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Simulation of tourists' wayfinding during evacuation based on experiments in Kyoto

Koichi Sabashi[a], Boaz Ben-Moshe[b], J.-D. Schmöcker[a]*, Yuval Hadas[c], Satoshi Nakao[a]

[a]*Department of Urban Management, Kyoto University, Nishikyo, Kyoto 6158540, Japan*
[b]*Department of Computer Science, Ariel University, Ariel, 4070000, Israel*
[c]*Department of Management, Bar-Ilan University, Ramat-Gan, 5290002, Israel*

Abstract

Tourists are often more vulnerable than residents in sudden disaster situations due to lack of knowledge regarding evacuation routes and safe areas. To establish protocols and the schemes for tourist evacuation to safe areas, it is necessary to gather their likely behavior during an evacuation. Since there are few actual data available we conducted a VR (Virtual Reality) experiment assuming a sudden disaster situation and estimated tourists' route choice based on the experiment. In the experiment pictures of intersection in the touristic Higashiyama area of Kyoto, Japan, where shown to participants and they could choose the direction they want to proceed until reaching an open space or designated shelter. As a result, we could quantify the impact of road width and, to some degree, network structure. The results reveal the tendency to select wide roads and to proceed straight. If the participants were put under time pressure these tendencies are intensified. Utilizing these results we constructed an evacuation simulation. We estimated the distribution and amount of tourists using data obtained from a mobile phone service provider. We conducted the simulation using VisWalk with various guidance situations and compared those results. The results illustrate potential capacity bottlenecks of designated shelter locations and the importance to provide route guidance and certain points in the network.

Keywords: Tourists' evacuation planning; Wayfinding; Virtual Reality; Evacuation simulation

1. Introduction

Tourism is one of the largest growing industries all over the world. At the same time tourists' concern for safety is increasing. This is due to increasingly frequent and severe natural hazards as well as terrorism, where large crowds of

* Corresponding author. Tel.: +81-075-383-3234; fax: +81-075-383-3236.
E-mail address: schmoecker@trans.kuciv.kyoto-u.ac.jp

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tourists can be easily targeted. Villegas et al. (2013) and Wachtel et al. (2020) discuss that tourists are more vulnerable than residents because they are often less informed and prepared. In many countries, there are protocols and schemes for evacuation of tourists from safe zones (shelters, city centers etc.) but in our review we find few solutions for the first step of the evacuation itself, that is, to get tourists to safe zones within an often densely crowded touristic area with narrow streets. Arguably, this is, however, the most important step in order to avoid panic.

There are a number of contributions discussing the behaviour of pedestrians during evacuation. Guo et al. (2012) use video recordings to observe behaviour and create microscopic simulation. Parisi and Dorso (2005) simulate indoor evacuation with the social force model which we will use in our simulation. Krüchten and Schadschneider (2017) introduce group size parameters into the evacuation model. Wang and Cao (2019) propose a revised social force model to consider limited visibility better. Others have used cellular automata to simulate pedestrian evacuation (Hu et al. 2018; Yi et al. 2020).

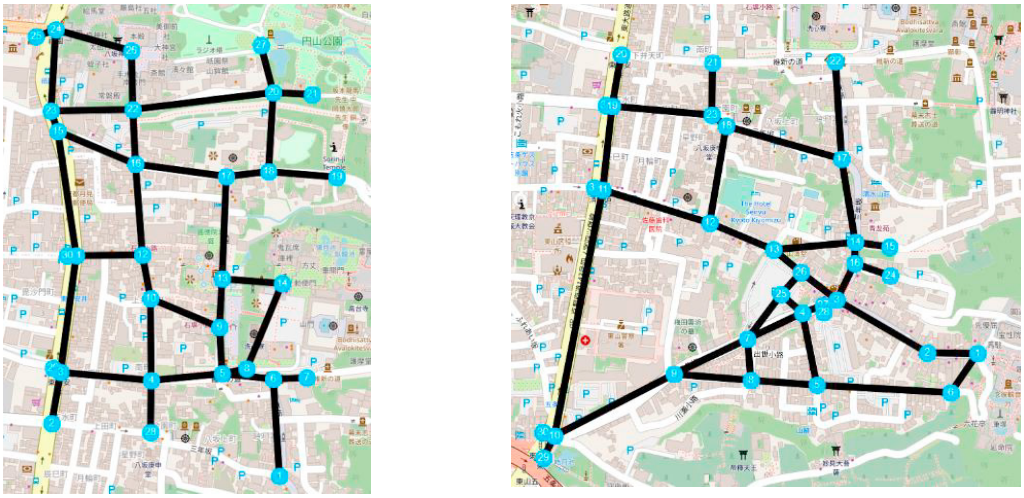
There are, however, only few contributions which simulate city tourists' evacuation in a wider area. Examples we find are Emori et al. (2016) and Kinugasa et al. (2012) who base their evaluation on a self-created simulation framework. We consider in this research partially guided evacuation to some safe areas over a fairly long period of time such as an hour. Potential scenarios where these assumptions might be realistic are, for example, if there is information of the danger of an attack or any kind of accident or weather condition that might require evacuation.

To simulate tourists' evacuation behavior on an urban city scale for such scenarios, it is necessary to estimate tourists' route choices during evacuation. The bottleneck for this, as for most evacuation studies but particular for tourists, is the lack of data and the large number of scenarios that can occur. In order to gain some general insight as to how tourists would choose their route we developed and conducted a VR (Virtual Reality) experiment that allows us to gain some understanding of route choice parameters.

2. The VR experiment

The experiment consists of virtual reality navigation games which emulate real-world urban scenarios. The goal is to construct tourists' route choice model during evacuation from sudden disasters. Figure 1 shows an image of the view that participants were posed to with the 3D glasses used. Each junction was shown as a 360° picture. Simple commercially available glasses were used with an Android smart phone inserted. A newly developed application allows participants to naturally scan the intersection by head movements, and proceed to the next downstream junction of the chosen direction (next image) by aligning their view (the central small white dot) to one of the yellow arrows for a few seconds. For brevity we omit details of the application here and focus on the experiment itself.

Figure 1. Snapshot of the VR game. (Text display was used for the "with time pressure" scenario)



a b

Figure 2. The network of VR game (a) Higashiyama Northern area; (b) Higashiyama Southern area (Map source: OpenStreetMap)

For our study location we chose the Higashiyama touristic area in Kyoto city (Japan). This is a heavily frequented district with the world heritage Kiyomizu temple as one of the main attractions. The fairly complex and dense network of narrow streets means that tourists sometimes get lost. The area is crowded with pedestrians and car traffic is limited to certain roads. We further note that Japan is at high risk for various natural disasters in particular earthquakes and Tsunamis, motivating this study. Although Kyoto city has no risk of tsunami because it is not facing the sea, there is a risk of huge earthquakes. Figure 2 shows the area and the junctions at which we took 3D pictures and that were prepared for the VR game.

At a shop near junction 3 in the Northern area, we recruited participants and conducted the VR experiment from November 21st to 23rd in 2020. Before conducting the experiment, we followed ethics guideline including explanations about potential health effects by wearing VR glasses'. We further asked participants to assume that they need to be evacuated after a huge earthquake occurred. In order to express anxiety during evacuation, we gave participants time pressure during playing the games by asking them to choose a direction within 10sec at each junction. The time limit was also displayed in the VR game. To allow understanding the effect of time pressure, we also constructed a no time pressure scenario and exposed each participant to both cases in random order. We further varied the choice of Northern and Southern area for the first game randomly and altered the network for the second game to control for specific network effects and for learning effects. After completion of the "with time pressure" game, we went with the participants through their decisions and asked them why they chose a specific direction at a junction. For the "without time pressure" game, participants were interviewed during the game. After both games were completed, participants answered a questionnaire asking, among others, their general familiarity with the area and their knowledge of evacuation procedures.

3. Constructing tourists' route choice model during evacuation

With this data we developed Multinomial Logit choice models (MNL) to explain whether participants tend to choose to go straight, left, right or back at the traversed junctions. The models were estimated in R 4.0.3 with the Apollo package (Hess and Palma, 2019). The panel characteristic of the data was considered in the error term. In the interviews after the VR experiment many participants stated that width was important for their route choice decisions leading us to test model forms width as one decision criteria.

The results in Table 1 including furthermore alternative specific constants for the Straight, Left, Right and Back choices. At t-junctions we adjusted the choice sets to omit the Straight option. We further tested including sociodemographics but found that these are not significant and do not improve the model fit. The parameter estimates show that tourists prefer wider roads and that they tend to go straight. Comparing the time pressure scenario and no time pressure scenario, we observe a higher model fit in the time pressure scenario and an increase in these tendencies. We suggest this is due to the fact that without time pressure, participants consider various information (e.g. buildings and distant view) obtained from intersections that is not explained with the model characteristics. In further work one might hence aim to extract additional infrastructure and junction layout characteristics that influence choice.

Table 1. MNL results for choices {Straight, Left, Right, Back} with and without time pressure scenarios

	Time pressure		No time pressure	
Explanatory variables	Coefficient	t-ratio	Coefficient	t-ratio
ASC Straight	ref.	NA	ref.	NA
ASC Left	-1.44	-4.35***	-1.47	-4.54***
ASC Right	-1.41	-4.58***	-0.57	-2.17***
ASC Back	-2.44	-6.35***	-1.35	-5.37***
Width [m]	0.20	4.07***	0.17	3.91***
LogLikehihood (0)	-139.730		-167.587	
LogLikehihood (final)	-88.827		-130.695	
Rho-square	0.364		0.220	
Adjusted Rho-square	0.336		0.196	

***: p<0.01

Number of individuals: 33, Number of observations: 112 (Time pressure)

Number of individuals: 37, Number of observations: 135 (No time pressure)

4. Application to simulation

4.1. Pedestrian walking parameters and validation

By using the tourists' route choice tendency, we constructed an evacuation simulation which was based on an assuming that an event occurs that requires all persons to immediately go to a shelter. We used "Viswalk" as the simulation platform. The software simulates pedestrian interaction based on the Social Force Model (SFM) but it can also reflect route choice probabilities at each intersection.

In the absence of site-specific parameters to calibrate the walking behavior during a disaster we utilize parameters from the literature. Our main source is Benner et al. (2017) who calibrated Viswalk model parameters by comparing simulation results and empirical data. If a disaster occurs, it is assumed that there will be counterflow in roads which Benner et al. considered in their calibration. We further utilize data from Liu et al. (2014) who measured the time it takes 200 people to pass through a small corridor with people entering the corridor from both sides. We suggest the experiment to some degree resembles the scenarios faced in our study area with its small streets. When testing with Viswalk default parameters for pedestrian behaviour in normal circumstances we find that there are significant differences in the time people require to traverse the corridor and that no pedestrian lanes formed as reported in Liu et al. (2014). With the parameters of Benner et al. (2017) instead we observe these lanes and we find similar "evacuation" times: In the experiment, it took 24 seconds for 100 people to across the measurement area and 50 seconds for 200 people to across the area. In the simulation, it took 19 seconds for 100 people to across the area and 46 seconds for 200 people to across the area. From this we concluded that these parameter settings appear to be appropriate for our study.

4.2. Evacuation demand estimation for worst case scenario

We constructed a network of the Higashiyama area in Viswalk. We set 11 safe zones as well as nodes which are at the network border as final destinations (Figure 3). We further require the estimation of tourist demand.

We estimated tourists' population distribution by using two data sources based on mobile phone signals. One is aggregate data of the population within 1km mesh. These data are obtained from Docomo, a mobile phone carrier in Japan with a large market share. The data are obtained for hourly intervals and several weeks during the autumn peak tourist season. For each hour we obtain the number of persons with a registered phone within Kyoto city, outside of Kyoto and with a foreign phone number. We furthermore obtained "Arukumachi data". This is a mobile phone application of Kyoto city with the main purpose of allowing one to check public transport timetables. Upon installation users are asked if they opt-in to provide occasional logs of their GPS location. It is used by Kyoto residents as well as tourists, but, understandably, mostly short-term users are willing to provide their GPS logs. As these disaggregate data are more detailed than the Docomo data but do not provide a good estimate of the total number of tourists in the area, we utilize this dataset only to determine the distribution of tourists within the 1km^2 mesh into smaller 100m^2 meshes (Figure 4). Within the simulation we generate tourists accordingly on links that belong to the 100m^2 meshes. The total number of tourists we obtain from Docomo data extrapolating between the larger meshes that partly cover our study area and considering the tourist distribution within these areas as again observed from the Arukumachi data. Considering that evacuation plans should be made for the worst-case scenario, we consider a potential disaster requiring evacuation at 2pm on November 23rd when the tourist demand peaks (the area is famous for its beauty of the temples in the autumn foliage). At that time a total of 14220 tourists are estimated to be in the area.

4.3. Construction of evacuation simulation in Higashiyama

We created a graph network of the Higashiyama area from available map data including information on road width. In the Viswalk simulation pedestrians' behavior on links is obtained based on the SFM. Upon generation mid-link we first assign the direction in which pedestrian walk randomly. At subsequent nodes (intersections) pedestrians follow the route choice probability obtained from our VR experiments (Table 1) or deterministically choose a certain link if that is prescribed by route guidance or if the junction is close to a safe area. As shown in Figure 6 Kyoto city has

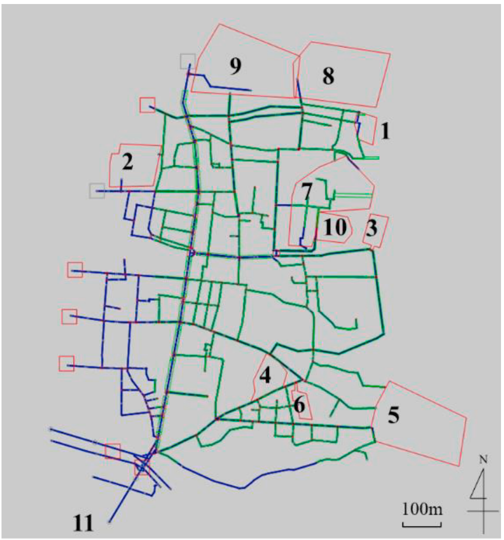


Figure 3. Network in the simulation with indication of the 11 safe zones

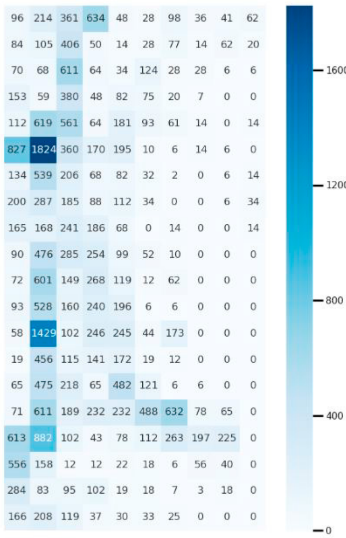


Figure 4. Tourists' population distribution (100m mesh) based on mobile phone GPS records

evacuation plans were route guidance at some junctions is planned to be implemented with the help of local volunteers. Once a pedestrian has reached any of the safe areas s/he is removed from the simulation. We assumed that the time the simulation starts is the time when the disaster occurred and simulate one hour. We measure the time it takes the pedestrians to reach a shelter or leave the network. We furthermore record density and speed on links to understand potential bottlenecks. From Kyoto City we also obtained information on the planned capacities of the safe places. As these are to be considered as guidelines, in the simulation we do not turn evacuees away from a safe place once capacity is reached. We measure, however, the overcrowding.

4.4. Simulation results under different guidance scenarios

First, we considered the case of simulation with no guidance. The mean time to reach the destination was 684 seconds and 70.4% of the evacuees reached the safe zones within the one hour period (Figure 5). The capacity of some of the safe zones (Area 3, Ryozengokoku-Shrine, and Area 5, Kiyomizu-dera Temple, in Figure 3) was exceeded. We note that we changed the random seed as to when the pedestrians are generated and executed the simulation ten times. The observed variance was fairly insignificant (min 670 sec and max 695 sec) and the distribution of evacuees among the shelters was fairly constant. From this we concluded that the simulation results are stable.

In order to investigate the importance of the route choice model, we constructed a simulation without and with the afore described route choice model. For the "without" model we used equal link choice probabilities at each node, except for nodes near safe zones where we assumed that the evacuees enter these safe zones. As a result the mean evacuation time increased to 1393 seconds (Figure 5) which we suggest as benchmark figure for an evacuation without orientation.

Next, we executed the simulation with a guidance scenario that is planned by Kyoto city (Figure 6). As a result, the evacuation time reduced to 466 seconds (Figure 5) and the number of evacuees who reached safe zones was 97.4%. However, the overcrowding at some safe places remained. In particular Kiyomizu-dera Temple and Kyoto national museum (Area 11 in Figure 3) are likely to be overcrowded. Furthermore, our simulation suggests that there is congestion at nodes located near Kodaiji Temple and on the main street where pedestrians experience densities larger than 1.0 [person/m^2].

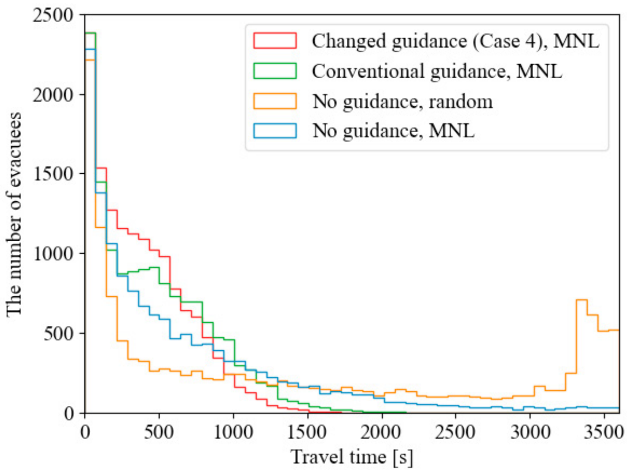


Figure 5. Distribution of travel time

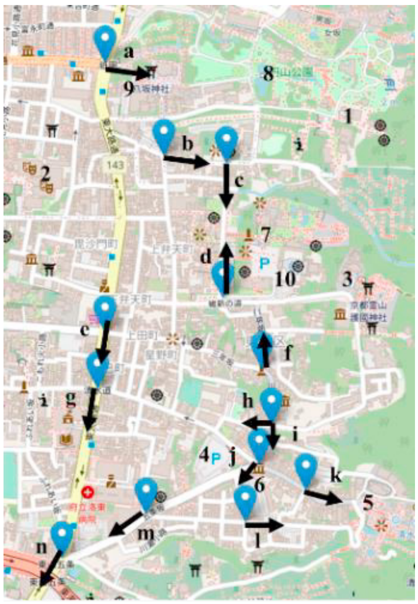


Figure 6. Route guidance planned by Kyoto city

We consider several alternative guidance situations in order to solve above problems. In order to relief the capacity and congestion problems, we changed the route guidance, aiming to deter evacuees from aiming for Kiyomizu-dera Temple, Kyoto national museum and Kodaiji Temple. Specifically, we changed d, e, g, k, l, m in Figure 6 (Case 1). As a result, the congestion near Kodaiji was solved but instead congestion on the main street occurs. Further, although the number of evacuees who reach Kiyomizu-dera Temple and Kyoto national museum decreased, the values remain above their capacities. In order to solve the congestion on the main street, we test a rearranged case (Case 2) with respect to guidance on the main street (arrow g in Figure 6) which indeed solved the congestion problems (see Table 2). In a further set of experiments we also changed the guides' locations. We re-arranged guides to nodes at which large flows occur (Case 3). For comparability the number of guides was unchanged. As a result, some additional, but only small, improvements in evacuation time were observed. In a final set of experiments both guidance directions and location of guides were changed (Case 4). We obtain the lowest evacuation time but congestion occurs at Kodaiji Temple and Yasaka Shrine.

Table 2. Summary of simulated scenario results

Guidance case	Mean Evacuation time [s]	The ratio of evacuees who reached safe zones [%]	Safe zones with capacity exceeded and excess number[1]	Road congestion (people / m^2)
No guidance, MNL	684	70.4[2]	Kiyomizu-dera Temple : 1295	No[3]
Conventional guidance	466	97.4	Kiyomizu-dera Temple : 1170 Kyoto national museum : 2682	Yes (2.3)
Changed Guidance (Case 1)	525	97.3	Kiyomizu-dera Temple : 735	Yes (1.5)
Changed Guidance (Case 2)	444	97.4	Kiyomizu-dera Temple : 735 Kyoto national museum : 166	No[2]
Changed Guidance (Case 3)	457	97.4	Kiyomizu-dera Temple : 1005 Kyoto national museum : 3510	Yes (1.5)
Changed Guidance (Case 4)	389	97.4	Kiyomizu-dera Temple : 880 Kyoto national museum : 313	Yes (1.5)

[1]Kiyomizu-dera Temple's capacity : 740, Kyoto national museum's capacity : 3250

[2]In the no guidance scenario persons "randomly" reaching the southern edge of the area are not counted as having reached a safe place, but in the scenarios with a planned guide at that point they are counted as they are led out of the area.

[3]On none of the links pedestrian experienced densities exceeding more than 1.0 person/m^2

5. Summary and conclusions

We conducted a VR experiment to understand pedestrians' route choice decisions in a scenario where they are pressured to find their way to safe places in a dense, narrow street network which they are not necessarily familiar with. As a result we could quantify the preference to take wider roads and to keep moving straight. Interestingly, we could not find that sociodemographics are significant. In the experiments we mentioned that one can imagine to evacuate after an earthquake (to be in a safe place for subsequent shakes, fires and possible building collapses) but did not specify the disaster further nor did we show any destruction nor panicked crowd. Clearly in case of large disasters and panic occurring wayfinding will be largely influenced by such factors and in particular many would simply follow people ahead of them. We suggest therefore that our results should be mainly considered for cases where an orderly evacuation can be planned. Furthermore, we suggest that even in a panic case our results might have some "benchmark" role as possibly the found tendencies for certain routes will still exist but amplified by the crowd. Nevertheless, in further work, one could clearly create VR experiments in which participants are presented with images in which crowds are moving in some directions. A further, but much more complex and expensive, alternative would be to consider the creation of a virtual reality game. Strength and weaknesses of such an approach are discussed in Lovreglio and Kinateder (2020) for building evacuation from a fire. We suggest our low-cost approach is instead a useful tool to generally extract an understanding of tourist behaviour in specific networks. With commercially available 3D cameras and VR glasses our experiments can be easily repeated for other areas.

We demonstrated how the data from the experiment lead to a route choice model that could be used within a simulation framework applied to Higashiyama, Kyoto. The simulation results demonstrated the importance of the wayfinding model. The results further showed that route guidance can significantly reduce the evacuation times and avoid crowding on the roads as well as reduce (but not eliminate) congestion at certain safe areas. Our specific case study showed that the existing guidelines by Kyoto City are fairly appropriate but that some improvements might be considered.

We close by noting other further work directions for both the wayfinding experiments as well as the simulation. Firstly, we aim to repeat the wayfinding experiments with persons who have not been to the Higashiyama area (or not at all to Japan) to better understand the role of familiarity with the general environment. To improve the route choice model we further consider to quantify the importance of the environment and landmarks at junctions such as the presence of large building, visibility of downstream junctions or the slope of the road. In the simulation furthermore, the above-mentioned group behaviour could be implemented.

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