JOURNAL OF THE ROYAL SOCIETY Interface

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Cite this article: Bode NWF, Kemloh Wagoum AU, Codling EA. 2014 Human responses to multiple sources of directional information in virtual crowd evacuations. *J. R. Soc. Interface* **11**: 20130904. http://dx.doi.org/10.1098/rsif.2013.0904

Received: 4 October 2013
Accepted: 25 October 2013

Subject Areas:
biocomplexity

Keywords:
decision-making, crowd behaviour, emergency evacuations, virtual environment, route choice, directional information

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Electronic supplementary material is available at http://dx.doi.org/10.1098/rsif.2013.0904 or via http://rsif.royalsocietypublishing.org.

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Human responses to multiple sources of directional information in virtual crowd evacuations

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The evacuation of crowds from buildings or vehicles is one example that highlights the importance of understanding how individual-level interactions and decision-making combine and lead to the overall behaviour of crowds. In particular, to make evacuations safer, we need to understand how individuals make movement decisions in crowds. Here, we present an evacuation experiment with over 500 participants testing individual behaviour in an interactive virtual environment. Participants had to choose between different exit routes under the influence of three different types of directional information: static information (signs), dynamic information (movement of simulated crowd) and memorized information, as well as the combined effect of these different sources of directional information. In contrast to signs, crowd movement and memorized information did not have a significant effect on human exit route choice in isolation. However, when we combined the latter two treatments with additional directly conflicting sources of directional information, for example signs, they showed a clear effect by reducing the number of participants that followed the opposing directional information. This suggests that the signals participants observe more closely in isolation do not simply overrule alternative sources of directional information. Age and gender did not consistently explain differences in behaviour in our experiments.

1. Introduction

Imagine a crowd of people leaving a building with multiple exits. Some exits are labelled with signs, while some people in the crowd remember that they have been told to use certain exits. Which exit route do people choose? Do they follow the signs, or other people, or the information they may or may not remember? Depending on the decisions of individuals, the crowd could split evenly between different exits or everyone could try to use the same exit. This scenario is a perfect example of collective behaviour in which the decisions of individuals combine and lead to the observed crowd dynamics [1]. Such collective behaviour phenomena, emerging from interactions between individuals, occur across a wide range of species including social animals, insects or bacteria and include the synchronized movement of schools of fish or the relocation of nest sites in ants, for example [2].

The evacuation of human crowds from confined spaces is one example that highlights the practical importance of understanding collective behaviour. Crowds are composed of many individuals and each individual makes movement decisions based on their surroundings. These individual-level decisions give rise to the movement dynamics of crowds and to make buildings or vehicles safer, we thus need to understand the individual-level decisions in crowd evacuations [3]. Individuals within a crowd are likely to make movement decisions at different temporal and spatial scales [4]. In particular, it has been suggested that we need to distinguish between microscopic ‘operational-level’ decisions and higher level ‘tactical-level’ decisions [5]. Operational-level decisions typically relate to the short timescale walking behaviour of pedestrians, for example the

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precise steps in a path an individual may take through a crowd to the nearest exit while avoiding collisions with other pedestrians or objects in the vicinity. Theoretical and empirical research on this type of behaviour suggests that humans seek to optimize their travel time or the directness of their path [6,7]. Tactical-level decisions occur over longer timescales, and examples include the decision on which exit route from a building to use, or the timing of when to initiate the personal evacuation. In the context of evacuations, tactical-level decisions about when to go and where to go can lead to high pedestrian densities and operational-level behaviours can subsequently lead to potentially dangerous collective phenomena, for example the build-up of pressure at bottlenecks in evacuation routes [5]. Empirical and theoretical work has greatly helped to reduce the risks posed by dangerous collective phenomena emerging from behaviour at the operational level [3]. In this study, we investigate the tactical-level movement decisions of humans in the context of crowd evacuations.

Different approaches have been developed and used to determine what individual-level behaviours may lead to observed collective phenomena, but there is currently no established solution for this particular problem. In one approach, different models for individual behaviour are fitted to empirical data. The model producing the best fit represents the most likely set of behaviours [8]. A drawback of this approach is that our knowledge is always limited by the available models for behaviour under consideration. A different approach treats individuals as particles and estimates the strength of the forces acting between these particles from the relative movement of individuals [9,10]. Manipulating the sensory abilities of individuals within groups (e.g. by blindfolding them) presents another approach to establish the sufficient and necessary basis for certain types of collective behaviour [11]. We employed an alternative approach by using a virtual environment to precisely control the signals and visual stimuli humans could obtain from their environment. By asking volunteers to complete an evacuation from a building in this interactive simulated environment, we investigated how humans respond to different sources of information when making movement decisions.

Interactive virtual environments are an established and proved tool to investigate dynamic human decision-making in response to changing circumstances in general [12,13] and in evacuations in particular [14–18]. At one end of a spectrum of simulated environments are ‘table-top’ pen and paper - scenarios developed to assess decision-making of miners, fire-fighters or military personnel in emergencies that can subsequently be used for training purposes [19]. At the other end of the spectrum for simulated environments are fully immersive scenarios for pedestrians that promise to be useful in calibrating models for pedestrian movement and in exposing volunteers to fully controlled emergency situations [20]. We opted for an intermediate level of simulation sophistication. This ensured that the simulated scenario was realistic enough to be easily understood by participants and that the controls for interactions with the environment were sufficiently simple to allow a wide spectrum of volunteers to participate. An additional advantage of performing experiments on human behaviour in crowd evacuations using a virtual environment is that we can expose many participants to different, potentially stressful, scenarios at low cost and without risk of injury or exhaustion. A disadvantage of conducting experiments in virtual environments, which we address further below, is the question to what extent findings from this type of research apply to real evacuations.

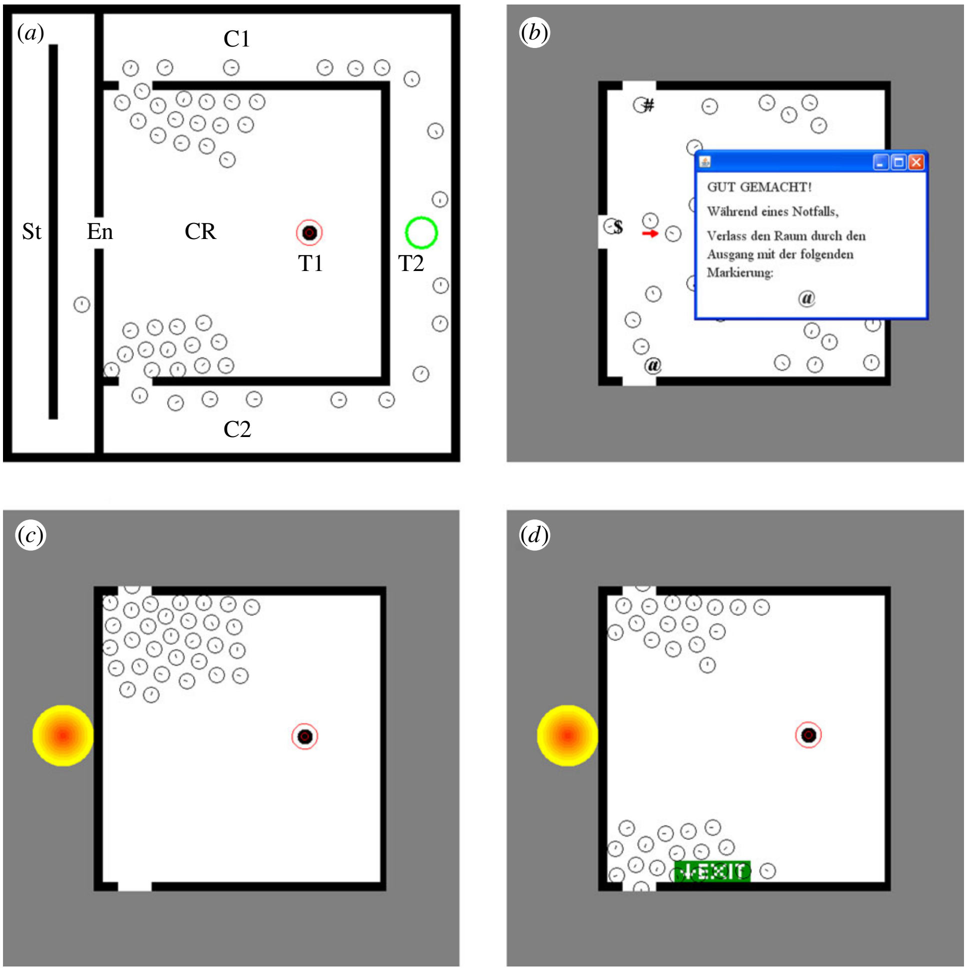
The scenario outlined in the introductory paragraph illustrates how individuals may base their movement decisions on different sources of information. We identified three ubiquitous sources of information or signals for the purpose of this study: emergency exit signs, the actions of other individuals within the evacuating crowd and memorized instructions. The common aspect of these three sources of information is that they provide directional information that can steer evacuees in a particular direction during emergencies. Emergency exit signs provide static information that does not change over time. The actions of other individuals within the evacuating crowd provide dynamic information that can change over time. Memorized information, for example verbal instructions given prior to the evacuation, may not be remembered correctly or could be forgotten. In the course of an evacuation, people are often confronted with possibly conflicting information from different sources [21]. Therefore, we suggest that it is particularly important to assess the effect of combinations of signals on individual decision-making in the context of evacuations. Previous research has used interactive virtual environments to assess the response of humans to different static environmental directional information [15,18,22]. By contrast, we investigate the impact of static, dynamic and memorized directional information and the interplay between these information sources on human movement decisions.

Although some research suggests that the layout of buildings could be more important in informing evacuees’ movement decisions [23], emergency exit signs are a commonly used and widely accepted tool to label exit routes [24]. Empirical research has also investigated where to best position signs and how to design signs to ensure their visibility [15,22]. Interactive virtual environments have previously been used to investigate the effect of signs on human movement decisions [16,18]. The results suggest that, on the one hand, signage can reduce evacuation times but, on the other hand, that humans tend to preferentially interact with other conspicuous features of the virtual environment, such as doors or brightly lit and wider corridors, and that only repeated exposure to signs has the desired effect [16,18].

Crowd-following behaviour is often considered to be an important aspect of evacuations and it has been suggested that this could be beneficial in some circumstances by helping people to find exits, but conversely, could also lead to overcrowding at exits in other circumstances [25]. In addition, proximity-seeking behaviour towards familiar people is considered to be important [26]. However, in general the question of whether evacuees follow others remains unresolved and is likely to depend on the specific context [5].

Official guidelines recommend that passengers of planes or trains are invited to familiarize themselves with the location of emergency exits and to note the closest emergency exit to their seat [27]. Similar instructions may be given on entering buildings or people may notice and possibly memorize exit routes on a tour around a building. While previous work investigated the importance of being familiar with one of a choice of exit routes [17,28], to our knowledge the effect of memorized information on the movement decision of evacuees has not been investigated systematically.

In summary, we used an interactive virtual environment to investigate how the information from three different sources of directional information influence the movement



GUT GEMACHT!
Während eines Notfalls,
Verlass den Raum durch den Ausgang mit der folgenden Markierung:
@

Figure 1. Layout of simulated environment and different experimental treatments. (*a*) Layout of the simulated environment. In the first task, participants started at the initial position 'St', followed arrows to the entrance 'En' into the central room 'CR' and to the first target 'T1'. The second task is outlined in the Material and methods and did not involve any simulated pedestrian movement. In the third task, participants started at 'T1' and subsequently left 'CR' through either exit into corridors 'C1' or 'C2' and moved to the final target 'T2'. The entrance 'En' was blocked in this task. The pedestrian steered by participants is represented by a black filled circle, located at 'T1', and simulated pedestrians are represented by white filled circles with a line indicating their movement direction. We show the control treatment in which the simulated crowd splits evenly between the two exits during the third task. For illustration purposes, the whole environment is visible, but participants had a limited view as shown in the other panels. (*b*) Memory treatment M (the message displayed translates to: 'Well done! During an emergency, leave the room through the exit marked with the following symbol: @'). (*c*) Crowd treatment C (the entire crowd exits through one exit). (*d*) Sign treatment S (the crowd splits evenly between the two exits and a sign labelled 'EXIT' indicates which exit to use). (Online version in colour.)

decisions of humans in simulated evacuations. Importantly and in contrast to previous work, we not only investigate the effect of different signals in isolation, but also explicitly consider combinations of signals in which the directional information of one signal is either reinforced or contradicted by another signal.

2. Material and methods

2.1. Methods summary

In this research, we extend established methodology for studying human route choices in a virtual environment [17]. We recruited participants from paid volunteers taking part in a separate large-scale experiment on pedestrian dynamics in Düsseldorf, Germany (19–22 June 2013; project details: www.basigo.de). Each participant was only allowed to take part in the experiment once and was presented with a top-down view of a virtual environment populated by 80 simulated pedestrians, the movement of one of which could be controlled by participants via mouse clicks. Figure 1 shows this environment: the layout was symmetrical and consisted of a central room, an entrance area and two corridors connecting the central room to an additional corridor stretching over the width of the environment. The global environment was hidden from participants, and only the contents of the rooms they were occupying were visible to them (figure 1). We recorded the timing and the on-screen location of mouse clicks for each participant, as well as the associated movement within the virtual environment. At the start of the experiment, participants received instructions on how to steer their pedestrian (see the electronic supplementary material for full instructions). Our experiment consisted of three tasks that participants had to accomplish within the virtual environment.

In the first task, participants were familiarized with the virtual environment and learned how to control their pedestrian by moving it from a starting position in the entrance area via a designated route marked with arrows to a fixed target in the central room (T1 in figure 1*a*). The symmetrical layout of our experiment allowed us to randomly choose one of the two possible routes into the central room for each participant to avoid inducing a directional bias. During this task, the simulated pedestrians moved randomly in the central room and the two corridors (see the electronic supplementary material for details). All participants successfully completed the first task. We did not use data from this task in our analysis.

At the start of the second task, participants were shown a message for 6 s instructing them to leave the (central) room in case there was an emergency. In the remainder of the second task, participants were presented with nine maths questions and were invited to answer as many as possible within 30 s. They were subsequently shown the results of their performance in this test for 15 s. This task was designed to distract participants from the instruction message at the start of the task. The content of the message was varied in one of the experimental treatments (see below).

The third task started with a 5 s countdown. Over the last 4 s of this countdown, participants were shown a message instructing them to leave the room because of an emergency. The entrance by which participants had entered the central room in the first task was blocked and participants were thus faced with a choice of two exits from the room: one at the top and one at the bottom (figure 1). The third task and the experiment ended when participants reached a new target that was outside the central room and equidistant from both remaining exits (T2 in figure 1*a*). During this task, the simulated pedestrians performed a simulated evacuation, exiting the room through the same exits that were open to the participants. To ensure that participants quickly grasped how to control their pedestrian, they were allowed to ask the experimenter questions throughout the experiment. Only answers on how to steer their pedestrian were given.

2.2. Treatments

Each participant was exposed to one treatment out of 10 possible treatments. To ensure an even split of participants across treatments, we allocated a unique number to each participant which was incremented by one between consecutive participants and allocated treatments according to modulo 10 of this number. Participants were not allowed to watch others before they took part in the experiment and participants who had already taken part in the experiment were not allowed to talk to others before they took part. In addition to the control treatment, we implemented three primary treatments. We obtained six additional treatments by pairwise combinations of the three primary treatments. The treatments were designed to provide participants with directional information about which exit route to take and are described below.

In the control treatment, the simulated pedestrians split evenly between the two exit routes from the central room during their simulated evacuation (figure 1*a*). This treatment was designed to establish the baseline behaviour of participants in a perfectly symmetrical set-up.

In the 'memory' treatment (M), participants were shown a different message at the start of the second task. While in the other treatments, the message only instructed participants to leave the room in case of emergency, in the M treatment, the message instructed participants to leave the room through a specific exit. Both exits and the entrance were labelled with unique symbols that were shown six times for half a second in half-second intervals (figure 1*b*). The message indicated the unique symbol of the exit participants should use when exiting the room. The M treatment was designed to test participants' ability or willingness to follow instructions on exit routes from memory. In real life, people might be distracted during or after receiving information on exit routes and we included the maths test in the second task to distract participants from the information received in the M treatment.

The 'crowd' treatment (C) presented participants with a simulated evacuation in which all simulated pedestrians exited through one exit (figure 1*c*). This treatment tested the response of participants to the dynamic directional information provided by the movement of simulated agents and it also tested participants' response to exit blockages induced by the simulated crowd.

In the 'sign' treatment (S), the simulated evacuating crowd split evenly between the two exits, but close to one of the exits was a green 'EXIT' sign with an arrow pointing upwards or downwards, depending on which direction people had to move to use the nearby exit (figure 1*d*). The S treatment was designed to test participants' response to static directional information provided by signs.

The remaining six treatments were pairwise combinations of the primary treatments M, C and S. In three of these treatments, the two primary treatments reinforced the directional information they provided to the participants. For example, in the reinforcing combination of the crowd treatment C and the sign treatment S (denoted interchangeably by C + S or S + C), the simulated crowd exited through the same exit that was also marked with an exit sign. Likewise, in treatment M + S (or S + M), the exit indicated to participants at the start of the second task was also labelled with an exit sign. The remaining treatment that reinforced directional information was M + C (or C + M).

To study the case when different sources of information provide conflicting directions, we combined the primary treatments in such a way that they suggested opposite exit routes. For example, in the conflicting combination of treatment C and treatment S (denoted interchangeably by C − S or S − C), the simulated crowd all exited through one exit while the opposite exit was marked with an exit sign. The other conflicting combinations of primary treatments led to treatment M − S (or S − M) and treatment M − C (or C − M).

2.3. Simulated individual behaviour

We used previously established methodology [17] based on well-accepted theoretical work [25,29] to simulate the movement of pedestrians in continuous space. We modelled interactions between pedestrians as social forces. Individuals' reactions to the built environment (e.g. walls) and movement preferences (e.g. towards a target) were encoded in a discrete floor field. At the start of the experiment, the simulated pedestrians were distributed randomly over the central room and the two adjoining top and bottom corridors (figure 1*a*). Pedestrian–pedestrian and pedestrian–wall overlaps were avoided throughout the experiment and simulated pedestrians were removed from the simulation and graphic display when they reached the final target of the evacuation in the third task. During the first task, a small number of pedestrians (less than 4%) occasionally entered the entrance area, where they got stuck when the entrance was blocked during the third task (this had no effect on experimental outcomes). The movement dynamics in the virtual environment were not updated during the second task and whenever messages were displayed to the human players. We ran the simulation with fixed parameter values to ensure that simulated pedestrians moved at a reasonable speed and participants had sufficient time to react to the dynamics. The full details of the simulation model can be found in the electronic supplementary material.

2.4. Data collection and statistical analysis

Only participants aged 18 or older were permitted to participate in the research. We recruited a total of 570 participants, 29 of whom had to be excluded from the study because they accidentally terminated the computer program before the complete data could be written to files. Of the remaining 541 participants, 450 (83%) reported their age. The median age across participants was 23 years (mean: 24.66 years), the minimum and maximum ages were 18 and 66 years, respectively. A total of 505 (93%) participants reported their gender. Slightly more men than women participated (287 and 218, respectively). We did not record data on nationality or ethnicity. We used the movement and mouse clicks of participants in the virtual environment during the third task to compute the following summary statistics.

Following information. Each of the primary treatments M, C and S provided participants with a signal in the form of directional information. This binary summary statistic took value 1, if participants used the same exit as indicated by this signal and value 0 otherwise. For example, if a participant used the same exit as the crowd in treatment C, this participant was assigned value 1 for this summary statistic. We then used the fraction of individuals who used the exit indicated by the crowd, P(same as signal), to summarize participant behaviour. When treatments were combined, we split P(same as signal) up into P(same as memory), P(same as crowd) and P(same as sign). In treatments where different signals reinforced directional information, the 'follow information' summary statistic was identical for both of the separate signals. For example, in treatment $\mathrm{M} + \mathrm{S}$, $P(\text{same as memory}) = P(\text{same as sign})$. In treatments where different signals provided competing directional information, the 'follow information' summary statistics were different for the two signals but summed to 1 as there was a binary choice of exits. For example, in treatment $\mathrm{S} - \mathrm{C}$, $P(\text{same as crowd}) + P(\text{same as sign}) = 1$.

Click number. We recorded the number of mouse clicks participants performed in the third task. This is a measure for how often individuals adjusted their movement and could be related to growing impatience, attempts to avoid the crowd or obstacles, or simply individual preferences for steering the agent.

Reaction time. We defined the time it took participants to show a reaction at the start of the evacuations as the number of simulation time-steps between the end of the countdown before the simulated evacuations and the first mouse click. This time could indicate whether participants contemplated different possibilities before making a decision or it could simply measure how fast participants can respond at the end of the countdown.

Adaptation. With this binary summary statistic, we measured whether or not participants changed their mind when leaving the central room. We defined these changes of mind as the case when participants moved at least one-fifth of the height of the central room in the vertical direction towards one exit before exiting through the opposite exit. This summary statistic could indicate the ability or willingness of participants to adapt their initial decision in response to the developing simulated evacuation. As for 'following information', we report the fraction of individuals who changed their mind, P(change mind).

We conducted our statistical analysis in the R programming environment, v. 2.15.2 [30], and applied two types of statistical tests to the data. First, we used binomial tests to determine separately for each treatment whether the probabilities P(follow signal) and P(change mind) were different to what we might expect by chance. We also obtained 95% CIs for these probabilities using the approach included in the binomial test implementation in R. Second, we compared summary statistics between different treatments using generalized linear models (GLMs), as described below.

We used GLMs to test for the influence of treatment, age, gender and performance in the maths test on summary statistics. We included participants' performance in the maths test in our statistical analysis to investigate whether the range of abilities needed to do well in the maths test had an effect on decision-making. In addition to arithmetic abilities, the maths test provided a measure for participants' computer literacy (text fields had to be filled in quickly) and their ability to perform under time pressure. For the two Boolean summary statistics (follow information and adaptation), models had binomial error structure with logit link functions. The other two summary statistics were fit to standard linear models with Gaussian error structure. We performed a log transformation to reaction time data prior to model fitting to meet normality assumptions. All models included an intercept, the response variable was the summary statistic and the explanatory variables were treatment (categorical), age, gender (categorical) and performance in the maths test (number of correctly answered questions). Using these statistical models, we conducted pairwise comparisons of treatments for the primary treatments. We also compared combinations of treatments against a baseline of each primary treatment in turn. For these comparisons, we used one of the above-mentioned statistical models to assess the effect of each combined treatment on a summary statistic, taking age, gender and performance in the maths test into account. We report the full output of the statistical models in the electronic supplementary material.

As a result of the number of treatments and summary statistics we consider, we conduct many comparisons in our statistical analysis. To avoid Type I errors (false positives), we would have to adjust our significance thresholds for multiple comparisons. However, doing so would inflate the false negative rate. We suggest that in the context of crowd evacuations, we should be careful not to rule out possible factors affecting human decision-making falsely (false negatives) as ignoring such factors may have disastrous consequences. Initially considering factors that are shown to have no effect by further experiments (false positives) may incur a cost in terms of research effort, but is less likely to lead to omissions in contingency plans for emergencies and in future research on the topic. Therefore, we do not adjust for multiple comparisons and set the significance threshold to $p < 0.05$ throughout. As we report all p-values, the inclined reader can perform an adjustment for multiple comparisons post hoc.

3. Results

We first present the effect of the primary treatments on the exit choices of human participants in our virtual environment. Subsequently, we show the effect of combining treatments on human route choice using each primary treatment in turn as a baseline for behaviour. As described in the Material and methods, the symmetrical set-up of the experiment enabled us to randomly choose the directional information provided by the treatments between the upper and lower route. While this should be sufficient to create a balanced experiment without bias, we nevertheless tested whether participants chose the upper or lower route more often than we would expect by chance in the absence of directional information (control treatment). We found this was not the case (binomial test: $p = 0.68$). We also found no consistent effect of the additional individual-level characteristics we recorded (age, gender, performance in the maths test) on subject behaviour. The specific results and a discussion relating our findings on the effect of individual characteristics to previous research can be found in the electronic supplementary material.

3.1. Effect of primary treatments (memory, crowd and sign)

Figure 2*a* shows significant differences in the fraction of participants following the directional information provided by the different primary treatments. For the memory treatment (M) and the crowd treatment (C), the proportion of participants following the directional information provided was not significantly different to that expected by chance (binomial test: $p = 0.15$ and $p = 0.13$, respectively). Nevertheless, the likelihood of participants to follow the directional information in the M treatment was so low that we found a statistically significant difference between this treatment and treatment C (see electronic supplementary material, table S2). The static directional information provided in the sign treatment (S) was followed by

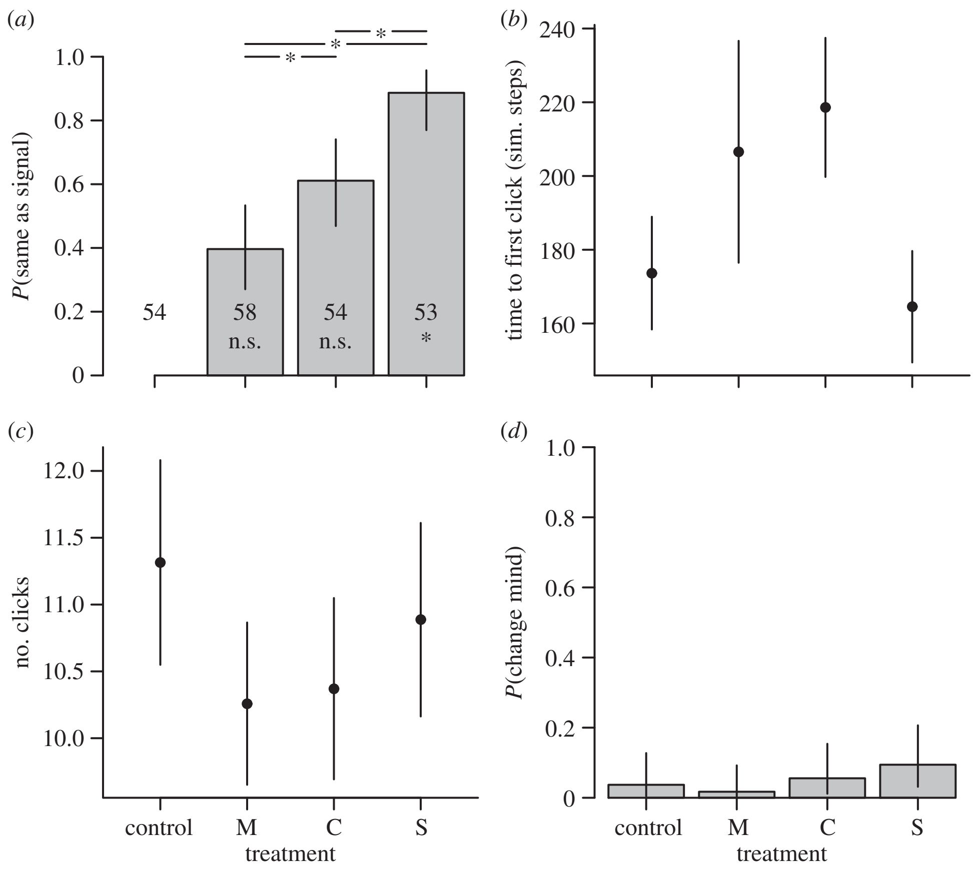


Figure 2. Human responses to directional information in simulated evacuations. We extracted four summary statistics from participants' movement in the simulated environment and show the primary treatments and the control treatment. Under the control treatment, the simulated crowd did not provide any directional information as it split evenly between the two exits. The primary treatments provided directional information: under treatment M, a message participants could memorize indicated the exit to use, in treatment C, the simulated crowd only used one exit and under treatment S, one exit was indicated by an 'EXIT' sign. (*a*) The proportion of participants using the same exit as indicated by the treatment (does not apply to the control treatment, as no direction is indicated). Numbers inside the bars indicate the number of participants per treatment and the symbols underneath indicate whether the observed proportion is significantly different from random ('*') or not ('n.s.'; from binomial tests, *p*-values are given in main text). (*b*) The average number of simulation steps taken to react at the start of the evacuation, (*c*) the average number of clicks performed during the evacuation and (*d*) the proportion of participants who changed their original decision about which exit to use. The reaction time in (*c*) is given in update steps of the simulation (corresponding to 0.05 s of simulated time, see the electronic supplementary material). Statistically significant effects of treatments on summary statistics in pairwise comparisons of treatments are indicated by horizontal bars and asterisks ('*') above the measured quantities (from GLMs, see Material and methods; electronic supplementary material). Error bars show standard errors in (*b*,*c*), and 95% CIs for the observed probabilities in (*a*,*d*). Further details on the statistical analysis can be found in the Material and methods section.

over 80 per cent of participants, more than expected by chance (binomial test: $p = 5.81 \times 10^{-9}$), and this response was significantly higher than the response in both treatments M and C (see electronic supplementary material, tables S1 and S3).

Neither the reaction time (figure 2*b*), nor the total number of clicks (figure 2*c*) of participants showed significant differences between treatments (see electronic supplementary material, tables S4–S15). The difference in reaction times between treatments C and S seems to be considerable under visual inspection (figure 2*b*), but these data had to be log-transformed before statistical analysis and the absolute differences between treatments were thus reduced.

The probability for participants to change their original decision was low for all treatments and significantly different from random (binomial test, treatments: control, M, C, S; $p = 1.65 \times 10^{-13}$, $p = 4.09 \times 10^{-16}$, $p = 2.92 \times 10^{-12}$, $p = 7.08 \times 10^{-10}$, respectively; figure 2*d*). Although this probability seemed to increase from treatment M to C to S, as with the probability to follow the directional information provided by the treatments (figure 2*a*), the difference between treatments was not statistically significant (see electronic supplementary material, tables S16–S21). Across the three treatments M, C and S, only nine people changed their initial decision. Six of these participants initially moved in the opposite direction as indicated by the treatment and then changed their mind. This proportion is not significantly different than expected by chance (binomial test: $p = 0.51$). As an aside, note that across all combined treatments that provided non-conflicting directional information (M + S, M + C, S + C), 11 out of 12 participants who changed their mind adjusted their initial decision to move in the direction suggested by the treatment. This proportion was higher than expected by chance (binomial test: $p = 0.0064$).

Considered on their own, these results suggest that the only source of directional information in our experiments that had a significant effect on participants' decision-making and behaviour was the static directional information provided by signs. Furthermore, these results also suggest that there is no significant difference in the time taken by participants to make their initial decision about where to move, and that participants tend to stick with their original decision about which exit to leave from.

In the following results, we no longer present the reaction time, number of mouse clicks participants performed and

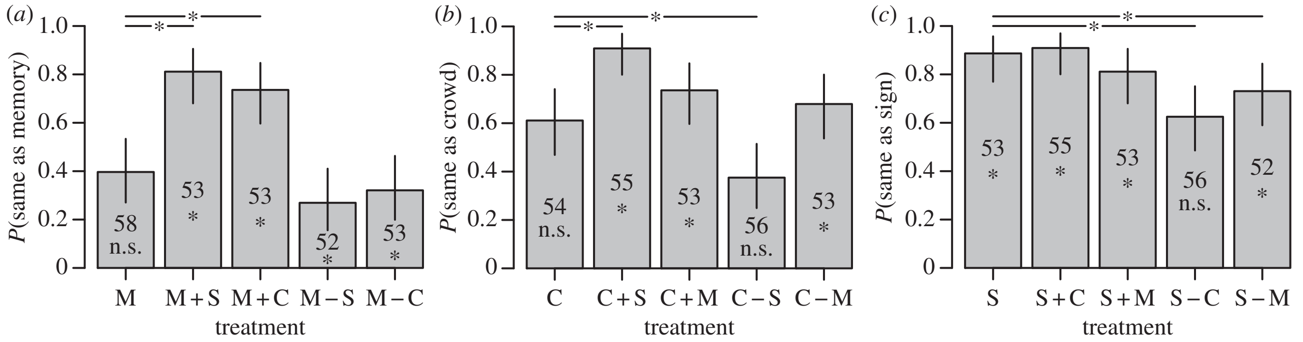


Figure 3. Human responses to reinforced or conflicting directional information in simulated evacuations. We used each of the primary treatments M, C and S in turn as a baseline (baseline M: *a*; baseline C: *b*; baseline S: *c*). We show the proportion of participants that followed the baseline signal. Additional summary statistics can be found in the electronic supplementary material. Statistically significant effects of combined treatments compared to the baseline primary treatment are indicated by horizontal bars and asterisks ('*') above the measured quantities (from GLMs, see Material and methods; electronic supplementary material). The summary statistics and figure labelling is otherwise identical to figure 2. Recall that treatments M − C in (*a*) and C − M in (*b*) denote the same treatment. For this treatment, we have *P*(same as memory) + *P*(same as crowd) = 1, as the directional information of M and C in this treatment points in opposite directions. Likewise, the values for M+C (or C+M) are identical in (*a*,*b*) as in this treatment the directional information for M and C coincide.

the probability of participants to adjust their initial decision as the different treatments had no significant effect on these summary statistics (with one exception, see the electronic supplementary material, figure S1). Results on these summary statistics can be found in the electronic supplementary material, figure S1.

3.2. Effect of crowds and signs in the presence of memorized information (M+S, M+C, M − S and M − C)

We compared reinforcing and conflicting combinations of primary treatments against the baseline of the memory treatment, M (figure 3*a*). When the directional information provided by memory was reinforced by the directional information of the sign (M+S) or crowd (M+C), the proportion of participants following this information increased significantly when compared with the baseline M treatment (see electronic supplementary material, table S22) and was significantly higher than expected by chance (binomial test: treatment M+S, $p = 5.55 \times 10^{-6}$; treatment M+C, $p = 8.02 \times 10^{-4}$; figure 3*a*). The effect of conflicting directional information on the route choice of participants in treatments M−S and M−C compared to treatment M was not statistically significant (see electronic supplementary material, table S22). However, the fraction of participants following the directional information provided by memory in these treatments was reduced and significantly lower than expected by chance, which was not the case in treatment M (binomial test: treatment M−S, $p = 0.0012$; treatment M−C, $p = 0.013$; figure 3*a*).

These results confirm that memory (treatment M) had a weak effect on subject behaviour. In the original treatment M, the proportion of individuals following the directional information provided by memory was no different than expected by chance. However, in treatments where the directional information from memory was reinforced by the movement of the crowd or the presence of a sign, significantly more participants than expected by chance followed the directional information provided by memory. In treatments with conflicting information, significantly fewer participants than expected by chance followed the directional information provided by memory.

3.3. Effect of signs and memory in the presence of crowds (C+S, C+M, C − S and C − M)

In figure 3*b*, we show comparisons of reinforcing and conflicting combinations of primary treatments against the baseline of the crowd treatment, C. When the directional information provided by the crowd was reinforced by a sign (treatment C+S), the proportion of participants following this information increased significantly (see electronic supplementary material, table S26). Combining the directional information of crowd and memory (C+M) also led to a higher proportion of participants following the information, but the increase compared with treatment C was not statistically significant (see electronic supplementary material, table S26). However for both treatments C+S and C+M, the proportion of participants following the directional information was significantly higher than expected by chance, which was not the case for treatment C alone (binomial test: treatment C+S, $p = 2.14 \times 10^{-10}$; treatment C+M, $p = 8.02 \times 10^{-4}$). When the directional information of the crowd conflicted with the information provided by a sign (C−S), the proportion of participants following the direction of the crowd was reduced significantly (see electronic supplementary material, table S26). This was not the case when crowd and memory suggested opposite directions (C−M; electronic supplementary material, table S26). The proportion of participants following the crowd actually increased slightly in treatment C−M compared with C and was now significantly different than expected by chance (binomial test: $p = 0.013$), whereas in treatment C−S it was not different than expected by chance (binomial test: $p = 0.081$). The latter *p*-value is only narrowly non-significant and further studies, possibly with more participants, may show a significant difference. These findings further corroborate the view that treatment S had a strong and treatment M a weak effect on participant decision-making and behaviour.

3.4. Effect of crowds and memory in the presence of signs (S+C, S+M, S − C and S − M)

The sign treatment, S, appeared to have the strongest effect on participants' movement behaviour and decision-making when only a single source of directional information was given (figure 2). We now consider treatment S as a baseline and investigate the effect of reinforcing or contradicting the directional information provided by the sign with the directional information provided by the memory and the crowd (figure 3*c*). Reinforcing the directional information had no statistically significant effect on the proportion of participants following the direction indicated by the signs, as this proportion was already at a high level for treatment S alone (treatments S+C and S+M; electronic supplementary material, table S30). However, when the primary treatments were combined to provide conflicting information, the proportion of participants following the direction of the sign was significantly reduced compared with treatment S (treatments S−C and S−M; electronic supplementary material, table S30). In treatment S−C, this resulted in a proportion of individuals following the direction of the sign not significantly different from random (cf. treatment C−S in §3.3). So despite the fact that treatment C appeared not to have a significant effect when it was the only source of directional information (figure 2*a*), the conflict between the directional information provided by the sign and the crowd was strong enough to significantly alter participants' tendency to follow the direction of the sign observed in treatment S alone (figure 2*a*). While the proportion of individuals following the direction of the sign was still higher than expected by chance in treatment S−M (binomial test, $p = 0.0012$), the fact that the difference between this treatment and treatment S was significant showed that memorized directional information had an effect when pointing in the opposite direction of signs. This finding was contrary to our previous results suggesting treatment M had a negligible effect when considered on its own.

4. Discussion

We have conducted an extensive experiment with over 500 participants and 10 experimental treatments to test the responses of humans in simulated evacuations to different sources of directional information: static signs, dynamic crowd movements and memorized instructions.

In agreement with previous work, we found that signs had a strong effect on human behaviour in simulated evacuations [16]. Previous work has suggested that the design, position and size of signs are important factors in determining people's response to them [15,22]. The strength of participants' response to the sign treatment in our experiment is therefore likely to be in part attributable to the comparatively large size and prominent position of the exit signs in our virtual environment. We found that people did not have a strong tendency to follow the simulated crowd. This agrees with the findings from an earlier study where we put participants under pressure to complete a task faster [17]. Evidence from survivors suggests that affiliation and proximity to familiar people and between socially connected people occurs during crowd evacuations [26]. Influential theoretical work has suggested for illustration purposes that during crowd evacuations and under stress, individuals may develop a tendency to follow others, a phenomenon called the 'herding effect' [25]. It can be debated to what extent participants in our experiment interacted with simulated agents as they would with real people. Nevertheless, based on our results, we recommend further research on this subject and propose that crowd behaviour in evacuations is perhaps more nuanced than simple 'herd-like' following behaviour. Our experiment suggests that the movement of other pedestrians is merely one of many potentially influential sources of directional information individuals use to make movement decisions (see also discussion on combinations of information sources below). It could be argued that the time the message in the memory treatment, M, was displayed for (6 s) was too short for participants to memorize the instructions, and that the treatment would have a stronger effect if this time interval was increased. While the effect of the specific design of our treatments is important, we did not conduct experiments on this as we were primarily interested in studying the effect of combining different sources of directional information.

The combination of primary treatments provided intriguing results. In particular, the fact that the memory and crowd treatments did not affect human decisions in isolation, but had a significant effect when combined in a conflicting way with the sign treatment (compared to the baseline of the sign treatment) was interesting. This has a number of implications. First, contrary to the initial impression from the results, the memory treatment did have a significant effect (although not in isolation). Second, the treatment in which the sign and crowd provided conflicting information significantly reduced the proportion of people following the direction of the sign suggesting that a considerable number of people followed the crowd. This is interesting as participants following the crowd risked getting stuck in the evacuating crowd even though the sign indicated an alternative that avoided this possibility. Third, these findings suggest that when treatments are combined, it is not the case that the treatment that participants observe more closely in isolation simply overrules the directional information suggested by alternative sources of information.

Controlled experiments on crowd evacuations from confined spaces all share one limitation: it is not ethical to recreate the real stress and potential dangers of evacuations. Thus, different approaches to investigate crowd evacuations are justified and valuable insights have been gained from interviews with survivors of crowd evacuations [26,28], evacuation drills with volunteers [31] and computer simulation models [7,25,29], for example. We have opted to use interactive virtual environments to study human behaviour in simulated evacuations. While the question of the extent to which our findings extend to real-life human behaviour remains, we suggest that our study demonstrates virtual environments are a powerful tool for high-throughput behavioural analysis. This type of experiment, possibly implemented online, could be used to select topics for further study in more life-like experiments from a large set of initial hypotheses.

One feature of our simulated evacuations that particularly distinguishes them from real life is that participants had a top-down view of the environment. We have previously argued that the tactical-level decisions we investigate are likely to be based on features of the crowd dynamics that humans would be able to detect without having a top-down view, such as the length of queues at exits or the crowd's movement towards exits [17]. In addition, this way of representing the environment facilitates simple steering controls for interacting with the environment. Simple controls avoid the potential problem of more realistic, three-dimensional representations of environments requiring more complicated controls that can lead to differences in performance between more and less experienced computer users (as reported in e.g. [32]). We additionally mitigated the problem of different levels in computer literacy between participants by focusing our study on route choices, as opposed to other performance measures, for example evacuation times, as studied in [16].

Fully explaining our findings on combined treatments is difficult with the data from our experiments. We only controlled the information participants had access to, but we did not collect self-report measures, such as data on the extent to which individuals identified with the pedestrian they controlled, to what extent they felt part of the simulated crowd and to what extent they trusted the different sources of directional information. Such measures could help to build up an understanding of the process of how participants made decisions based on the information available. An interesting avenue to explore could be the proposition that people have different propensities to react to different sources of information, in a similar way that different people prefer to learn from different sources of information (e.g. by classroom lessons, by reading, by working with peers [33]). While the explanation of our findings remains for future research, we can conclude that it is important to provide evacuees with consistent directional information throughout the course of an evacuation. We acknowledge this can be difficult owing to the specific circumstances of an evacuation [21]. However, our research shows that even memorized information that may not affect evacuees' behaviour in isolation may become an important factor in human decision-making when combined with other sources of information.

All procedures of our experiment were approved by the Ethics Committee of the University of Essex.

Acknowledgements. We thank the editor and three anonymous referees for their constructive and insightful comments on an earlier version of this manuscript. We also thank Mohcine Chraibi, Michael Darius, Stefan Holl, Anja Meister, Armin Seyfried and Lisa Wagner, as well as the rest of the BaSiGo team for their help in collecting the data.

Data accessibility. The data presented in this manuscript are published as the electronic supplementary material alongside this article.

Funding statement. N.W.F.B. gratefully acknowledges financial support from the AXA Research Fund.

References

1. Camazine S, Deneubourg J-L, Franks N, Sneyd J, Theraulaz G, Bonabeau E. 2001 *Self-organization in biological systems*. Princeton, NJ: Princeton University Press.
2. Sumpter DJT. 2010 *Collective animal behavior*. Princeton, NJ: Princeton University Press.
3. Helbing D, Johansson A. 2010 Pedestrian, crowd and evacuation dynamics. In *Encyclopedia of complexity and systems science* (ed. RA Meyers), pp. 6476–6495. Berlin, Germany: Springer.
4. Couzin ID, Krause J. 2003 Self-organization and collective behavior in vertebrates. *Adv. Stud. Behav.* **32**, 1–75. (doi:10.S0065-3454(03)01001-5)
5. Schadschneider A, Klingsch W, Kluepfel H, Kretz T, Rogsch C, Seyfried A. 2009 Evacuation dynamics: empirical results, modeling and applications. In *Encyclopedia of complexity and systems science* (ed. RA Meyers), pp. 3142–3176. Berlin, Germany: Springer.
6. Hoogendoorn SP, Bovy PH. 2004 Pedestrian route-choice and activity scheduling theory and models. *Transp. Res. B* **38**, 169–190. (doi:10.1016/S0191-2615(03)00007-9)
7. Moussaïd M, Helbing D, Theraulaz G. 2011 How simple rules determine pedestrian behavior and crowd disasters. *Proc. Natl Acad. Sci. USA* **108**, 6884–6888. (doi:10.1073/pnas.1016507108)
8. Mann RP, Faria J, Sumpter DJT, Krause J. 2013 The dynamics of audience applause. *J. R. Soc. Interface* **10**, 20130466. (doi:10.1098/rsif.2013.0466)
9. Katz Y, Tunstrøm K, Ioannou CC, Huepe C, Couzin ID. 2011 Inferring the structure and dynamics of interactions in schooling fish. *Proc. Natl Acad. Sci. USA* **108**, 18 720–18 725. (doi:10.1073/pnas.1107583108)
10. Bode NWF, Franks DW, Wood AJ, Piercy JJ, Croft DP, Codling EA. 2012 Distinguishing social from nonsocial navigation in moving animal groups. *Am. Nat.* **179**, 621–632. (doi:10.1086/665005)
11. Pitcher TJ, Partridge BL, Wardle CS. 1976 A blind fish can school. *Science* **194**, 963–965. (doi:10.1126/science.982056)
12. Gonzalez C, Vanyukov P, Martin MK. 2005 The use of microworlds to study dynamic decision making. *Comput. Hum. Behav.* **21**, 273–286. (doi:10.1016/j.chb.2004.02.014)
13. Lipshitz R, Klein G, Orasanu J, Salas E. 2001 Taking stock of naturalistic decision making. *J. Behav. Decis. Making* **14**, 331–352. (doi:10.1002/bdm.381)
14. Drury J, Cocking C, Reicher S, Burton A, Schofield D, Hardwick A, Graham D, Langston P. 2009 Cooperation versus competition in a mass emergency evacuation: a new laboratory simulation and a new theoretical model. *Behav. Res. Methods* **41**, 957–970. (doi:10.3758/BRM.41.3.957)
15. Kobes M, Oberijé N, Groenewegen K, Helsloot I, De Vries B. 2009 Hotel evacuation at night: an analysis of unannounced fire drills under various conditions. In *Proc. of Human Behavior in Fire Symp., 13–15 July 2009, Cambridge, UK*, pp. 219–242. London, UK: Interscience Communications Ltd.
16. Tang CH, Wu WT, Lin CY. 2009 Using virtual reality to determine how emergency signs facilitate way-finding. *Appl. Ergon.* **40**, 722–730. (doi:10.1016/j.apergo.2008.06.009)
17. Bode NWF, Codling EA. 2013 Human exit route choice in virtual crowd evacuations. *Anim. Behav.* **86**, 347–358. (doi:10.1016/j.anbehav.2013.05.025)
18. Vilar E, Rebelo F, Noriega P, Teixeira L, Duarte E, Filgueiras E. 2013 Are emergency egress signs strong enough to overlap the influence of the environmental variables? In *Design, user experience, and usability. User experience in novel technological environments* (ed. A Marcus), pp. 205–214. Berlin, Germany: Springer.
19. Cole HP, Vaught C, Wiehagen WJ, Haley JV, Brnich Jr MJ. 1998 Decision making during a simulated mine fire escape. *IEEE Trans. Eng. Manag.* **45**, 153–162. (doi:10.1109/17.669762)
20. Kretz T, Hengst S, Roca V, Perez Arias A, Friedberger S, Hanebeck UD. 2011 Calibrating dynamic pedestrian route choice with an extended range telepresence system. In *Computer Vision Workshops (ICCV Workshops), 2011 IEEE Int. Conf., 6–13 November 2011, Barcelona*, pp. 166–172. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE).
21. Johnson CW. 2005 Lessons from the evacuation of the World Trade Center, Sept 11th 2001 for the future development of computer simulations. *Cogn. Tech. Work* **7**, 214–240. (doi:10.1007/s10111-005-0009-5)
22. Wong LT, Lo KC. 2007 Experimental study on visibility of exit signs in buildings. *Build. Environ.* **42**, 1836–1842. (doi:10.1016/j.buildenv.2006.02.011)
23. Raubal M, Egenhofer MJ. 1998 Comparing the complexity of wayfinding tasks in built environments. *Environ. Plann. B* **25**, 895–913. (doi:10.1068/b250895)
24. Department of Culture, Media and Sport. 2008 *Guide to safety at sports grounds, the green guide*, 5th edn. London, UK: The Stationery Office.
25. Helbing D, Farkas I, Vicsek T. 2000 Simulating dynamical features of escape panic. *Nature* **407**, 487–490. (doi:10.1038/35035023)

26. Sime JD. 1983 Affiliative behaviour during escape to building exits. *J. Environ. Psychol.* **3**, 21–41. (doi:10.1016/S0272-4944(83)80019-X)
27. ICAO—International Civil Aviation Organization. 2003 *Human factors digest no. 15. Human factors in cabin safety. Circular 300-AN/173*. Montreal, Canada: ICAO.
28. Donald I, Canter D. 1992 Intentionality and fatality during the King's Cross underground fire. *Eur. J. Soc. Psychol.* **22**, 203–218. (doi:10.1002/ejsp.2420220302)
29. Burstedde C, Klauck K, Schadschneider A, Zittartz J. 2001 Simulation of pedestrian dynamics using a two-dimensional cellular automaton. *Physica A* **295**, 507–525. (doi:10.1016/S0378-4371(01)00141-8)
30. R Core Team. 2012 *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. (http://www.R-project.org/)
31. Seyfried A, Rupprecht T, Passon O, Steffen B, Klingsch W, Boltes M. 2009 New insights into pedestrian flow through bottlenecks. *Transp. Sci.* **43**, 395–406. (doi:10.1287/trsc.1090.0263)
32. Smith SP, Trenholme D. 2009 Rapid prototyping a virtual fire drill environment using computer game technology. *Fire Saf. J.* **44**, 559–569. (doi:10.1016/j.firesaf.2008.11.004)
33. Riding R, Rayner S. 1998 *Cognitive styles and learning strategies: understanding style differences in learning and behaviour*. London, UK: D. Fulton Publishers.