [RMP*15]). Importantly, the perceived level of safety could be decreased if people have to interact and share their walking space with other road users like cyclists, potentially resulting in the avoidance of walking due to the inherent fear of collisions [Tho08]. Such fears are more pronounced in some urban designs like Shared Spaces [HB08].

In Shared Spaces, integrated movement spaces are created through the reduction of physical separations between road users. Such a design intends to increase the awareness and also the attention of all traffic participants towards each other - and thus also reduce the speed and increase the usage of the space by all travellers. Such spaces are characterised by the removal of kerbs and lanes, resulting in more frequent interactions between pedestrians and cyclists; which might further prompt a pedestrian's feeling of unsafety, and contribute towards the growing resentment towards such urban designs [PS12].

So far, most studies have applied computer vision based analyses to observe and characterize the interaction between pedestrians and cyclists. A recent study investigated the interaction behaviour of a group of pedestrians with a cyclist on a shared road [HWY*21] via a series of controlled experiments. However, the work only focused on the macroscopic influence of a pedestrian crowd on individual cyclist's paths. Further, the generalizability of the study results is limited by the particular study setting and group behavior. Another controlled experimental study investigating the interaction of cyclists [YDGRH18] restricted the research to cyclists and did not include pedestrians as interaction partners and their potential mutual influence. To the best of our knowledge, pedestrians' walking behavior upon seeing a cyclist sharing or conflicting their movement space has not been studied so far. A recent work has published a pedestrian-cyclist traffic dataset to support research in this direction [MYHM23], but needs further investigations. Hence, gaining an understanding of such pedestrian-cyclist interactions could be beneficial to both traffic planners and urban designs to help designing mixed traffic environments.

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On the other hand, immersive virtual environments and walking experiments have been implemented to study interactions amongst pedestrians and how they avoid collisions [BBBL03]. The outcomes of such studies suggest that people react to virtual persons in the same way as they would do in a real-world situation, requiring the initiation of collision avoidance behavior [NKKM23]. Interestingly, extending such walking experiments to study cyclist safety has not received much research attention, yet. Though, the use of virtual environments to study pedestrian-cyclist interactions could alleviate the safety risks inherent in conducting such experiments in a real-world setting, where cyclists would be otherwise expected to move very close to the pedestrians, in order to ensure ecological validity as well as complexity and dynamics of natural environments. However, fully immersive virtual spaces like VR are often limited by the mode of motion within these environments. Here, mixed-reality methods might represent a promising approach.

For this reason, the current study aims at investigating whether mixed reality can be effectively used to study walking and collision avoidance behavior of pedestrians when interacting with a virtual cyclist in shared spaces. On this account, we take a conflicting traffic situation which might arise from pedestrians and cyclists crossing each others path. To explore the potential influence of the virtual cyclist on the pedestrians real-world walking behavior, spatial and temporal movement characteristics of the pedestrian, as well as pedestrian-cyclist interaction characteristics are analyzed. Consequently, the main contributions of this work are: (a) applying mixed reality to study pedestrian-cyclist interactions, (b) using high-resolution motion data to estimate the effectiveness of pedestrian-virtual cyclist interaction in mixed reality with regard to the induction of collision avoidance behaviour, and (c) evaluating collision avoidance behavior using traffic safety measures like Post Encroachment time (PET) along with motion dynamics in a virtual study.

2. Related Work

2.1. Interaction Analyses in Shared Space Safety Studies

In the field of traffic safety, surrogate safety measures have often been applied to estimate the level of threat originating from the built environment [NDZ*23]. Amongst them, two popular measures are: time-to-collision (TTC) and post encroachment time (PET). The time-to-collision concept, which was introduced in 1971 by the US researcher Hayward, builds up on a constant motion speed and direction assumption for predicting the temporal distance to a potential collision of two road users in the future. PET on the other hand directly measures the actual temporal distance by which two road users reach the point at which their motion trajectories cross. In other words, PET is defined as "the minimal delay of the first road user which, if applied, will result in a collision course and a collision" [LSH10]. Low values of PET would reflect severe traffic conflicts and PET=0 would represent a crash. Due to its ability to overcome the constant motion and direction constraints of colliding agents while computing TTC, it has been often used in shared space studies ([CGA*21], [ZAIA*21]).

2.2. Virtual Agents to influence Walking Behaviour

The presence of virtual agents like AR-pets have proven to affect both the awareness and proxemics - *the amount of space needed between people while walking* - of nearby walkers in MR studies. In [NKL*19], the presence of a virtual dog taken for a walk significantly changed the way how people moved and oriented themselves, compared to when walking alone. In line with this finding, further work has emphasized the potential of virtual dogs as walking companions [NKBW20], and to further exploit the potential of their presence and motion to interact and encourage walking behaviour of older adults.

While multiple virtual studies have focused on walking in virtual environments, fewer studies have investigated collision avoidance in mixed-reality settings. In an early work by Olivier and colleagues [OOP*10], participants observed the interaction with a virtual pedestrians in a desktop based study. The observering participants were able to both detect a potential collision and also anticipate whether they had to cross first or give way. Similar avoidance behaviours have been studied in VR settings either when both interacting persons were represented virtually ([PK18b], [BRNB19]), or when persons interacted with a virtual 3D pedestrian avatar ([PK18a], [NKKM23]) ; investigating factors contributing to conflict avoidance ([ZNO*20], [PZP*21]). However, the interaction with virtual agents when walking in realistic environments remains under-investigated, yet.

3. Study Design and Mixed Reality Apparatus

Our study focuses on capturing the interaction and collision avoidance behaviour of walking persons with a virtual cyclist. For this, we developed a Unity application which allowed participants, wearing a Hololens AR headset while walking towards a defined destination, see a moving virtual cyclist crossing their path. We used a client-server based mixed reality approach for our work, as the application had to support the dual purpose of allowing the headset user to naturally move and perform collision avoidance maneuvers while also recording the resulting interactions by measuring the trajectories.

Figure 1 details the client-server application and its **primary** and **secondary** interface. The primary interface consisted of a Hololens client running a mixed-reality scene where the users were able to both view and react naturally by adjusting their motion dynamics (walking path and/or speed) based on how close the virtual cyclist would appear near them. The client periodically transmitted the position of the virtual cyclist and the location of the moving Hololens camera to the server. The secondary interface on the server consolidated the motion paths of both the person wearing the Hololens and the virtual cyclist for each time stamp. This second interface in our work is synonymous to an overhead camera capturing trajectories of a person responding to a conflicting cyclist in a real-world interaction scenario.

Our experimental setting for the study consisted of an open space 10m x 10m indoor lab environment. As shown in Figure 2, each participant was expected to walk from a predefined start-point to the end-point in the lab under three experimental conditions:

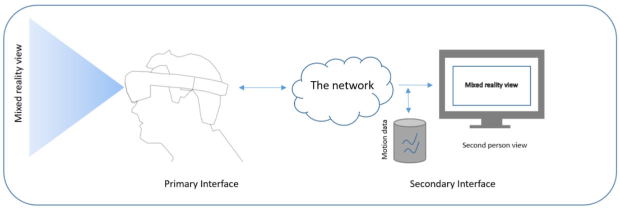

Figure 1: *The two interfaces that help to view and interact with virtual content.*

- **no AR:** In this condition, no virtual mixed reality content was visible for the participants while walking from start to end point.
- **AR w\o vInteraction**†**:** In this condition, a virtual bench and tree were added as static environmental infrastructure to the left and right of the walking path of the participant.
- **AR with vInteraction** †**:** In this condition, both the static infrastructure and a moving 3D cyclist were added as virtual objects to the indoor lab environment.

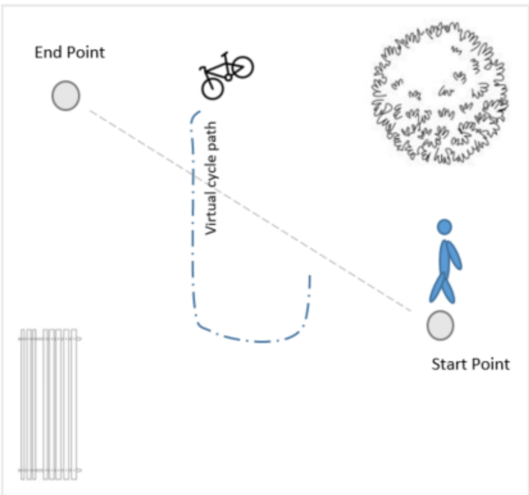

Figure 2: *Graphical depiction of the experimental scene from a top view persective, with the cyclist crossing the walking path and the bench and the tree to the left and right, respectively*

For each of the three experimental conditions, participants were asked to walk in three different speeds - **slow, normal** or **fast**. Hence based on the presence of AR content (condition) and walking speed (speed), we designed a 3 (*condition*: no AR vs AR w\o vInteraction vs AR with vInteraction) x 3 (*speed*: slow vs normal vs fast) within-group study. Three trials were recorded for each of the nine combinations of condition x speed, resulting in a total of 27 walking trials per participant.

† The term vInteraction refers to pedestrian-virtual cyclist interaction in this work.

3.1. Implementation and User Study

In the two experimental conditions, which tested the mixed reality application to include virtual content in the environment, participants were wearing a Hololens. The mixed reality application for this work was implemented using Unity and MRTK. The 3D cyclist was designed using real cyclist motion data as detailed in [KKS23]. The motion path for the cycle was scripted to start from a fixed start point and to cross the straight line between start and end point of the participants. The virtual cyclist moved continuously, with fixed speed without stopping. All other virtual 3D objects (bench and tree) were adopted from freely available packages from the Unity Asset store ‡. All the server-side logic for this study was implemented using ROS § and Java and each experiment data was recorded using ROS Bags. To finely track participants' walking positions, in addition to the MRTK camera positions that were transmitted by the Hololens, optical markers were placed on the Hololens and anatomical landmarks of the participants. Marker positions were recorded at 200 Hz using a 10 camera optical motion tracking system (Qualisys Motion Capture Systems, Sweden).

Before the start of testing, participants were briefed about the walking task to be performed. We instructed participants to walk along the straight line path while freely deciding to react to the virtual content if present based on the interaction condition. They were also informed that the cyclist was not intelligent and hence would not react to the participants if they blocked its movement path. All participants were expected to complete all the nine iterations that included the three AR conditions with slow, medium and fast walking speed trails in random order. In the study, each participant was informed to commence walking in their natural slow, medium and fast speeds when an auditory beep signal was broadcasted by the experimenter. At the same instance, the cyclist started moving for all trails of the AR with vInteraction condition. A volunteer was responsible for recording all the motion trajectories of the experiment at the secondary interface.

In this pilot study, five young adults (mean age = 27.8 years, Range: 22-39 years, 2 female) voluntarily participated. They all had normal or corrected-to-normal vision and provided informed consent before their participation.

3.2. Data Analysis

The complete data set consisted of 135 trials (5 participants x 27 trials), of which 45 trials involved interactions with the virtual cyclist. One of these 45 iterations had to be discarded due to errors in post-processing and time synchronisation (see below). All analyses were completed using Python.

For each participant, walking trajectories were recorded by two sources: a) the external motion tracking system, recording at a high frame-rate (200Hz), and b) the Hololens camera, recording at a lower frame-rate on the secondary interface server. While the Hololens camera allowed to record both the motions of the pedestrians' and the virtual cyclist in an joint and fixed Unity coordinate

‡ https://assetstore.unity.com/
§ https://wiki.ros.org/

Figure 3: *Mixed reality view of the crossing cyclist as seen from the Hololens. The figure shows the walking path along with the virtual tree that was added to the scene.*

system of the MR application, it is also potentially prone to noise and motion drifts due to MR capture. Hence, the high frequency recordings of the external motion tracking system were used to correct for any time lags and to spatially align walking trajectories to get noise free movement trajectories of all pedestrian-cyclist interactions recorded.

For all three experimental conditions and three walking speeds, mean maximum walking speed (averaged across the three trials) was calculated for each participant. Further, for the AR with vInteraction condition, we computed *PET*, *Euclidean distance* and *min distance* to quantify both the involved participant motion dynamics and level of safety in the virtual interaction.

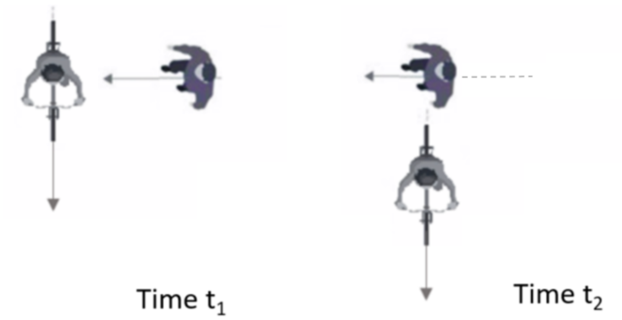

Figure 4: *The time instance t_1 when the cyclist enters the conflict zone and t_2 when the cyclist leaves the conflict zone and the person enters it*

The *post encroachment time (PET)* as shown in Figure 4, estimates the encroachment time with which either the cyclist or the person passes the crossing point and represents a temporal interaction measure. The value for this metric is computed as:

$$PET = t_2 - t_1 \tag{1}$$

To spatially characterise the interaction, we also computed the *Euclidean distance* between the pedestrian and the virtual cyclist at the time point when the PET was estimated. This measure indicated how distant the two agents were from each other when the crossing was finished. The last metric *minimum distance*, represents the absolute minimum separation between the pedestrian and the virtual cyclist throughout the virtual interaction. This value was computed by replaying the path of both the cyclist and pedestrians as in the experiment and recursively estimating their distance. The computation was stopped when the point of min distance was reached for the experiment iteration.

3.3. Results

In the following, the results in terms of walking and interaction behaviour are reported. Due to the pilot character of the study, only descriptives are reported.

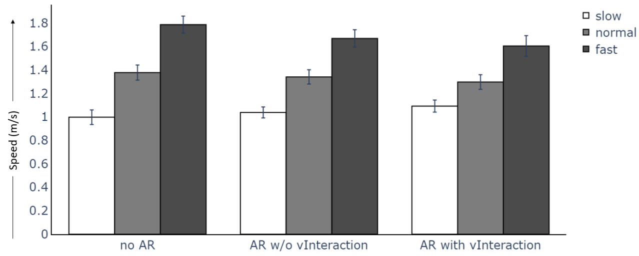

Figure 5: *Max speed variations for no AR, AR w\o and with vInteraction for slow (white), medium (gray) and fast (black) walking speeds. The error bars represent the confidence intervals for the max speeds*

Maximum Walking Speed: As illustrated in Figure 5, participants were following the instruction on different walking speeds in the three speed-conditions. Specifically, participants were walking slower and faster than normal in the slow and fast walking condition, respectively. Further, the maximum walking speed does not seem to be affected by additional virtual content in the the walking environments.

Interaction Behaviour: For the *AR with vInteractions* condition, we analyzed the crossing order to understand choice of the interaction behaviour upon pedestrians seeing a virtual cyclist crossing their walking path. Of the total 44 trials, participants were giving way to the cyclist in 3/4th of the trials, while decided to pass first in 1/4th of the trials. As role attribution has been shown to result in different collision avoidance strategies ([OMC*13]), separate descriptives are reported for all further analyses.

Table 1 illustrates the mean of the temporal and spatial crossing metrics. Values for all three metrics were larger when pedestrians were giving way to the virtual cyclist as when they were crossing first. Consequently, giving way to the virtual cyclist, a strategy chosen in the majority of trials, resulted in larger temporal and spatial crossing distance.

For being able to further explore the factors that contributed to the selection of a pedestrian crossing first-strategy, we separately analyzed all 11 vInteraction$_{PC}$ pedestrian first trials.

Table 1: *The interaction metrics computed based on different crossing orders – cyclist first (vInteraction$_{CP}$) or pedestrian first (vInteraction$_{PC}$).*

Interaction metric (mean)	vInteraction$_{CP}$	vInteraction$_{PC}$
PET (sec)	2.23	1.68
Euclidean dist (m)	2.11	1.37
Min dist (m)	0.995	0.809
cases (in %)	3/4	1/4

Table 2: *Speed and participant wise categorisation of trials with vInteraction$_{PC}$ crossing strategy*

	slow	normal	fast
Total Trial Count	1	3	7
Trial Count per Participant	- 1 for P2 -	1 for P1 2 for P2 -	3 for P1 3 for P2 1 for P3

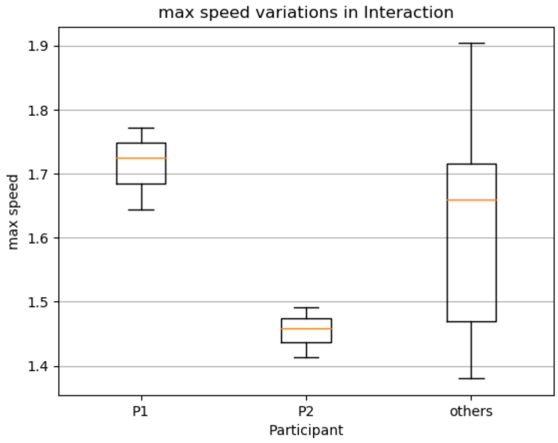

Figure 6: *Max speed and its spread representation when comparing the speed of P1 and P2 to that of the other particiapants (P3 to P5) for fast-paced walking trials.*

As can be noted from Table 2, the selection of a crossing first-strategy seem to be influenced by both walking speed and individual preferences of single pedestrians. The majority of trials (7 out of 11) can be assigned to the fast walking speed condition. Further, the crossing first-strategy was mainly selected by two pedestrians (10 out of 11 trials), only.

As the speed of walking could be an attribute that might have been specific to each of the participants P1 and P2, we compared the maximum walking speed for the *fast* iterations and compared it to the speeds of participants P3-P5. It can be noted that P1 tended to walk faster than the average of P3-P5 (Figure 6), while the opposite seems to be true for P2. Still, P2 was able to cross in front of the virtual cyclist. This has been an interesting early finding of our work, which implies that not just speed but other factors seem to have contributed towards the crossing decisions made.

3.4. Discussion

In this study we investigated how pedestrians react to AR content and its influence on their decisions to either cross first or give way to a virtual moving cyclist crossing their walking path. On that account, we analyzed maximum walking speed as well as different interaction metrics. As collision estimation always contains both a spatial and temporal aspect, we computed the PET metric to represent the temporal aspect and the corresponding Euclidean as well as minimum passing distance between the participant and cyclist to characterise the spatial crossing behaviour.

An interesting finding from our study was that both collision avoidance strategies, i.e. giving way as well as crossing first, could be observed in the present study. Previous research on role attribution in pedestrian-pedestrian crossing scenarios suggest that the person giving way contributes more to successful collision avoidance ([OMC*13], [KWH*16]). In this regard, the choice of crossing first in the current study is particular interesting, as lower values for both temporal and spatial crossing metrics were noticable under this condition. In contrast, higher PET and euclidean distance were observed when cyclist crossed first. From a safety perspective, this finding suggest that pedestrians, when crossing first, decided to cross less safely. We hypothesize that this could be due to the high level of predictability in estimating cyclists' motion and the non-reactive nature of the virtual cyclist in the present study, which would have allowed to precisely estimate the potential risk of collison. As described above, the virtual cyclist behaviour was scripted to move using a constant velocity and was not reactive to pedestrians walking behaviour [KMSM22] as e.g. to slow down if a pedestrian approached closer. This has been one of the limitations of our current pilot study and could be further developed in future research.

On the other hand, the third interaction metric, i.e. *min distance*, yielded nearly similar values for both passing strategies, with *min distance* being only slightly lower when pedestrians were crossing first. This metric, unlike the Euclidean distance, was computed to estimate how close the two agents (pedestrian and virtual cyclist) were actually passing each other throughout the experimental trials. Taken all three metrics together, the outcomes of our study suggest that, under high predictability of the virtual cyclist's behaviour, even when being non-reactive, participants are able to predict the temporal and spatial distance to the cyclist and flexibly choose collision avoidance behaviour accordingly. Importantly, multiple factors, as e.g. maximum walking speed but also pedestrian-specific preferences, seem to influence the actual choice of the crossing strategy. Future research should further explore the interaction of these factors in less predictable pedestrian-cyclist-interaction scenarios.

To conclude, this paper presents some early insights gained through our work towards using mixed reality in studying pedestrian-cyclist interactions. This research is of particular practical relevance as, to the best of our knowledge, pedestrian-cyclist interactions have not been in the focus of research yet, but are of interest with regard to shard space safety. Consequently, this pilot study provides important first insights into pedestrians' walking behavior in reaction to a virtual cyclist: the outcomes of our pilot study are principally in line with collision avoidance strategies often observed in pedestrian-pedestrian interactions and suggests that parameters that are known to be sensitive to pedestrian-pedestrian interactions are also sensitive to pedestrian-cyclist interactions. Future work could focus on replicating our current findings and extending them to more complex interaction scenarios. In this context, it might be particularly interesting to investigate how collision avoidance strategies change when the cyclist behaviour is becoming less predicable. Findings from such studies could then be compared to real-world pedestrian-cyclist interactions

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