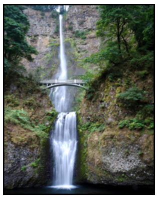
Journal of Environmental Psychology 65 (2019) 101320

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep



The effect of crowdedness on human wayfinding and locomotion in a multi-level virtual shopping mall

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ARTICLE INFO

Keywords:
Crowdedness
Wayfinding strategies
Route choices
Locomotion
Navigation

ABSTRACT

This study investigates how social and physical environments affect human wayfinding and locomotion behaviors in a virtual multi-level shopping mall. Participants were asked to locate a store inside the virtual building as efficiently as possible. We examined the effects of crowdedness, start floor, and trial number on wayfinding strategies, initial route choices, and locomotion behaviors. The results showed that crowdedness did not affect wayfinding strategies or initial route choices, but did affect locomotion in that participants in the high crowdedness condition were more likely to avoid crowds by moving close to the boundaries of the environment. The results also revealed that participants who started on the second floor were more likely to use the floor strategy than participants who started on the third floor, possibly because of the structure of the virtual building. These results suggest that both physical and social environments can influence multi-level indoor wayfinding.

1. Introduction

Navigation in public buildings can be difficult because of the complexity of physical and social environments. Lack of visual access to global landmarks, incongruent floor layouts, incomprehensible signage, and disorienting staircases have all been related to the complexity of multi-level indoor wayfinding (Carlson, Hölscher, Shipley, & Dalton, 2010; Hölscher, Büchner, Meilinger, & Strube, 2009, 2006; Li, Corey, Giudice, & Giudice, 2016; Li & Giudice, 2018; Passini, 1984; Weisman, 1981). The social environment (e.g., crowds) may add to this complexity by diverting locomotion (Yi, Li, & Wang, 2015) and provoking people to adapt their wayfinding choices (Bode, Kemloh Wagoum, & Codling, 2014).

Previous research in social psychology has investigated the effects of crowds on human behavior and physiology (Evans, 1979; Freedman, Klevansky, & Ehrlich, 1971; Griffit & Veitch, 1971; Langer & Saegert, 1977; Mackintosh, West, & Saegert, 1975; Paulus & Matthews, 1980; Stokols, 1972b, a; Stokols, Rall, Pinner, & Schopler, 1973). Some studies have indicated that crowds can impair performance on complex spatial tasks such as drawing a sketch map based on incidental memory or solving a difficult puzzle (Evans, 1979; Langer & Saegert, 1977; Mackintosh et al., 1975; Paulus & Matthews, 1980). Researchers have also found that crowds disturbed participants' overall experience of a public space, as evidenced by increased anxiety (Mackintosh et al., 1975) and elevated blood pressure and pulse rate (Evans, 1979). In contrast, some studies have not found negative effects of crowds on human behavior (Freedman et al., 1971; Griffit & Veitch, 1971; Stokols et al., 1973). For example, Stokols et al. (1973) found that crowds in a classroom did not impair performance and enjoyment during a trivia game. Accordingly, Freedman (1975) proposed a theoretical framework that views crowds as an intensifier (rather than a stressor) that strengthens human reactions at high density. Here, the effects of crowds on human behavior and physiological states depend on individual differences in habits, attitudes, and values with respect to interpersonal distances (Freedman, 1975; Freedman et al., 1971; Hall, 1966).

There is a dearth of research on the effects of crowds on human navigation. This is surprising given that navigation in public spaces often occurs among crowds. The relationship between crowds and navigation behavior must account for both locomotion and wayfinding (Montello, 2001, 2005). Locomotion refers to the physical movements involved when executing a route plan such as steering and avoiding obstacles. In contrast, wayfinding incorporates all of the cognitive, decision-making, and planning processes used to reach a goal location (Golledge, 1999). Wayfinding can be further divided into strategic and tactical levels (Hoogendoorn & Bovy, 2004). The strategic level defines a plan of action designed to achieve an overall wayfinding goal, and the

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https://doi.org/10.1016/j.jenvp.2019.101320
Received 22 January 2019; Received in revised form 28 June 2019; Accepted 29 June 2019

tactical level describes the manner in which navigators choose specific route options along the way.

For multi-level indoor environments, Hölscher, Meilinger, Vrachliotis, Brösamle, and Knauff (2006) distinguished between three wayfinding strategies. Navigators using the central point strategy find their way by frequently returning to well-known parts of the building, even if this behavior requires considerable detours. Navigators using the direction strategy first move towards the horizontal position of the target (irrespective of floor changes) and then move between floors to the target. Navigators that employ the floor strategy find their way to the target floor irrespective of the horizontal position of the target. Hölscher et al. (2006) found that participants unfamiliar with the environment tended to use the central point strategy, whereas familiarity with the environment led participants to adopt either the direction strategy or the floor strategy.

Previous research has also found that navigators tend to use exhaustive search strategies in completely unfamiliar environments. Exhaustive search strategies include the perimeter strategy (i.e., following the perimeter of the environment in order to avoid exploring the same corridor twice; Ruddle & Lessels, 2009), the lawnmower strategy (i.e., searching in a series of straight parallel lanes; Pingel & Schinazi, 2014), and the directed random search strategy (i.e., choosing the path alternative at a decision point with the lowest likelihood of returning; Buechner, Hölscher, & Wiener, 2009). These exhaustive search strategies are primarily applicable to open environments, but many indoor environments consist of multiple floors with various corridors and obstacles. In addition, it is difficult to distinguish between navigators who use the directed random search strategy and navigators who are completely lost. For the present study, we thus categorized exhaustive search strategies together as unclear strategies.

At the tactical level, navigators make route choices at decision points (i.e., locations at which multiple paths are possible; Schinazi & Epstein, 2010). Route choices can be affected by both physical and social constraints. With respect to physical constraints, route choices can be related with measures of spatial configuration such as connectivity (i.e., the number of accessible connections in a corridor to all other immediate spaces) and integration (i.e., the normalized graph distance from an origin to all other locations in a system; Haq & Zimring, 2003; Hölscher, Brösamle, & Vrachliotis, 2012). Other physical constraints include access to staircases and escalators (Cheung & Lam, 1998), environmental attractiveness (Morrall, 1985), and the proximity of obstacles (Bovy & Stern, 2012; Ciolek, 1978; Hoogendoorn & Bovy, 2004). With respect to the social constraints, researchers have found that pedestrians under stress follow others during a real evacuation (i.e., the collective herding effect; Helbing, Farkas, & Vicsek, 2000) and during experiments in both real and virtual environments (Kinateder et al., 2014; Kinateder & Warren, 2016; Moussaïd et al., 2016). Bode et al. (2014) found that route choices were affected by various sources of directional information such as signs, simulated crowds, and previous experience. However, these participants tended not to follow crowds, unless when the sign and crowd provided conflicting information.

At the locomotion level, previous literature has investigated collective patterns of pedestrian movements such as the formation of pedestrian lanes and circulating flows at intersections, using empirical observations (Moussaid et al., 2009; Moussaïd et al., 2016), video-based experiments (Moussaïd, Perozo, Garnier, Helbing, & Theraulaz, 2010; Yi et al., 2015), and simulation studies (Helbing et al., 2000, 2005; Piccoli & Tosin, 2009). These studies have shown that a variety of factors including environmental layouts (e.g., entrances, exits, walls, and obstacles) and interactions with other pedestrians can influence an individual's locomotion. For example, Hoogendoorn and Bovy (2004) argued that low population density may have an attractive effect on pedestrian walking because pedestrians tend to walk in areas populated by other pedestrians. In contrast, Yi et al. (2015) found that stationary crowds can dramatically decrease walking efficiency in terms of walking distance and travel time, but moving crowds (even at high densities) did not affect pedestrian flow. However, the conditions under which pedestrians avoid moving crowds at high densities are still unclear, as well as the extent to which pedestrians bypass or walk through the crowd.

The present study investigates the effects of physical and social constraints on strategic, tactical, and locomotion behaviors. We used a virtual shopping mall with two levels of crowdedness (high versus low) in terms of the number of computer-controlled agents. Each level of crowdedness was intentionally designed to be homogeneous (i.e., evenly distributed) among different route options but not within each route option (i.e., different for interior and boundary parts of each corridor). Participants were asked to locate a store inside the mall as efficiently as possible in two consecutive trials from two different start floors. The visual access provided by these different start floors represents a manipulation of physical constraints. Compared to the low-crowdedness condition, we expected participants in the high-crowdedness condition to execute different wayfinding strategies, choose different initial route options, and steer away from the agents as if they were physical obstacles. To anticipate, while we did not find effects of crowdedness at strategic or tactical levels, participants in the high-crowdedness condition were more likely to move along boundaries of the environment in order to avoid the crowd. In addition, participants starting on a lower floor (i.e., with more physical and visual access to escalators) differed in their strategic decision-making.

2. Method

2.1. Participants

Sixty-four students (32 females; mean age = 23.3 years; SD = 3.8; age range = 18 to 35) were recruited from universities in Singapore. Each experimental group contained the same number of men and women. A power analysis indicated that this sample was sufficient for detecting a medium to large effect size ($f = 0.4$, $\alpha = .05$, power = .8). Notably, this sample size is also sufficiently large to perform a multinomial logit regression on our categorical dependent variables (over 40 cases per independent variable). The main inclusion criteria were that participants were unfamiliar with the Westgate Mall in Singapore and had normal or corrected-to-normal vision. All participants completed an informed consent form before the study. Participants required approximately 45 minutes to complete the task and were paid 20 SGD for their participation. The study was approved by the Research Ethics Committee of ETH Zurich (2016-N-73).

2.2. Materials

The virtual environments were displayed with an HTC Vive head-mounted display (https://www.vive.com). The Vive has 360-degree head-tracking with a 110-degree field of view, 2160 x 1200 pixels resolution, and a refresh rate of 90Hz. The experiment was conducted on a desktop computer (Intel Core i7-6700K, 3.40 GHz) running Windows 10 Enterprise with a GeForce GTX 1080 graphics card. We used the Unity 5.4 VR engine (http://unity3d.com) to render, control, and record movement in the virtual environment. Trajectories were recorded by logging participants' positions and orientations every 0.5 s. An HTC Vive Controller was used for translational movements. Rotations in the virtual environment were controlled by physical body rotations in the real world.

The virtual environments were created based on the plans of the Westgate Mall in Singapore using 3DsMax (https://www.autodesk.com). The mall consists of seven floors, but we focused on the second and third floors, as they are the most crowded locations during rush hour based on gate counts provided by the shopping mall operators. The layouts of these two floors are presented in Fig. 1.

As shown in Fig. 2, we simulated two levels of crowdedness for each

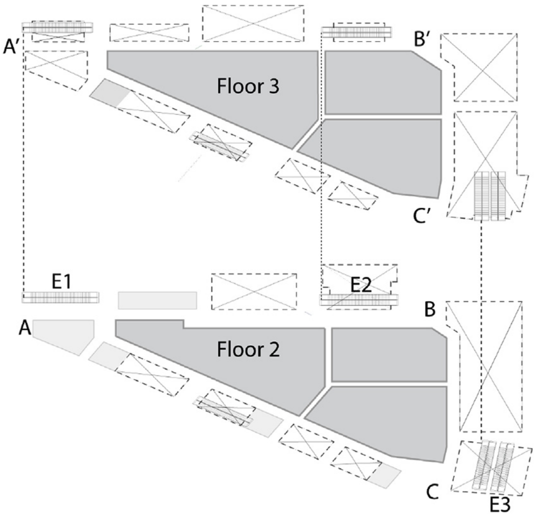

Fig. 1. The layouts of Floors 2 (bottom) and 3 (top) of the Westgate mall. The six vertices of the two floors were denoted as A, B, C, A', B', and C'. Three sets of escalators (i.e., E1, E2, and E3) were used for vertical transitions between floors.

of the corridors in terms of population flow (i.e., avatar counts/m^2/minute). On average, the pedestrian flow for the low and high crowdedness conditions at the three main hallways were 8 and 79 avatars/m^2/minute, respectively. These pedestrian flows were based on the level of service A (less than 23 pedestrians/m^2/minute) and level of service E (between 66 and 82 pedestrians/m^2/minute) developed by Fruin (1971). The distribution of simulated avatars for a given crowdedness level was not 100% homogeneous within a corridor because of the structure of the space. Specifically, the proportion of avatars along the boundaries to the interior of the corridors was approximately 1:2 (44:98 for high crowdedeness and 5:9 for low crowdedness). For these calculations, approximately one third (1332/(1332 + 2493) m^2) of the three main hallway areas in the virtual environment was considered "along the boundary." In the study, participants navigated at a slightly faster speed (1.4 m/s) than the simulated avatars (1.3 m/s) so that they could overtake simulated avatars when necessary. Collisions with simulated avatars were indicated by vibrations of the controller, but participants were not explicitly instructed to avoid simulated avatars. Ambient sounds from a shopping mall were played at both crowdedness levels.

The start point for a wayfinding task was located at either A of the second floor or A' of the third floor. On the second floor, participants could easily reach the nearest escalator and ascend to the third floor. On the third floor, participants had to turn to reach the nearest escalator and descend to the second floor. The corresponding target location for each wayfinding task was located at either C' of the third floor or C of the second floor. This ensured that all participants performed a between-floor wayfinding task.

2.3. Procedure

There were three phases in this experiment. First, participants practiced navigation in VR by moving through corridors and ascending/descending via the escalators in a different section of the larger virtual

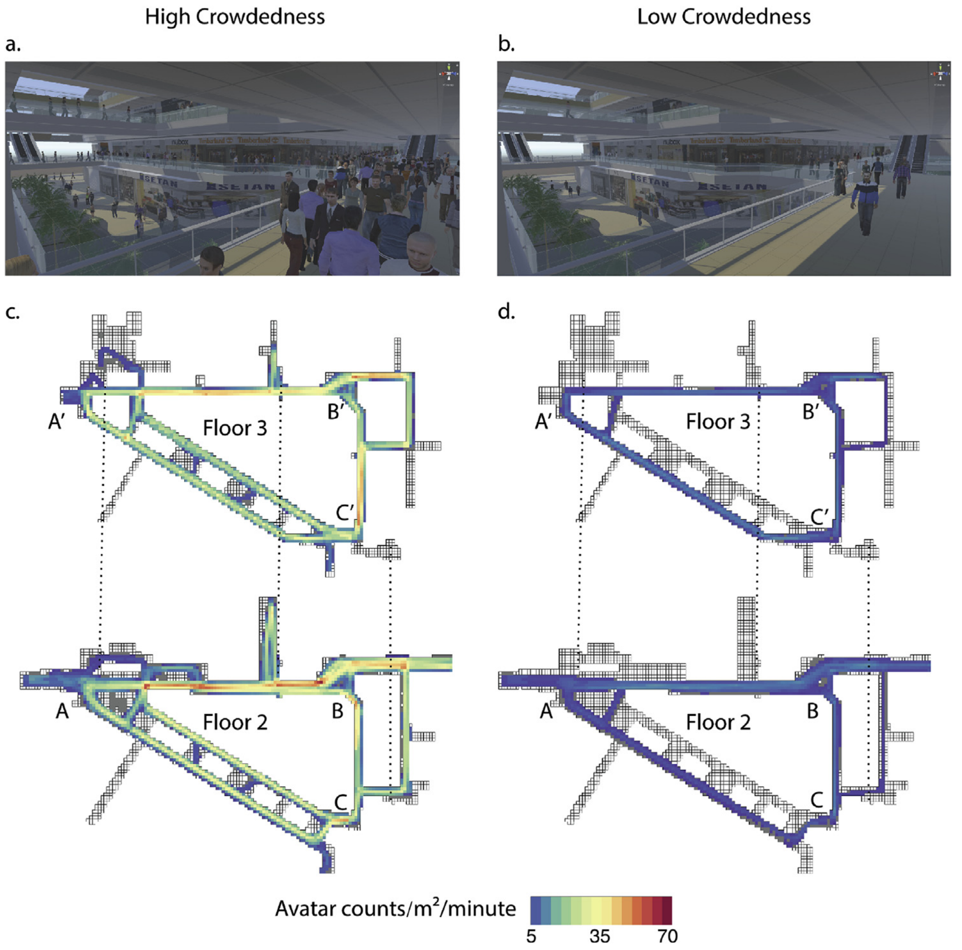

Fig. 2. Screenshots of the virtual environment and crowd density maps with two levels of crowdedness: high crowdedness (a and c) and low crowdedness (b and d).

environment (not used during testing). Participants were also familiarized with the task and instructions. Second, we familiarized participants with locations B or B', depending on their start location (i.e., A or A', respectively). This phase emphasized these locations in order to establish a central point and thus the opportunity for using a central point strategy during the subsequent wayfinding trials. Towards this end, blue arrows on the ground guided participants to three stores within this central area. Participants then walked from B (or B') to the start location A (or A') by following another set of blue arrows on the ground. Participants did not visit the target store during the familiarization phase. Third, during the wayfinding trials, participants were asked to search for a specific target store as efficiently as possible. Each trial began once participants were located at a specific position and orientation facing the middle of the two route options. At this time, a picture of the target store was displayed at the bottom-right corner of the screen and remained there throughout the trial. After participants found the target store, they were teleported back to the start point (i.e., A or A'). Participants then rested for 1.5 min after this phase in order to reduce the risk of simulator sickness. This wayfinding task was then repeated on a second trial.

2.4. Design and analysis

We adopted a 2 x 2 x 2 mixed factorial design with two between-subjects variables (i.e., crowdedness and start floor) and one within-subject variable (i.e., wayfinding trial number). Participants were randomly assigned to two levels of crowdedness (high versus low) and two start floor conditions (the second versus the third floor). Each participant performed two wayfinding trials (trials 1 and 2).

The dependent variables can be divided into four categories: wayfinding performance, wayfinding strategy, initial route choice, and locomotion. Wayfinding performance measures included total wayfinding distance and total wayfinding time. The effects of crowdedness, start floor, and trial number on distance and time were analyzed with two separate 2 x 2 x × 2 mixed-design ANOVAs.

Following Hölscher et al. (2006), participants' trajectories were classified as either central point strategy, direction strategy, floor strategy, or unclear strategy by the experimenter who was familiar with the hypotheses (see Fig. 3). Two additional naive raters classified these trajectories in the same manner. Fleiss' κ ($\kappa = .92$, $z = 28.9$, $p < .001$) was computed to indicate almost perfect agreement among these three raters. A trajectory was classified as representing the central point strategy if participants moved through the presumably most well-known area of the building (location B or B'). A trajectory was classified as representing the direction strategy if the participant first moved towards the horizontal position of the target store before changing floors. For example, if participants started on the second floor at location A, the direction strategy would be indicated by movement through corridors AC and CC'. A trajectory was classified as representing the floor strategy if the participant first changed to the target floor irrespective of the target's horizontal position. For example, if participants started on the second floor, the floor strategy would be indicated by movement through corridors AA', A'B', and B'C'. The remaining trajectories were then classified as unclear strategies. The fixed effects of all three independent variables on wayfinding strategies were analyzed with a multinomial logit regression model using the *nnet* package (Venables & Ripley, 2002) in R. Multinomial logit regression is used when the dependent variable consists of two or more categories (e.g., four wayfinding strategies). Many software packages use the most frequent category as a reference to which the other frequencies are compared. Each coefficient represents the logarithm of the odds between the corresponding category and the reference category over changes in an independent variable. For an independent variable with two categories, a significant coefficient indicates that the relative probability of observing the corresponding category changes with levels of the independent variable. We conducted this analysis with three different reference categories (i.e., central point, floor, and direction) in order to detect any non-redundant effects of crowdedness, start floor, and trial number on all four wayfinding strategies.

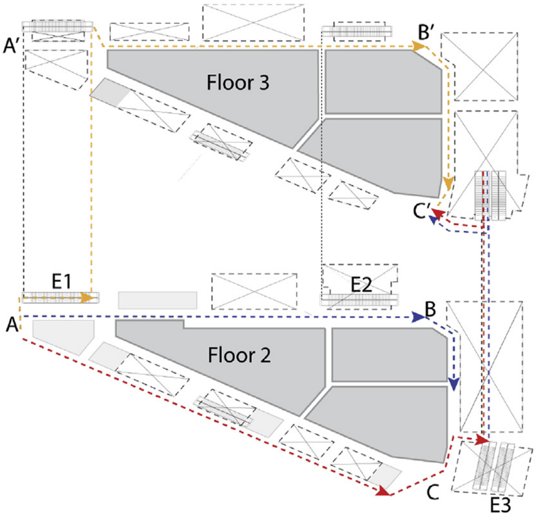

Fig. 3. Routes corresponding to central point (blue), direction (red), and floor (orange) wayfinding strategies, assuming that participants began the trial at location A and searched for a target at location C'. In this case, the corridor between location A' and location C' was blocked in order to facilitate classification of the wayfinding strategies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Our classification of initial route choices was similar to the classification of wayfinding strategies with the exception that we only considered each participant's direction of movement from the start location at the beginning of each trial. Fleiss' κ ($\kappa = .71$, $z = 18.4$, $p < .001$) was again computed and indicated substantial agreement among the three raters. Because there were three possible choices at each start location, this approach resulted in three categories of initial route choices: central point route choice, direction route choice, and floor route choice. As with wayfinding strategies, we used a multinomial logit regression model in order to examine the fixed effects of each independent variable on initial route choice. Here, central point and direction route choices were used as the reference categories.

Our measures of locomotion included number of stops, normalized rotations, locomotion area, and locomotion boundary ratio. Separate 2 (crowdedness) x 2 (start floor) x 2 (trial number) mixed factorial ANOVAs were conducted for each of these locomotion measures. A stop was defined as when a participant remained in the same location (within a meter) for over 3 s. Normalized rotations were calculated by dividing the overall amount of rotation during a trial by wayfinding time. In order to calculate locomotion area and locomotion boundary ratio, all walkable areas of the virtual Westgate Mall were divided into 1 m^2 tiles. These tiles were also categorized as either boundary or interior tiles. Boundary tiles were less than 1 m from the nearest barrier (e.g., a wall or railing). Locomotion area refers to the total number of unique tiles that a participant traversed on each trial. The locomotion boundary ratio was calculated by dividing the total number of traversed boundary tiles by the total number of traversed tiles during a wayfinding trial. Because the proportion of avatars in boundary to interior tiles was similar for high and low crowdedness conditions, any difference in locomotion boundary ratios would be attributable to levels of crowdedness.

In order to determine whether the virtual crowds were attractive or repellant, we also calculated the locomotion correlation between the number of avatars in the virtual crowd at each grid tile and the number of participants at each grid tile (aggregated over trials and start floors). A positive correlation would indicate that participants tended to pass

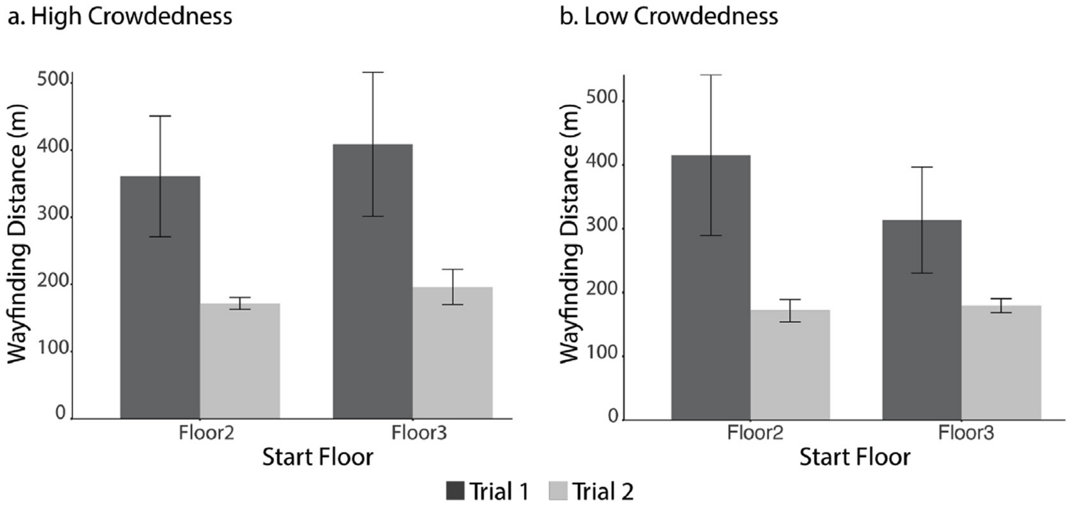

Fig. 4. Wayfinding distance for high crowdedness (a) vs. low crowdedness (b).

through the same tiles as the virtual crowd (i.e., attraction), and a negative correlation would indicate that participants tended to pass through different tiles than the virtual crowd (i.e., repellant). Also, a significant decrease in the locomotion correlation in the high crowdedness condition would indicate that participants in the high crowdedness condition were more likely to avoid crowds than in the low crowdedness condition. The locomotion correlations between the high and low crowdedness conditions were independent, so the test of the difference between two correlation coefficients is a z-test of the difference (i.e., the Fisher's z transformed correlations divided by the standard error of the difference).

3. Results

3.1. Wayfinding performance

Separate 2 x 2 x 2 mixed factorial ANOVAs revealed main effects of trial number on wayfinding distance, $F(1, 60) = 70.669$, $MSE = 17187$, $p < .001$, $\eta_G^2 = .345$, and wayfinding time, $F(1, 60) = 84.536$, $MSE = 12283$, $p < .001$, $\eta_G^2 = .378$. Wayfinding distance and wayfinding time both decreased with trial number (see Fig. 4). There were no significant main effects of crowdedness on wayfinding distance, $F(1, 60) = 0.309$, $MSE = 21322$, $p = .580$, crowdedness on wayfinding time, $F(1, 60) = 0.332$, MSE = 16215, $p = .566$, start floor on wayfinding distance, $F(1, 60) = 0.042$, $MSE = 21322$, $p = .838$, or start floor on wayfinding time, $F(1, 60) = 0.063$, $MSE = 16215$, $p = .803$. No interactions in these analyses were significant (all $p > .11$).

3.2. Wayfinding strategies and initial route choices

Fig. 5a represents the proportion of participants that exhibited each strategy for each of the two trials. The results of the multinomial logit regression for wayfinding strategies (AIC = 287.802) revealed a significant effect of trial number on the proportion of trajectories represented by the unclear strategy compared to the central point, direction, and floor strategies (all $ps < .01$; see Table 1). This finding suggests that fewer participants adopted an unclear strategy for the second trial compared to the first trial. We also found a significant effect of start floor on the adoption of the floor strategy compared to the direction strategy ($p < .05$; see Table 1). When direction strategy was used as the reference category, participants who started from the second floor appeared more likely to adopt the floor strategy than those who started from the third floor. There was no significant effect of crowdedness on any of the wayfinding strategies.

Fig. 5b represents the proportion of participants who exhibited each strategy for each of the two trials. The results of the multinomial logit regression for initial route choices (AIC = 236.395) revealed a significant effect of trial number on the proportion of trajectories represented by the floor route choice compared to the central point and direction route choices (both $ps < .05$; see Table 2). This finding suggests that more participants adopted the floor route choice on the second trial compared to the first trial. Here again, there was a significant effect of start floor on the adoption of the floor route choice compared to the direction route choice ($p < .01$). When the direction route choice was used as the reference category, participants who started from the second floor appeared more likely to adopt the floor route choice than those who started from the third floor. There was no significant effect of crowdedness on any of the initial route choices.

3.3. Locomotion

Two 2 x 2 x 2 mixed factorial ANOVAs were used to analyze number of stops and normalized rotations (see Fig. 6). For number of stops, we found a main effect of trial number, $F(1, 60) = 46.793$, $MSE = 7.2$, $p < .001$, $\eta_G^2 = .236$, indicating that there were more stops in the first trial than in the second trial. No other main effects or interactions were significant for number of stops (all $p > .296$). For normalized rotations, we found a main effect of trial number, $F(1, 60) = 34.390$, $MSE = 18.2$, $p < .001$, $\eta_G^2 = .118$, and an interaction between crowdedness and start floor, $F(1, 60) = 4.914$, $MSE = 59.9$, $p = .031$, $\eta_G^2 = .06$. Normalized rotations were higher for the first trial compared to the second trial. When participants started on the second floor, normalized rotations were higher in the low crowdedness condition than the high crowdedness condition, but when participants started on the third floor, normalized rotations were higher in the high crowdedness condition than the low crowdedness condition. No other main effects or interactions were significant for normalized rotations (all $p > .185$).

Separate 2 x 2 x 2 mixed factorial ANOVAs were used to analyze locomotion area and locomotion boundary ratio (see Fig. 7). For locomotion area, we found a main effect of trial number, $F(1, 60) = 78.655$, $MSE = 30582$, $p < .001$, $\eta_G^2 = .375$, indicating that participants traversed more unique tiles on the first trial than on the second trial. No other main effects or interactions were significant for locomotion area (all $p > .07$). For locomotion boundary ratio, we found a main effect of crowdedness, $F(1, 60) = 17.750$, $MSE = 0.014$, $p < .001$, $\eta_G^2 = .170$, start floor, $F(1, 60) = 4.050$, $MSE = 0.014$, $p = .049$, $\eta_G^2 = .045$, and trial number, $F(1, 60) = 10.249$, $MSE = 0.006$, $p = .003$, $\eta_G^2 = .050$. Locomotion boundary ratios were lower for the low crowdedness condition than the high crowdedness condition, higher for participants who started on the second floor than for those who started on the third floor,

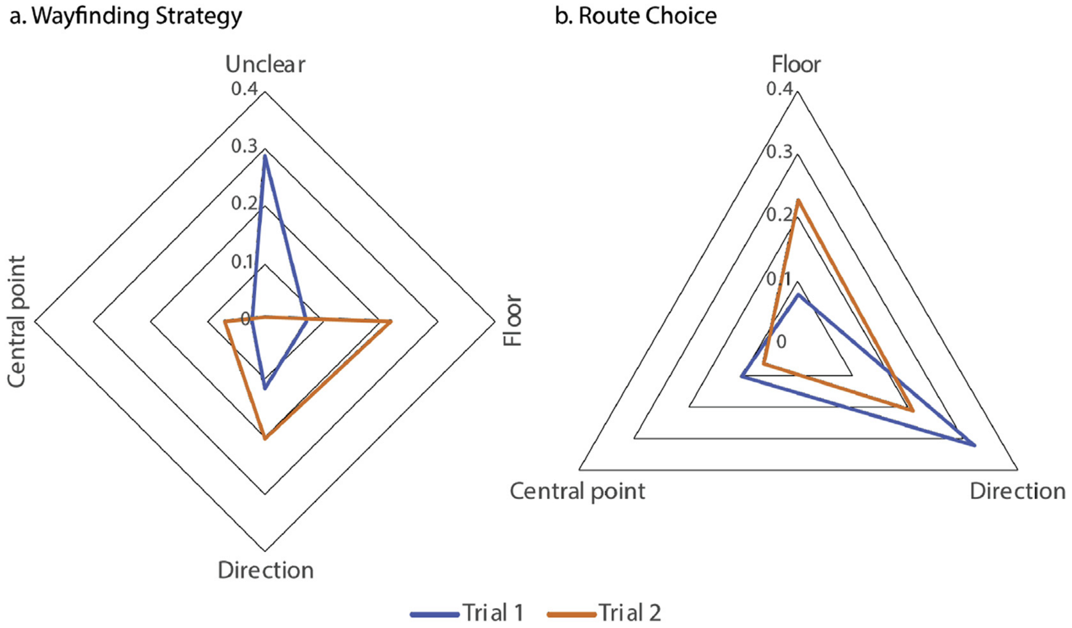

Fig. 5. The proportion of participants who exhibited each wayfinding strategy (a) and route choice (b) for each of the two trials.

and lower for the first trial than for the second trial. No interactions among these three factors were significant for locomotion boundary ratio (all $p > .18$).

The locomotion correlations for both high ($r(6185) = 0.610$, $p < .001$) and low ($r(6074) = 0.787$, $p < .001$) levels of crowdedness were positive. We also found that participants in the high crowdedness condition had a significantly lower locomotion correlation than in the low crowdedness condition, $z = 19.594$, $p < .001$. These results indicate that participants in the high crowdedness condition were more likely to avoid crowds compared to the low crowdedness condition.

4. Discussion

We conducted the present study in order to examine the effects of crowdedness, start floor, and trial number on strategic, tactical, and locomotion behaviors during goal-directed navigation in a virtual shopping mall. The results revealed that crowdedness only affected locomotion behavior and did not affect wayfinding performance, wayfinding strategies, or initial route choices. Specifically, navigators were more inclined to avoid crowds in more crowded environments by walking close to the boundaries of the environment. We also found that trial number affected wayfinding performance, wayfinding strategies, initial routes, and locomotion behavior (in terms of number of stops, normalized rotations, locomotion area, and locomotion boundary ratio). Start floor also affected wayfinding strategies, initial route choice, and locomotion boundary ratios. Together, these findings indicate that familiarity, as well as social and environmental factors, influence locomotion behavior in crowded environments. However, the strategic and tactical levels of navigation are not necessarily affected by crowdedness.

There are at least two reasons why crowdedness did not significantly affect strategic or tactical levels of navigation. First, according to intensifier theory (Freedman, 1975), individuals may react to crowds positively or negatively, depending on their values, beliefs, and attitudes. Any individual differences in these characteristics would be exacerbated by the density of the crowd and would reduce the

Table 2
Coefficients and standard errors (in brackets) for the multinomial logit regression of initial route choices.

	Central point route choice as the reference category		Direction route choice as the reference category
	Floor route choice	Direction route choice	Floor route choice
(Intercept)	0.575	1.485**	−0.910*
	(0.607)	(0.540)	(0.442)
Trial number	1.445*	−0.236	1.681**
	(0.603)	(0.543)	(0.470)
Start floor	−0.617	0.888	−1.505**
	(0.603)	(0.538)	(0.460)
Crowdedness	−0.819	−0.963	0.144
	(0.605)	(0.555)	(0.445)

Table 1
Coefficients and standard errors (in brackets) for the multinomial logit regression of wayfinding strategies.

	Central point strategy as the reference category			Direction strategy as the reference category		Floor strategy as the reference category
	Unclear strategy	Floor strategy	Direction strategy	Floor strategy	Unclear strategy	Unclear strategy
(Intercept)	2.715**	1.931*	2.042*	−0.111	0.673	0.784
	(0.864)	(0.86)	(0.84)	(0.514)	(0.491)	(0.516)
Trial number	−4.691**	0.150	−0.504	0.654	−4.188**	−4.841**
	(1.215)	(0.785)	(0.752)	(0.524)	(1.069)	(1.096)
Start floor	−0.023	−1.075	0.146	−1.220*	−0.168	1.052
	(0.755)	(0.688)	(0.678)	(0.482)	(0.541)	(0.598)
Crowdedness	−0.322	−0.748	−1.015	0.267	0.693	0.426
	(0.769)	(0.704)	(0.692)	(0.476)	(0.538)	(0.581)

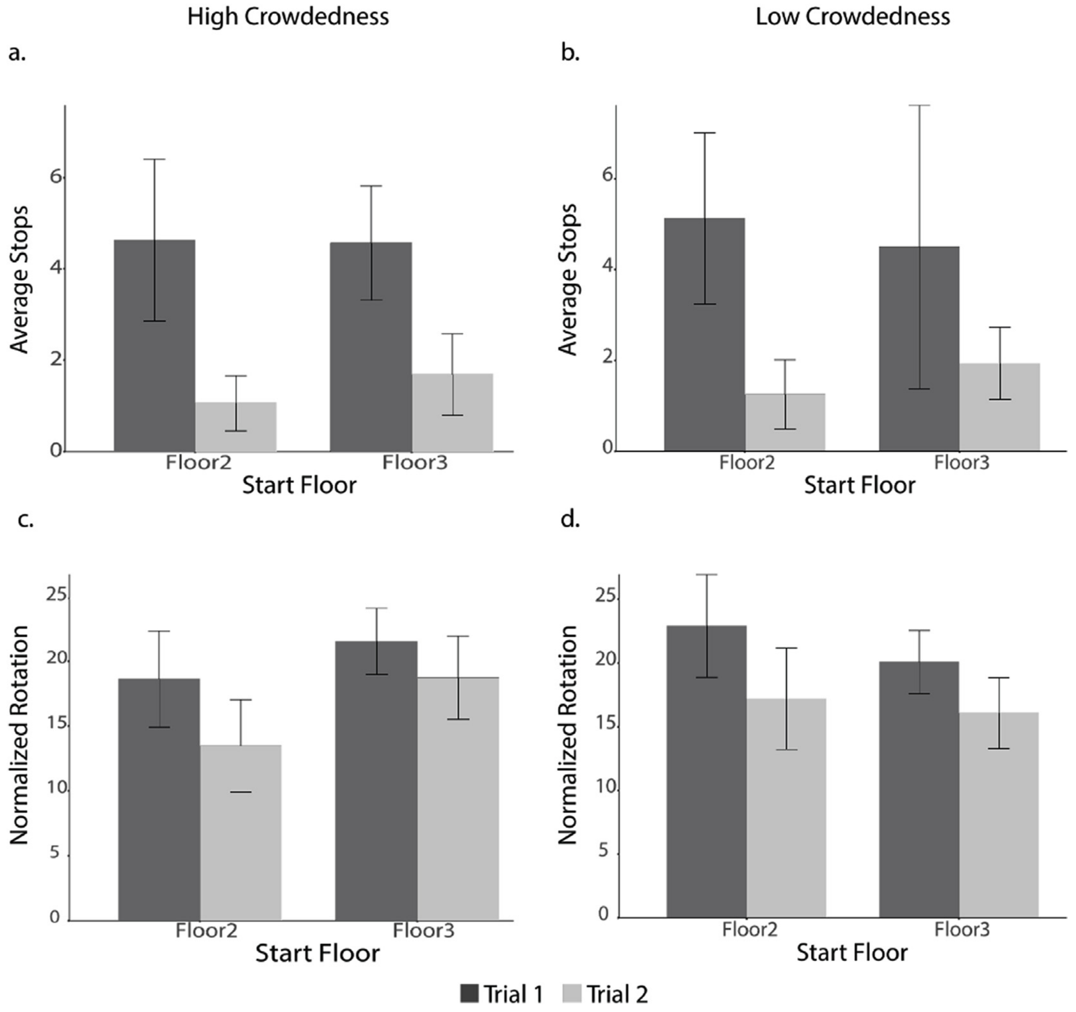

Fig. 6. Average stops and normalized rotation in a wayfinding task for high crowdedness (a and c) vs. low crowdedness (b and d).

likelihood of finding an effect of crowdedness. Future research should assess and control for these individual differences in order to determine their possible influence on spatial reasoning. Second, crowdedness (whether interpreted positively or negatively) may not affect spatial reasoning in general. This possibility is particularly relevant for experiments in virtual reality because participants may not infer agency from the avatars' behaviors. In order to assess the effect of crowds on spatial decision making, future studies should directly compare navigation in real and virtual environments. However, many real environments (e.g., Westgate Mall) have uneven distributions of crowds that could confound such comparisons. Another approach would be to program the agents based on actual pedestrian trajectories in order to influence participants' strategic and tactical behavior.

The lack of crowd effects on strategic and tactical levels of navigation conflicts with some previous literature that suggests that crowds can act as environmental stressors (Evans, 1979; Evans & McCoy, 1998; Mackintosh et al., 1975). Specifically, crowds can increase inhabitants level of anxiety and impair their incidental memory of the environment. In the present study, the virtual crowds were purely visual and were not accompanied by loud noises, queuing behavior, and unwanted physical contact. The anticipation of such annoyances may lead pedestrians in real environments to choose different routes. Recently, researchers have developed VR systems that provide haptic feedback and sound rendering (for a review, see Moussaïd, Schinazi, Kapadia, & Thrash, 2018). For example, Ryu and Kim (2004) developed a device that provides a combination of aural and vibro-tactile feedback and found that this device led to greater self-reported presence than aural feedback per se, but there was no significant difference in terms of the accuracy of collision detection. For crowd research, such devices may provide a more realistic sense of crowded environments. However, the potential effects of this experience on the strategic and tactical levels of navigation are still unclear.

Our results indicate that crowdedness affects locomotion behavior. Specifically, participants in the high crowdedness condition were more likely to avoid crowds than in the low crowdedness condition. Here, participants in the high crowdedness condition tended to move close to boundaries of the environment, which were less crowded than the interiors. These findings suggest that participants considered the virtual crowd as a set of moving obstacles rather than cues indicating a more popular route (cf. Kinateder et al., 2014; Moussaïd et al., 2016). This finding also builds on Yi et al. (2015) in that moving crowds did not affect walking efficiency (i.e., distance and time) but did affect the overall pattern of movement. At high crowd densities in the real world, pedestrians can bypass crowds without influencing the efficiency with which they reach their destination. However, this type of detouring may be less effective at extremely high densities (Helbing et al., 2000).

As a possible indicator of familiarity in the present study, trial number significantly affected wayfinding performance, wayfinding strategies, initial route choices, and locomotion behavior. Unsurprisingly, wayfinding performance improved over trials as participants learned the location of the goal. Wayfinding strategies also changed with trial number. Specifically, participants tended to switch from an unclear strategy to either floor or direction strategies over trials. This first finding is consistent with previous literature in that

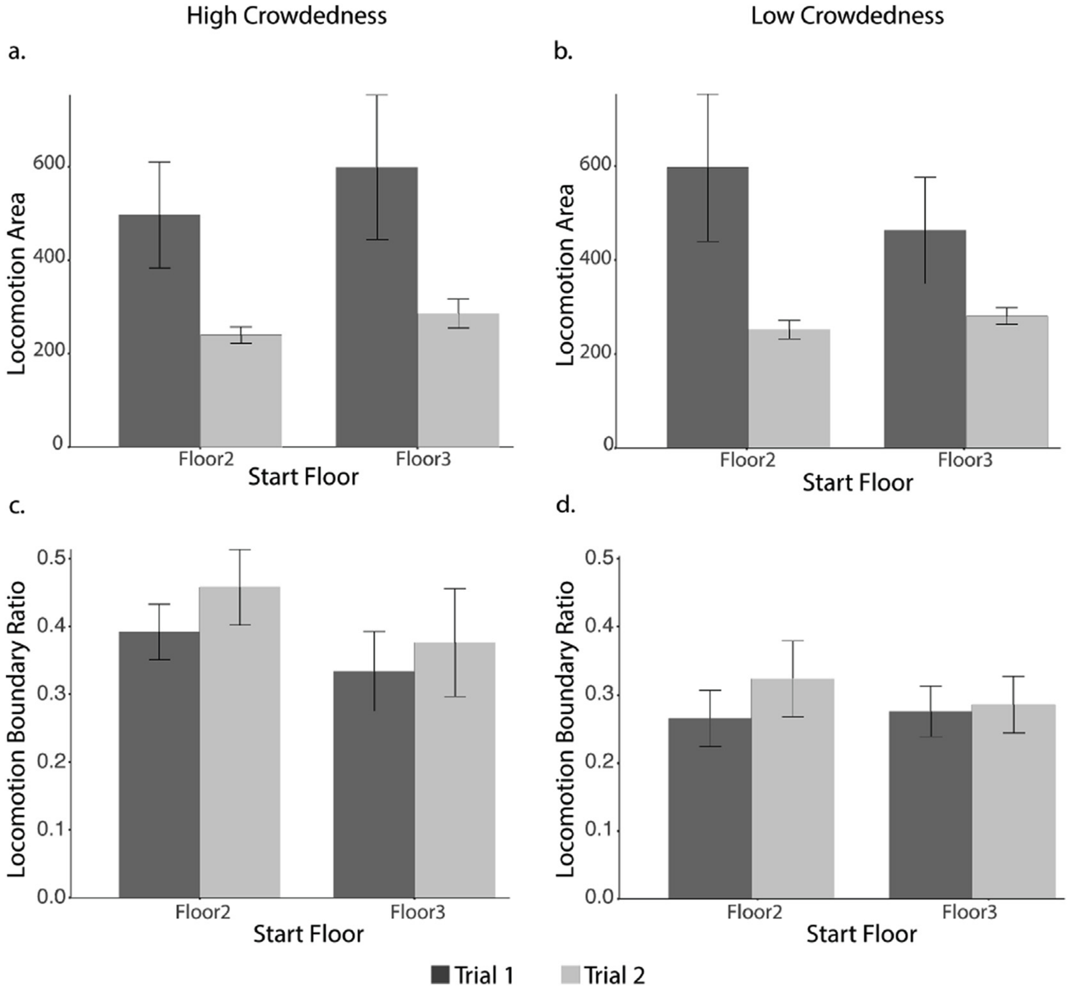

Fig. 7. Average locomotion area and locomotion boundary ratio in a wayfinding task for high crowdedness (a and c) vs. low crowdedness (b and d).

navigators tend to use exhaustive search strategies when they have no prior knowledge of the location of the target (Darken & Sibert, 1996). In terms of initial route choices, participants were also more likely to immediately switch floors in the second trial compared to the first trial. These findings are somewhat consistent with Hölscher et al. (2006) in that the proportion of participants who employed the floor strategy increased with familiarity. In contrast to Hölscher et al. (2006), participants in the present study tended not to use the central point strategy (regardless of familiarity). The central point strategy in the present study was defined with respect to a familiarization phase, but there may have been no visually salient cues to indicate the main hall of the virtual building (i.e., central point). The effects of familiarity on locomotion behavior are consistent with previous literature in virtual reality (Grübel, Thrash, Hölscher, & Schinazi, 2017). Over trial number, participants stopped less, rotated less, covered less area of the floorplan, and moved more along the boundaries of the corridors. All of these findings indicate that participants were maximizing the efficiency of their routes while reducing their exploration of the space.

With respect to the independent variable of start floor, we found that participants who started from the second floor were more likely to adopt the floor strategy (and the floor route choice) than those who started from the third floor (compared to the direction strategy/route choice). One possible explanation for these findings is that participants who started from the second floor were able to easily access (both visually and physically) the upwards escalator near the start point. In contrast, participants who started from the third floor were obliged to make a large turn to descend to the second floor. The variable start floor may have also affected locomotion boundary ratios because of different layouts on the second floor and third floor of the virtual environment. This pattern may be attributable to differences in the width of the corridors on the two floors. Specifically, corridors on the second floor were wider than corridors on the third floor. With respect to the interaction between start floor and crowdedness on normalized rotation, the results demonstrated that participants rotated more in the low crowdedness condition than in the high crowdedness condition when they started on the second floor and the opposite pattern when they started on the third floor. This interaction may be due to differences in visual or physical access between the two floors, but future studies will need to disentangle these possibilities by systematically varying whether participants could move their viewpoint and avatar simultaneously.

In summary, participants in the present study avoided the crowd by moving along the boundaries of the virtual environment, but this pattern does not appear to have affected their wayfinding strategies or initial route choices. One reason that crowdedness did not affect wayfinding strategies or initial route choices may have been that the crowd varied within routes but not between routes. In addition, familiarity with the virtual environment affected all three levels of navigation. Together, these findings suggest that the crowded virtual environment was sufficiently realistic to induce differences in locomotion behavior but that these differences may not always necessitate differences at strategic and tactical levels. Future research in virtual and real environments should investigate the extent to which crowds that vary across route options and other social factors (e.g., the agents' intentions) can lead to the adoption of different wayfinding strategies. For example, researchers can vary crowd density along different route options in order to investigate under which conditions participants choose the more or less crowded route options. This approach could extend the present study in terms of the effects of local crowdedness at decision points rather than the effects of overall crowdedness on strategic decision-making. In addition, future studies can manipulate the movement characteristics of the agents (or the instructions given to participants) to indicate different intentions.

Supporting information

A video shows multi-level indoor wayfinding at high and low crowdedness levels.(MP4)

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.jenvp.2019.101320

Acknowledgements

The research was conducted at the Future Cities Laboratory at the Singapore-ETH Centre, which was established collaboratively between ETH Zurich and Singapore's National Research Foundation (FI 370074016) under its Campus for Research Excellence and Technological Enterprise programme. We wish to thank SPOTWORKS (https://spotworks.com.sg) for designing the virtual model.

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