OXFORD

Interacting with Computers, 2023, **35**, 628–636
https://doi.org/10.1093/iwc/iwad021
Advance access publication date 3 March 2023
Special issue paper

Using an Immersive Video Environment to Assess Pedestrians' Compliance With COVID Distance Keeping Interventions

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Physical distancing is a key measure to slow the spread of many highly infectious diseases, e.g. COVID-19. Streetscape interventions such as pedestrian signage can contribute to ensuring distances are kept, but it is unclear to what extent people comply with these in practice. This paper tackles this question using an immersive video environment to realistically simulate real-life streetscapes in the lab. In a controlled user study, we augmented panoramic video footage with pedestrian one-way street signage and recorded route decisions to assess compliance with distance keeping measures. Our results indicate that such signage affects routing decisions and can thus help pedestrians to avoid crowded situations where distance keeping is difficult. We also identified further factors affecting decisions and a correlation between intention to comply and actual compliance. The experimental method we used enabled us to effectively and safely carry out a study of a phenomenon that in the real world depends on interaction with the physical environment. This method may have applications in other areas in which simulations of physical environments are important.

RESEARCH HIGHLIGHTS

- We propose a method based on an immersive video environment to conduct user studies investigating the impact of interventions in the physical environment on human behaviour.
- We show that this method allows for realistic, safe and controlled studies involving human–streetscape interaction in a pandemic context.
- We report on compliance with distance keeping measures and discuss potential uses of the method to run user studies during a pandemic or in other situations where simulation of a physical environment is important.

Keywords: *empirical studies in HCI; human–computer interaction (HCI); human-centered computing; model development and analysis; modeling and simulation; computing methodologies*

1. INTRODUCTION

In order to combat COVID-19, governments around the world implemented a number of measures, including vaccinations, mask wearing mandates and remote work policies (e.g. CDC, 2021). Distance keeping is another essential measure, as research has shown that physical distances substantially reduce infection risks (Chu *et al.*, 2020). One way of operationalizing distance keeping are streetscape interventions in pedestrian areas (Fig. 1), such as closing a street, turning it into a one-way street or setting up a network of dynamic signage (Langner and Kray, 2014). Understanding compliance with physical-distancing policies and/or interventions as well as their effectiveness is essential for policy (re)design and operationalization. Existing studies focusing on gaining this understanding typically *ask* participants how they *would* respond to physical-distancing policies (e.g. Briscese *et al.*, 2020) or *have* responded in the past (e.g. Beca-Martínez *et al.*, 2021) instead of measuring their actual behaviour while navigating a physical environment. This might be due to several challenges attached to measuring this behaviour in the wild. These include how to control (potentially relevant) factors of influence (e.g. signage, crowdedness), how to install distance keeping interventions (if they are to be tested) and how to ensure the safety of participants in terms of infections.

We aim to address these challenges by proposing a novel approach to assess compliance with distance keeping measures when navigating on foot. It uses an immersive video environment (IVE) that can overlay content over panoramic video footage to realistically simulate distance keeping measures. The measure investigated in our study is static one-way street signage for pedestrians in pedestrian and mixed traffic zones. (A pedestrian zone is a traffic area where pedestrians have exclusive right of use or priority over other road users.) The two main contributions of the work reported here are as follows:

Received: October 27, 2022. **Revised:** October 25, 2022. **Accepted:** December 7, 2022

FIGURE 1. Streetscape interventions to fight COVID-19 in Utrecht, NL: (a) pedestrian one-way street, (b) sign asking to keep right, (c) pedestrian roundabout, including examples of non-compliance. ©Judith Verstegen

(i) a better understanding of how pedestrian signage embedded in the streetscape influences pedestrian navigational behaviour in public spaces, and
(ii) an approach to safely conduct user studies that require interaction with the physical environment and interventions therein during the pandemic.

These contributions can benefit researchers studying interactions with the streetscape and/or interactive technologies embedded in such environments. In addition, our contributions can help to improve models incorporating distance keeping behaviour, e.g. agent-based models to predict the spread of COVID-19. Finally, they can inform decision-makers (e.g. at city councils) regarding the effectiveness of pedestrian signage aimed at encouraging distance keeping.

In the remainder of this article, we first review related work and introduce our approach. This approach was applied in a user study, which we describe in the following section. We then report on the results we obtained and discuss their relevancy, implications and limitations in the penultimate section. The final section briefly summarizes our main contributions.

2. RELATED WORK

Assessing the effectiveness of measures to facilitate distance keeping poses several challenges, in particular during an ongoing pandemic. These include the effort of deploying such measures in the real world, the potential health hazard resulting from field studies, the lack of control in such studies and the lack of realism in questionnaire-based studies. Previous work has proposed simulation-based studies to address these issues, which we briefly review in the following.

By simulating different scenarios in a laboratory, researchers can control very precisely what stimuli a participants is exposed to, experiments can be repeated easily under the same conditions and the method is also applicable to situations difficult to access in real life (Feng *et al.*, 2021). In addition, strict hygiene measures can be implemented to ensure the safety of participants. Typically, participants are exposed to synthetic virtual worlds that they access on different devices, e.g. desktop computers (Sousa Santos *et al.*, 2009), tablets (Zhao *et al.*, 2020), cave-like visualization environments (van Veen *et al.*, 1998) or through head-mounted displays (Sousa Santos *et al.*, 2009). The latter are less feasible in a pandemic setting due to hygienic considerations and their interference with face masks. Previous work has shown that there is a strong correlation between navigation behaviour in such virtual environments and in the real world. Coutrot *et al.* (2019), for example, found wayfinding and path integration performance in a mobile app to be similar to corresponding real-world tasks. Similarly, Li *et al.* (2019) compared results of field studies and virtual experiments in the scenario of pedestrian choices of exit routes. Both settings showed similar results, for instance people preferred to take routes with lower pedestrian density. This conformity thus indicates that virtual experiments can be a valid method of studying simple pedestrian behaviour.

Various navigation-related questions can be examined in such virtual environments. For example, studies have been run that looked at basic navigation performance in different participant groups, like the influence of the gender (Martens and Antonenko, 2012) or age (Moffat *et al.*, 2001). Basu *et al.* (2022) found 105 factors associated with pedestrian route choice investigated in past research and categorized them into three groups, with age and gender belonging to the group of pedestrian socio-demographic factors. The other two groups are trip characteristics like the length of the trip and built environment factors like sidewalk characteristics or the pedestrian density. In most studies, they observed a route is less likely chosen if it has a higher pedestrian density. Zhao *et al.* (2020) investigated the love parade disaster in Duisburg, Germany (a fatal event that involved large crowds). They created an agent-based simulation and rendered virtual reality scenes that participants then were exposed to. They also added various streetscape interventions to the agent-based simulation to evaluate whether they could have prevented the disaster. This research is closely related to the work presented in this paper, where we also evaluate interventions as a means to reduce risks. In contrast to Zhao et al.'s work, we do not use synthetic images but rely on panoramic video footage of real places. In addition, we plan to do this the other way around: in future work, we will use behavioural rules derived from the current study to construct an agent-based model rather than exposing participants to scenes generated by such a model.

Video-based environments are less frequently used for evaluation tasks than synthetic worlds. While they provide an unparalleled degree of realism and are comparatively easy to create, they lack the freedom of movement that true 3D worlds enable. The latter also allow for stereoscopic viewing, which can increase immersion. Singh *et al.* (2006) used such an environment to prototype and evaluate mobile applications. Ostkamp and Kray (2014) proposed a toolkit that facilitates the design and evaluation of public display systems using virtual environments. The toolkit

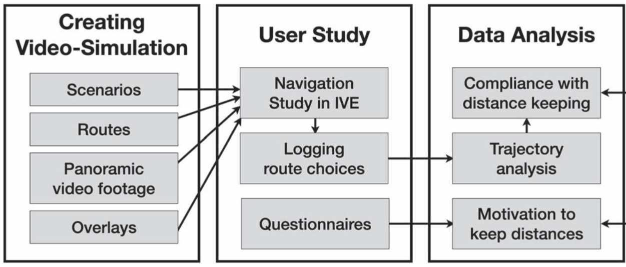

FIGURE 2. Overview of the proposed approach.

FIGURE 3. Participant inside the immersive video environment (IVE) showing panoramic footage of a streetscape with four overlays: (a) and (c) annotations supporting route choice, (b) and (d) pedestrian signage.

supports embedding additional content (overlays) in panoramic footage. The approach we are presenting in this paper follows a similar approach but instead of public displays we embed pedestrian signage and study-related information into the footage. In addition, we include structured transitions between decision points to support navigation. We also track the participants' movement through the simulated world in order to analyse their trajectories afterwards.

The measures implemented by the signage we present to the user are pedestrian one-way streets to reduce encounters between pedestrians. Mello (2020) simulated such encounters of pedestrians on closed paths, and one of the findings was that imposing one-way traffic on a walking path reduces the number of encounters to one fifth compared to bidirectional ways. Besides implementing one-way streets, another effective measure to decrease encounters between pedestrians can be to separate them by their respective walking speed.

3. APPROACH

The overall goal of our approach was to carry out a controlled user study that minimized infection risks while investigating interaction with a physical environment and distance keeping measures embedded therein. Specifically, we wanted to assess the impact of pedestrian one-way street signage embedded in the streetscape on pedestrian navigation behaviour during the COVID-19 pandemic.

For this purpose, we developed an approach consisting of three main phases (Fig. 2): the creation of a video simulation, the user study and data analysis. The first phase focused on creating a video simulation that facilitates investigating the specified research questions (cf. section 4.3). After selecting a suitable location, we specified a set of routes that enabled us to analyse navigation behaviour. We then captured panoramic video footage for all decision points on these routes and for all possible transitions between them. This footage was post-processed and uploaded to the IVE. Since we were particularly interested in the effect of streetscape interventions on navigation behaviour, we specified three different scenarios: (i) no pandemic and no interventions; (ii) pandemic with known measures, i.e. wearing masks; and (iii) pandemic with streetscape interventions. The latter consisted of pedestrian one-way signage that was not present in the real world, which we added as overlays (cf. Fig. 3b and d). We also added relevant information pertaining to the participants' decision as overlays (cf. Fig. 3a and c and section 4.3).

The second phase of our approach was the user study itself (section 4.5) that we ran in the IVE, using the previously created video-simulation. Participants were placed in a realistic audiovisual simulation of a streetscape via panoramic videos with the corresponding sound being played back through a surround sound system (section 4.4). They were tasked with navigating from a predefined origin to a destination in the context of each of the three defined scenarios. While they were navigating, the IVE tracked their route choices as they traversed the video simulation so they could later be analysed. After completing the three tasks, the participants filled in a questionnaire (section 4.3).

The final phase of our approach focused on data analysis (section 5). We translated route choices of the participants to trajectories, which then enabled a number of further analyses, i.e. differences in route lengths between the three scenarios and the level of compliance with the streetscape interventions. We also analysed motivational factors derived from the questionnaire and correlated them with compliance levels derived from the user study. The data underlying this article will be shared on reasonable request to the corresponding author. The software driving the IVE is web-based. The video-viewer runs in a chrome-less web browser window. Overlays are web pages as well that can display any content that a web browser can. A graph-based database stores all locations, routes, video materials, etc. The software is available as open source on GitHub (https://github.com/sitcomlab/IVE).

In the next two sections, we provide a detailed description how we applied our approach in practice. Section 7 includes a reflection on its application and its generalizability to other research questions.

4. USER STUDY

Using the method described in the previous section, we carried out a user study to assess the impact of pedestrian signage embedded in the streetscape on compliance with distance keeping measures while navigating on foot during the COVID-19 pandemic. Specifically, we wanted to answer the following three research questions:

- RQ1: How does the presence of a pandemic affect route choice of pedestrians in an urban area?
- RQ2: How does pedestrian signage aimed at facilitating distance keeping affect route choice of pedestrians in an urban area?
- RQ3: How does motivation to comply correlate with actual compliance with policy measures aimed at facilitating physical distance keeping?

Since our goal was to expose participants to realistic situations and to record their decisions while not exposing them to unnecessary infections risks, we chose to use the method described in the previous section. A field study would have entailed transferring participants to an unknown town, installing signage in the town and then having them perform navigation tasks on site. This was both impractical and would have incurred infection risks during transport and navigation. Instead, we recorded panoramic footage of three different routes in a small town and also took 360-degree photographs to create a realistic simulation of the town within the IVE. In the IVE, we were also able to add pedestrian signage as overlays and to instruct participants to imagine they are navigating without a pandemic being present. In addition, we were able to reliably record route decisions at each decision point, which we needed to answer RQ1 and RQ2. We also included a questionnaire in our research design to record motivation to comply. We used a within-subject design and systematically varied the order of exposure to different conditions while keeping the number of participants manageable.

4.1. Ecological validity

Though previous work has demonstrated that navigation behaviour in virtual environments and in the real world can be similar, e.g. Coutrot *et al.* (2019), there are a number of issues to consider in our case. The lack of actual movement in the IVE is one of those as, for example, the duration of the navigation could affect route decisions. In order to tackle this, we incorporated transitions between decision points, which took an amount of time proportional to time it would have taken to walk from one decision point to the next. Related to this is the issue of route-related knowledge participants might have, i.e. how long they have walked already and how long it will be until they reach their destination. The transitions provide information about the former and the latter was conveyed via additional overlays. In addition, it is important to assure that the added signage is well integrated into the simulated world so that it does not unduly ‘jump out’ to the participants. We tackled this issue by placing added signage in realistic locations, e.g. over actual signs recorded in the footage. Finally, we also asked participants about how immersive their navigation experience was to determine to what degree they felt like navigating in an actual town.

4.2. Participants

We recruited 30 participants via a university-wide newsletter and an announcement in a large lecture. The first four participants had to be excluded due to technical issues with the playback of the panoramic videos. We also slightly reworded the description of the scenarios based on their feedback. A total of 26 participants (14 male, 12 female; average age, 23; youngest, 18; oldest, 35) finished the study with valid data. A total of 25 of them were students and one was unemployed. Five participants reported a previous COVID-19 infection, while three belonged to a high risk group regarding a COVID-19 infection. Only one participant reported to have been to the small town, where we recorded the video material. The study was run in German. All participants were native German speakers.

4.3. Materials

4.3.1. *Routes*

We created three routes with the given material (Fig. 4). A route consists of an origin, a destination and a set of decision points that are connected by transitions. The origin is the first decision point. At each decision point, the participant can decide between two or three options of where to go. In order to ensure comparability, all routes had a similar number of decision points. Depending on their decisions, participants can pass between five and eight decision points per route. The routes have minimal overlap so

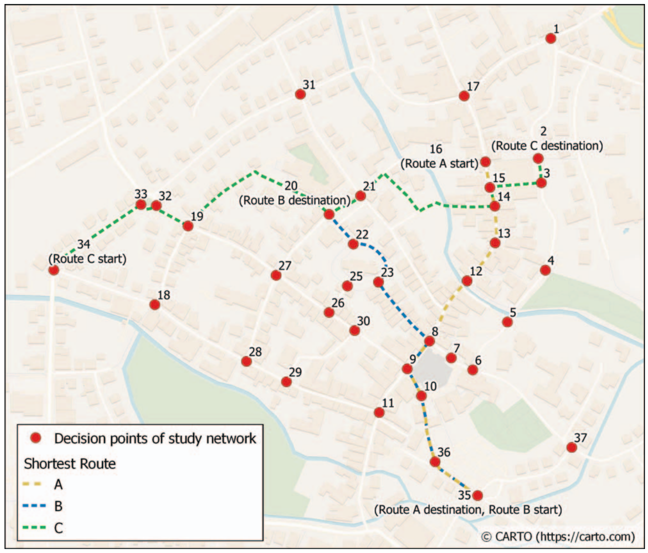

FIGURE 4. Origin and destination of the three routes (A, B and C), the shortest possible route per route network and all possible decision points in the study area.

that participants did not see the same location from the same angle twice. Transitions between decision points correspond to the real-life path one would walk from one decision point to the next. The playback speed of transitions was proportional to the length of the corresponding path in reality. This was to facilitate orientation and immersion, and to intuitively relay the length of a route segment to participants.

4.3.2. *Scenarios*

At the beginning of the study, we provided participants with a description of their main task: ‘You are on foot in a city on your way to a certain shop to buy something. You do not have an appointment so there is no time pressure to make a decision or to reach the destination.’ We then asked participants to imagine one of three different scenarios when navigating the route:

1) ‘There is no pandemic (no COVID). Pandemic clues such as masks are to be ignored, as the videos were recorded at pandemic times.’
2) ‘There is a pandemic, with infection incidence similar to the current one. The municipality implements the measures currently in force.’
3) ‘There is a pandemic, with infection incidence similar to the current one. The municipality has introduced additional measures for pedestrians.’

While the study took place, the seven-day incidence in Germany was around 1500 per 100 000 population. Several nation-wide and local measures were in place, e.g. in some parts of the city where the study was conducted it was mandatory to wear masks.

4.3.3. *Video footage*

Overall, we recorded panoramic video footage at 37 locations (decision points), each about 3 min long. In addition, we took panoramic photographs every 20 m on the path from one decision point to the next (230 images in total). All footage was recorded using a 360-degree camera, the Kandao QooCam 8K Enterprise, which allowed us to choose which 180-degree view to show during the study.

FIGURE 5. Street signs for pedestrians used as overlays in the user study. (a) One-way street, correct sense, text reads 'Corona measure for pedestrians: One-way street', (b) One-way street, wrong sense—no entry, text reads 'Corona measure: One-way street for pedestrians'.

For the video footage, we created somewhat seamless loops so that the footage could be played back without jarring seams when it looped back to the beginning. We created 47 180-degree videos from the recorded 360-degree footage for playback in the IVE. For decision points that could be approached from different directions, we created separate videos for each direction. After informally testing several different visualizations for transitions to avoid motion sickness (Kennedy *et al.*, 2010) while providing high immersion, we settled on the following approach to create the transitions: for each photo along a path, we added an arrow pointing from the current location to the location where the following photo was taken. The latter would then appear at the head of the arrow and be scaled up linearly until it filled the entire view. This process was repeated until the next decision point was reached. If the path contained curves, we made use of the 360-degree footage and rotated through the image to simulate the turn (see Appendix B for an example). We used a commercial video editor to create all transitions.

4.3.4. *Overlays*

In our study, we used two different kinds of overlays. One kind depicted street signs that served as pedestrian one-way street measures (see Fig. 3b and d)—similar to what has already been implemented in practice, see Fig. 1. Figure 5 shows the two signs we used in the study. The left one indicates that pedestrians are allowed to enter from this direction. The second one indicates that the street should not be entered from this direction. We designed both signs based on existing traffic signs in Germany, so that participants could easily understand them. Signs were placed so that in most cases, complying with them meant taking a detour from the shortest path. The second type of overlay conveys routing information to participants: they displayed the distance in time and meters to the final destination for each of the available route choices (see Fig. 3a and c). The latter was marked by a letter (A, B and C) so that participants could convey their route choice to the experimenter verbally.

The video footage and the overlays were stored in a graph-based database for playback in the IVE. The nodes in graphs correspond to decision points that are connected by directed edges, which correspond to transitions.

4.3.5. *Questionnaire*

In order to gather further information and feedback on participants' experience in the IVE, we asked them to fill out a questionnaire after completing all three navigation tasks. It also contained demographic and COVID-19 related questions, e.g. about their usual distance keeping behaviour during the pandemic. We asked participants to rate how immersed they felt (e.g. 'I could imagine the circumstances in the real world'), which factors affected their route decisions (e.g. distance to the destination, beauty of the route) and how much detour is acceptable for them. In addition, we enquired whether they had perceived the pedestrian signs, how they interpreted them and whether they caused any frustration. Participants were free to skip answering any question or to indicate that they could not answer a question. See Appendix A.1.1. for the full questionnaire.

4.4. Apparatus

The study was carried out inside an IVE, cf. Fig. 3. It consisted of three back-projection screens arranged in a semi-circular fashion. Each screen had a resolution of 1920 × 1080 pixels or 5760 × 1080 pixels for the entire system. The system also included a surround sound system to increase immersion when playing back panoramic video footage. The IVE was separated from the rest of the lab by heavy black curtains. Participants stood at a predefined location in front of the screens (as shown in Fig. 3), ensuring that their field of view was filled by the panoramic video played back on the system. Movement through the simulated world was controlled remotely from a workstation located in the lab but outside of the IVE.

4.5. Procedure

Participants were welcomed outside the lab, their vaccination status was checked and they were offered a fresh FFP2 mask. Next, they were handed a consent form. The experimenter explained it and answered any questions participants had. After they sign the form, the actual study began inside the lab.

The experimenter first explained the setup and overall procedure. The experimenter showed the different kinds of videos participants would see during the study and explained how participants can communicate with the experimenter during the study. Subsequently, the participants could try out a testing route consisting of one decision point with two options to choose from and a consecutive transition. We emphasized that participants should immediately let the experimenter know if they feel motion sick—this was also mentioned in the consent form. Once all questions of the participants were answered, they were tasked to navigate the three routes and scenarios. All three tasks followed the same procedure: first the particular scenario was explained using the instructions listed in section 4.3. Then, a video showing the starting location of the route was displayed and participants started to navigate. At each decision point, participants had to verbally announce which path they wanted to follow from two or more shown (as depicted in Fig. 3). The experimenter then triggered the corresponding transition in the IVE. After the transition, the next decision point was shown and the process repeated until the destination is reached. We used a Latin square to counterbalance the order of exposure to routes and scenarios in order to eliminate order effects. After completing all three routes, participants filled in a questionnaire, were debriefed and received a compensation (€15) for their time.

The study was approved by the local ethics committee. Due to the ongoing pandemic, we implemented several measures. The participants were able to get tested voluntarily and free of charge at a nearby COVID testing centre. We provided free masks to all participants before the study. The experimenters took tests on each day the study was run. During the entire study, the participants and the experimenter wore masks. Hand sanitizer was offered after signing forms and filling in the questionnaire. The lab was aired extensively before a new participant arrived as well as before and after each route. In addition, participant and experimenter were separated during the navigation study by a heavy curtain.

5. DATA ANALYSIS

5.1. Creating trajectories

In order to record the participants' route choices, we logged information on what decision points and overlays users came across and what directions they chose at these points. In addition, the time of arrival at decision points and decisions taken were stored. Trajectories for each route a participant took were produced from the logging files by mapping decision points and route choices to street segments from the underlying study area. Subsequently, the mapped street segments could be merged to trajectories for further analysis.

5.2. Behaviour change and compliance analysis

Since complying with the added pedestrian signage led to a detour, the deviation from the shortest metric path can be used to compare routing behaviour in different scenarios. Since the three routes varied in terms of minimum lengths, we computed the normalized observed detour to facilitate analysis across all routes:

$$\frac{PL\,(p,r)}{SPL(r)} - 1 = NOD\,(p,r)\,,$$

where *PL(p,r)* is the path length of the trajectory of participant *p* on route *r*, *SPL(r)* the shortest available path length on route *r* and *NOD(p,r)* the normalized observed detour taken by participant *p* on route *r*. In order to answer research questions 1 and 2, we tested for differences in the mean normalized observed detours across the three scenarios using Welch's analysis of variance (ANOVA), which we used instead a default ANOVA since the null hypothesis of equal variances was rejected using Bartlett's Test (Bartlett, 1937). Pairwise Games–Howell tests (Games and Howell, 1976) were used for *post-hoc* analysis. Furthermore, the significance of the differences between the three scenarios was plotted as compound letter display (Piepho, 2004).

In scenario 3, we also counted how often participants entered roads with signage that forbade entry (see Fig. 5b). This trespassing count allowed us to directly analyse compliance with signs prohibiting access to streets. To answer research question 2, we tested for difference in the mean number of street entries of the previously stated type. Since the data violated the assumption of homogeneity of variance, Welch's ANOVA was used. Pairwise Games–Howell tests (Games and Howell, 1976) were used for *post-hoc* analysis. All data preparation and analyses tasks were performed with Python version 3.8.10 and QGIS version 3.22.3.

5.3. Motivation and actual compliance

In order to address research question 3, we computed Spearman's correlation between participants' reported influence of the signage on their routing and the normalized observed detour. This allowed us to analyse how their motivation to comply with signs correlated with their actual behaviour, i.e. whether added detours were taken because of the signage. Additionally, we computed Pearson's correlation between the self-reported maximum acceptable detour for a 1000 meter long route and the actual detour they took in the study. We used the 1000 m route as it is closest to the mean shortest-path length of the three routes in the study (which varied between 866 and 1502 m).

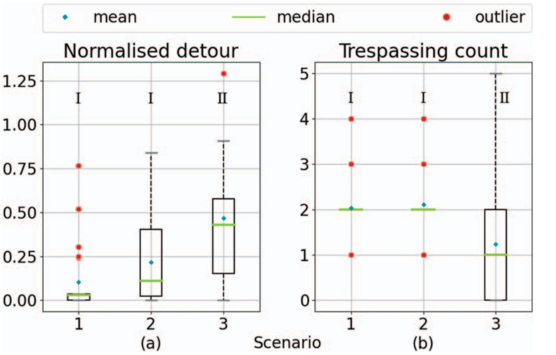

FIGURE 6. Normalized observed detour (a) and trespassing count (b) by scenario. Letters I and II indicate two groups with significant differences in mean values.

6. RESULTS

The mean deviation from the shortest path was 10% in scenario 1, 22% in scenario 2 and 47% in scenario 3 (Fig. 6a). Welch's ANOVA found a significant difference between groups ($P < 0.001$). The pairwise Games–Howell *post-hoc* test gives the following probabilities of falsely rejecting the null hypothesis of equal mean deviation from the shortest path between the scenarios: $P = 0.125$ for 1–2, $P < 0.001$ for 1–3 and $P = 0.015$ for 2–3 (Appendix A.3.1. Table A1). Differences between scenarios 1 and 3, and 2 and 3 were significant, but not between 1 and 2 (Fig. 6a, roman numbers). The presence of a pandemic did thus not significantly influence route length, while the added signage did.

The results of the questionnaire confirmed that the signs were perceived by most participants: 25 out of 26 agree or fully agree (see Table 1). Furthermore, many participants stated that the signage influenced their decisions: 14 participants rate its influence as very strong (3) or strong (11) versus 5 as none (1) or little (4) (Appendix A.1.2. Table A3). The mean number of streets entered, where entry was not allowed in scenario 3, was 2.13 in scenario 1, 2.10 in scenario 2 and 1.23 in scenario 3 (Fig. 6b). Welch's ANOVA found a significant difference between groups ($P = 0.009$). The pairwise Games–Howell *post-hoc* test gives the following probabilities of falsely rejecting the null hypothesis of equal mean number of streets entered, where entry was not allowed in scenario 3, between the scenarios: $P = 0.975$ for 1–2, $P < 0.002$ for 1–3 and $P = 0.002$ for 2–3 (Appendix A.3.2 Table A2). The streets where entry was not allowed in scenario 3 were thus traversed significantly less in scenario 3 than the same streets in scenarios 1 and 2 (Fig. 6b, roman numbers).

All participants were willing to accept a detour to comply with distance keeping measures. The mean accepted detour increased with the length of the original route (Fig. 7). Excluding those who said they would accept any length of detour, the average accepted detour for the 100 m route was 177 m, 344 m for the 500 m route and 363 m for the 1000 m route. We observed a significant strong correlation between the actual detours taken in the study and those reported as acceptable in scenario 3 (see Table 2) but not in the other two scenarios. See Appendix A.2.1, Fig. A1, for the trajectories of route B and a description of the differences between scenarios 1, 2 and 3. Figure 8 summarizes the influence of different factors on the routing decisions as reported by the participants.

A total of 96% of the participants (strongly) agreed that they could imagine the local circumstances depicted by the video material, and 84% reported that they could orientate well (cf.

TABLE 1. Participants' replies to the question: 'Look at the sign and rate the statements listed.' Options: strongly disagree (1), disagree (2), neutral (3), agree (4), strongly agree (5).

Question	1	2	3	4	5	Avg.
I noticed sign **(a)** in the study	1	0	0	4	21	4.69
I felt addressed as a pedestrian by sign **(a)**	0	1	0	8	15	4.54
I noticed sign **(b)** in the study	1	0	0	5	20	4.65
I felt addressed as pedestrian by sign **(b)**	1	2	2	7	12	4.13

TABLE 2. Pearson's correlation between detour observed in the study and self-reported acceptable detour (left) as well as Spearman's correlation between observed detour and self-reported influence of signage (right). Correlations listed are for the 1000 m route; 'any length' option not included.

	Observed detour and self-reported acceptable detour (Pearson)		Observed detour and self-reported influence of signage (Spearman)	
Scenario	Correlation	P	Correlation	P
1	0.08	0.72	0.04	0.85
2	0.11	0.61	0.40	0.04
3	0.45	0.03	0.75	1.1e-5

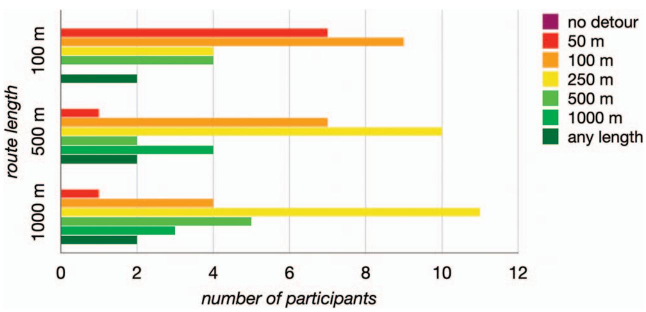

FIGURE 7. Self-reported length of detour participants would accept for routes of 100 m, 500 m and 1000 m length.

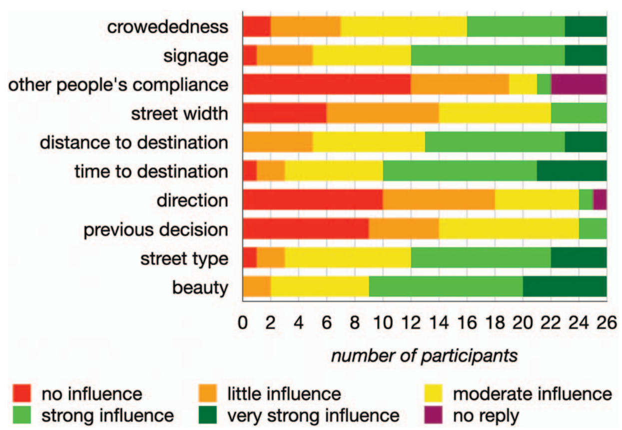

FIGURE 8. Influence of different factors on routing decisions as indicated by participants in the questionnaire.

Appendix A.1.2. Table A2). Two participants reported not understanding the meaning of the signs; both thought the entry forbidden sign had the same meaning as the one-way street sign, i.e. they thought they would comply if they entered. One participant did not notice the signs at all (see Table 1).

7. DISCUSSION

The analysis of our results revealed a significant difference in the deviation from the shortest path between scenarios 1 and 3 and 2 and 3, but not between scenarios 1 and 2. The participants also stated in the questionnaire that they were influenced by the street signs in their decisions, and that they were willing to take a detour in order to comply with them. Further analysis revealed a significant correlation between the accepted detour stated by the participants and the detour they actually took in the study.

The lack of significant differences between the scenario without a pandemic and those with it indicate that the presence of a pandemic did not influence navigation behaviour in our study (RQ1). Since our footage mostly showed streets with little foot traffic, it is possible that this outcome might also result from the lack of crowdedness. Regarding the impact of pedestrian signage (RQ2), we found significant differences between the scenario where it was present and those where it was not. Since participants also confirmed that they noticed the signage, there is good evidence now that such signage does indeed affect behaviour. This in turn opens the door for further developments and research into such interventions as a means to help fight a pandemic. When analysing the trajectories and the willingness to take detours reported in the questionnaire, we found a correlation between both, thereby providing an answer to RQ3. Interestingly, we also found that detours are acceptable but there is no clear indication to what degree the length of the acceptable detour depends on the length of the shortest path or whether there is an individual maximum threshold.

7.1. Reflections on the proposed approach

In applying our approach, we observed several positive aspects. The mean deviations from the shortest path found in our experiment (10–47%, cf. Fig. 7) are in line with observed deviations from the shortest path in other empirical studies, e.g. 15% for a 548 m long route by Kim (2015) and 33% for routes of on average 700 m by Foltête and Piombini (2010), and in pedestrian simulation models, e.g. 33% and 43% for routes of 3.4 and 3.8 km by Filomena et al. (2020). This implies realistic pedestrian behaviour in our experiment, and indicates we created meaningful and realistic simulations that participants could engage with. The questionnaire results further support that a high level of immersion was achieved via the IVE with overlayed signs and annotations.

In addition, we were able to analyse the logged interactions to derive useful results that helped us answer our research questions. We are also confident that these results—in particular those relating to the intention to comply, to the impact of signage and the acceptance of detours—will be very useful to define agent behaviour in an agent-based model we plan to develop. The proposed hygiene measures were easily implemented and accepted by the participants, and we are not aware of any infections resulting from participation.

However, there were also a number of issues that emerged during the study. When capturing the footage, our original goal was to capture scenes with different degrees of crowdedness. Despite scheduling our visit to the town to the most busiest day of the week, we were not able to film very crowded locations. In addition, weather conditions changed between recordings, which was noted by participants and could have affected immersion. This hints at a general problem with our method: unless scenes are staged on site and then filmed, the resulting footage is depending on the situation on site when it is recorded. Further research is needed to investigate to what degree overlays can help overcome this issue. In addition, the post-processing of the footage proved time-consuming due to the very large files resulting from recording 8K panoramic footage that we then had to cut, reduce and render. Designing, testing and then rendering the transition videos also took a lot of effort and time. While the produced footage can now readily be reused, having access to custom tools to automate some of these processes would greatly reduce the effort involved. Creating routes that were comparable but did not share decision points was difficult and thus would benefit from automation as well. An interesting alternative approach would be to decouple footage from reality, i.e. create routes based on filmed decision points that do not correspond to reality.

7.2. Limitations

The work we reported here is subject to a number of limitations that might have affected the outcomes and conclusions of our study. We ran the study with a small, non-representative group of participants using a single town as our environment. Other groups or environments might have resulted in different outcomes. In addition, the routes were quite short and there were only three in total. Since participants did not have any time pressure to reach their destination, it is possible that they took detours as one would leisurely strolling through a city. The high importance people associated with the beauty of a route (Fig. 8) indicates that this might have affected the results. However, making detours due to scenic route qualities is in fact realistic behaviour (see e.g. Koh and Wong (2013)). Another limitation might be that two participants misunderstood the pedestrian signage. However, we believe that this is realistic because policy measures implemented during a pandemic were often *ad-hoc* and/or new, and would thus not have been experienced beforehand. It is also worth noting that we did not explicitly investigate distance keeping at a micro-level, i.e. avoidance behaviour when encountering other people. We focused on a larger scale, i.e. avoiding streets for which physical-distancing streetscape interventions have been put in place. Finally, there was an actual pandemic going on while we ran our study, which might have affected the study in several ways. For example, people might have had trouble imagining a situation without pandemic and the real-life situation might have affected the results we recorded for the two scenarios with a pandemic.

7.3. Future work

There are several promising directions for future research based on our results. Our next step will be to create an agent-based model for distance keeping that incorporates the findings of the current study. This will enable us to model and assess different interventions in the streetscape with respect to how they can help to minimize close encounters. In addition, we are considering re-running the study to gather more evidence and insights. In particular, such re-runs could include participants with different demographics and cultural backgrounds or use different environments. Recent work in our group has also resulted in an agent-based model that relies on dynamic signage to minimize contacts. Testing such signage with our approach would not only enable us to calibrate this model but also to investigate different designs and the effect of observed real-time changes in those signs on distance keeping. A further line of research we are considering is to create a bi-directional link between the ABM and the IVE, where the ABM identifies decisions where more behavioural data is needed and then presents the corresponding decision point to human participants in the IVE (similar to what Zhao et al. (2020) did in the context of the love parade disaster). Their responses can then help to further improve the ABM. Here in particular, decoupling footage from the real-life situation would be beneficial as it would make it much easier to generate decision points *ad hoc* based on what the ABM identified. On a more general level, it would be interesting to apply the proposed method to other types of use cases. This includes, for example, evacuation scenarios and mass events such as concerts, where it would be very useful to assess the impact of (dynamic) signage on crowd behaviour.

8. CONCLUSION

In this paper, we reported on research investigating how streetscape interventions such as pedestrian signage affect compliance with distance keeping measures. We proposed and applied a novel approach to safely carry out user studies that require interaction with the physical environment during a pandemic. The approach relies on an IVE that overlays interventions, in our case pedestrian signage, over panoramic videos. In our study, we found evidence that such pedestrian signage affects route decisions and thus can contribute to keeping safe distances. We also observed a correlation between intention to comply and actual compliance. We thus contribute to the understanding of how streetscape interventions can affect pedestrian behaviour, which can benefit other researchers as well as decision-makers considering the implementation of such measures. Our second main contribution is the proposed method to safely carry out controlled user studies that require interaction with the physical environment. We were able to successfully apply this method to our specific research questions and produce meaningful results that also align with what previous field studies reported regarding route length. Feedback from participants indicated a high degree of immersion. This method can thus benefit researchers planning to carry out similar studies during a pandemic, for example when investigating ubiquitous technologies such as dynamic public displays or implicit interaction.

Acknowledgements

We thank Norwin Roosen for contributing large parts to the implementation of the IVE and the design of the user study. We acknowledge the Volkswagenstiftung for providing funding for our project 'Distance-Keeping: Influence of the StreetScape (Dist-KISS)' in the call 'Corona Crisis and Beyond—Perspectives for Science, Scholarship and Society'.

Supplementary Material

Supplementary data is available at *Interacting with Computers* online.

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