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The effect of person order on egress time: a simulation model of evacuation from a Neolithic visitor attraction

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Précis

A slow moving individual exerts a powerful influence on building egress time where width is restricted. Where overtaking and contraflow are unlikely, understanding the dynamics of egress via simulation models based on observations can optimise evacuation of historic and other similar buildings.

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Abstract

Objective. To model the egress of visitors from a Neolithic visitor attraction.

Background. Tourism attracts increasing numbers of elderly and mobility-impaired visitors to our built environment heritage sites. Some such sites have very limited and awkward access, and were never designed for mass visitation and may not be modifiable to facilitate disabled access. As a result emergency evacuation planning must take cognizance of robust information, and in this study we aimed to establish the effect of visitor position on egress.

Method. Direct observation of three tours at Maeshowe, Orkney informed typical time of able-bodied individuals, and a mobility impaired person through the 10 m access tunnel. These informed the design of egress and evacuation models running on the Unity gaming platform.

Results. A slow-moving person at the observed speed typically increases time-to-safety of 20 people by 170%, and reduces the advantage offered by closer tunnel separation by 26%. Using speeds for size-specific characters of 50th, 95th and 99th centiles increases time-to-safety in emergency evacuation by 51% compared with able-bodied individuals.

Conclusion. Larger individuals may slow egress times of a group, however a single slow-moving mobility-impaired person exerts a greater influence on group egress, profoundly influencing those behind.

Application. Unidirectional routes in historic buildings and other visitor attractions are vulnerable to slow moving visitors during egress. The model presented in this study is scalable, applicable to other buildings and can be used as part of a risk assessment and emergency evacuation plan in future work.

Key Words

Simulation; Risk assessment; Designing for the elderly; Architecture; Discrete event simulation;

Introduction.

Historic buildings constitute some of the world's foremost tourist attractions. Although never designed for mass visitation, such sites attract increasing numbers, requiring carefully considered management for visitor access, circulation and egress. This may prove especially challenging in light of their archaic configuration, especially where steep gradients and restricted space demand levels of fitness and coordination to navigate. Attempts to facilitate easy access to historic buildings may be limited by regulatory restrictions which prohibit alteration and defy building code compliance, despite a requirement to implement an egress system (Watts, 2001). However, the gap between regulatory adherence and optimised crowd movement may be wide, and has spawned a range of research efforts which span crowd behaviour (Chu et al., 2015), visualisation (Guest et al., 2015) and evidence-based disaster planning (Auf der Heide, 2006). However, individuals with disabilities require special consideration, especially where the default position is the provision of rescue assistance (Christensen et al., 2007). It is within the realm of human factors that the interdependence of historic building visitation, operation and safety lies, interfacing with tourism and the local economy on one hand, and regulatory authorities on the other.

At many ancient historic sites the challenge to mobility-impaired or elderly visitors is obvious, especially where high crowd density or restricted space compromises movement and results in limited opportunities for passing. Under such circumstances, the visitor flow dynamic may be expected to be sporadic and influenced by slow moving individuals, a reality which may be considered appropriate under normal conditions of visitation, but has the potential to become problematic in egress (an orderly exit) and more particularly in an emergency evacuation (where the aim is for all individuals to exit as rapidly as possible) .

Prehistoric chambered cairns are a unique example of ancient buildings, whose less complicated design and modest size enable convenient observation of the behaviour of visitors. Such sites are common throughout the Northern Isles of the UK. Maeshowe, in Stenness, Orkney dates from about 2700 BC and is the largest and best known of these, and was designated a UNESCO World Heritage Site in 1999 as part of the 'Heart of Neolithic Orkney'. The site is under the care of Historic Environment Scotland and comprises a conical mound approximately 30 m in diameter, and a tunnel 10.25 m in length accesses a large central chamber, and from within this a further three side chambers where it is believed that the remains of the dead were ritually placed. The midwinter sun shines directly down the passage in winter illuminating the rear wall and aligns with other standing stones in the vicinity, indicating Maeshowe's significance in the calendar. Approximately 15,000 visitors visit Maeshowe each year, and while several other chambered cairns in Orkney are more restrictive in terms of entrance and exit, none approaches the visitor numbers seen at Maeshowe.

Ordinarily, groups of visitors of around 20 individuals visit the Maeshowe site in each tour lasting one hour, but numbers may exceed this figure under some circumstances, for instance when a coach party is divided into two separate groups. Individuals are gathered immediately outside the entrance and are led by guides through the tunnel to access the main chamber moving forward slowly in a single line. All individuals taller than young children must stoop to enter the tunnel which is only 104 cm wide and 118 cm high, before progressing forwards in a shuffle gait. Inside the main chamber the available space for the group is restricted by a rail enclosing an area of approximately 12.25 m^2 behind which the guide addresses the group and illuminates key features of the chamber using a hand-held torch. While there have been very occasional medical emergencies involving individual visitors as might be anticipated by their throughput in a season, to date the research team is unaware of there ever having been a full emergency evacuation, real or simulated, of Maeshowe.

Egress research, especially involving emergency evacuation of buildings is an important consideration of urban safety planning, especially in respect of fire, earthquake or other natural disasters. Such eventualities cannot be duplicated under laboratory conditions without placing participants at risk, and the sources of insight as to enhance the survivability of building evacuations rely on examination of past events, in addition to simulations which cast light on the parameters of the evacuation problem (Still, 2007). Evacuation models not only consider reaction time and movement time which may be a function of crowd density and route complexity, but an unfolding emergency where fear and panic and herding behaviours may prevail which may override social norms to create a stampede as individuals compete with one another to reach exits (Kamkarian & Hexmoor, 2014). In addition, models should reflect population changes to describe an appropriate demographic, although this may be difficult to achieve in practice. Attractive and repulsive forces applied via a 'social force model' suggest the greater the desired velocity of egress, the greater the time of queuing in a 'faster means slower' phenomenon (Helbing et al. (2000), and the likelihood of blocking clusters at exits (Parisi & Dorso, 2005).

While these models flag general concerns over evacuation routes, they presume there is a degree of spatial freedom and path choice for the individual. However, this is not the case for Maeshowe or other similar chambered cairns. Inside, individuals are by necessity constrained inside a fixed area, with no choice as to the available exit route, and a probability of overtaking that approaches zero in the access tunnel. In addition, the limited group size means visitors may react to an evacuation instruction simultaneously. In its most simple form, a model for evacuation discharge (the cumulative number of individuals reaching safety plotted against time) relates to two factors: the order in which the individuals enter the tunnel, and the rate which individuals proceed along it. However in such constrained physical environments, evacuation has never been modelled based on empirical observational data. If such a model could be constructed, it would have wide appeal, not only for historic buildings, but for other visitor attractions such as amusement parks, special public events or transportation.

In historic sites such as Maeshowe, tour operators are unlikely to be sympathetic to the notion of their groups becoming Guinea-pigs for experimentation, and closing the site to tourist groups to conduct such research would be costly and would adversely affect the local economy. As a result, a practical solution for researching egress from such sites requires a combination of empirical observation and simulation. Such scenarios have various elements of randomisation but can be run multiple times and offer the prospect of a solution to predicting egress which is both plausible and cost-effective. However, such an approach has never been used previously, therefore this study aimed to address these challenges and produce a model for evacuation which has direct application to Maeshowe and other similar historic sites.

Methods

The study adopted a multi-method approach. The study team acquired data from direct observation from three tours on August 10th, 2016, in the peak visitor season, both as participants as well as observers. Two members of the research team acted as observers, one inside and one outside the building manually timed visitors using a stopwatch, and data were recorded in a field notebook and augmented via video footage filmed from inside the chamber. Guide interviews with 3 guides and 1 manager with 70 years' collective experience of Maeshowe were conducted to furnish the research team with a greater understanding of movement dynamics and rare events.

Terrestrial laser scanning of Maeshowe was undertaken in 2010 as part of the Scottish Ten project (Wilson et al., 2013), by The Centre for Digital Documentation and Visualisation. 3D laser scan point cloud data were captured at the highest possible resolution and accuracy, providing an average point spacing of <4mm for the interior and exterior of the chambered tomb. Point cloud data were registered in Leica Cyclone software (http://leica-geosystems.com/products/laser-scanners/software/leica-cyclone), then the registered data used to create a meshed model in Meshlab (http://www.meshlab.net/). The meshed 3D model was then imported into a game engine (Unity 3D - https://unity3d.com/) to virtually replicate the Maeshowe environment and allow interactive simulation modelling to be undertaken. Six digital characters were created using animation software (www.makehuman.org/) and for plausibility, and to simulate less favourable space availability per person, scaled to the 50th, (n=12) 95th (n=6) and 99th (n=2) centiles of the male and female Scottish population data from the Scottish Health Survey, 2014 (The Scottish Government, 2015). Digital characters were animated using Autodesk 3D Studio Max (www.autodesk.co.uk/) and imported into the virtual environment with a set of constraints derived from direct observation. This included randomly positioning inside the chamber, and protection by an invisible 'collider' - a cylinder of radius 0.45-0.5 m representing a personal space envelope as depicted in figure 1A. The scene was scripted to produce random movement of characters, constrained by the available space, before an egress scenario.

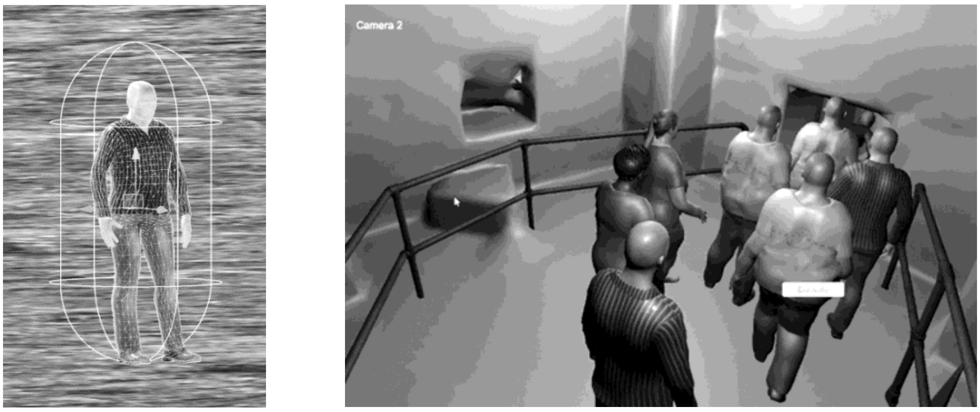


Figure 1 A) Personal space identified in Unity game engine via the 'collider'; B) digital characters egressing the chamber into the tunnel

Once the evacuate command was initiated, the characters move towards the entrance tunnel and await the opportunity to exit as depicted in figure 1B. The character nearest the tunnel would then crouch and proceed into the tunnel in a stooped walk. Once inside the tunnel the collider radius was programmed to become 1.5 m to reflect the observed separation between individuals.

The egress model first adopted the mean speed of able-bodied adults in the tunnel seen from direct observation, and subsequently by a randomly selected speed for each individual in the group from within the observed range (0.45 – 0.6 $m.s^{-1}$). Refinements to the basic egress model included reducing the separation inside the tunnel from a radius of 1.5 to 0.5 m to reflect an emergency evacuation, the option to include a randomly positioned 'wildcard' slow moving individual at the observed speed (0.045 m.s^{-1}) and double this speed (0.09 m.s^{-1}). The four conditions (fixed, random, wildcard double speed and wildcard actual speed) were compared using univariate Analysis of Variance using time-to-safety for the 20th individual as the dependent variable, and randomised speed function (0 or 1) and the wildcard (absent = 0, double speed = 2, actual speed =1) as fixed factors with Bonferroni adjustment. Subsequently, an algorithm was created for a size-specific movement speed based on the established relationship of body size and walking speed (Spyropoulos et al., 1991). Relative to those of a healthy weight, morbidly obese individuals walk at approximately two thirds the speed and double the step width. The resulting speed for the 99th and 95th percentile-sized figures was further adjusted because of their reduced clearance space imposed by enlarged body size and exaggerated lateral movement. The resulting speeds selected for the model were for 0.5 m.s^{-1}, 0.4 m.s^{-1} and 0.3 m.s^{-1} for the 50th, 95th and 99th percentile figures respectively. Again a univariate analysis of variance was used to compare the time to safety for the 6th person as the dependent variable, with fixed factors as random, size specific and wildcard functions.

Results.

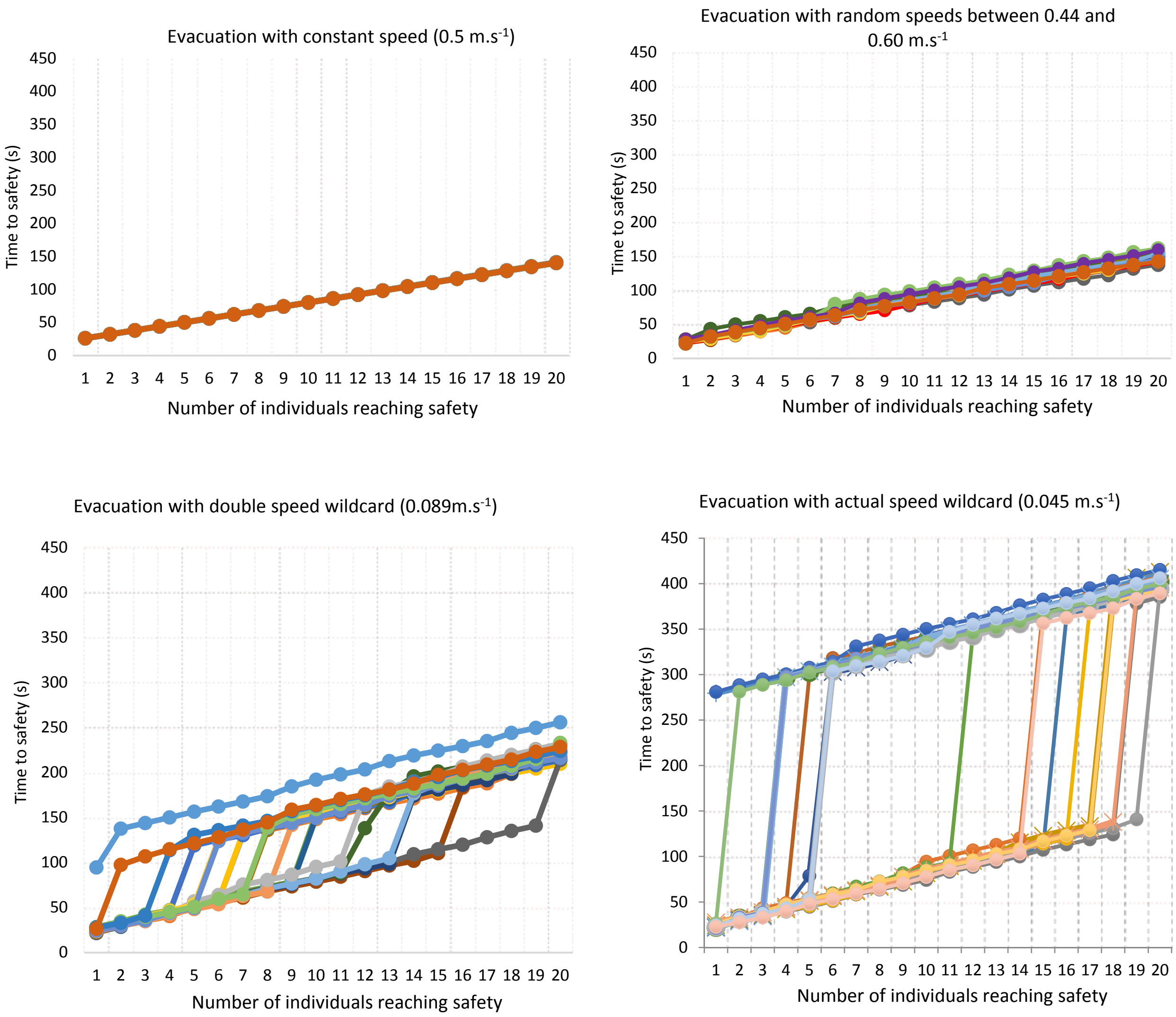
Observation of actual speeds of travel in Maeshowe on 10th August 2016.

Tour 1 involved 23 visitors entering the chamber (including the four research team members, and one young ambulatory child). The time to progress through the tunnel varied between 19 and 23 s, with a mean velocity of 0.49 m.s^{-1}. Tour 2 involved 27 visitors (including two ambulatory children) and the research team observed from outside the chamber. All 27 visitors entered the tunnel in 132 s, giving a typical spacing of 4.9 s between individuals. The group split when exiting, with some remaining to ask questions to the guide still inside the chamber. 18 individuals came out directly within 90 s, yielding a typical spacing of 5.0 s between individuals. Of the remaining nine individuals, it was not possible to determine when they entered the tunnel.

Tour 3 involved a total of 27 visitors (including two members of the research team, and one child). One visitor had impaired mobility, arriving outside the site on a powered scooter. On entering the chamber he walked with the aid of a stick and took 172 s to progress through the tunnel (0.06 $m.s^{-1}$) to the chamber and 230 s to egress (0.045 $m.s^{1}$). When entering the tunnel, those behind him became noticeably uncomfortable, and after the tour most of the tour participants made a deliberate attempt to exit before him. Two other notable timed tunnel exits were recorded. One able-bodied male visitor exited the tunnel in 17 s using a normal crouched walking gait. The other was a child of approximately 8 y who ran as fast as she could through the tunnel, exiting in approximately 4 s.

Able-bodied individuals exited the tunnel in a mean time of 20.5 s, (range 17-23 s). In addition to adopting these values, the simulation also incorporated an atypical slow-moving individual as a ‘wildcard’ at the observed egress speed (0.045 $m.s^{-1}$) and also at double and triple this speed. Due to the random placing of individuals inside the chamber and the egress order being determined by proximity to the midpoint of the entrance, the position of the wildcard person in the egress order was random.

Scenarios were initially run under four conditions for a normal (non-emergency) egress. These were A) A constant speed model; B) A random speed model based on observed able-bodied speeds; C) A random speed model including one wildcard slow moving individual at double the observed speed; D) A random speed model including one wildcard at the observed speed. Individual scenarios are described in figure 2, and summarised in figure 3.


Evacuation with constant speed (0.5 $m.s^{-1}$)

Evacuation with random speeds between 0.44 and 0.60 $m.s^{-1}$

Evacuation with double speed wildcard (0.089$m.s^{-1}$)

Evacuation with actual speed wildcard (0.045 $m.s^{-1}$)

Figure 2. Time to safety for the four scenarios. Each depicts 20 runs of the same model.

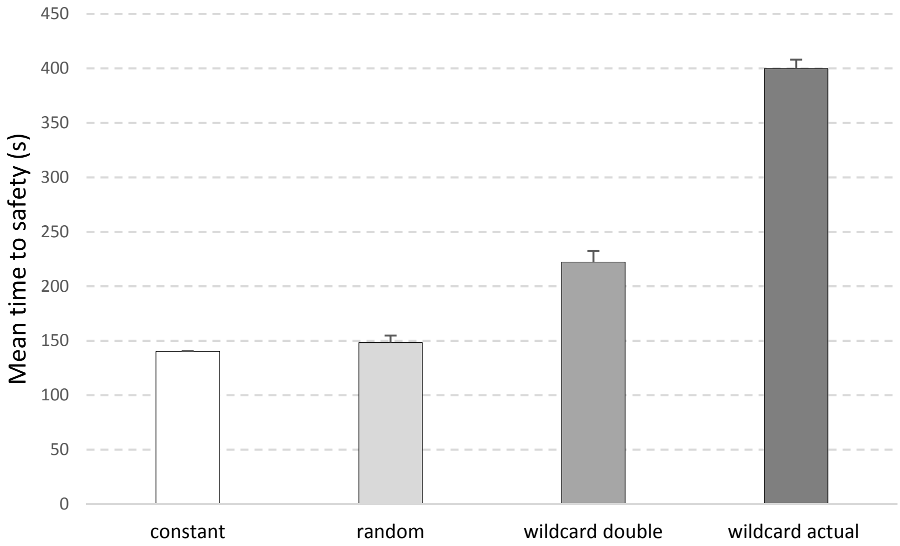


Figure 3. Comparison of evacuation performance of the four scenarios' results for 20 individuals to reach safety, averaged over 20 trials. Error bars refer to 1 standard deviation. Differences between scenarios were significant ($P<0.0001$).

Mean evacuation times (± SD) for the four scenarios were 140.2 (± 0.4); 148.2 (± 6.5), 222.1 (± 10.2) and 399 (± 8.2) s, respectively. Examination of figure 2 illustrates the pivotal influence of person order on evacuation time, depending on where the slow moving individual comes.

Further modelling was conducted using only six characters, two from each of the 50th, 95th and 99th percentiles, using the emergency evacuation mode. This involved the use of random speeds within the observed range, the use of size-specific speeds for the three different sized models, with and without the inclusion of a single wildcard slow moving individual, randomly positioned, moving at 0.0134 $m.s^{-1}$, (three times the observed speed). Results for the time-to safety generated by the model are illustrated in figure 4.

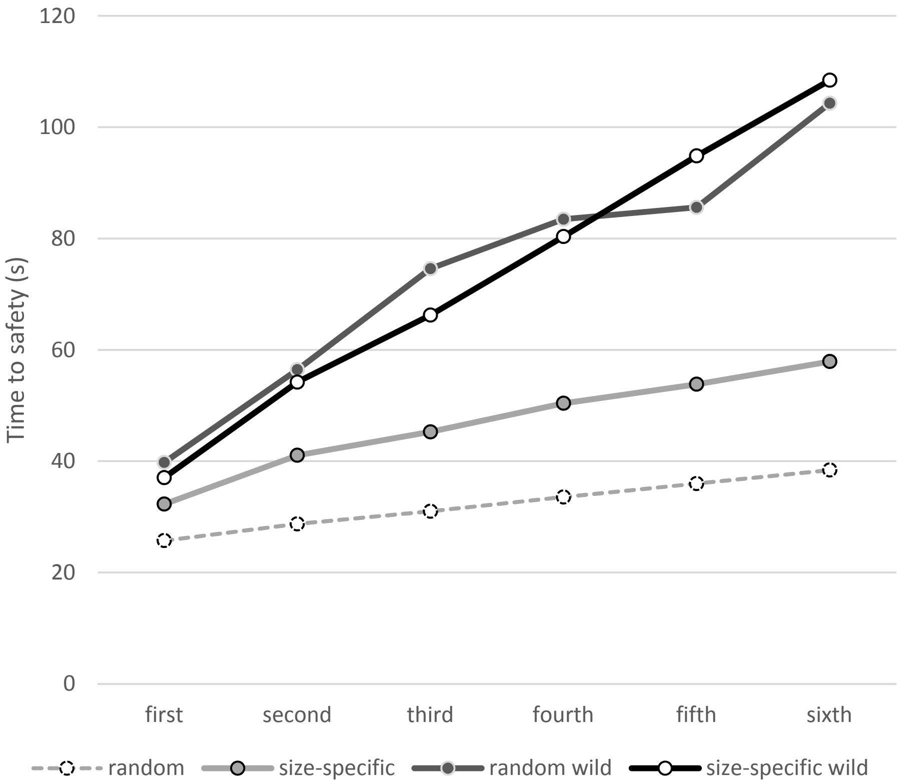


Figure 4. Mean egress of 20 trials for six individuals under different conditions

Mean times (±SD) for 20 trials of random, size specific, random with wildcard and size-specific with wildcard yielded time-to-safety for the group of six of 38.4 (± 2.0), 57.9 (± 1.7), 104.3 (± 1.9) and 108.8 (± 2.2) s respectively ($P<0.0001$) and an interaction between mode (i.e. random or size-specific) and the wildcard ($P<0.0001$).

A further analysis was done using time points at 30 s, 40 s, 50 s and 60 s, to compare the different scenarios for predicting how many individuals would reach safety, the results for which appear in figure 5.

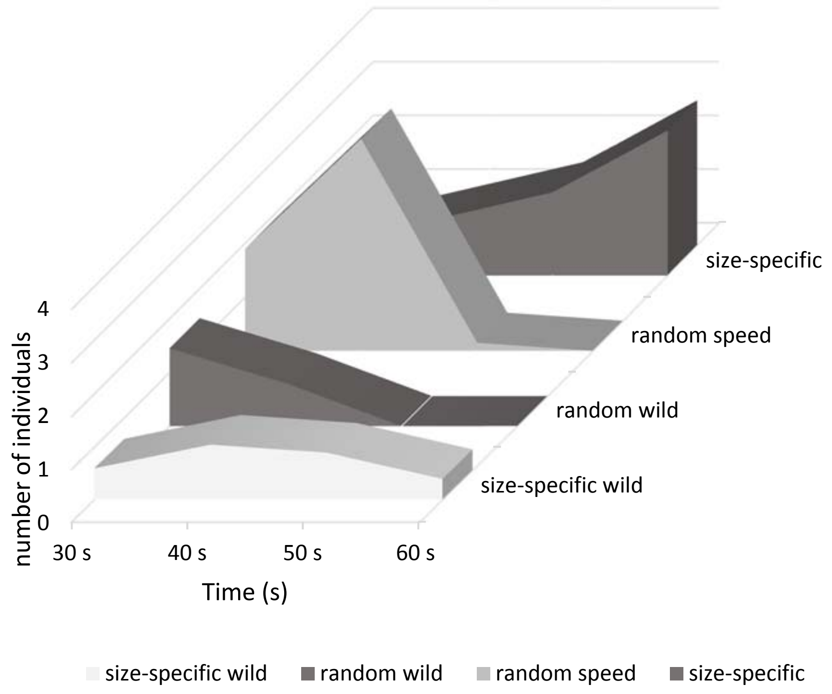


Figure 5. Time point analysis of egress, depicting mean values of 20 trials. Values depict numbers exiting within each 10 s segment.

Discussion

Main findings

The ability of able bodied individuals to evacuate Maeshowe in a certain time is severely compromised by a slow moving individual within the group. Impaired mobility and increased body size both have an impact on the group's time to safety.

The challenge of evacuating Maeshowe and similar buildings is determined by the proximity of individuals to the access tunnel, which, in the absence of other rule-based behaviours, determines the order in which individuals enter the tunnel. A single slow-moving individual profoundly influences the speed of egress of the group, and the position of this person in the line dictates the speed of those behind.

Variability in speed in individuals slows the average time-to-safety under normal egress conditions, which for the 20th person equates to 8 seconds or 5.7%, assuming there is no overtaking. In normal walking, a lateral space allowance of 71-76 cm has been considered a minimum to avoid contact with others, and 152 cm for fluid bi-directional movement (Fruin, 1971). Applying the work to the design of busy corridors, Fruin proposed a further 15 cm clearance from walls to provide the net effective width. In Maeshowe tunnel, the width is only 104 cm, which would reduce to just 74 cm if this were applied. Although the research team did determine that overtaking and contra-flow movement was possible in the tunnel, it had to be carefully staged and was judged to be highly unlikely. Firstly, contact would be virtually unavoidable unless one individual turned sideways, a strategy which improves passing ability (Stewart et al., 2015). For overtaking, the person in front would not easily see the approach of person behind, making the manoeuvre difficult to anticipate. Secondly, there would be limited time-saving benefit if individuals all moved at speeds of able-bodied individuals observed. However, in the event of someone being stuck behind a slow-moving individual, the perceived benefit in terms of time saving may outweigh perceived risks of possible loss of balance, or appearing to be inconsiderate when pushing past an individual in front. Should an emergency evacuation be required in a chambered cairn such as Maeshowe, then the exit order, as well as the composure of those inside, will be of paramount importance.

Under normal egress, the number reaching safety in two minutes for the constant speed model is 16, with random able-bodied speeds this drops to 15, and with a wildcard (double speed), to 8, and wildcard (actual speed) to 4. Maeshowe guides had reported even slower visitors than the 0.045 m/s tunnel speed in this example. Clearly, in situations where individuals move slower than this speed, the consequences of non-optimised position in the egress line would be even more disadvantageous, with even more severe consequences for safety outcomes, than the four-fold difference documented here. Using the emergency evacuation model (figures 4 and 5) the effects of a slow moving individual (in this case at triple the observed speed), and size-specific speeds are readily apparent early in the evacuation process. A number of model runs should be adopted which yield stable predictions (Ritter et al., 2011). The present study used 20 trials, which was considered adequate, due to the large effect sizes found for the effect of wildcard (0.99) and size-specific versus random speed (0.905) and models producing % coefficient of variation (CV) of egress time of 2.1 to 4.6%. Applying the theoretical framework of Ritter et al.'s article (P109) we required to establish the time-to-safety difference between scenarios which was sufficiently small. If 5 seconds is selected, applying the standard error data from 20 trials, then 5/1.96 = 2.55 runs. For the random speed model the SD is 6.49, then substitution yields 7 runs. If a time-to-safety difference was selected to be 3 seconds the number of runs would be 18. Because the mean differences in the scenarios between fixed and random is 8 seconds and for fixed and wildcard to be ~260 seconds, it is clear that 20 runs is more than adequate.

Consideration has been given only of a single mobility impaired person within a scenario. There is the possibility that several slow moving individuals could be present at the same time, and the interaction of these on egress can be modelled using this approach as well.

Emergency evacuation literature

While the scientific disciplines of crowd behaviour and emergency evacuation modelling have made significant advances over recent years, these still need to consider specifics of restricted space and visitor movement in ancient buildings, and to move beyond the theoretical framework for behavioural influences on outcome (Zoumpoulaki, Avradinis & Vosinakis, 2010). Some insight may be gained from transportation research which alludes to pedestrians' waiting times at controlled pedestrian crossings. In Canada, where it is compulsory to cross only at designated places, unlawful crossings were more likely to be made by young adult males than others, and when the perceived clearance time exceeded the crossing time (Brosseau et al., 2013). This suggests that the limits of human patience in some individuals may be all too easily reached even in the absence of any major incident, and that neither personal danger nor the threat of punitive action is sufficient to persuade them otherwise. On the contrary, in an unfolding disaster, the literature highlights separation from attachment figures as a greater stressor than physical danger, and also expressions of mutual aid and a sense of community with others (Mawson, 2005). In his review, Mawson describes behavioural models of mass escape from disasters, and points to the fact that survival may be threatened by the delay imposed by offering assistance. Time pressures along with situations where information is novel, ambiguous or incomplete may lead to poor decisions and inappropriate behaviours in an emergency (Robinson, 2012; Ariely & Zakay, 2008). In response to an evacuation of Maeshowe, this evidence suggests groups of family and friends are likely to seek one another within the chamber before exiting the tunnel. This may, in turn, lead to a sub-optimal egress order in the tunnel which has a slower clearance. Procedures which reinforce the wisdom of slower individuals exiting last, although controversial, would, according to this study, have the potential to enhance safety.

The travel industry demographic

The travel industry has not been slow to appreciate the importance of the growth in the ‘seniors’ market, with its increasing market potential (Jang et al., 2009). Global demographics point to profound increases in life expectancy (UNFPA & Help Age International, 2012), and further evidence suggests the post-war baby boomer generation may be increasingly novelty-seeking and prepared to travel (Jang et al., 2009). However, compared with younger adults, a more elderly tourist is likely to have a slower walking speed (Bohannon, 1997), poorer visual field efficiency (Sekuler & Bennett, 2000), decreased coordination and postural control (Speers et al., 2002), as well as greater body size and weight (Dey et al., 2001). The global obesity pandemic has adverse consequences for disability-free life years and quality of life via excess body weight and obesity (Swinburn et al. 2011; Wang et al., 2011), both of which bring unique challenges to society, and the tourist industry in particular. In the USA, obesity prevalence trebled between 1986 and 2010, whereas super-obesity (Body mass index ≥ 50 kg.m^{-2}) prevalence increased more than 10-fold (Strum & Hattori, 2013). As a result, the risk of such extremely large individuals for affecting visitor movement or even for blocking narrow passageways is thus considerably greater than it used to be.

In short, tourist attractions can anticipate increasing numbers of tourists, an increasing proportion of whom are older, larger, slower and less agile than they have been in the past.

Implications for practice at historic sites

Maeshowe guides are practiced at identifying slow moving individuals and asking them to remain behind while other visitors departed the chamber after the tour was complete. However, it is not certain that all slow moving individuals will be identified in all situations, due to the piecemeal arrival of individuals as some groups assemble. This may result in a slow moving person being inadvertently positioned in front of several other visitors in the line as was observed by the research team. The guide is not in a position to control the order on the way in to the chamber as he/she is first in. On the way out, visitors may elect to leave at different times, as some continue to ask the guide questions while others depart the chamber – so the guide may not be able to have full control of the visitor order as the group leaves the chamber either.

Controlling numbers is already achieved via ticketing procedures, and local rules regarding mobility scooters and wheelchairs ensure there are none in the tunnel which could obstruct movement. Whether or not movement should be assessed to optimise person order is ethically challenging and likely to touch on sensitivities, but should be considered if there is a clear desire to optimise safety in all foreseeable circumstances. This could be done in practice by having visitors self-time the walk of a segment of the approach path, or alternatively this could be automated via optical timing gates. The time could thus inform position in the line akin to that of a citizens’ fun run.

As a case study, Maeshowe presents an example of a small heritage site, with limited access/egress options. The data presented represent a vital first step to modelling body size and mobility in a simple scenario of normal egress. The authors accept that there are several limitations of this approach, for instance relating to limited sampling and assumptions regarding the size, separation and speed of visitors. However, the principles and the models developed within this study are capable of customisation in light of new data, and in consideration of a range of human factors challenges, are scalable with potential application at much larger and more complex heritage attractions. For example, Historic Environment Scotland constantly seeks to improve visitor movement and therefore visitor experience at large sites such as Edinburgh Castle, which fall under its care. Further study is proposed to investigate the potential benefits of this modelled approach to practical heritage management and in assessing risk, crowd movement and emergency evacuation planning. This will necessarily include research which is capable of generating much more robust information on the prevalence and extent of mobility impairment and how this impacts movement of such individuals, their carers and the wider public. While historic buildings may represent a special case, such a research effort could yield tangible benefits not only for other public buildings, but for other areas such as transportation, event management and tourism. Within the realm of tourism alone, not only do we find an increasing popularity of subterranean visits including working or historic lead, coal and salt mines, but also networks of underground caves, labyrinths and tunnels. In the case of Vietnam's Cu Chi tunnels, these have been especially widened to accommodate the larger size of western tourists (BBC, 2000).

In such scenarios body size and crowd modelling approaches may lend useful information to the debate on how to keep the public safe. Importantly, visitors require education regarding what to do in an emergency. Human factors research can inform this process, and results from simulations of real emergencies can be compared with actual observations which will provide an evidence base which can highlight the appropriateness and resilience of current practice, and strengthen the prevailing safety culture. If egress outcome is to be optimised, consideration of key information to be presented to the varied visitor demographic should also include the importance of person-order based on walking speed. However, special consideration is warranted for mobility impaired individuals for optimised egress time to benefit the entire gathering. Such deliberation may prove even more important in an emergency where the stakes are higher and emotional investment greater. Ultimately, wherever mass gatherings occur in limited space availability, they will create additional risk. Research for egress from historic buildings has much to learn from other areas. In aircraft evacuation modelling new and large cabin configurations can be tested via computer simulations, validated by in-vivo experimentation (Galea et al., 2011), while visual simulation using gaming technology has been demonstrated to enhance user knowledge and self-efficacy in emergency landing and evacuation (Chittaro, 2012). In passenger ship evacuation modelling, a number of sophisticated models are capable of performing advanced evacuation analysis, which can, for example combine virtual reality, real-time interactivity, heterogeneous data input and agent trajectory calculation (Ginnis et al., 2010) or a risk-base approach relating to critical accident scenarios (Vanem & Skjong, 2006). As far as the authors are aware, such approaches have yet to be adopted for specific historic buildings, and it is likely that such a move would significantly advance both the understanding of risk and the understanding of appropriate control measures.

Modelling egress remains an important consideration in what amounts to a fine balance between excessive freedom and managed control at historic tourist sites. While such a balance of resilience and vulnerability might be difficult to achieve in practice, future research will undoubtedly render this goal more easily achieved.

Key Points

- Simulations based on observed speeds highlight the importance of person order in an egress line in a restricted width setting.
- Time-to-safety of a group exiting a restricted space is governed by the speed of slower individuals, affecting those behind.
- Research evidence suggests larger obese individuals generally move more slowly than those of a healthy weight, and this may be exacerbated due to diminished clearance space within a corridor.
- Impaired mobility due to a health disorder other than body size alone may exert a larger effect and is a necessary component of future evacuation research.

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