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Exploring single-line walking in immersive virtual reality

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ABSTRACT

With increasing rates of elderly and obese people in the population, questions are being raised about the validity of inputs used by computer evacuation models to predict the movement of crowds in the built environment. The objective of this study is to examine the movement of individuals in a VR environment. Exploring individual movement in VR (where the individual is exposed to a virtual environment with virtual agents while actually moving alone in the physical environment) is a necessary step on the path to determining if VR is a useful tool to gather new crowd movement data. Specifically, this work presents the results of two experiments that were conducted to measure the correlation between inter-person distance (the distance from a participant to a virtual agent) and walking speed. Results show a positive correlation between walking speed and the inter-person distance for inter-person distances between 1.0 and 1.5 m. Above inter-person distances of 1.5 m, walking speed was not dependent on inter-person distance. An important finding from this work is no observed significant difference in the relationship between walking speed and inter-person distance across both experimental setups – 'pushing' or 'following' configurations. Finally, this work shows the potential of gathering individual movement data using VR.

1. Introduction

Pedestrian and crowd simulations are an integral part of contemporary infrastructure design in cases where large crowds gather or where egress performance is important. The study of pedestrian movement is an area of research interest in several different fields, such as urban transportation design [1,2], event planning for large crowd events [3,4], and evacuation in emergencies [5–8] such as fire evacuation from tunnels [9]. Each of these sub-fields has an interest in predicting crowd movement with the aim of estimating evacuation times or predicting pedestrian flows and congestion in the built environment.

There are a wide variety of computer evacuation models available [10,11] with the most popular amongst fire safety practitioners being agent-based continuous models [12]. For any evacuation model results to be credible, it is important that the user inputs are appropriate to the scenario and minimise uncertainty in input values as much as possible [13]. One of the most important relationships when modelling crowd movement is the one between walking speed and density; this relationship can be graphically represented by a 'fundamental diagram' [13–16]. Fundamental diagrams are traditionally investigated using empirical methods with groups of people walking in different densities in either field or laboratory experiments [14].

Since much of the fundamental diagram movement data has been gathered, there have been non-trivial changes in population demographics which influence the way pedestrians move within crowds, such as increasing proportions of the elderly [17] and the obese [18]. Elderly people are shown to have slower walking speeds in general [13]. Although there is limited data on the effect of obesity on walking speed, some studies show a negative correlation between BMI and walking speed [19]. Some design data, such as the commonly used SFPE fundamental diagrams [20], are based on data which is relatively old and has an unknown level of uncertainty with respect to representing populations of today and the future. It has been noted the authors of some of the original data sets have stated their data is no longer suitable and they requested additional research due to the changes in demographics since the data was collected [21–23].

In addition to the age of some empirical data sets and associated change in demographics, reviews of fundamental diagrams from a range of laboratory and field experiments show significant variation across different situations, such as pedestrian composition, location etc [14,16,24,25], aspects such as level of stress or motivation [26], or occupants characteristics and culture [27]. This variation makes it challenging to

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extrapolate results from one setting for general design purposes. Despite the familiarity with pedestrian fundamental diagram concept, the extent to which individual 'microscopic' characteristics influence the shape of the fundamental diagrams are still not well understood and are not universally applicable.

Thompson, Nilsson [22] discuss the reliance of contemporary models on historic data and suggest evacuation models are running out of time and not keeping pace with changes in population demographics; they propose re-examining crowd movement taking into account the interaction between people on a microscopic level to explore the fundamental parameters governing individual movements in crowds. With this 'bottom-up' approach, it is posited fundamental diagrams can be generated to cater for a range of diverse populations now and into the future, and not simply rely on the old way of collecting data from crowd experiments. Finding these fundamental parameters requires the collection of person-specific variables, such as anthropometrics (e.g. height, weight), and biomechanical parameters (e.g., step length, walking speed, inter-person distance) to develop a generic model that is not backward looking, but flexible enough to be applied to crowd movement analyses across various domains [28–30].

One-dimensional in-line walking is a common experimental setup which is adopted to reduce the complexity of the phenomenon and it enables insight without the influence of other more complex factors, such as passing, lateral influence, and self-ordering effects [31]. This type of experimental setup is often carried out in a laboratory environment with an oval walking track setup with participants injected into the loop; the more pedestrians within the loop, the lower the inter-personal distance (also described as 'headway', or 'spatial headway') and hence the greater the density [27,31–33].

Gathering data and exploring the fundamental parameters related to individual pedestrian movement in crowd experiments can present challenges, such as risk of psychological stress [34], injury with high density crowds, experimental time and cost, control of environmental and experimental conditions, and consent and privacy issues particularly if using video capture in public places [25]. However, the main challenge is crowd blocking [35,36]; an individual in the centre of the crowd cannot be fully observed due to blocking of visual observation by the crowd which limits the type of data that can be collected. In contrast to a crowd experiment, it is posited that simulating a crowd using Virtual Reality (VR) can enable researchers to collect detailed and accurate individual pedestrian movement data without the disadvantages of real-life crowd experiment. For the purposes of this paper, the term VR will be used to describe immersive VR in which the user wears a Head-mounted Display (HMD) to encounter a virtual environment simulation. A major advantage of this approach is the removal of any crowd-blocking or obscuration of the individual, i.e., an individual can be placed in a virtual environment where they feel immersed within a crowd, however in reality, they are alone in a physical laboratory making observations and data collection easier as a participant is not occluded by the other participants. Hence, the use of VR as a method to gather data to calibrate models and 'grow' fundamental diagrams from fundamental parameters is considered useful.

It is recognised that people potentially move differently when immersed in a virtual environment and there is a clear need to validate and calibrate any VR methodology [37]. Reasons for different movement could be related to egocentric distance perception, with distance compression observed in virtual environments [38]; there are also questions about walking speed and gait stability in VR, with researchers finding differences in VR compared with the real world. Janeh, Langbehn [39] showed a 6% reduction in walking speed in VR, but in follow up research with older and younger cohorts [40] there was a reduction in walking speed of 6.5% for younger adults, but no significant difference for older adults. Horsak, Simonlehner [41] found a 7.3% reduction in VR as well an increased gait instability in the VR condition indicating a more cautious gait pattern within the VR environment. There is no clear consensus on the cause of these gait differences, but researchers posit the gait changes in the VE could be due to a range of factors such as; reduced field of view [41,42], increased weight of the HMD [42], fear of walking without seeing real world obstacles [43], underestimation of optic flow (a radial pattern of image motion) [44], distance perception and the role of visual control of locomotion [44], previous experience in VR [45], and the influence of adaption time (with mixed results) [46,47]. These challenges and the need for further validation lead to the question; Given VR is not real, is it close enough to be used as a data gathering tool to draw meaningful conclusions from? Before a validation study can be carried out, it is first necessary to carry out a proof-of-concept study to explore the effects of a simulated crowd on individual movement. Using a one-dimensional in-line walking experiment is useful for a VR experiment as it allows for comparison against a well-established physical experimental methodology and, importantly, it allows for relatively unobstructed observation to collect the data needed for any assessment and calibration.

It is hypothesised that the fundamental relationship of individual movement within a crowd in a virtual environment is similar to that observed in reality, i.e., walking speed reduces with increased density (the observed variations in fundamental diagram data from real environment experiments related to experimental sampling, culture, and such like, is still expected to arise across VR experiments). The aim of this study is to examine the step length and walking speed with inter-person distance for one-dimensional walking in-line in an immersive virtual environment and assess if and how VR can support new investigation of crowd dynamics. To achieve this aim, two VR experimental setups were developed and tested.

2. Material and methods

In 2021, two immersive VR experiments were carried out in the VR Evacuation Laboratory at the University of Canterbury in Christchurch, New Zealand. The two different experiments which were performed are called Experiment 1 (pushing) and Experiment 2 (following). Experiment 1 (pushing) explores the interaction between inter-person distance as the independent variable (IV), and participant walking speed as the dependent variable (DV). Experiment 2 (following) explores this interaction with variables switched i.e., agent walking speed is the IV and inter-person distance is the DV. The correlation between walking speed and step length was also assessed for both experiments. Walking speed was selected as a measure of interest as it relates directly to the fundamental diagram, and step length was selected as a useful measure which can provide more information to explain observed changes in the walking behaviour.

The two experiments involved participants wearing an HMD through which they saw a virtual replica of the laboratory and a virtual agent. The method of VR locomotion was continuous motion room-scale-based, i.e., real walking – where the participants were able to freely move through the physical environment, with their position and orientation directly translated to the virtual environment. Further detail on the experimental setup is provided in section 2.2.

2.1. Participants

Convenience sampling was used with participants recruited from around the Christchurch area using flyers distributed primarily on the University of Canterbury campus and posted on selected social media community pages (LinkedIn and Facebook). Participants were predominantly university students. Each participant was provided an information sheet and consent form prior to the experiment. Participants were offered a $10 shopping voucher as a form of inducement. All participants needed to be over 18 years, have the ability to walk unaided, and have no prior history of epilepsy or related conditions (due to any potential triggering effects from the VR HMD).

Thirty participants undertook Experiment 1 (pushing), and twenty-nine participants undertook Experiment 2 (following). Demographic and anthropometric data for participants is presented in Table 1.

2.2. Virtual laboratory environment (VE)

For simplicity, the walking configuration was a straight-line layout where participants passed across a measuring zone. Markings were applied to the floor to delineate this 4.0 m × 0.8 m measuring area and to mark 1 m increments along the z-axis within the measuring area (to allow for calibration during the post-experiment video analysis).

A virtual representation of the laboratory interior layout (1:1 scale) was modelled using Revit 2021 and imported to Unity (version 2020.1.16f1) via the rendering engine Twinmotion 2020. With the Revit model imported as a 3D object in Unity, refinements were then carried out, which included applying surface materials and textures to 3D geometry and adding light sources and adjusting lighting effects for a realistic appearance. The virtual environment (VE) was designed to be close in geometry and appearance to the real-world environment (RE), albeit without many of the finer details such as switches and small furniture items, see Fig. 1 (b) and (c). Although the entire laboratory environment was modelled, participants were restricted to the walkable tracked area within the virtual environment, identified as the highlighted portion of Fig. 1 (a). A sufficient distance of 2.5 m was provided to allow for acceleration/deceleration at either end of the 4 m long measuring area [48]. This distance also allowed for a relatively steady-state spacing to be established between the participant and the virtual agent.

A virtual non-player character (agent) was added to the scenario. The inter-person distance was defined as the spacing between agent centreline and the tracked position of the HMD worn by the participant as shown in Fig. 2(a). The participant did not have an avatar (a virtual representation of the user's body) within the VR environment, instead they were a disembodied viewpoint in space which was tracked to match their real-world movements through the space.

Fig. 3 shows a still image from a short video taken from the camera location with an inset picture-in-picture view which shows the view from the participants perspective in VR. refer Appendix A Supplementary data.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.firesaf.2023.103882

Unity allows for game objects to have properties and behaviours defined by C# scripts. The agent's behaviour in these experiments was defined in a C# script with the following rules:

Both experiments.

- The agent is free only to move along the z-axis (the length axis of the measuring zone).
- The agent remains facing the direction of travel (participant only ever sees the back of the agent).
- The agent can only move forward in the direction of travel (i.e., if the participant moves backward the agent remains in place).
- The agent animation is configured to change with respect to the walking speed (i.e., at a standstill the agent does not show a walking animation, but just a slight 'natural movement' shifting weight from side to side).

Experiment 1 (pushing).

- The inter-person distance, (the agent position with respect to participants position, see Fig. 2 (a), is always fixed for each scenario, i.e., the participant 'pushes' the agent in front of them – excepting if the participant moves backward as noted above.

Experiment 2 (following).

- The agent walking speed is fixed for each scenario, i.e., the participant 'follows' the agent in front of them, with the agent starting from a speed of zero and accelerating to the set speed at the conclusion of an audible and visual countdown (30s) displayed in the HMD. The agent was at their terminal speed before data collection commenced.

Table 1
Experimental demographic data and anthropometric measurements.

Description	Experiment 1 (pushing)	Experiment 2 (following)
	Mean [S.D., range]	Mean [S.D., range]
Gender (males/females)	16/14	17/12
Age (years)	30.9 [14.6, 18–69]	21.4 [0.9, 19–24]
Body height (m)	1.72 [0.10, 1.52–1.93]	1.78 [0.10, 1.61–1.98]
Weight (kg)	69.7 [17.7, 45–118]	75.9 [17.2, 50–140]

2.3. Equipment

Consumer grade (commercial off the shelf) equipment was used for these experiments.

A GoPro Hero 4 Black video camera was used to capture video for analysis [50]. See Fig. 1 for camera location. This device was selected due to its wide field of view. Camera settings were 1080p wide, with frame rates of 120 fps (Experiment 1) and 25 fps (Experiment 2).

The HMD used was an Oculus Quest 1 which has a visible field of view of 93° horizontal and 93° vertical, a screen resolution of 1440 × 1600 per eye, and a refresh rate of 72 Hz [51]. For context, the typical visual field of a human is approximately 200° horizontally and 130° vertically in static conditions (head and eyes fixed) [52,53], accounting for eye movements can extend the available visual field significantly [54].

The Quest 1 is a 6DoF self-contained VR system with inside-out tracking using computer vision algorithms, such as Simultaneous Location and Mapping (SLAM). Being a non-tethered HMD meant that participants had no cable connection to a PC and are therefore free to walk around without restriction or distraction due to the cable within the tracked area (Room-scale VR). One of the disadvantages to the standalone non-tethered system was the need for the HMD to be removed from the participant after each scenario to allow the subsequent scenario to be loaded and set up by the researcher.

2.4. Study protocol

For Experiment 1 (pushing), five different scenarios were set up where the inter-person distance was varied; scenarios had inter-person distances of 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m. For Experiment 2 (following), three different scenarios were set up where the agent's walking velocity was varied, and the inter-person distance was measured; scenarios had agent walking speeds of 0.8 m/s, 1.0 m/s, and 1.2 m/s.

For both experiments, the experimental design was 'within-groups', such that each participant was exposed to multiple conditions. The order of scenario was either ascending or descending, with the order randomised between participants to allow for any order effects. Qualitative data was collected via a post-experiment questionnaire.

2.4.1. Initial procedure – both experiments

Participants arrived at the laboratory individually where the experiment information and consent form were completed, and a general brief was conducted. This brief explained some of the hazards and controls (nausea, contact with walls) and re-iterated the participant was free to cease the experiment at any time without penalty, and would still receive their voucher. Participants were allowed to ask questions at any time. In order to reduce any bias in the experiment, the purpose of the experiment was not explained to participants.

Before the HMD was fitted, a measurement of unimpeded walking speed was first carried out with the time taken for participants to walk along a straight line within the real-world laboratory environment. After these measurements, the participant was introduced to the experimental

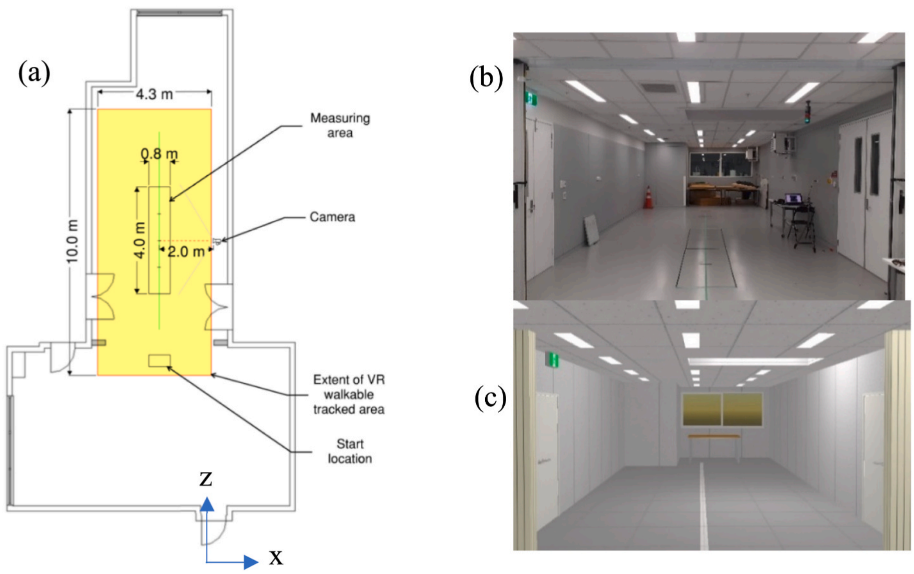

Fig. 1. (a) Layout of the experimental setup, and views from the start location of (b) RE compared with (c) VE.

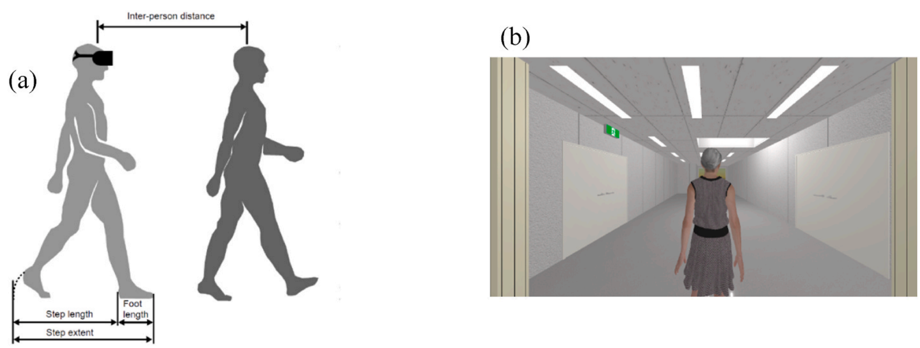

Fig. 2. (a) Inter-person distance and step length parameters (figure adapted from Thompson, Nilsson [49]), and (b) view of the agent from the participant perspective in VR.

Fig. 3. Side view showing participant walking in the 1.5 m 'pushing' scenario; top-right inset shows the view as seen by the participant in VR.

scenarios. To obtain the correct inter pupillary distance setting (the distance between the centres of each pupil), the researcher made adjustments while asking the participant for feedback on the clarity of the HMD display. Once the initial fitment was completed a familiarisation exercise was carried out to reduce any training effects. Participants were provided the base scenario which displayed the virtual laboratory environment with the inclusion of an agent (at the far inter-person distance scenario of 3 m) and were instructed to "walk along the white line, turn around and walk back to the beginning". As a safety measure, the Guardian feature of the Oculus Quest HMD was enabled which gave the user a visual indication of when they were approaching the limits of this tracked area. During the familiarisation period, the Guardian visualisation function was demonstrated. The Guardian is a function within the Oculus Quest which allows the user to visualise the boundary of the playable area and provides visual cues superimposed over the virtual experience when the user is near to the pre-determined boundary edge, see Fig. 4. During the training period the participants were able to experience the Guardian visual cues and remove the HMD to verify they were still at least approximately 2 m from the end of the room. The intent of this was to build the confidence of the participant so they could move freely without fear of walking into any walls or obstructions.

Participants were given the opportunity to walk the length of the room and back again three times. This familiarisation exercise was not recorded for Experiment 1 (pushing) but was recorded for Experiment 2 (following). For Experiment 2 (following), the participants walked one length of the room, the Guardian feature was demonstrated to them, the HMD was removed, and they returned to the start location. At this point the HMD was refitted, and the participants then walked to the end of the room and back two times. The time taken for participants to walk along the straight-line measuring zone was determined and two values were recorded, with the mean value taken as the unimpeded virtual environment (VE) walking speed.

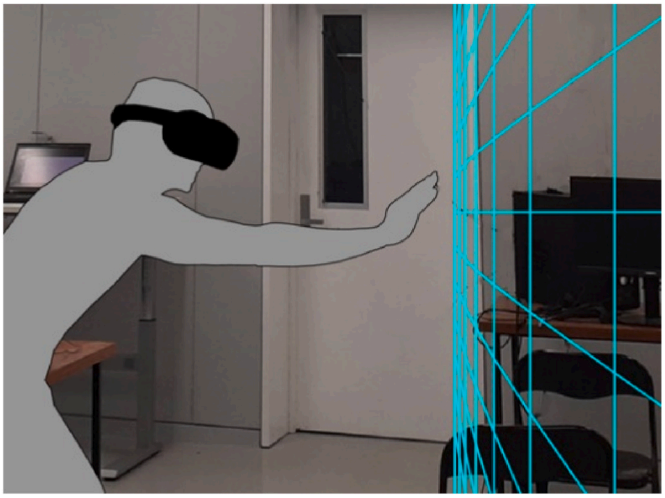

Fig. 4. Oculus Guardian boundary concept.

2.4.2. *Experiment 1 (pushing)*

After the familiarisation exercise was completed, the first of five scenarios were selected, the HMD re-fitted, and the video camera set to record. The participant was then given the instruction to "walk along the white line as if you were walking normally down the street, don't overtake the other person". As the participant neared the edge of the tracked area, the instruction was given "hold there, turn around and walk back to the start". At this point the HMD was removed, and the researcher selected the next scenario. This process was repeated until all five scenarios were completed, at which time the video camera was stopped, and the experiment terminated.

2.4.3. *Experiment 2 (following)*

After the familiarisation exercise was completed, the first of three scenarios were selected, and the HMD re-fitted. The participant was then given the instruction to "walk along the white line as if you were walking normally down the street, don't overtake the other person". As the participant neared the edge of the tracked area, the instruction was given "hold there, and remove the headset". At this point the HMD was removed from the participant and passed to the researcher, who put on the HMD and stepped forward to activate a previously hidden display within the VR environment which allowed the captured inter-person distances (measured at six points throughout the measuring zone) to be read and recorded. Inter-person distances were read out aloud in such a way that participants could not easily know what they were. This process was repeated until all three scenarios were completed, at which time the video camera was stopped, and the experiment terminated.

2.4.4. *Completion – both experiments*

After each experiment terminated, the participants were asked to complete a short questionnaire and given a chance to provide any additional feedback or general comments on the experience. At this point participants were given their $10 voucher before they left the laboratory.

2.5. *Data analysis*

Measurements were extracted from the video recordings of each participant. Post-experiment data collection was carried out using Kinovea (version 0.9.3), an image and video analysis tool developed for sport science movement measurement and evaluation [55]. Two parameters were extracted from the video capture: walking speed, and step length. To obtain accurate measurements, a camera calibration process was necessary. The lens calibration coefficients were determined using Agisoft Lens software (version 0.4.1).

2.5.1. *Walking speed*

The mean walking speed over the 4-m measuring zone was calculated using the time taken for the hip marker point to traverse the length of the measured zone, see Fig. 5.

2.5.2. *Step length*

Step length is defined as the distance between alternating heel touchdown points as shown in Fig. 2 (a). For each participant, a mean value for step length was calculated for each scenario based on all measured steps within the measuring zone. Step length parameters were normalised by a height of 1.72 m to allow comparison with previous research [49], according to $SL^* = SL\frac{1.72}{H}$, where: SL^* = normalised step length, SL = measured mean step length (m), H = participant's height (m).

The uncertainty associated with distance measurements was dependant on camera position and there were slight variations noted as the camera position changed between experiments (for SD card and battery changes). The calibration error was determined using the known 1 m increments marked on the measuring zone. The measured distances for the 1 m portions on each end of the measuring zone (where the effects of lens distortion were the greatest) varied; in the majority of cases this distance was within 0.05 m (±5%), but the worst cases were from 0.93 m to 1.08 m or (±8%) for Experiment 1 (pushing), and from 0.90 m to 1.09 m (±10%) for Experiment 2 (following).

2.5.3. *Inter-person distance*

For Experiment 2 (following), inter-person distance was measured using the HMD. The inter-person distance, as described in Fig. 2 (a), was calculated as the relative difference along the z-axis (+z is oriented along the length axis of the walking track) between the agent's body centre and the tracked HMD location. This distance was sampled each time the participant passed over one of six evenly spaced capture points along the walking path for each scenario. At the end of each scenario these six values were recorded, and a mean value taken as the inter-person distance for that participant/scenario combination.

2.5.4. *Analysis*

Statistical analysis was performed using SPSS (version 28.0.1.0). Where multiple instances of a variable were measured such as step length, walking speed, or inter-person distance for Experiment 2 (following), a single mean value was taken over the measuring zone for each participant in each experimental condition. The collected data was checked for normality (Shapiro-Wilks), and a repeated measures one-way ANOVA test was used to investigate the differences between conditions for each experiment. The data was tested using Mauchly's test for sphericity and depending on the results either a Greenhouse-Geisser correction was applied (where there was no evidence to assume sphericity), or Huynh-Feldt correction was applied (where there was evidence to assume sphericity). A p-value of 0.05, with Bonferroni correction applied, was used as a threshold for statistical significance for the post-hoc tests.

For comparison of walking speed in the RE vs. VE conditions a paired T-test was performed to compare the sample means between conditions. SPSS was used to calculate regression models for the data. For the walking speed vs inter-person distance relationship, a hierarchical multilinear regression model was applied to examine the difference between regression lines for the two experiments (pushing and following). For the walking speed vs step length relationship, a 2nd order polynomial regression model was applied.

Although the experiments use inter-person distance as the dependent variable, in crowd experiments it is more useful to think in terms of occupant density. Occupant density is commonly reported in two ways; persons/m (commonly used in one-dimensional walking experiments) or measured in persons/m^2 (more common in crowd experiments). In this paper, occupant densities are reported in the 1D form (i.e., persons/

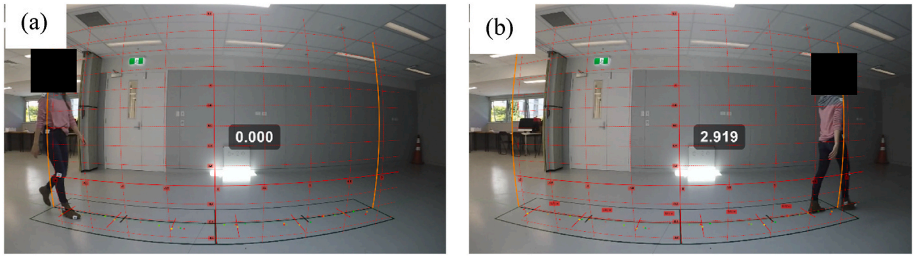

Fig. 5. Illustration of time to traverse measuring zone.

m). A linear persons/m density is simply calculated as the inverse of the inter-person distance according to

$$\rho = \frac{1}{d_t} \qquad \text{Equation 1}$$

where: ρ = occupant density (persons/m), d_t = inter-person distance (m).

To convert inter-person distance to density, Thompson [56] uses a method based on a circular packing approach, see Fig. 6, namely

$$\rho_{2D} = \frac{1}{0.87 \times d_t^2} \qquad \text{Equation 2}$$

where: ρ_{2D} = 2D occupant density (persons/m^2), d_t = inter-person distance (m).

Equation (2) can be rearranged to convert existing unidirectional experiments from 2D occupant density, ρ_{2D} (persons/m^2) to 1D occupant density, ρ_{1D} (persons/m) according to

$$\rho_{1D} = \left(\frac{1}{0.87\rho_{2D}}\right)^{-0.5} \qquad \text{Equation 3}$$

The resulting Equation (3) is used in the results section to compare experimental findings with other published fundamental diagrams [57–59]. While it is recognised that a crowd exists in 2 dimensions, single file movement has been shown to have a surprising level of conformity to movement in a plane [60,61].

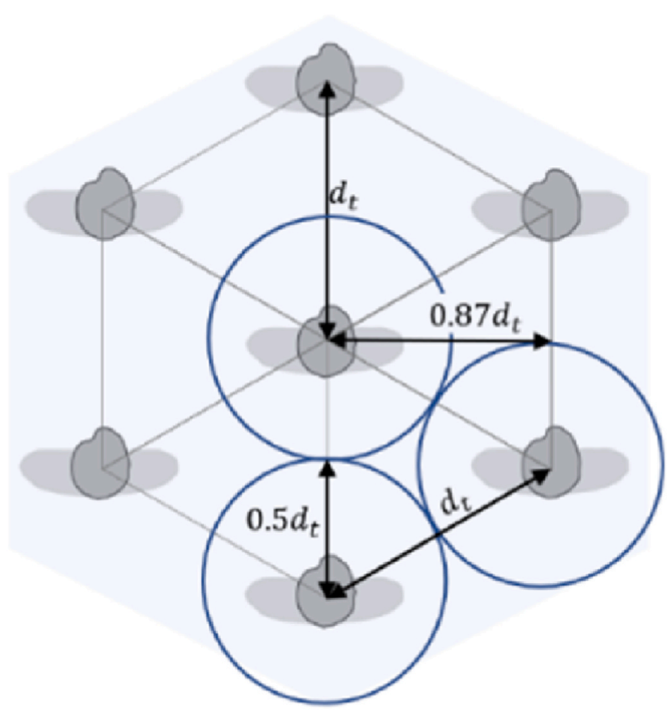

Fig. 6. Reducing the circular packing configuration to linear dimensions, adapted from Thompson [56].

3. Results

Table 2 and Table 3 summarise the descriptive statistics for Experiment 1 (pushing) and Experiment 2 (following).

3.1. *Walking speed and inter-person distance*

Fig. 7 (a) shows the distribution of walking speeds with different inter-person distances measured from Experiment 1 (pushing). Results suggest that walking speed reduces with inter-person distance at inter-person distances below 2 m, but is constant above inter-person distances of 2 m. Fig. 7(b) shows the distribution of the mean participant walking speed ordered by inter-person distance measured from Experiment 2 (following), showing a similar trend to Experiment 1 (pushing) but with lower participant walking speeds. As there is considerable scatter, for Fig. 7 (b), the inter-person distances were grouped into 0.5 m bins.

Fig. 8 shows the distribution of inter-person distances with different agent walking speed conditions measured from Experiment 2 (following). Results suggest that inter-person distances increase as agent walking speed increases.

3.1.1. *Statistical analysis – experiment 1 (pushing)*

A one-way repeated measures ANOVA was conducted to compare the effect of inter-person distance (IV) on walking speed (DV), in five conditions (inter-person distances of 1.0, 1.5, 2.0, 2.5, and 3.0 m). The results of the one-way repeated measures ANOVA with Greenhouse-Geisser correction showed there was a statistically significant difference in walking speed between at least two inter-person distances, [F (1.534, 41.419) = 15.250, $p < 0.001$].

Post-hoc tests using pairwise comparisons with Bonferroni correction showed that participants had a statistically significant lower walking speed in the 1.0 m inter-person distance condition (mean = 1.07 m/s, S.D. = 0.29 m/s), compared with inter-person distance conditions of 1.5 m (mean = 1.21 m/s, S.D. = 0.25 m/s, $p < 0.001$), 2.0 m (mean = 1.30 m/s, S.D. = 0.17 m/s, $p < 0.001$), 2.5 m (mean = 1.31 m/s, S.D. = 0.18 m/s, $p < 0.001$) and 3.0 m (mean = 1.28 m/s, S.D. = 0.21 m/s, $p = 0.006$). However, the differences in walking speed between inter-person distances of 1.5 m, 2.0 m, 2.5 m, and 3.0 m were not significant (p =>0.05). Between subject effects showed no statistically significant difference between the order participants were presented with the conditions ($p = 0.757$).

3.1.2. *Statistical analysis – experiment 2 (following)*

A one-way repeated measures ANOVA was conducted to compare the effect of agent walking speed (IV) on inter-person distance (DV), in three conditions (agent walking speeds of 0.8, 1.0, and 1.2 m/s). The results of the one-way repeated measures ANOVA with Huynh-Feldt correction showed that the inter-person distance differed significantly between agent walking speeds [F (1.762, 49.327) = 1.141, $p < 0.001$].

Post-hoc tests using pairwise comparisons with Bonferroni correction

Table 2
Descriptive statistics for Experiment 1 (pushing) results.

Inter-person Distance (m)	Walking Speed (m)					Step Length (m)				
	N	Min	Max	Mean	SD	N	Min	Max	Mean	SD
1.0	28	0.21	1.58	1.07	0.30	28	0.27	0.75	0.59	0.11
1.5	28	0.35	1.72	1.21	0.26	28	0.36	0.83	0.65	0.09
2.0	28	0.89	1.68	1.30	0.17	28	0.57	0.84	0.67	0.58
2.5	28	0.98	1.74	1.31	0.18	28	0.59	0.84	0.68	0.06
3.0	28	0.88	1.80	1.28	0.21	28	0.57	0.86	0.67	0.06

Table 3
Descriptive statistics for Experiment 2 (following) results.

Agent Velocity (m)	Inter-person distance (m)					Step Length (m)				
	N	Min	Max	Mean	SD	N	Min	Max	Mean	SD
0.8	27	0.65	1.98	1.26	0.32	27	0.45	0.60	0.53	0.04
1.0	27	0.82	1.95	1.44	0.30	27	0.55	0.69	0.61	0.04
1.2	27	1.24	2.38	1.63	0.29	27	0.61	0.76	0.66	0.04

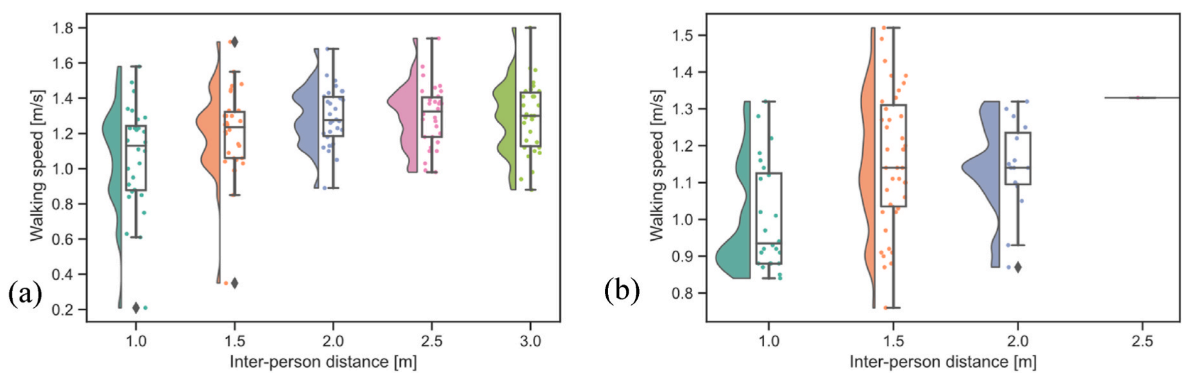

Fig. 7. (a) Experiment 1 (pushing) participant walking speed vs inter-person distance, and (b) Participant walking speed vs inter-person distance (in 0.5 m/s bins) for Experiment 2 (following). This 'Raincloud plot' combines an illustration of the data distribution (the 'cloud') with jittered raw data (the 'rain'), and a supplementary boxplot [62].

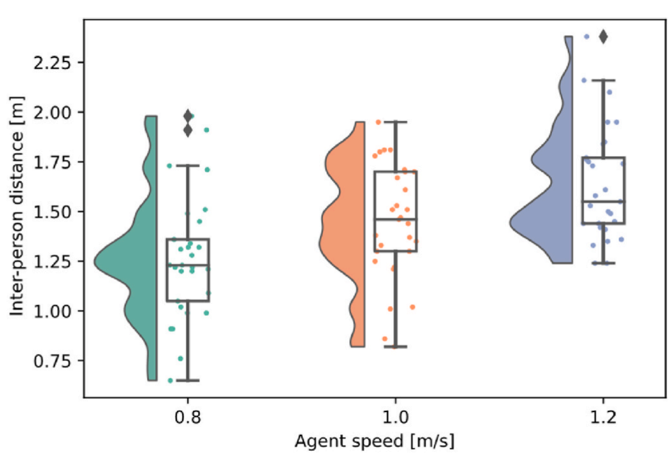

Fig. 8. Measured inter-person distance vs agent speed for Experiment 2 (following).

showed that participants had a lower mean inter-person distance in the 0.8 m/s agent walking speed condition (mean = 1.26 m, S.D. 0.31 m), compared with agent walking speed conditions of 1.0 m/s (mean = 1.44 m, S.D. = 0.29 m, $p < 0.001$) and 1.2 m/s (mean = 1.63 m, S.D. = 0.28 m, $p < 0.001$). Similarly, participants had a lower inter-person distance in the 1.0 m/s agent walking speed condition compared with the 1.2 m/s agent walking speed condition ($p < 0.001$). At these walking speeds, inter-person distances are generally below 2.0 m, which is in the region of constrained flow. Between subject effects showed no statistically significant difference between the order participants were presented with the conditions ($p = 0.650$).

3.2. Walking speed and step length

Fig. 9 (a) plots walking speed vs inter-person distance with a linear regression line for each experiment. Both experiments appear to show a similar relationship between walking speed vs. inter-person distance. There was a strong positive correlation between step length and walking speed. This relationship was approximated by a 2nd order polynomial regression according to $s = a_3v^2+a_2v + a_1$, where: s = normalised step length (m), a_1, a_2, a_3 = coefficients, v = walking speed (m/s). These regression lines have been plotted alongside other published data at Fig. 9 (b) where the trends follow similar patterns observed in other experiments. The limits of the experimental results presented in this figure are different due to the nature of the experimental set up (e.g., the pushing experiment had lower inter-person distances and resulting lower walking speeds).

3.3. Walking speed and density

Pedestrian densities have been converted from inter-person distances using Equation (1) and a plot of walking speed vs density (fundamental diagram) for each experiment is shown at Fig. 10. There is significant scatter across both experiments, with Experiment 1 (pushing) data being

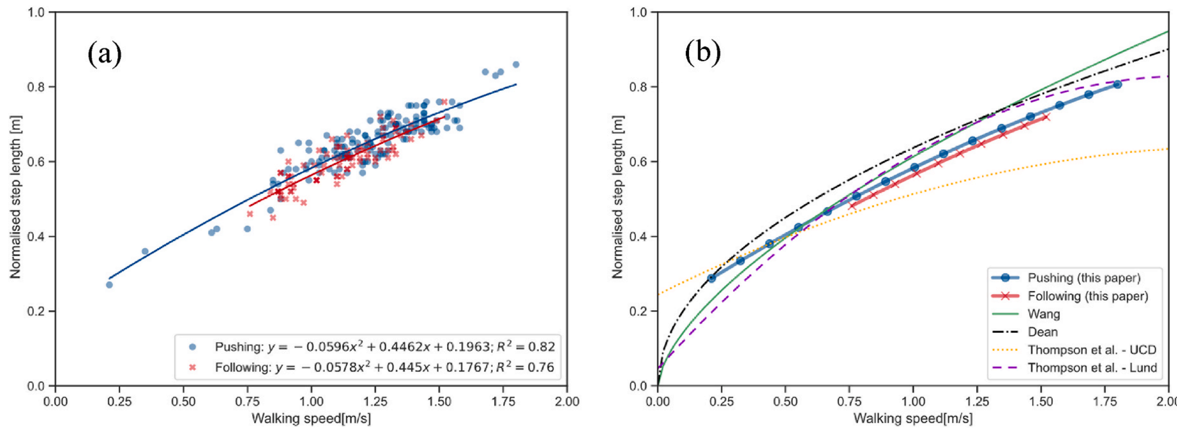

Fig. 9. (a) Step length vs walking speed with polynomial curves fitted, (b) Step length vs. walking speed, comparing experimental data to published data.

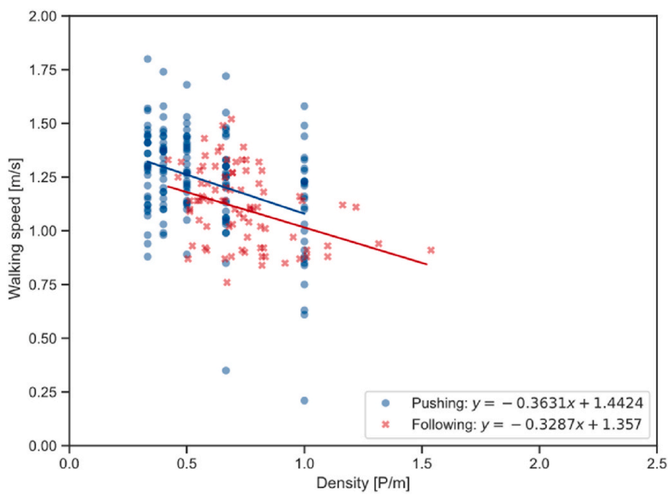

Fig. 10. Walking speed vs density for both experiments.

notable in that the five distinct inter-person distance scenarios are obvious with the banding of the data. For both experiments a negative correlation is observed between walking speed and density. This can be approximated by the linear relationship $v = \kappa_0 + \kappa_1 D$, where: v = walking speed (m/s), κ_0 = constant, κ_1 = density coefficient, D = Density (p/m). For Experiment 1 (pushing), $\kappa_0 = 1.442$, $\kappa_1 = -0.363$, for Experiment 2 (following), $\kappa_0 = 1.357$, $\kappa_1 = -0.329$.

A hierarchical multilinear regression model was applied to the combined data from both experiments. This model showed that there is no statistically significant difference between the two regression curves ($p = 0.383$). Noting a simple linear regression does not appropriately consider the portion of movement at unimpeded walking speed (low densities), a segmented nonlinear (piecewise) regression is applied using a Python package '*piecewise-regression*' [63] which is based on Muggeo [64], which for a single breakpoint has the general form of:

$$y = \alpha x + c + \beta(x - \psi)H(x - \psi) + \zeta \qquad \text{Equation 4}$$

Where given some data, x, y, the gradient of the first segment, α, the intercept of the first segment, c, the change in gradient from first to second segment, β, and breakpoint position, ψ. H is the Heaviside step function [63]. For the combined data from both pushing and following experiments, $\alpha = 0$ ($p = 0.817$), $c = 1.289$ ($p < 0.001$), $\psi = 0.400$, such that the piecewise regression has the form of Equation (5) with $R^2 = 0.172$:

$$y = 1.289 - 0.422(x - 0.400)H(x - 0.400) \qquad \text{Equation 5}$$

This piecewise regression is plotted at Fig. 11 with a breakpoint position, ψ, of 0.40 P/m, which is the point at which walking speed changes from the unconstrained to the constrained regime. Fig. 11 also shows other published fundamental diagram relationships [57,58] using single-file unidirectional loop walking experiments; where applicable, data from others has been converted to 1D density (P/m) using Equation (3). It can be seen that walking speed decreases with increasing density.

3.4. *Walking speed in the real environment (RE) vs. virtual environment (VE)*

For Experiment 2 (following), measurements of unimpeded (preferred) walking speed were recorded for both RE and VE. As can be seen in Fig. 12, participants appear to have higher walking speeds in the RE condition than in the VE condition.

Unimpeded walking speed data for VE and RE conditions was examined and a paired sample *t*-test was performed to compare unimpeded walking speed. There was a significant difference and reduction of 19% in walking speed between RE (mean = 1.47, S.D. = 0.19) and VE (mean = 1.19, S.D. = 0.17); $t(28) = 8.58$, $p < 0.001$.

3.5. *Comments from post-experiment questionnaire*

During the experiments, several qualitative observations were made.

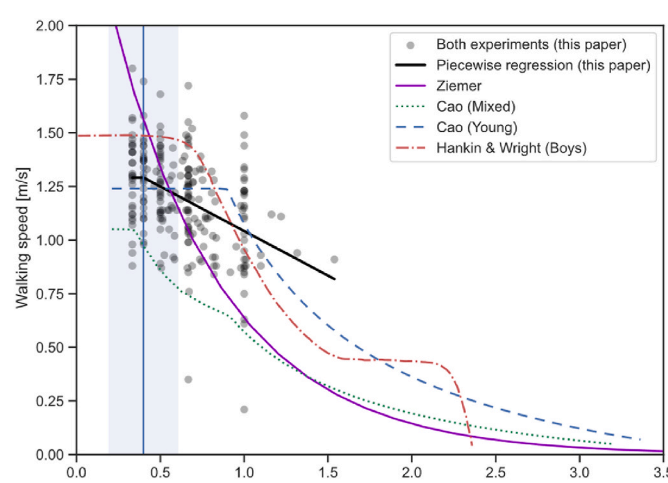

Fig. 11. Piecewise regression of walking speed vs density: Unidirectional walking - loop configuration. Piecewise regression with breakpoint and associated confidence interval in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

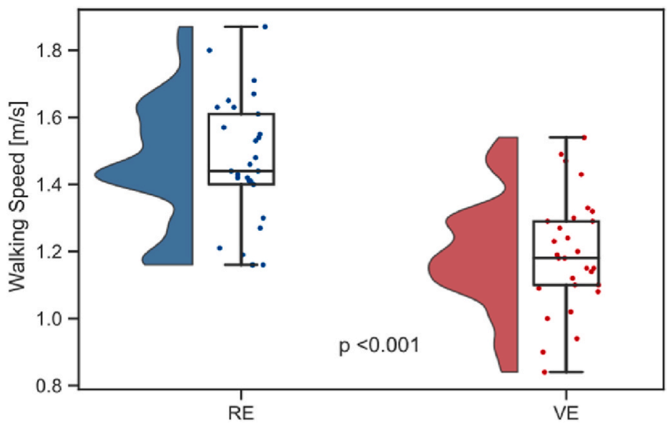

Fig. 12. Unimpeded walking speed for the VE compared with RE.

In addition, a post-test questionnaire was completed for Experiment 1 (pushing), which provided a means for qualitative commentary on the experiment. In general, Experiment 1 (pushing) results showed decreasing walking speed with decreasing inter-person distances, however there were some isolated instances where participants showed contrary results. Comments returned from these participants included "because I noticed the pedestrian being closer, I initially took shorter steps, then I figured out she matched my speed, so I could walk like normal, the distance would stay the same …" indicating some participants understood the spacing mechanism and they could walk as fast as they liked, with the agent always remaining at a fixed distance from them.

Comments varied from low levels of perceived realism "the woman in front of me was unrealistic", and "the whole background, and lighting were unrealistic", through to some participants perceiving the scenario as quite realistic including "the lady in front of me", "the space (dimensions) and the motion/movement in that space" being realistic features, and empathetic responses such as "not wanting to bump into the old lady in front of me". Many participants decided the room could have more fidelity including additions of furnishings and improved textures on windows, walls, and ceilings for it to be perceived as realistic. Comments related to visibility of the Oculus Guardian grid displaying indicated breaks in presence when the participants reached the extreme end of the tracked area. Subjective perceptual comments were also noteworthy, with some participants commenting on the perceived feeling of space within the room, with some feeling "like I was tall and close to the roof". Others commented that they still had a fear of bumping into something in the real lab and "clashing with real objects in VR".

4. Discussion

The aim of this study is to examine the relationship of step length and walking speed with inter-person distance for one-dimensional walking in-line in immersive VR. This was achieved using two VR experiments. In Experiment 1 (pushing), a virtual agent had a 'pushing' configuration at a fixed distance ahead of the participant, while the participant 'follows' a virtual agent who moved at a fixed walking speed in Experiment 2 (following). Virtual reality lends itself well for this type of experiment as the independent variables of inter-person distance for Experiment 1 (pushing), or agent walking speed for Experiment 2 (following) can be exactly manipulated by the researchers allowing a high degree of experimental control. In contrast, a similar experiment in a real environment either needs to use a researcher trying to walk at a pre-determined speed in front of a group of people, and/or injection of a certain number of people into a loop walking scenario in an attempt to achieve the desired density and thus inter-person distance. This work did not intend to represent a traditional validation study and was a stepping stone on the path to validation. However, the experimental results were broadly in line with the existing literature values, supporting a preliminary validation of the concept study using existing published data. Limitations associated with this preliminary validation include the VE scenario only including a straight portion and a single (virtual) agent, where the existing experimental data had multiple people walking in the straight portion of a loop configuration.

4.1. *Effect of experimental configuration – pushing vs. following*

Results showed no significant differences between the relationship of inter-person distances and walking speeds across both pushing and following experiments. This finding is important as it shows the relationship between walking speed and inter-person distance (related to occupant density) in an in-line walking scenario within a virtual environment, is essentially the same regardless of whether the participant is pushing the virtual agent ahead or following a virtual agent who is walking at a pre-determined speed. It is therefore worth considering the relative merits of each experimental method. The key advantage of a fixed inter-person distance as used in Experiment 1 (pushing) is tighter experimental control of the scenario, exploiting one of the advantages of virtual reality experimentation. This method is clearly quite removed from reality, noting that in a physical in-line walking experiment a participant in front will be unable to keep a fixed distance from a participant behind them; yet this demonstrates one of the great advantages of VR, where a variable of interest can be controlled which is impossible to control in reality. However, it was noted by some participants that the initial walking appeared to be 'artificial' where the agent acceleration was exactly matched to that of the participant. In contrast, the method of agent movement in Experiment 2 (following) could be perceived as more natural with an acceleration from zero up to the fixed walking speed for each scenario. However, the 'following' method does not have the ability to set a fixed inter-person distance. While a fundamental diagram can still be generated from the 'following' method, the data is more scattered, and it is considered the 'pushing' configuration offers a better ability to explore the fundamental movement parameters related to an individual walking in a virtual crowd.

Given the discussion on the merits and drawbacks of the methods for each experiment, and noting the results are not significantly different, for future work it is recommended the spacing algorithm (which sets the inter-person distance between participant and virtual agents) is given further attention for a more realistic distance keeping mechanism – recall that some participants found the 'pushing' scenario "unrealistic" and others figured out the underlying algorithm and decided they could walk as fast as they wanted knowing a fixed distance would be maintained between themselves and the virtual agent. An example of an improved spacing algorithm is a hybrid approach where the scenario begins in the 'following' regime employed in Experiment 2 (following), where a countdown is provided and the agent accelerates to a walking speed, and then transitions to a 'pushing' regime as per Experiment 1 (pushing). This approach would have the advantage of a more realistic following condition initially before a transition to a pushing condition which offers more experimental control (with an exact inter-person distance being set).

4.2. *Effects of inter-person distance on walking speed*

Experiment 1 (pushing) showed the influence of inter-person distance in the virtual environment and resulting walking speed in the real environment. The experiment demonstrated that as inter-person distance reduces (occupant density increases), the participant walking speed reduces. This is an important result as it demonstrates the general hypothesis that people walk slower with increased density when immersed in a virtual environment, in a similar fashion to walking behaviour in reality. It is noted this relationship only holds until an inter-person distance of between 1.5 and 2.0 m is reached, after which point there is no further increase in walking speed as this inter-person distance increases to 2.0 m, 2.5 m, or 3.0 m. This finding is not surprising, given these inter-person distances used in Experiment 1 (pushing) equate to densities of 0.5 p/m, 0.4 p/m, and 0.33 p/m respectively; and these are each considered low densities. When comparing these occupant densities to some common fundamental diagrams, as shown in Fig. 11, it can be seen that these are densities which are at the lower end of the scale for crowd density experiments, i.e., in the region of inflection between an unimpeded walking speed regime and a constrained walking regime. Similar findings were observed in Experiment 2 (following), where lower agent walking speeds were correlated with reductions in inter-person distance. The range of agent walking speeds were chosen to be in the region of constrained flow, so the results are not surprising.

The inter-person distance, (also referred to as headway) is often measured between centrelines of individuals [58,65]. This method of measurement does not directly consider the body dimensions of individuals, i.e., the perceived inter-person distance between two large obese people would hypothetically be lower than the perceived inter-person distance between two slim people, even though the measured inter-person distance from centreline to centreline was the same. A consideration could be to either consider this inter-person distance as the space between the chest of one person and the back of the person in front, or alternatively (and preferably) consider the incorporation of body dimensions while leaving the defined inter-person distance as centreline to centreline.

4.3. Empathetic response to virtual agents

Some of the qualitative observations from participants were regarding the associations toward the virtual agent with comments about how “realistic” she appeared. This raises the question about empathetic responses to virtual agents and how this may change the levels of social interaction in the experiment. Many previous studies have shown degrees of empathy and collision avoidance toward virtual agents [66–68], and that the phenomena associated with social interaction observed in the real world can be replicated in the virtual world [69]. While there were ranges of empathetic responses noted toward the agent, for future work it is recommended to implement a level of manipulation to assess the empathetic response of participants based on the Threshold model of social influence [70] as cited in Ref. [69], which posits that increased perception of agency, i.e., the virtual agent is perceived to be an avatar (a digital representation of a real human) leads to stronger social interaction effects.

4.4. Effect of environment (real vs. virtual) on walking speed

There was a noticeable decrease in unimpeded walking speed when participants were walking within a virtual reality when compared to the real environment. This effect can be partly due to novelty, noting participants were provided only a very limited opportunity to become familiar with the concept of overground room scale walking in an immersive VE before having preferred walking speed measured. However, as indicated by other researchers [39–41,47], VR can be shown to induce a sense of instability resulting in slower walking speed and increased gait variability measures such as step-width and duration of double-support phase (the portion of the stride cycle where both feet are on the ground). However, there are other factors which should also be considered noting the discrepancy between virtual and real environment walking speeds is not universally understood [71]. One factor is the cautiousness noted by some participants due to a fear of bumping into real world obstacles while navigating in VR; as the natural field of vision is fully obscured by a digital display, it is proposed there is an element of trust and familiarity which must be developed to reduce this inhibition. Future research in this area could explore the implications of psychological factors such as a lack of trust in the visual display and subsequent cautiousness when walking. Another potential factor is related to technological limitations, such as field of view and resolution of HMDs, or fidelity of the virtual environment. In addition, further work could be carried out to investigate the effect of egocentric distance perception in VR, as it has been noted that there are potential discrepancies between estimated of virtual and real distances [38]. These egocentric perceptual factors could be significant enough to explain the tendency for participants to walk slower in VR compared with reality.

4.5. Self-embodiment

Some of the comments from participants noted they felt the situation was artificial. It is proposed a significant part of this was due to a low value of presence (the feeling of ‘being there’). To increase ecological validity, recommendations for future work are to provide the participant with an avatar body in the VE; at the least this should include hands which are tracked by use of hand tracking or controller tracking to match the participants physical movements in the real to the virtual environment. Ideally tracked feet should be included to improve proprioception and foot placement, and to enable participants to see their feet in relation to the agent in front. The inclusion of an avatar body provides an illusion of self-embodiment and can add to the feeling of presence (itself an important aspect in measuring distance, and in enabling ‘realistic’ behaviours). Further, the inclusion of a tracked avatar body is important when considering the walking behaviour, foot placement and maintaining a contact buffer between an individual and a virtual agent.

4.6. Representativeness of participants and environment

It is recognised these experiments are performed on small samples consisting of mostly students and are not diverse and representative of the wider population. Future work could consider having the exact same participants walk in a group experiment and then in VR to mitigate difference between, for example, the age of VR agents and the actual physical crowd. It is also recognised there was no data collection regarding a participant’s previous experience in VR, which could influence results. Further collection of diverse participants is clearly beneficial. All participants and the virtual agent could walk unaided and there was no consideration of any persons of mixed ability or with any movement aids such as crutches, walkers, or wheelchairs. Further, these results and finding are only interpreted in the context of single directional walking in a following configuration and there was no consideration of overtaking, lane formation or bi-directional flows. As such, any conclusions must be considered with understanding the limitations of the research – and care must be taken when generalizing results to other groups or contexts.

It is also noted that extrapolation from this VR laboratory experiment and a real-life crowd scenario (with or without stress) was not the intent of this research. In an effort to explore the phenomena in this research a level of design simplification and artificiality was necessary, and as noted by Haghani [72] this is often the case where experiments seek to gain internal validity at the expense of comprising generalisability.

5. Conclusion

The piecewise regression determined for data from both experiments showed similar trends to existing single-file loop walking experiments including a breakpoint in the lower density region where walking speed changed from a constrained to unconstrained regime. This result indicates the trends observed in previous single file loop walking experiments (in reality) appear to hold for single-file walking in a virtual environment.

A key finding from the experiments of this study is that no significant difference between walking speed and density (inferred from inter-person distance) could be observed, regardless of the method of spacing ('pushing' or 'following'). This is a useful result for future experiments as it gives the researcher flexibility in experimental design and indicates a hybrid spacing configuration between the participant's avatar and virtual agents (with 'following' to begin and transition to the 'pushing' configuration) is likely to be effective.

Results suggest that movement in VR is slower than in RE, but the study could not determine the factors. This reduction in speed requires further exploration to better understand the root causes and potential calibration methods to correct for this discrepancy.

Experiments in VR showed similar step length vs walking speed relationship in a virtual environment, which was comparable to other real-world experiments indicating this long-established relationship holds in the virtual environment, as well indicating a natural walking pattern (albeit at a slower walking speed) when in VR. Noting this is a single measure and does not fully describe gait, other biomechanical measures which describe walking gait should also be explored in future work.

These experiments represent a compelling case for future research in this area to further explore the differences between individual movement in crowds when in VR compared with the real world.

6. Ethical considerations

The project was subject to review and approval by the University of Canterbury Human Ethics Committee. The research was classified as low risk and was reviewed and approved, reference HEC 2020/94/LR Amendment 1 for Experiment 1 (pushing), and HEC 2021/65/LR for Experiment 2 (following). Key considerations included informed and voluntary consent, privacy and confidentiality of participants and their data (including video recordings and images) and identifying and applying controls for health and safety risks. Although a $10 voucher was provided to thank participants for their time, it was explained to the participants they could end the experiment at any time of their choosing and still receive this reimbursement. However, none of the participants terminated the experiment.

CRediT author statement

Luke de Schot: Conceptualization, Methodology, Software, Formal analysis, Investigation - Experiment 1 (pushing), Writing – original draft. **Daniel Nilsson:** Conceptualization, Methodology, Resources, Supervision, Writing - Review and Editing. **Ruggiero Lovreglio:** Conceptualization, Methodology, Software, Supervision, Writing – Review and Editing. **Tyler Cunningham:** Investigation - Experiment 2 (following). **Shane Till**: Investigation - Experiment 2 (following). All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Corrigendum

Corrigendum to "Exploring single-line walking in immersive virtual reality" [Fire Saf. J. 140 (2023) 103882][☆]

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