Spatial Differences in Pedestrian-AV Interactions in Future Urban Environments: A Large-Scale VR Study

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1 INTRODUCTION

Since the 1950s, scholars have been studying how pedestrians cross streets, primarily examining how they interact with vehicles operated by humans (5). While studying these interactions remains important, there's a growing urgency to investigate pedestrian behaviour within the framework of automated vehicles (AVs). Addressing the interaction between pedestrians and AVs at conflict zones stands out as one of the pivotal challenges to overcome prior to the widespread deployment of AVs on streets. This includes the interaction with pedestrians, where concerns arise regarding how AVs might handle situations such as pedestrians crossing mid-block locations. A poor execution of such interaction can lead to fatalities or injuries, especially at unmarked mid-block locations—accounting for 14% of pedestrian fatalities (4). Therefore, it is crucial to understand pedestrian behaviour in various AV operational scenarios to respond appropriately. Overall, studies agree that other pedestrians influence pedestrian behaviour, specifically, the wait time to cross (2). Since pedestrian gap acceptance can differ widely depending on the country and environment (3), it can be concluded that pedestrian wait time to cross will be different between countries, which signifies the importance of conducting international studies to gain a deeper insight into such differences.

This study uses virtual reality (VR) to simulate two urban mid-block environments, one in downtown Toronto, Canada and the other in central Newcastle, UK, to investigate the crossing behaviour of 428 participants (9,092 observations). To the best of our knowledge, this is the largest study of such kind conducted on two different continents with different traffic rules and walking/driving norms. The research questions addressed in this paper, in the context of unmarked mid-block crossing, are: (a) Do various vehicle types, i.e., normal vehicles and AVs, impact pedestrian behaviour? (b) How do other pedestrians influence one's crossing behaviour? (c) How do traffic characteristics, road type, and environmental characteristics impact pedestrian behaviour? (d) What is the influence of demographics on pedestrian behaviour? and, Are there differences in pedestrian behaviour in different countries?

2 METHODOLOGY

VR was used for the purpose of this study for two main reasons: (a) replicability of the scenarios for each participant and (b) preserving the safety of participants. Two locations were simulated in VR to be presented to the participants; Front Street West in Toronto and Northumberland Street in Newcastle, as depicted in Figure 1. A Valve Index headset was used to project the environment for the participants in Toronto and an HTC VIVE headset in Newcastle.

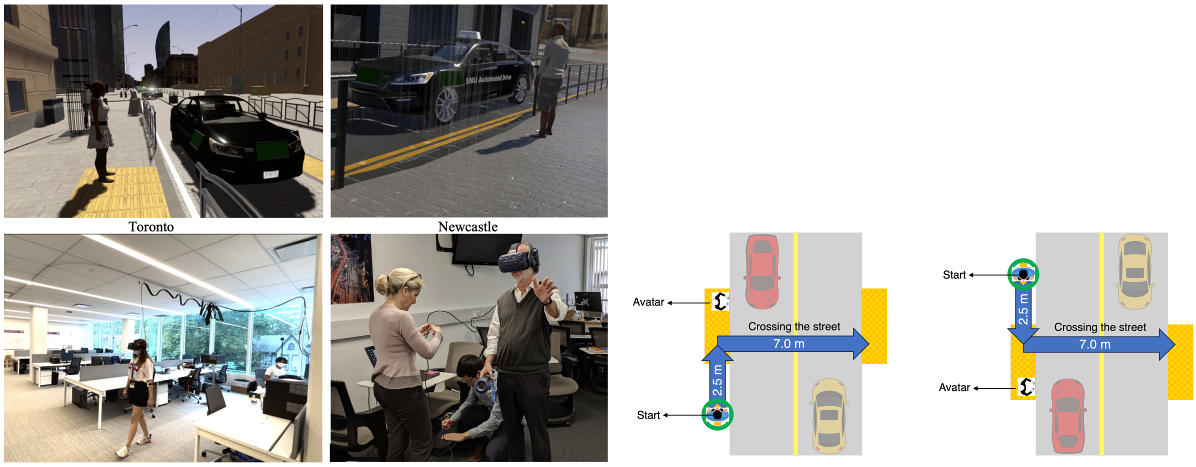

Figure 1 – *VR setup in Toronto and Newcastle*

Based on the existing literature, the research incorporated five factors aimed at manipulating diverse environments for participants. Table 1 shows all factors, the associated variables, and variable levels. Several vehicle types and vehicle appearances were designed, including AVs with external human-machine interfaces (eHMIs). An avatar (simulated pedestrian) was positioned on the tactile paving facing the street. This avatar had either of these three behaviours: (a) A standing avatar simply waiting on the sidewalk, (b) A conservative avatar crossing the street in a cautious manner at a regular walking pace, and (c) An adventurous avatar who chose a more daring approach of running to cross the street. The remaining design elements were influenced by street medians and various environmental factors.

Table 1 – *Experiment factors, variables, and variable levels*

Factor	Variable	Levels			
Vehicle type	Vehicle type	Normal car	AV with roof sign	AV with eHMI	
Social influence	Avatar's behaviour	No avatar	Standing avatar	Conservative avatar	Adventurous avatar
Traffic characteristics	Traffic flow	High arrival rate + low speed (20 km/hr)	Low arrival rate + high speed (40 km/hr)		
	Vehicle distance	2.5 m	3 m		
	Vehicle share	0% AV	100% AV		
Road type	Street design	No median	With median		
Environmental characteristics	Time of day	Day	Night		
	Weather	Clear	Rain	Snow	

The experimental design was executed with consideration of all research variables and practical factors, including the maximum VR immersion duration and the overall experiment duration. In total 12 different sessions were constructed for each participant to go through and each session was repeated twice. The initial combinations were tested with pilot participants to evaluate the performance of the VR experiment and observe participant's reactions to different environments. All variable levels were incorporated in the final experimental design randomly, having avatar behaviour levels being repeated equally for each participant. A random sampling of the variable levels was performed for each session. Participants were placed on a sidewalk and they were instructed to go to the tactile paving and then find a safe and suitable moment to cross the street. Participants were given a 60-second time limit to complete the task, and if they did not finish within that time frame, the session would be terminated and the next session would be automatically loaded. In Newcastle, 3% sessions resulted in failure to cross, while in Toronto it was 10%. Figure 1 shows the details of the experimental task. Overall, 171 and 257 individuals participated in the experiment in Toronto and Newcastle, respectively, resulting in 9,092 ($\approx (171 + 257) \times 12 \times 2$) observations after removing the unsuccessful crossings. The majority of participants were recruited by a panel provider to retain population profiles and they were compensated.

Here, pedestrian behaviour is represented by the time they wait before they start crossing. Survival analysis has been widely used in the literature to study pedestrian wait time. In survival analysis, the aim is to analyze the time until an event occurs. A collection of statistical modelling methods can be designed for this purpose. In this study, we fit a multivariate Cox Proportional-Hazards (CPH) model (1) to estimate the effects of different variables on the waiting time for the scenarios in which the participants managed to cross the street. CPH model is a semi-parametric model that assumes the time component and the covariate component of the hazard function to be proportional.

3 INITIAL RESULTS

Figure 2 shows that in general the wait times in Toronto were longer than in Newcastle. Weather played an important role in both cities, with pedestrians waiting longer in rain and snow. The difference was more pronounced in Newcastle. The change in wait time in Newcastle and Toronto in the presence of AVs didn't show the same trend. In the presence of another pedestrian (avatar), the behaviour of the participant showed noticeable changes, however, they differed between the cities. The female pedestrians waited slightly longer than others.

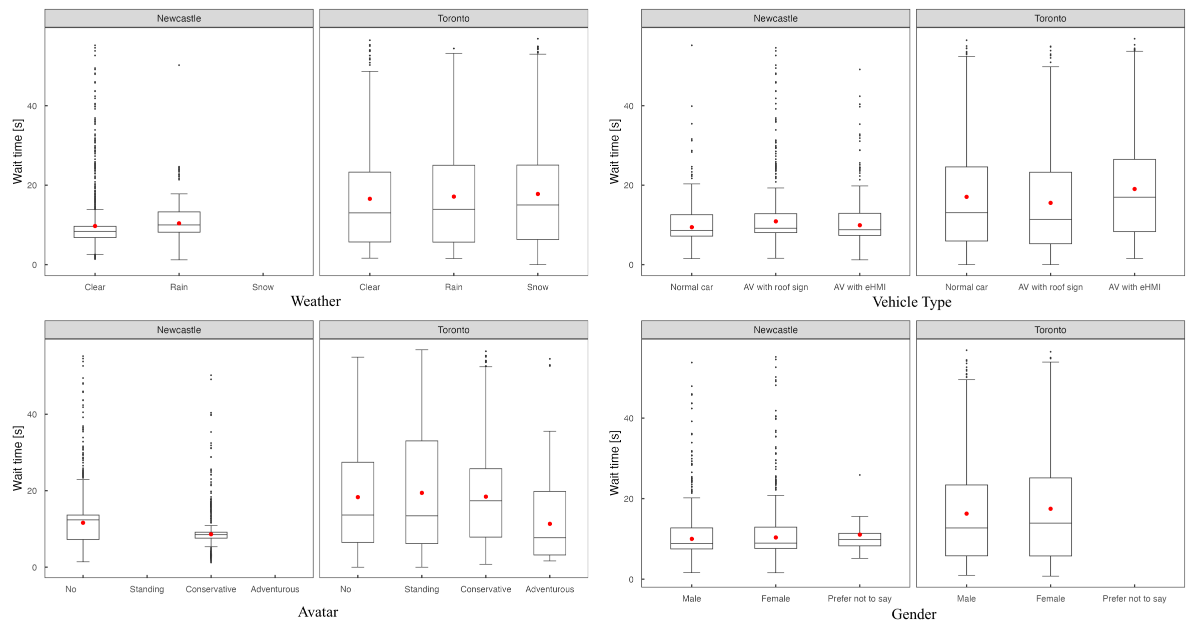

Figure 2 – *Wait-time distribution in Newcastle and Toronto conditional on various factors*

Table 2 shows the estimated coefficients of the CPH model. It should be noted that a positive coefficient sign means that the chance of starting a cross is higher, and thus, it leads to a shorter wait time. A hazard ratio greater than one indicates that as the value of the variable increases, the event's hazard increases, and thus waiting time decreases. The participants waited significantly longer for the AVs with roof sign, compared to normal vehicles. AVs with eHMI did not have any significant influence on the wait time change of the pedestrians, which exhibits how explicit interactions between pedestrians and AVs are less dominant in the decision-making processes of pedestrians, as compared to implicit interactions such as vehicle motion cues. The presence of a standing avatar significantly increased participants' wait time. Initially, participants expected the avatar to cross the street and intended to follow the avatar. However, after a few seconds, they decided to make their decisions independently to cross the street, before the one-minute available time was up. The adventurous avatar on the other hand, encouraged participants to cross the street faster, regardless of the existing conditions. The social influence findings were in line with the previous research that demonstrated how waiting pedestrians encourage others to wait, too, and adventurous pedestrians who cross at a red light encourage others to cross, as well (2).

Having a median in the middle of the road significantly reduced the wait time and helped pedestrians make their decisions quicker to cross the street. The estimated coefficient for night implies that wait times were shorter compared to days, which is counter-intuitive and needs further investigation. It is expected that pedestrians have a better visibility and consequently, make the crossing decisions faster and more confidently. Wait times were significantly shorter during the rain and longer during the snow weather conditions. Shorter wait times for rain conditions can be due to having imbalanced observations between Toronto and Newcastle (nearly 1 to 2 ratio) and the fact that people in the UK are more used to rainy conditions. Furthermore, there were no snowy conditions considered for the Newcastle participants. Male participants were found to have significantly less wait times compared to female participants, while age groups 45 to 54 and older than 65 waited significantly longer than the reference age group, i.e., 18 to 24.

Table 2 – *Results of initial Cox proportional-hazards model*

Variable Type	Variable	Coefficient	Hazard ratio	p-value
	Normal vehicles	–	–	–
Vehicle type	Autonomous taxis with roof sign	-0.08	0.92	< 0.05
	Autonomous vehicles with eHMI	-0.03	0.97	0.41
	No avatar	–	–	–
Avatar's behaviour	Standing avatar	-0.57	0.57	< 0.05
	Conservative avatar	-0.02	0.98	0.70
	Adventurous avatar	0.25	1.28	< 0.05
Street median	No median	–	–	–
	With median	0.36	1.44	< 0.05
Time of day	Day	–	–	–
	Night	0.16	1.18	< 0.05
	Sun	–	–	–
Weather	Rain	0.26	1.30	< 0.05
	Snow	-0.40	1.67	< 0.05
Gender	Female	–	–	–
	Male	0.09	1.10	< 0.05
	18 to 24	–	–	–
	25 to 34	0.06	1.06	0.30
Age group	35 to 44	0.07	1.07	0.22
	45 to 54	-0.14	0.87	< 0.05
	55 to 65	-0.03	0.97	0.58
	65+	0.30	1.35	< 0.05
	Concordance (C) Index	0.61		
	- log2(p) of ll-ratio test	344.89		

4 DISCUSSION

This study investigates the impact of AVs, social influence, and environmental characteristics on the crossing wait time of pedestrians, using VR in two very different geographic areas and 428 participants. The findings emphasized on heterogeneous pedestrian behaviour across different variables, which can assist in many application domains such as intelligent driving systems, transportation planning, and traffic analysis. The next steps involve estimating pedestrian reaction times and incorporating location effects (Toronto and Newcastle), accepted/rejected gaps, time to collision, and post-encroachment time in the modelling framework and developing fully-interpretable deep residual learning CPH models to enhance the results.

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