Exit choice during evacuation is influenced by both the size and proportion of the egressing crowd

Max Kinateder[1,2]

William H Warren[2]

[1] National Research Council Canada, 1200 Montreal Road, Ottawa ON, K1A0R6, Canada (present address)
Corresponding author: max.kinateder@nrc-cnrc.gc.ca

[2] Brown University, Department of Cognitive, Linguistic and Psychological Sciences, Box 1821, Providence, RI 02912, USA

Abstract

It is unclear how building occupants take information from the social and built environment into account when choosing an egress route during emergency evacuation. Conflicting tendencies have been previously reported: to follow the crowd, to avoid congestion, and to avoid unknown egress routes alone. We hypothesize that these tendencies depend on an interaction between social influence and the affordances (opportunities for egress) of the built environment. In three virtual reality (VR) experiments (each $N = 15$), we investigated how social influence interacts with the affordances of available exits to determine exit choice. Participants were immersed in a crowd of virtual humans walking to the left or right exit, and were asked to walk to one of the exits. Experiment 1 tested the role of social influence by manipulating both the proportion of the crowd walking toward one exit (Crowd Proportion of 0 to 100%, in 10% increments) and the absolute number of virtual humans going to the exit (Crowd Size of 10 or 20). Experiment 2 tested the role of affordances by introducing two visible exit doors (1m width) in a closed room, and following the same protocol. Experiment 3 tested larger exit doors (3m width) that afford rapid egress for more people. In the small crowd, participants were increasingly likely to follow the majority as its proportion increased. In the large crowd, however, participants tended to avoid the more crowded exit if the doors were narrow (Experiment 2), but not if the doors were wide (Experiment 3). Participants tended to follow a 100% majority in all experiments, thereby avoiding going to an exit alone. We propose that the dynamics of exit choice can be understood in terms of competition between alternative egress routes: the attraction of an exit increases with the *proportion* of the crowd moving toward it, becoming dominant at 100%, but decreases with the absolute *number* in the crowd moving toward it, relative to the exit's affordance for egress.

Keywords: evacuation; virtual reality; crowd behavior; social influence; affordances

1. Introduction

What factors influence the egress routes people choose when leaving a building during a fire evacuation? In terms of evacuation behavior, this is a tactical question (“Which exit should I take?”), as opposed to a strategic decision (“What should I do?”) or the operationalization of a decision (“How should I go to the exit?”) [1]. Past research has reported conflicting tendencies in how evacuees choose exits: to follow other people, to avoid congestion, and to avoid unknown egress routes alone.

The first tendency – *following others* – has been well documented. For instance, observing a single person going to an exit may attract another occupant to that exit. Several studies have shown that observing the behavior of others can influence the decision to evacuate, exit choice and egress routes [2-6]. Such social influence can even override information from the built environment. For instance, real world and virtual reality (VR) laboratory studies found that participants can be more likely to follow people than an emergency exit sign [5, 7, 8].

In many cases, evacuations involve groups or large crowds of occupants (see [9] for a real world case study). When larger numbers of occupants evacuate, more complex behavioral patterns emerge (see Warren [10] for an overview) and the question of social influence on exit choice becomes more complex. One study showed several hypothetical scenarios to over 1500 participants in an online survey [11]. In each scenario participants viewed a video of an animated crowd of virtual humans evacuating from a room with two exits. The videos were taken from a first-person perspective, i.e. as if participants were embedded in the crowd. Participants had to indicate which of the two exits they would choose to evacuate. Participants reported that they would follow the crowd majority towards an exit. In addition, the authors found that an exit became less attractive as more virtual humans were observed near it. Another multi-user VR study found that participants followed each other when trying to evacuate in groups (sometimes inadequately referred to as ‘herding’ [12, 13]): specifically, participants were more likely to choose a certain route as they observed more people taking that exit [14].

The second tendency refers to *avoiding congested exits*. Any exit only affords swift unhindered egress for a limited number of people and may become congested as more and more people attempt to use it [15]. Specifically, it has been shown that the flowrate of people moving through an aperture decreases linearly as the opening becomes narrower, and thus the egress time for a given size crowd increases linearly [e.g., 16]. This suggests that occupants in a crowd might be able to use visible congestion or flowrate as information to avoid bottlenecks when possible. As mentioned above, Lovreglio and colleagues conducted a series of studies in which participants had to choose between two possible exits in virtual fire evacuation scenarios [3, 11, 17]. In one study, the authors presented videos in which a crowd of virtual humans was placed in front of the participant and then moved to the two exits. Participants had to indicate which exit they would use. Participants tended to avoid the more crowded exit, and the larger the difference between the numbers of virtual humans at the two exits, the less likely participants were to follow the majority. Interestingly, this tendency to avoid congestion seems to contradict the first tendency to follow the crowd.

In a series of real-world behavioral studies and modeling exercises, Haghani and Sarvi [18], [19] investigated the consequences of social influence in several crowd evacuation scenarios (n = 117). In one scenario, for instance, participants in a hallway connecting two rooms with exit doors essentially had to choose which direction to turn in the hallway and which door to use as an exit. The authors similarly observed that participants did not tend to follow the majority of the crowd. This appears to be adaptive behavior since in their simulation results, following the crowd increased evacuation time.

The dependence of egress time on the ratio of crowd size to aperture width [e.g., 16] characterizes the *affordance* of an exit, that is, the opportunity for egress it offers. According to Gibson's theory of affordances [20], what the environment affords for behavior depends on a specific relationship between properties of the environment and properties of the actor. To the extent that this relationship is visually available, the affordance may be perceived and used to guide behavior [21]. In the present case, if both exit width and crowd size are visible to an occupant, affordance theory predicts that the occupant should be able to perceive the affordance for egress and use this information to guide exit choice. Thus, the perceived affordances of the built environment might explain the second tendency to avoid potentially congested exits, and predicts that it should depend on the ratio of crowd size to exit width. Some empirical evidence for this notion was shown in a series of studies where pedestrians in a crowd prefer routes with wider exits, but also take exit crowdedness into account [6].

Finally, the third tendency – *to avoid unknown exits* – has also been studied, but less systematically. The observation that occupants tend to evacuate via familiar routes can also be interpreted as avoiding unknown exits [4, 22-24]. In the aforementioned work by Lovreglio [17], participants were actually more likely to follow the crowd when *all* of the virtual humans went to the same exit, despite it being more crowded. This third tendency thus seems to conflict with the second tendency to avoid congestion. However, the behavior intuitively makes sense: avoiding the more crowded exit might reduce evacuation time, but avoiding an unfamiliar exit by oneself during an emergency might reduce risk [25].

A related study demonstrated this trade-off in groups of normally-sighted participants who repeatedly egressed from a classroom either with unimpaired vision or blindfolded. When unimpaired, participants tended to select egress routes that were not used by others, even if that meant taking a longer route. When blindfolded, however, participants tended to follow each other by remaining in physical contact [26]. The finding suggests that in uncertain situations, building occupants might rely on the behavior of other people for guidance. This may lead to efficient and safe evacuation, assuming that some occupants have knowledge of appropriate egress routes. It becomes problematic, however, when occupants ignore safe egress routes in order to stay with the crowd.

There is thus evidence that people exhibit each of these three conflicting tendencies in the context of evacuation. However, it should be noted that there may be additional explanations for the inconsistencies reported in the literature. For instance, methodological differences between observational studies, experimental scenarios with repeated trials, and experiments using videos or virtual reality, may affect the participants' motivation, familiarity with exits, and knowledge of outcomes, in different reports. The purpose of the present study is to investigate how the three tendencies trade off, based on systematic manipulations under controlled conditions. We hypothesize that they depend on an interaction between social influence and the affordances of the built environment. Specifically, we investigate whether the tendency to follow or avoid the majority depends on the proportion or absolute number of pedestrians going to each exit. Second, we ask whether these tendencies depend on the relationship between the absolute number of pedestrians and the width of the exit doors, as expected by affordance theory.

We used an evacuee walking paradigm in a controlled immersive virtual reality (VR) setting, as it allows balancing ecological validity and experimental control [27]. Participants were asked to walk to one of two exits while immersed in a virtual crowd, and the number of virtual humans walking to each exit was varied. Previous work observed comparable evacuation behavior in matched virtual and real-world simulated evacuation scenarios [4]. Recently, several studies have investigated the usefulness of VR simulation tools and found that at least for certain scenarios, behavior observed *in virtuo* is comparable to behavior *in vivo* [14, 28-30]. Although the technique has several limitations, VR has become a more and more established research tool in crowd dynamics [For an overview and more detailed discussion, see 1, 31, 32].

In this article, we report the findings of three experiments. Experiment 1 investigated the role of social influence by testing whether the proportion of the crowd, or the absolute number of virtual humans, walking to one exit had a stronger influence on exit choice, in the absence of other information about the exits. Participants had to choose between two illuminated exit points, without visible doors. Based on previous findings [11], we predicted that manipulating *Crowd Proportion*, the percentage of agents moving to one of the two exits, would influence participants' exit choice. In addition, we manipulated *Crowd Size*, the total number of agents in the crowd, to test whether social influence also depends on the absolute size of the crowd. Experiment 2 tested the contribution of affordances; the Crowd Proportion and Crowd Size manipulations were repeated, but two narrow exit doors were added in the virtual environment. Finally, Experiment 3 introduced wider exit doors that afford faster egress, to test whether the observed effects depend on the absolute number of virtual humans relative to exit width. Overall, we found support for effects of social influence and crowd size across experiments, which depend on the affordance of exit width.

2. Design and methods

2.1. Design

We used the following within-subjects design and manipulated two independent variables; Crowd Size and Crowd Proportion. *Crowd Size* refers to the absolute number of virtual humans in the crowd and was set to either 10 or 20. *Crowd Proportion* describes the proportion of the crowd going to one exit (0-100% in 10% increments, 11 levels); the crowd majority was counterbalanced between the left and right exits. Each condition was presented three times, resulting in a total of

66 trials per participant. The conditions were presented in block-wise random order to each participant.

Experiments. The three experiments followed the same procedure and study design, but the virtual environments varied in appearance:

- *Experiment 1* (Baseline): The virtual test environment consisted of an empty roughly rectangular space; a "fog wall" was used to define a perimeter within which participants could walk. Two bright white lights hovering at a height of 2 m were used to indicate the exit points.
- *Experiment 2* (Normal doors): The virtual environment imitated the appearance of the physical test space (rectangular room with gray carpet). Two doors (width 1 m) were located at the same locations as the exit points in Experiment 1
- *Experiment 3* (Wide doors): Same appearance as Experiment 2, but exit doors were 2 m wide.

2.2. Participants and recruiting

Three different groups of participants were recruited from an undergraduate student pool (Table 1; see limitations section for discussion of the study sample). Each participant completed only one experiment (total sample size was N = 45). All participants had normal or corrected to normal vision, gave informed consent, and were compensated for their participation. The protocol was approved by the Brown University Institutional Review Board and complied with the declaration of Helsinki.

Table 1 Age and gender in the three experiments

Experiment	N	Mean age (sd)	Gender
Experiment 1 (Baseline)	15	21.9 (5.51)	9 females, 5 males, 1 other
Experiment 2 (Narrow doors)	15	22.47 (6.61)	8 females, 6 males, 1 other
Experiment 3 (Wide doors)	15	22.00 (6.95)	11 females, 4 males

2.3. Virtual Reality lab

Data were collected in a 14×16 m^2 room in all experiments. Head position (4mm RMS resolution) and orientation (0.1˚ RMS resolution) were recorded using a hybrid ultrasonic-inertial tracking system (IS-900, Intersense, Billerica MA) at a sampling rate of 60 Hz, within a tracking area of 12×14 m^2. The virtual environment was presented in a head-mounted display (HMD; for

Experiment 1: Rift DK1, Oculus, Irvine CA; resolution of 640 × 800 pixels per eye, 90˚H x 65˚V field of view, refresh rate 60Hz, weight 380 g, fixed IPD of 6.4 cm). Participants carried a small backpack with the HMD control box and a battery pack that powered the HMD. Displays were generated on a Dell XPS workstation (Round Rock TX) at a frame rate of 60 fps, using the Vizard 4 software package (WorldViz, Santa Monica CA), transmitted wirelessly to the HMD using two HDTV transmitters, and presented stereoscopically in the HMD (including monocular and binocular depth information). Head coordinates from the tracker were used to update the display with a latency of 50-67 ms (3-4 frames). The set-up allowed participants to physically walk in virtual spaces and required no additional input devices for navigation.

2.4. Virtual Environments

In all experiments, the initial virtual environment consisted of an unbounded gray ground plane with a black background. A small gray pole (0.75 m tall, 0.1 m radius) indicated the participant's starting position, located equidistant (about 10.87 m) from two exit locations, and a taller gray orientation pole (1.5 m tall, 0.1 m radius, 4.5 m from the start pole) indicated the participants initial facing direction. In Experiment 1, the test environment consisted of a rectangular space 12 x 12 m) with a black ground plane, bounded by an indistinct "fog wall". Two exit points were indicated by two identical bright white lights 6.8m apart, hovering 2m above the ground plane. In Experiment 2, the test environment was a rendering of the lab room 12 x 12 m) with a gray carpeted ground plane, a grid ceiling, and black walls. The exit points were two wooden doors (1 m W x 2.03 m H, **Figure 1**b). A red fire alarm appeared above and between the two doors. In Experiment 3, the test environment was identical except that each door was 3 m wide.

The virtual crowd consisted of 10 or 20 different 3D human models (WorldViz Complete Characters), randomly positioned between the starting position and the two exits, animated with a walking gait at a randomly varied phase. From a pool of 20 virtual humans, a different configuration was randomly generated for each trial; all participants received the same set of configurations, but virtual humans were randomly assigned to the positions. At the beginning of a trial, all virtual humans turned towards one of the exit points and started walking at a speed of 1.2 m/s. Walking speed remained constant until they passed through the exits. In order to isolate the affordance relation between Crowd Size and exit width, we did not simulate a decrease in flow rate through the exit, which might also indicate a bottleneck.

2.5. Procedure

The participant's task was to walk to one of two exit points after an audio fire alarm was triggered (**Figure 1**). On each trial, the initial virtual environment appeared; then the starting pole appeared, the participant walked to it, and turned to face the orientation pole. At this point the poles and ground plane disappeared and were replaced by the test environment, with the virtual crowd (Crowd Size of 10 or 20). Three seconds after the room appeared, a fire alarm sounded from the red alarm box, and the virtual humans started walking to the two exits (depending on Crowd Proportion condition), and data collection began. Participants were instructed to "pick whichever door seemed to be appropriate". A trial ended either when participants reached one of the exits or after a time-out of 60s, then the two poles reappeared to begin the next trial. Participants completed two practice trials without any virtual agents visible, followed by the 66 test trials. To minimize the risk of side effects of VR, participants took a break every 15 trials (three breaks total).

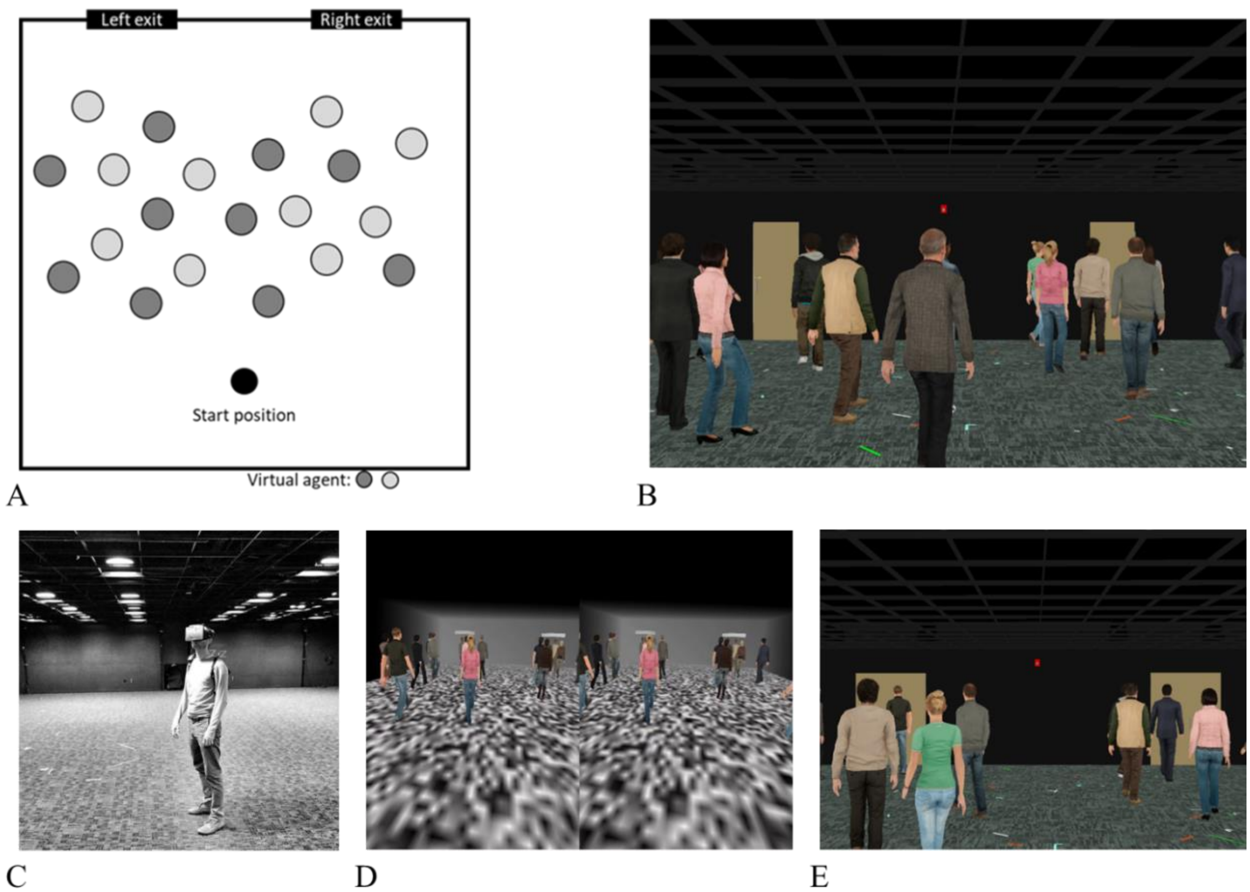

Figure 1 (A) Schematic layout of experimental set-up. Participants chose between two exit points after a fire alarm sounded and then walk with a crowd of either 10 (light gray) or 20 (light and dark gray) virtual agents. (B) Example screenshots taken from the

starting position in Experiment 2 and (E) Experiment 3. (C) Picture of participant immersed in the virtual environment. (D) Binocular screenshot of Experiment 1, illustrating the stereoscopic presentation of stimuli.

After behavioral testing, participants completed a series of questions in which they rated the realism of the alarm and virtual humans (4-point Likert scale from *very unrealistic* to *very realistic*) and answered questions about the experiment. The questions asked them to report on a 5-point Likert scale how strongly they felt influenced by the virtual humans, and to identify strategies they used during the task ("followed crowd majority", "avoided crowded majority" , "mostly went to right door", "mostly went to left door", "followed nearest virtual agent in crowd", "no strategy/random selection" and "other").

2.6. Data Analysis

The main behavioral dependent variable measured whether or not participants followed the majority of the crowd. For each trial, we analyzed the time series of head position to determine whether the participant walked to the left or right door. A trial ended once a participant was within 0.5 m of one of the doors. Holding aside the ambiguous 50/50 condition, we collapsed trials in which the majority of virtual humans moved to the left or right door into five levels of Crowd Proportion (60%, 70%, 80%, 90%, and 100% going to one door). This yielded six observations per participant in each Crowd Proportion condition at each Crowd Size, for a total of 900 analyzed trials per experiment (see Table 2 for an overview). For each participant, we then computed the percentage of trials in each condition in which they followed the majority of the crowd.

Table 2 Data processing and analysis overview

Raw data	Processed data
• Crowd size (2 levels) • Crowd proportion (11 levels) • Each condition repeated 3 times • 15 participants per experiment • Dependent measures: exit choice (left/right); trial time • 990 data points per experiment	• Data collapsed over left/right preference • 50% crowd proportion condition removed • Crowd size (2 levels) • Crowd proportion (5 levels) • Each condition repeated 6 times • 15 participants per experiment • Dependent measures: followed majority (yes/no); trial time • 900 data points per experiment

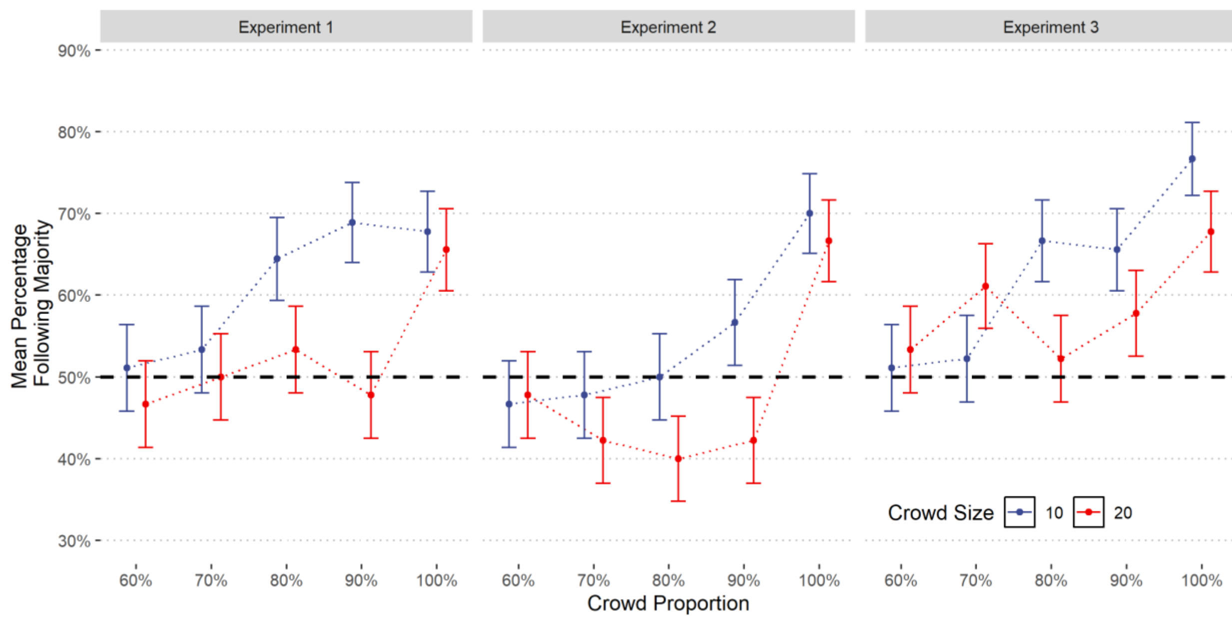

Figure 2 Exit choice in the three experiments: Experiment 1, fog wall; Experiment 2 door width 1m; Experiment 3, door width 2m. Each graph plots the mean percentage of trials in which a participant followed the majority of the crowd. Each data point represents the mean of 15 participants. Error bars correspond to the standard error of the mean.

The data were analyzed using binary mixed effects regression, followed by Analysis of Variance (ANOVA) techniques. Not surprisingly, a Shapiro-Wilk test revealed that the dependent variable (a percentage) was not normally distributed (W = 0.929, $p < .001$); given the relative robustness of ANOVA against violation of the assumption of normality, however, we decided not to transform the dataset. We ran a 3x2x3 ANOVA with Crowd Proportion and Crowd Size as within-subjects factors and experiment as a between-subjects variable. Mauchly's tests revealed violation of sphericity for the effects of Crowd Proportion, its two-way interaction with Crowd Size, and its three-way interaction with Crowd Size and Experiment. We report adjusted p-values for these tests. Bonferroni-corrected p-values were used for post-hoc pairwise comparisons.

3. Results

3.1. Exit choice

Exit choice in each experiment is represented in Figure 2, which plots the mean percentage of trials in which a participant followed the majority as a function of Crowd Proportion. It is apparent that participants followed the majority of the crowd more frequently as Crowd Proportion increased, but somewhat surprisingly, this effect was greater in the small crowd than the large crowd.

We tested binary mixed models that predicted whether or not a participant went with the majority in a given trial. We iteratively increased the complexity of the model, beginning with random intercepts for Participant, Trial, and Left/Right preference (to check for potential left/right bias). Of these random effects, only trial and participant significantly improved model fit. Next, we sequentially added fixed effects for Crowd Proportion, Crowd Size and Experiment. We also ran models that included interaction terms. The experiment factor did not improve the fit in any of these models. The final model which best explained the data included fixed effects for Crowd Proportion and Crowd Size and their interaction, as well as random intercepts for Participant and Trial. **Table 3** Comparison of Random and Fixed Effects in binary mixed models. AIC = Akaike information criterion (lower values indicate better fit); X^2statistics refer to model comparisons. Best fit model is indicated in bold.Table 3 compares these models. Table 4 summarizes the findings for the best fitting model

Table 3 Comparison of Random and Fixed Effects in binary mixed models. AIC = Akaike information criterion (lower values indicate better fit); X^2statistics refer to model comparisons. Best fit model is indicated in bold.

Random Effects	*Fixed Effects*	*AIC*	X^2	*df*	*p*
Participant		3203.7			
Participant + Trial		3194.1	11.56	1	<.001
Participant + Trial + Left/Right		3196.1	0	1	.998
Participant + Trial	Crowd Proportion	3144.8	57.33	3	<.001
Participant + Trial	Crowd Proportion + Crowd Size	3133.1	13.75	1	<.001
Participant + Trial	Crowd Proportion + Crowd Size + Experiment	3136.2	0	2	1
Participant + Trial	Crowd Proportion + Crowd Size x Experiment	3139	1.21	2	.546
Participant + Trial	**Crowd Proportion x Crowd Size**	**3128.7**	**10.32**	**0**	**<.001**
Participant + Trial	Crowd Proportion x Crowd Size + Experiment	3131.9	0.83	2	.660
Participant + Trial	Crowd Proportion x Crowd Size x Experiment	3153.2	14.65	18	.685

Table 4 Summary of the best fitting binary logistic mixed effect model with random effects for participant and trial.

Fixed Effects	***Estimate***	***Std. Error***	***z***	***p***
(Intercept)	-0.036	0.240	-0.148	.882
Crowd Proportion = 70%	0.063	0.199	0.315	.753
Crowd Proportion = 80%	0.551	0.200	2.760	<.001
Crowd Proportion = 90%	0.740	0.201	3.675	<.001
Crowd Proportion = 100%	1.190	0.209	5.684	<.001
Crowd Size = 20	-0.021	0.197	-0.109	.913
Proportion = 70% * Size20	0.040	0.283	0.141	.888
Proportion = 80% * Size20	-0.593	0.280	-2.116	<.05
Proportion = 90% * Size = 20	-0.751	0.283	-2.654	<.001
Proportion = 100% * Size = 20	-0.269	0.290	-0.928	.354

Supporting these findings, the ANOVA revealed significant main effects of Crowd Proportion and Crowd Size on the dependent variable, as well as a significant interaction between them (see Table 5). These results confirm that participants increasingly followed the majority as the majority grew larger, but more so in the small crowd. However, we did not observe a main effect of, or any interactions with, Experiment, implying that the pattern of behavior was comparable across the three types of exits.

Table 5 Results of ANOVA predicting 'followed majority" by Experiment, Crowd Proportion and Crowd Size; no interaction effects of experiment with any of the other factors was observed.

Effect	***Statistics***
Experiment	$F(2, 42) = 0.60, p = .551, \eta_p^2 = .03$
Crowd Proportion	$F(4, 168) = 11.17, p < .001, \eta_p^2 = .21$
Crowd Size	$F(1, 42) = 11.77, p = .001, \eta_p^2 = .22$
Crowd Proportion x Crowd Size	$F(4, 168) = 3.26, p = .019, \eta_p^2 = .07$

Consequently, the mean data are plotted in Figure 3, collapsed across Experiment. Overall, with the small crowd participants increasingly followed the majority as Crowd Proportion increased, whereas with the large crowd, exit choice remained near the chance level (50%) until the entire crowd went to one exit. Post-hoc pairwise comparisons confirmed that participants were more likely to follow the majority in the smaller crowd than in the larger crowd at Uniformities of

80% ($t(44) = 3.14$, $p_{corr} = .015$, d = 0.47) and 90% ($t(44) = 3.80$, $p_{corr} = .002$, d = 0.57) (Figure 3). It is possible that large crowds are less attractive due to a higher risk of congestion, whether or not the exit doors are visible.

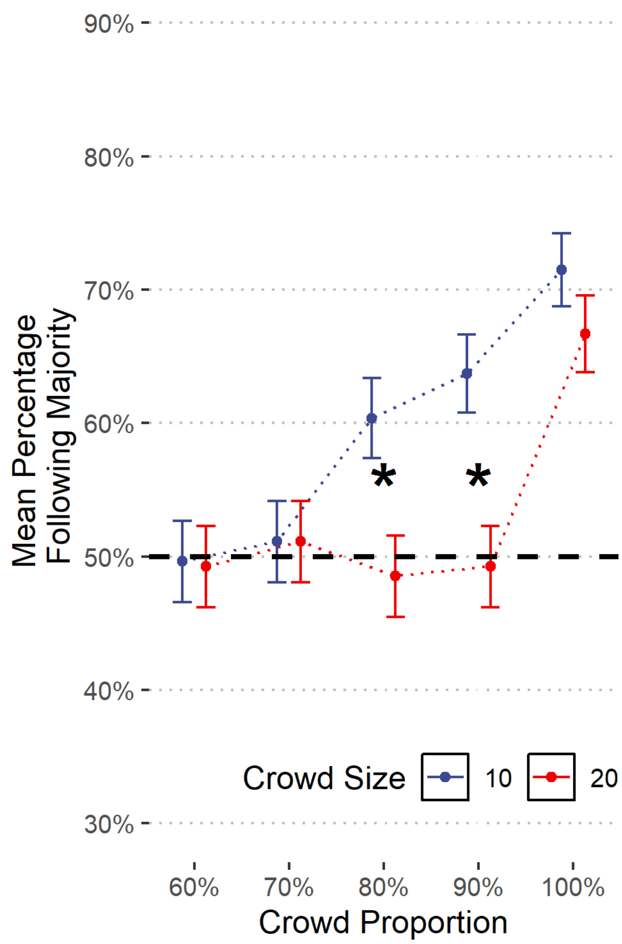

Figure 3 Exit choice in the three experiments combined: mean percentage of trials in which the participants in all experiments followed the majority. The asterisk indicates significant differences between the two Crowd Sizes.

To further investigate the affordance hypothesis, we tested whether preference for the less crowded exit depended on the relation between Crowd Size and exit width (refer to Figure 2), using directional one sample Bayesian t-tests [33]. This approach allowed us to evaluate the evidence favoring the Null Hypothesis (i.e., participants do not prefer the less crowded exit) as well as the Alternative Hypothesis (i.e. participants prefer the less crowded exit). Specifically, for the large crowd, we compared the mean percentage following the majority to the 50% chance level (null hypothesis), where <50% indicates choosing the less crowded exit (alternative hypothesis). In

Experiment 2 (1m doors) we found moderate evidence in favor of the less crowded exit with a Crowd Proportion of 80% (Bayes factor, $BF_{10} = 5.54$), and anecdotal evidence with a Proportion of 90% ($BF_{10} = 1.12$). In contrast, in Experiment 3 (2m doors) there was moderate evidence in favor of the null hypothesis at Proportions of 80% ($BF_{01} = 2.42$) and 90% ($BF_{01} = 6.38$), indicating that when exit doors were wide, neither exit was preferred. At 100% Proportion, there was decisive evidence that the majority was followed in both experiments ($BF_{10} >> 100$). Taken together, these results indicate that participants tend to avoid following the majority of a large crowd to a narrow exit (1m), but not to a wide exit (2m), consistent with the affordance hypothesis. However, when the entire crowd went to one door, participants were likely to follow them, consistent with avoiding an unknown exit alone.

Although there a Left/Right preference did not significantly contribute to the mixed model, we pursued the question of bias toward the left or right door by separately analyzing the data from the ambiguous 50% Crowd Proportion trials. Descriptively, we observed a systematic but unreliable bias towards the right exit (Figure 4). Since the virtual environment visually resembled the physical lab space, and the physical entrance to the lab was close to the right exit door in the virtual environment, it seemed plausible that participants may have been attracted to the more familiar door [22, 24]. To provide another check on the possibility of a rightward bias, a fourth small follow-up test ($N = 4$) was conducted. It followed the same protocol as Experiment 1, except that participants were led into the lab through a different door located closer to the left virtual exit. In this case participants descriptively preferred the left door, although the observations did not reach statistical significance. Thus any left/right door bias in the present experiments could be due to an influence of familiarity.

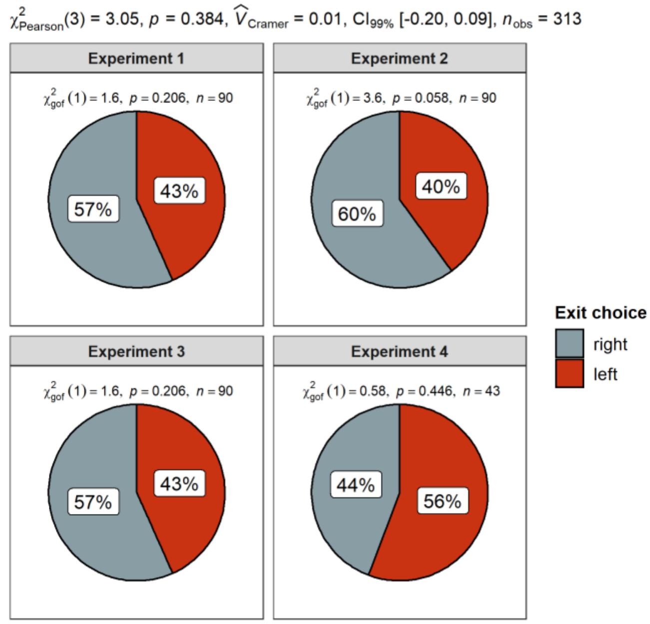

Figure 4 Exit choice in ambiguous conditions; n = number of trials in each experiment; created with ggstatsplot [34]

3.2. Timing

In order to explore, whether certain conditions would cause participants to hesitate, we measured trial duration, i.e., the time it took participants to evacuate from trial start until they reached one of the exits (Figure 5). The gross mean trial duration across all experiments was 11.38 s (sd = 6.39 s). In 22 out of 2700 trials, participants needed longer than 30s to complete a trial. Fifteen participants contributed these outliers, with none more than two. These outliers were excluded from the following timing analysis. For the most part there were no strong variations in trial duration across Experiments and conditions. We found small but reliable effects of Crowd Size, $F(1, 42) = 7.41$, $p = .009$, $\eta_p^2 = .15$ and Crowd Proportion, $F(1, 42) = 21.84$, $p < .001$, $\eta_p^2 = .34$. There were no differences between Experiments, $F(2, 42) = 2.49$, $p = .095$, $\eta_p^2 = .11$, but there was a significant interaction between Experiment and Crowd Size, $F(2, 42) = 4.31$, $p = .020$, $\eta_p^2 = .17$. Post-hoc comparisons revealed that participants evacuated slightly faster in the smaller crowd than the larger crowd only in Experiment 2. Post-hoc comparisons found no significant differences between individual levels of Crowd Proportion.

Inspired by findings reported by Haghani and Sarvi [18], we compared trial duration of participants who followed the majority to those who tended to avoid the more crowded exit, but found no significant differences, $t(1408.54) = 0.25$, $p = .799$.

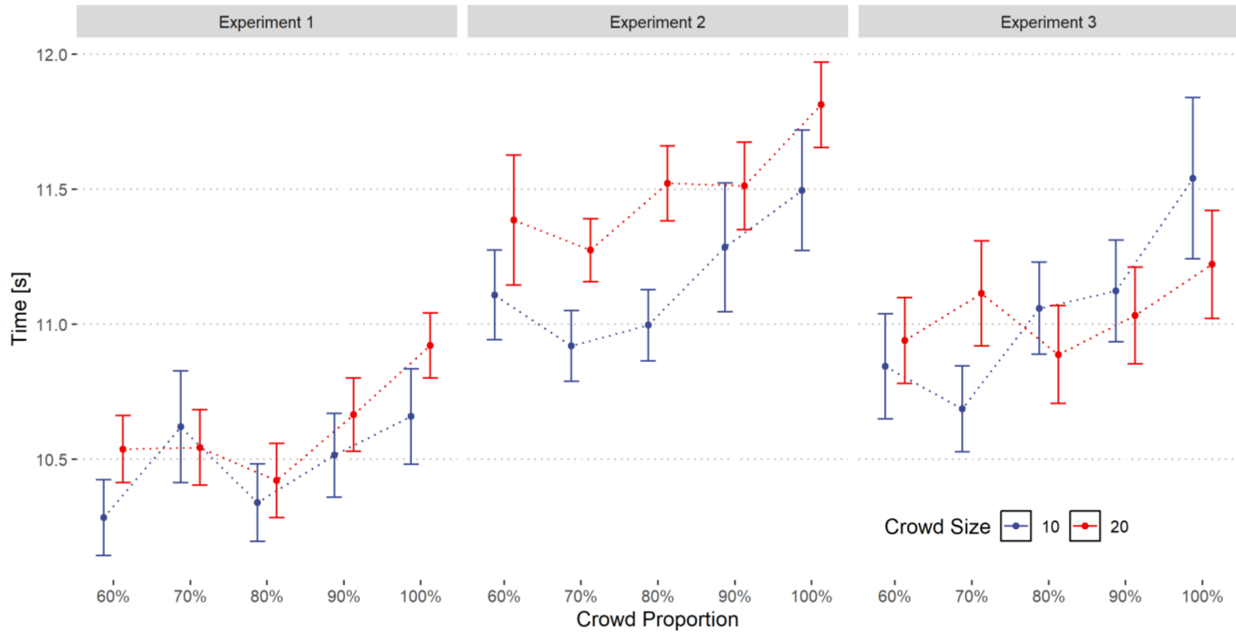

Figure 5 Trial duration as a function of Crowd Proportion;

3.3. Questionnaire data

After behavioral testing, participants completed a series of questions in which they rated the realism of the alarm and virtual humans. 90% of participants stated that they immediately recognized the fire alarm, when it was triggered. 89% of participants rated the scenario as either "realistic" or "very realistic", thus, providing support for the ecological validity of the virtual environment.

In addition, participants were asked to report how strongly they felt influenced by the virtual humans. Across experiments, participants stated that they had been influenced at least to some degree by the virtual humans. Only 11% stated that they felt not influenced by the virtual humans at all. This response is also reflected in the self-reported strategies, where the most commonly cited strategies were either to go with or avoid the majority of the crowd (Figure 6).

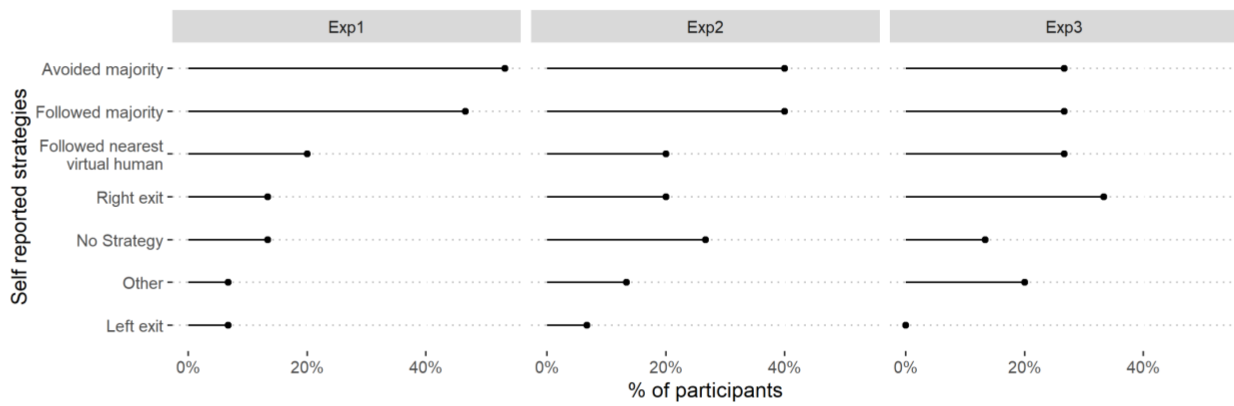

Figure 6 Self-reported strategies employed by participants.

4. Discussion

The goal of the present studies was to investigate the interaction of social influence and the affordances of the built environment in determining exit choice in a simulated evacuation scenario. We found that both *Crowd Proportion* and *Crowd Size* influenced participants' behavior. Specifically, we observed that the probability of participants following the majority increased more or less monotonically with Proportion in a small crowd of 10 virtual humans (Figure 2, Figure 3). However, in a large crowd of 20, participants only followed the majority when the entire crowd went to one exit; at lower proportions, they tended to avoid the more crowded exit when the doors were only 1m wide (Experiment 2) and had no preference when they were 3m wide (Experiment 3) (Figure 2).

The primary contribution of the present work is the finding that three previously reported tendencies trade off in exit choice. First, the tendency to follow others leads the participant to go with the majority [14, 16, 18, 24], based on the *proportion* of the crowd moving toward one exit. Second, the tendency to avoid congestion leads the participant away from a potential bottleneck [26], based on the absolute *number* of crowd members going to one exit [19]. This effect is not due to a decreased flow rate through the exit, which was held constant in the present experiments, but can be attributed to the perceived crowd size relative to exit width, consistent with Gibson's affordance theory [20]. Third, the tendency to avoid an unknown exit that no one else has chosen [17, 25] leads the participant to follow a 100% majority independent of crowd size. The surprising interaction between Crowd Proportion and Crowd Size implies that pedestrians tend to follow the majority in the small crowd. But in a large crowd, this social influence is counteracted by perceived congestion, especially with narrow exit doors. The exception is when the entire crowd goes to one exit, in which case participants eschewed an unknown exit and reverted to following others.

These conflicting trade-offs might be better understood within a specific theoretical framework known as *behavioral dynamics*, which formalizes how individuals dynamically interact with each other in a changing environment [35]. In this approach, control laws govern how agents avoid obstacles (repellers), steer towards goals (attractors), and interact with each other, ultimately giving rise to global patterns of collective crowd motion [10, 36-38]. In a recent series of experiments on walking with virtual crowds (e.g. Wirth & Warren, 2019), the authors found that pedestrian decision-making can be framed in terms of dynamic competition between alternatives. For example, when a crowd splits into two groups, the participant is attracted to the majority group, but is also attracted to the group that deviates less from walking straight ahead; these two tendencies compete to determine the participant's chosen route.

Exit choice can be similarly understood in terms of competition between alternatives. We propose that the attraction of an exit increases with the *proportion* of the crowd moving toward it, but decreases with the absolute *number* of crowd members moving toward it, relative to exit width. In a small crowd, participants are increasingly attracted to follow a greater majority. But in a large crowd, attraction to the majority can be outweighed by attraction to the exit that affords faster egress. When the majority reaches 100%, however, the attraction of the open but unknown exit collapses and the participant follows the majority. Further work is needed to model and test these proposed dynamics of exit choice.

Several other phenomena commonly observed in emergency evacuation may also interact with the behavioral patterns reported here. These phenomena relate to the dynamics of egress behavior within the context of a building. First, in the present study, participants started equidistant from the two exit points. Recent simulation studies suggest that the relative distance to and visibility of exits may play a more important role during emergency evacuations in crowded buildings compared to non-emergency egress behavior [25, 39]. Future behavioral research should determine how the attraction of an exit depends on its distance, and interacts with the effects observed here. Second, familiarity with both members of the crowd and particular exits has repeatedly been shown to influence exit choice and other relevant aspects of egress [9, 22, 24]. For instance, evacuating in groups can slow average movement speed [40, 41] and flowrate, but also increase cooperation among evacuees [41]. While the present study did not explicitly manipulate exit familiarity, future studies could test, for example, whether the attraction of an empty exit increases with its familiarity. Third, on a more practical note, the present findings should be considered with regard to exit signage. A recent study on dynamic exit signs showed that clear signals above exit doors can dissuade occupants from choosing an exit, even if it is normally marked as an emergency exit [42]. However, other studies found that occupants may ignore exit signage when they see an individual moving away from an exit [5, 7]. Fourth, the virtual pedestrians in the present study walked at a constant speed and did not "rush" towards the exit; a recent study showed that evacuation speed is dependent on the proportion of evacuees rushing [43]. Cleary, more work is needed to better understand the dynamics of crowd behavior in the built environment.

The dynamics of exit choice may also depend on the characteristics of the crowd population and individual differences. For instance, early crowd research found that groups of people who know each other tend to choose similar exit routes [22]. In a more recent study, participants without disabilities were less likely to choose the same exit as those with disabilities, suggesting that the visibly slower movement of impaired occupants could render an exit less attractive because it is potentially more congested [44]. In the present work, we observed a variety of individual differences in behavioral patterns. For example, there were cases of participants who consistently followed the crowd majority, but also the exact opposite (compare participants 7 and 11 in Experiment 2, **Figure 7** in the Appendix A).

The present findings have potential implications for agent-based [45] or cellular automata [46] evacuation models. Recently, a number of simulation tools have been developed to predict exit choice during fire evacuation based on hypothetical mechanisms describing how agents choose between two exits [e.g., 3, 11, 17]. Typically, these models attempt to predict an evacuee's exit choice through utility functions or other stochastic models, where the probability of choosing one exit over another is assigned by combining and weighing a number of factors. This approach allows researchers and practitioners to pose questions about complex aspect of building evacuation. The present dataset could be used to test certain model predictions and support the verification and validation process [47].

4.1. Limitations

The present study, along with several other experiments, conceptualizes exit choice as a decision between discrete options: choose one of two exits [48]. There are several theoretical and practical open questions regarding this approach. For instance, it is unclear whether and how occupants change their initial decision as they approach an exit. It is conceivable that occupants update their decision if, for example, new information suggests that another option than the currently selected one is more favorable. Do they plan and decide once and then follow a route that may have many turns? Or do they make decisions on the fly after starting to walk? How are strategic (pre-decision) and tactical (en-route) decisions taken into account [49]? Future research is needed to study dynamic changes in decision making during evacuation. Answers to those questions, particularly if accompanied by realistic estimates on how these affect the timing of evacuations would be of high value to safety practitioners. In addition, evacuation behavior typically occurs in more complex scenarios, in which decision-making goes beyond deciding between two visible exit doors. More research is needed, for example, considering building complexity and familiarity of occupants with complex evacuation routes.

In the present experiments, the virtual humans passed through the apertures unimpeded, i.e. we did not simulate conditions of higher crowd density and reduced flow rates. With increasing crowd density, flow rates through given doors decrease and can ultimately come to a halt [e.g., 50, 51]. Observing changes in flow rate, not merely the number of crowd members approaching an exit, might cause pedestrians to change their exit choice [15, 18, 52]. That is, pedestrians likely take dynamic changes such as perceived crowdedness as a function of exit width and number of visible pedestrians into account [53]. For instance, one study found that participants were both drawn to wider exits and less crowded exits when making route choice decisions [6]. This could enhance differences in exit choice or trial duration across experiments. Further research is needed to understand how changes in flow rate influence exit choice.

The present study used a VR paradigm. Although increasingly used in fire evacuation research, VR has its limitations, since virtual displays are obviously a simulation of a hypothetical scenario, and participants are typically aware that they are taking part in an experiment; this may reduce the ecological validity of the findings [54]. However, several recent studies have shown that VR and real life experiments can produce similar results [e.g., 4, 31].

While we argue that the present study sheds further light on the tendencies of occupants to follow other people, to avoid congestion, and to avoid unknown egress routes alone, there may be other potential explanations for the present findings. For instance, it is possible that participants motivation (e.g., to be a compliant subject) or the degree of immersion in the virtual environment influenced their decision-making. While this limitation cannot be ruled out, it is worth pointing out that participants in VR experiments on fire evacuation report behavioral intentions that are comparable to real world incidents (e.g., [55]). In addition, a number of studies have shown that VR experiments produce comparable behavioral results to real world experiments, if sometimes with a reduced effect size [4].

Another limitation of the present study is the use of a relatively small undergraduate sample, which raises two potential concerns. The first is the statistical power of the sample size given the effect size; this concern is largely alleviated by the significant results. The second is whether the present findings will generalize to other populations, such as children, older adults, pedestrians with limited mobility, non-Western cultures, and heterogeneous groups. That question obviously needs to be explored in further research.

Finally, while within-subject designs with multiple trials per participant have the advantages of experimental manipulation control compared to observational studies, they run the risk of carry-over effects. For example, a participant experiencing repeated trials may exhibit habituation, yielding regression to the mean; or once a participant has walked to an "unknown" empty exit with no ill effects, it may no longer be avoided. However, the fact that we observed statistically significant differences between conditions – including continued avoidance of an empty exit in the 100% Proportion condition – mitigates this concern. We thus believe that the advantages of experimental control outweigh the risk of any carry-over effects, and complement the strengths of observational studies.

4.2. Conclusions

In conclusion, the present study provides insights into how exit choice during an evacuation is shaped by both the behavior of other people and the architectural environment. We found that exit choice between two equidistant exit options changes as a function of both Crowd Proportion and Crowd Size, depending on the affordance of an exit for egress.

Appendix A

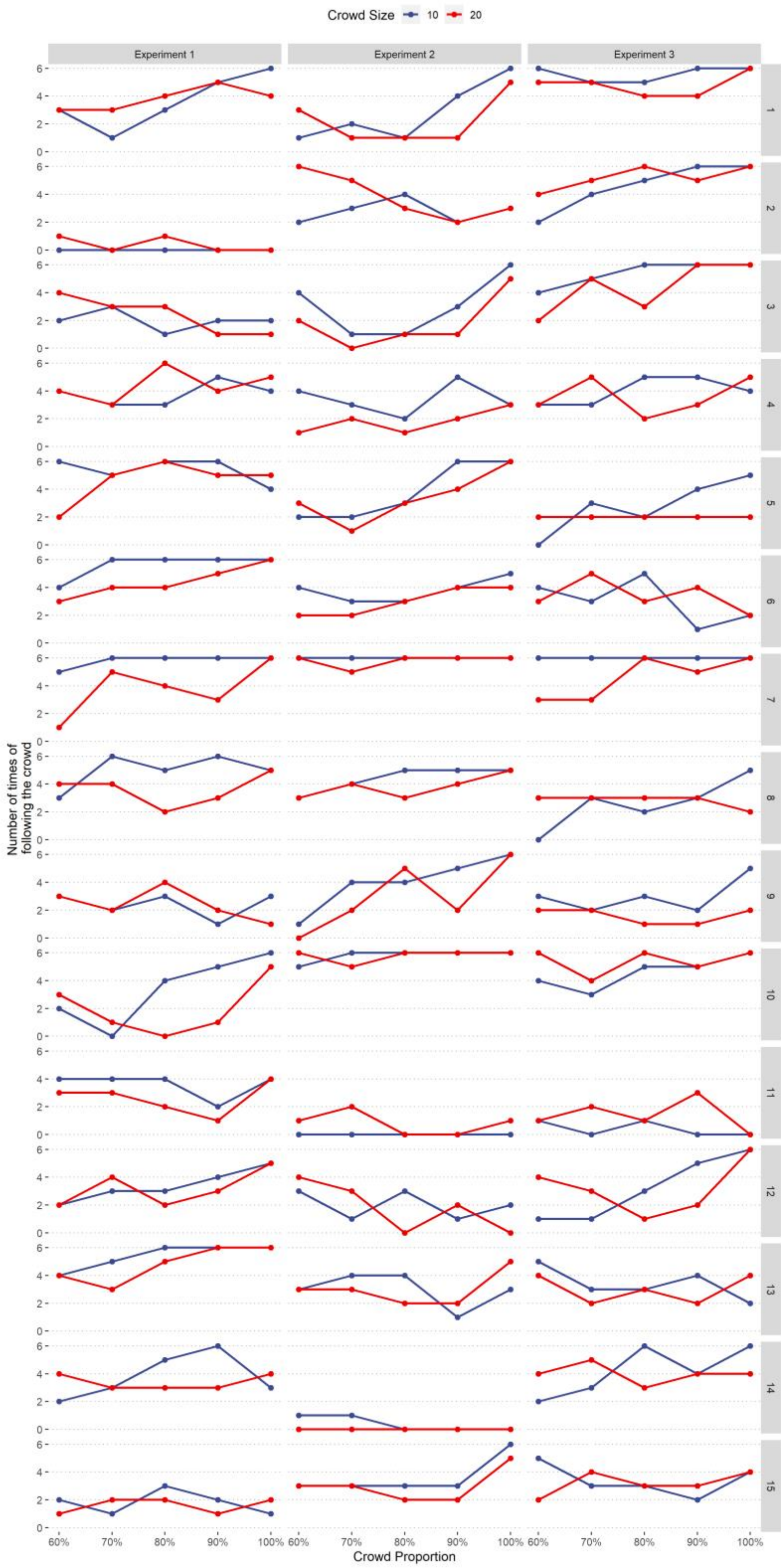

Figure 7 Data for individual participants; each plot shows counts of observations a participant followed the majority of the crowd as a function of Crowd Proportion. Note that a separate set of participants was recruited for each experiment.

References

[1] M. Haghani and M. Sarvi, "Crowd behaviour and motion: Empirical methods," *Transportation research part B: methodological,* vol. 107, pp. 253-294, 2018.

[2] M. Kinateder, E. Ronchi, D. Gromer, M. Müller, M. Jost, M. Nehfischer*, et al.*, "Social influence on route choice in a virtual reality tunnel fire," *Transportation research part F: traffic psychology and behaviour,* vol. 26, pp. 116-125, 2014.

[3] R. Lovreglio, D. Borri, L. dell'Olio, and A. Ibeas, "A discrete choice model based on random utilities for exit choice in emergency evacuations," *Safety science,* vol. 62, pp. 418-426, 2014.

[4] M. Kinateder and W. H. Warren, "Social Influence on Evacuation Behavior in Real and Virtual Environments," *Frontiers in Robotics and AI,* vol. 3, 2016-July-25 2016.

[5] Y. Zhu, T. Chen, N. Ding, M. Chraibi, and W.-C. Fan, "Follow the evacuation signs or surrounding people during building evacuation, an experimental study," *Physica A: Statistical Mechanics and its Applications,* p. 125156, 2020/08/26/ 2020.

[6] W. Liao, A. U. Kemloh Wagoum, and N. W. Bode, "Route choice in pedestrians: determinants for initial choices and revising decisions," *J R Soc Interface,* vol. 14, Feb 2017.

[7] M. Kinateder, M. Müller, M. Jost, A. Mühlberger, and P. Pauli, "Social influence in a virtual tunnel fire–influence of conflicting information on evacuation behavior," *Applied ergonomics,* vol. 45, pp. 1649-1659, 2014.

[8] N. W. Bode, A. U. Kemloh Wagoum, and E. A. Codling, "Human responses to multiple sources of directional information in virtual crowd evacuations," *J R Soc Interface,* vol. 11, p. 20130904, Feb 6 2014.

[9] A. Chen, J. He, M. Liang, and G. Su, "Crowd response considering herd effect and exit familiarity under emergent occasions: A case study of an evacuation drill experiment," *Physica A: Statistical Mechanics and its Applications,* vol. 556, p. 124654, 2020/10/15/ 2020.

[10] W. H. Warren, "Collective Motion in Human Crowds," *Curr Dir Psychol Sci,* vol. 27, pp. 232-240, Aug 2018.

[11] R. Lovreglio, A. Fonzone, and L. dell'Olio, "A mixed logit model for predicting exit choice during building evacuations," *Transportation Research Part A: Policy and Practice,* vol. 92, pp. 59-75, 2016.

[12] M. Haghani, E. Cristiani, N. W. Bode, M. Boltes, and A. Corbetta, "Panic, irrationality, and herding: three ambiguous terms in crowd dynamics research," *Journal of advanced transportation,* vol. 2019, 2019.

[13] J. Adrian, M. Amos, M. Baratchi, M. Beermann, N. Bode, M. Boltes*, et al.*, "A glossary for research on human crowd dynamics," *Collective Dynamics,* vol. 4, pp. 1-13, 2019.

[14] M. Moussaid, M. Kapadia, T. Thrash, R. W. Sumner, M. Gross, D. Helbing*, et al.*, "Crowd behaviour during high-stress evacuations in an immersive virtual environment," *J R Soc Interface,* vol. 13, Sep 2016.

[15] S. Gwynne, E. Galea, P. J. Lawrence, and L. Filippidis, "Modelling occupant interaction with fire conditions using the buildingEXODUS evacuation model," *Fire Safety Journal,* vol. 36, pp. 327-357, 2001.

[16] M. Haghani and M. Sarvi, "Simulating pedestrian flow through narrow exits," *Physics Letters A,* vol. 383, pp. 110-120, 2019/01/12/ 2019.

[17] R. Lovreglio, A. Fonzone, L. dell'Olio, and D. Borri, "A study of herding behaviour in exit choice during emergencies based on random utility theory," *Safety Science,* vol. 82, pp. 421-431, 2016/02/01/ 2016.

[18] M. Haghani and M. Sarvi, "Imitative (herd) behaviour in direction decision-making hinders efficiency of crowd evacuation processes," *Safety Science,* vol. 114, pp. 49-60, 2019/04/01/ 2019.

[19] M. Haghani and M. Sarvi, "'Herding'in direction choice-making during collective escape of crowds: How likely is it and what moderates it?," *Safety science,* vol. 115, pp. 362-375, 2019.

[20] J. J. Gibson, *"The theory of affordances," in Perceiving, Acting, and Knowing. Towards an Ecological Psychology*: Hoboken, NJ: John Wiley & Sons Inc., 1977.

[21] W. H. Warren and S. Whang, "Visual guidance of walking through apertures: body-scaled information for affordances," *Journal of experimental psychology: human perception and performance,* vol. 13, p. 371, 1987.

[22] J. D. Sime, "Affiliative behaviour during escape to building exits," *Journal of environmental psychology,* vol. 3, pp. 21-41, 1983.

[23] W. L. Grosshandler, N. Bryner, D. Madrzykowski, and K. Kuntz, "Report of the technical investigation of the station nightclub fire," 2005.

[24] M. Kinateder, B. Comunale, and W. H. Warren, "Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior," *Safety Science,* vol. 106, pp. 170-175, 2018/07/01/ 2018.

[25] M. Haghani and M. Sarvi, "Human exit choice in crowded built environments: Investigating underlying behavioural differences between normal egress and emergency evacuations," *Fire Safety Journal,* vol. 85, pp. 1-9, 2016/10/01/ 2016.

[26] R.-Y. Guo, H.-J. Huang, and S. C. Wong, "Route choice in pedestrian evacuation under conditions of good and zero visibility: Experimental and simulation results," *Transportation Research Part B: Methodological,* vol. 46, pp. 669-686, 2012/07/01/ 2012.

[27] M. Kinateder, D. Nilsson, M. Kobes, M. Müller, P. Pauli, and A. Mühlberger, "Virtual Reality for Fire Evacuation Research," in *Federated Conference on Computer Science and Information Systems*, Warsaw, Poland, 2014, pp. 319-327.

[28] E. Ronchi, D. Mayorga, R. Lovreglio, J. Wahlqvist, and D. Nilsson, "Mobile-powered head-mounted displays versus cave automatic virtual environment experiments for evacuation research," *Computer Animation and Virtual Worlds,* vol. 30, 2019.

[29] M. Haghani and M. Sarvi, "Identifying latent classes of pedestrian crowd evacuees," *Transportation Research Record: Journal of the Transportation Research Board,* pp. 67-74, 2016.

[30] M. Haghani and M. Sarvi, "Stated and revealed exit choices of pedestrian crowd evacuees," *Transportation Research Part B: Methodological,* vol. 95, pp. 238-259, 2017.

[31] M. Kinateder, T. D. Wirth, and W. H. Warren, "Crowd Dynamics in Virtual Reality," in *Crowd Dynamics, Volume 1: Theory, Models, and Safety Problems*,

L. Gibelli and N. Bellomo, Eds., ed Cham: Springer International Publishing, 2018, pp. 15-36.
[32] R. Lovreglio, "Virtual and augmented reality for human behaviour in disasters: A review," presented at the 5th Fire and Evacuation Modeling Technical Conference online, 2020.
[33] J. N. Rouder, P. L. Speckman, D. Sun, R. D. Morey, and G. Iverson, "Bayesian t tests for accepting and rejecting the null hypothesis," *Psychonomic bulletin & review,* vol. 16, pp. 225-237, 2009.
[34] I. Patil, "Ggstatsplot:'Ggplot2'based plots with statistical details," ed: CRAN. Retrieved from https://cran. r-project. org/web/packages/ggstatsplot …, 2018.
[35] W. H. Warren, "The dynamics of perception and action," *Psychol Rev,* vol. 113, pp. 358-89, Apr 2006.
[36] K. W. Rio and W. H. Warren, "The visual coupling between neighbors in real and virtual crowds," in *Conference on Pedestrian and Evacuation Dynamics 2014 (Ped 2014)*, 2014, pp. 132-140.
[37] K. W. Rio, G. C. Dachner, and W. H. Warren, "Local interactions underlying collective motion in human crowds," *Proc Biol Sci,* vol. 285, May 16 2018.
[38] T. D. Wirth, G. C. Dachner, K. Rio, and W. H. Warren, "The neighborhood of interaction in human crowds is metric, not topological, due to the laws of optics " *(submitted),* 2020.
[39] M. Haghani and M. Sarvi, "Social dynamics in emergency evacuations: Disentangling crowd's attraction and repulsion effects," *Physica A: Statistical Mechanics and its Applications,* vol. 475, pp. 24-34, 2017/06/01/ 2017.
[40] B. Zhang, W. Chen, X. Ma, P. Qiu, and F. Liu, "Experimental study on pedestrian behavior in a mixed crowd of individuals and groups," *Physica A: Statistical Mechanics and its Applications,* vol. 556, p. 124814, 2020/10/15/ 2020.
[41] Y. Ma, L. Li, H. Zhang, and T. Chen, "Experimental study on small group behavior and crowd dynamics in a tall office building evacuation," *Physica A: Statistical Mechanics and its Applications,* vol. 473, pp. 488-500, 2017/05/01/ 2017.

[42] J. Olander, E. Ronchi, R. Lovreglio, and D. Nilsson, "Dissuasive exit signage for building fire evacuation," *Applied Ergonomics,* vol. 59, pp. 84-93, 2017/03/01/ 2017.

[43] H. R. L. Lee, A. Bhatia, J. Brynjarsdóttir, N. Abaid, A. Barbaro, and S. Butail, "Speed modulated social influence in evacuating pedestrian crowds," *Collective Dynamics,* vol. 5, pp. 1-24, 2020.

[44] N. Gaire, Z. Song, K. M. Christensen, M. S. Sharifi, and A. Chen, "Exit choice behavior of pedestrians involving individuals with disabilities during building evacuations," *Transportation research record,* p. 0361198118756875, 2018.

[45] E. Ronchi and D. Nilsson, "Fire evacuation in high-rise buildings: a review of human behaviour and modelling research," *Fire science reviews,* vol. 2, p. 7, 2013.

[46] Y. Li, M. Chen, Z. Dou, X. Zheng, Y. Cheng, and A. Mebarki, "A review of cellular automata models for crowd evacuation," *Physica A: Statistical Mechanics and its Applications,* vol. 526, p. 120752, 2019/07/15/ 2019.

[47] R. Lovreglio, E. Ronchi, and D. Borri, "The validation of evacuation simulation models through the analysis of behavioural uncertainty," *Reliability Engineering & System Safety,* vol. 131, pp. 166-174, 2014.

[48] G. Antonini, M. Bierlaire, and M. Weber, "Discrete choice models of pedestrian walking behavior," *Transportation Research Part B: Methodological,* vol. 40, pp. 667-687, 2006/09/01/ 2006.

[49] S. P. Hoogendoorn, F. van Wageningen-Kessels, W. Daamen, D. C. Duives, and M. Sarvi, "Continuum Theory for Pedestrian Traffic Flow: Local Route Choice Modelling and its Implications," *Transportation Research Procedia,* vol. 7, pp. 381-397, 2015/01/01/ 2015.

[50] W. Daamen, "Modelling passenger flows in public transport facilities," 2004.

[51] P. Geoerg, J. Schumann, M. Boltes, S. Holl, and A. Hofmann, "The influence of physical and mental constraints to a stream of people through a bottleneck," presented at the Pedestrian Evacuation Dynamics, Lund, Sweden, 2018.

[52] S. Gwynne, E. Galea, P. Lawrence, M. Owen, and L. Filippidis, "Adaptive decision-making in building EXODUS in response to exit congestion," *Fire Safety Science,* vol. 6, pp. 1041-1052, 2000.

[53] N. W. F. Bode, A. U. Kemloh Wagoum, and E. A. Codling, "Information use by humans during dynamic route choice in virtual crowd evacuations," *Royal Society open science,* vol. 2, pp. 140410-140410, 2015.

[54] M. Kinateder, E. Ronchi, D. Nilsson, M. Kobes, M. Müller, P. Pauli*, et al.*, "Virtual reality for fire evacuation research," in *Computer Science and Information Systems (FedCSIS), 2014 Federated Conference on*, 2014, pp. 313-321.

[55] S. Arias, R. Fahy, E. Ronchi, D. Nilsson, H. Frantzich, and J. Wahlqvist, "Forensic virtual reality: Investigating individual behavior in the MGM Grand fire," *Fire Safety Journal,* vol. 109, p. 102861, 2019/10/01/ 2019.