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Behavioural-design-based risk assessment and mitigation against floods in historical urban built environment: a virtual reality approach

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Abstract: Risk-mitigation in historical Urban Built Environments (UBEs) should be designed by considering not only historical scenarios and hazard features but also their users and how they respond to emergencies. Flood is a critical disaster in historical UBEs, mainly in outdoor public spaces, essentially because of users' interactions with floodwaters spreading in the complex and narrow urban fabric. A behavioural-design (BD) approach could support risk assessment and effectiveness evaluation of mitigation strategies since it relies on analyses of users' emergency behaviours. This work is aimed at developing and verifying a novel approach to these tasks, by employing Virtual Reality (VR) and Serious Game (SG) criteria. VR allows representing and testing different UBE features, flood conditions and mitigation strategies in a sustainable manner. SG ensures a high volunteers' engagement in tests. A module VR-SG tool is here developed and tested for a typical riverine historical UBE, involving more than 100 volunteers. Preliminary tests demonstrated how the approach provides results similar to those of real-world scenarios, while insights on how to improve the tool are also discussed. The proposed system can be used by stakeholders to preliminary assess risk and verify the impact of mitigation strategies under different scenarios before their implementation.

Keywords: historical urban built environment; risk mitigation; flood; virtual reality; behavioural design

1. Introduction

Risk in historical Urban Built Environment (UBE) due to flood is mainly due to the combination of vulnerability and hazard [1,2], which affects the water spreading into the UBE layout and the possible damages to the Heritage and to the related users' interactions with the floodwater levels (i.e. the depth and speed of the water can reduce the users' evacuation speed and pose problems for their stability). To mitigate flood risk, structural and non-structural measures can be implemented in the UBE [3]. Structural measures are more related to engineered interventions aimed at reducing the volume of floods so as to impede or reduce floodwaters spreading in the historical UBE, and therefore, from a general perspective, they also try to limit the necessity of evacuation procedures [1,4]. Other structural measures rely on architectural-implemented strategies in the UBE, such as layout configuration, building components and furniture installation, which can be indeed useful in case of evacuation too, giving direct support to the population (i.e. to pedestrians). Non-structural measures aim instead to implement on one side building codes, land-use planning laws, and regulations; and on the other side flood-adapted design, preparation, and evacuation planning [5]. Both structural and non-structural measures can be reactive (response-oriented) or proactive (risk reduction). Among all these measures, the non-structural ones are surely more related to users' behaviour and can be useful to reduce the exposure factor in flood risk and could be combined with UBE layout-oriented strategies.

Implementing such measures in historical UBEs should consider how conservation tasks and requirements tasks are essential in the process, thus also facing the specificities of historical buildings construction (i.e. materials and techniques), the particularities of urban fabrics (i.e. special typologies and irregularities of pathways), the presence of non-resident people and so not aware of the escape routes (i.e. tourists), and moreover the cultural significance of assets [6]. For this reason, they should be placed in the UBE where needed and how they are needed, so as to minimize their impact on the Heritage.

Insights from previous works investigating users' behaviours in case of flood emergency and evacuation can be hence exploited in view of the behavioural connection between mitigation measures and human response, as for other kinds of disasters [7]. Such studies took advantage of both experimental activities and real floods analysis [8,9]. In particular, pedestrian evacuation is one of the most critical investigated scenarios in view of safety problems for people while moving in floodwaters. Furthermore, in complex historical UBEs characterized by narrow streets, pedestrian evacuation could be the only way to escape from flood, especially in case of poor early warning systems [1,10]. Besides the analysis of pedestrian evacuation speed depending on the floodwater height and depth [11], previous works succeeded in defining critical interactions in the UBE depending on the UBE elements themselves by also highlighting specific interactions in outdoor public spaces. Protective behaviours are deliberately activated respectively towards fixed and movable objects in the UBE [8,12]. Fixed obstacles are perceived as support elements in motion since people can also hang on them by limiting stability problems due to the floodwater levels [13] and additionally improving motion speeds [14]. People generally try to move 1m to 2m far from buildings to take advantage of these kinds of physical support [15]. On the contrary, movable obstacles are perceived as dangerous elements since they are dragged by floodwaters. Protective behaviours also refer to the attraction towards areas with lower floodwater levels, i.e. depth, including raised areas in the urban fabric, are also noticed [8]. Pedestrians hence try to collect information on danger issues due to the floodwater-induced modifications to the UBE, as for other kinds of emergencies [16]. If moving upstairs is not possible [17], pedestrians tend to move towards raised platforms, on top of hills or even climb onto benches or low walls and wait for rescuers' arrival in a temporary safe area [8]. Attractive phenomena are generally noticed between pedestrians while moving to gain reciprocal support and between pedestrians and rescuers to directly receive help and support on where to go and what to do [8,9]. Anyway, such a social attraction to other pedestrians can lead to the activation of hazardous phenomena, such as wrong evacuation choices due to herding behaviours and time-wasting behaviours, such as waiting for other people in hazardous areas or trying to support people in danger without having proper preparedness and resources. Finally, as for other kinds of disasters, people can take advantage of wayfinding and risk signs while selecting their evacuation paths [16], by overlapping such data with the other behavioural interactions defined above.

Thus, a Behavioural Design (BD) approach [7] could be used to support risk assessment and mitigation in historical UBEs stricken by floods, focusing on how proposed solutions can increase the users' safety in the immediate emergency evacuation phases because of these pedestrian behaviours. The BD approach can be firstly used to investigate human behaviours in an emergency to assess risks due to individual and collective dynamics and interactions with the UBE and its disaster-affected conditions. The analysis of real-world events is one of the most used ways to collect such data, but drills, including those in Virtual Reality (VR), could be exploited to reproduce emergency scenarios and vary specific stimuli to the people (e.g., for flood, the floodwater conditions or the UBE configuration) [11,18]. Then, according to such behavioural results, solutions to support, guide and suggest to users how to properly behave in an emergency can be proposed and tested again by means of drills or simulation models [7].

In case of floods, drills are very hard to be organized in view of the dimension of the area affected by the disaster, as well as the necessity to properly reproduce floodwater conditions in the UBE. Thus simulation models are generally used [1,17,19], but they could be affected by behavioural assumptions of the models due to limitations in the input data. In this sense, Virtual Reality (VR) tools to support BD can be used by recreating different scenarios conditions in a sustainable and more effective manner [20–22], thus moving towards more immersive conditions for drills, with the possibility of reproducing different dangerous scenarios, allowing users to interact with the digital environment without any risk [20].

Serious Games (SG) methods can be coupled with VR tools for BD. SG can assess risk and train different kinds of users, including both decision makers, rescuers and citizens [23,24]. It has the advantage of using techniques typical of simulation games to create more engaging approaches in which a strong emphasis is put on emotional aspects, with a much greater retention potential [25]. VR and SG are often used to train people on how to respond in case of an emergency, but their combined use is not generally exploited to evaluate the effectiveness of different risk-mitigation strategies to be implemented in the UBE. In this sense, developed methods and the related tools should be validated to understand if SG-VR tests performed according to the BD criteria can replicate the phenomena noticed in real-world flood emergencies in UBEs.

In view of the above, this work is aimed at developing and preliminarily verifying a VR-based approach to support risk assessment in historical UBE and to evaluate the effectiveness of risk-mitigation strategies before their implementation in the physical scenario. According to the aforementioned BD perspective, the proposed approach implies a direct involvement of users who can be exposed to floods in UBEs. This approach is pursued thanks to SG. The preliminary verification phase involves tests with volunteers to assess similarities between behaviours activated in the VR environment in view of the proposed SG storyline, and in real-world UBEs, according to literature works. Verification tests are carried out by implementing a typological, historical UBE into the VR-SG tool.

2. Phases, materials and methods

This work is divided into two phases. The first one concerns the development of the VR-SG approach and of the related tool (Section 2.1). The second phase regards the exploitation of the tool in the BD approach and its verification with respect to real-world behaviours in flood emergencies in UBEs (Section 2.2). These phases have been applied to a significant application scenario by involving more than 100 volunteers to perform verification tests (Section 2.3).

2.1. VR-SG approach and tool development

The VR-SG tool was developed using the Unity game engine (version 2020.3.10f1), ensuring its application in both Immersive VR and non-immersive VR tests. Elements of references composing the BE are buildings, roads, signs, benches and raised areas in outdoor public spaces. These elements affect both floodwater conditions and pedestrian movements, according to Section 1. Water elements are simulated to represent such a flood scenario.

Moreover, Non-Players Characters (NPCs) are modelled to represent the avatars of other pedestrians and rescuers, including their animations.

In detail, the following literature evacuation behavioural interactions were modelled and considered as “interaction elements” [8,17,26]:

A. *evacuation path choice*, both depending on the UBE layout and on the possibility of collecting information on floodwater features (i.e. height) where the pedestrian is placed. To this end, some common objects are included in the VR environment, such as street poles, benches and cars), which are considered as not dragged by the flood. Furthermore, urban and emergency wayfinding signs were also modelled ;

B. *safe area choice*, to perform “shelter-in-place” strategies by moving upstairs, to reach an outdoor gathering area, or to prefer to stop the evacuation in a temporarily safe position (e.g. climbing on a bench to wait for rescuers’ arrival). In the last case, volunteers were informed that the bench could not represent a final evacuation target;

C. *interaction with obstacles*, including both fixed (i.e. see point A) and movable (i.e. dragged by floodwaters, such as bins) obstacles, to verify if attractive and repulsive phenomena in motion;

D. *interaction with other people*, modelled as NPCs, to verify attractive and repulsive phenomena in motion, including herding behaviours and the increased support to the evacuation due to the rescuers’ presence.

Different “story modules” were defined according to SG concepts to create a storyline for the BD tests in the VR environment, to include one or more of these behavioural interactions. Although “story modules” are generally aimed at outlining training objectives for recipients [27], in this work, they are used as interactive elements for the pedestrians to evaluate how volunteers interact with them during the VR experiments and so to assess if they can increase or decrease the pedestrian safety in the evacuation process due to their positioning in the historical UBE. 5 story modules were elaborated in reference to the layout of the historical UBE, and then combined according to the storyline in Figure 1 (numbers of the list refers to the “story modules” in Figure 1):

1. *Ground floor of a building*. The tests started from such an architectural space (1a in Figure 1) to verify the initial evacuation path choice. The volunteer could move downstairs or outside. Moving downstairs implied reaching a risky area, thus leading to “game-over” (that is, the end of the test). Moving outdoors implied moving into the UBE. Another building ground floor scenario was considered (1b in Figure 1) in connection with the square module. In this case, the volunteer should move upstairs towards a final indoor gathering area;

2. *Street with obstacles*. The volunteers moved along the street by interacting with fixed and movable obstacles (i.e. trash bins). This module also included the use of fixed obstacles and urban wayfinding signs for path selection (i.e. towards or far from the river);

3. *Crossroads*. The volunteers needed to choose the evacuation path by having the possibility to exploit common objects with known dimensions and urban wayfinding signs. The volunteers’ test ended (“game over”) if they selected a path characterized by critical floodwater conditions;

4. *Street with other pedestrians*. The volunteers moved along a street where NPCs were placed to assess interactions with other people;

5. *Square*. The volunteers moved into this outdoor public space to reach safe areas placed on a raised platform or inside a building (see previous point 1 of this list). Obstacles and NPCs were present too.

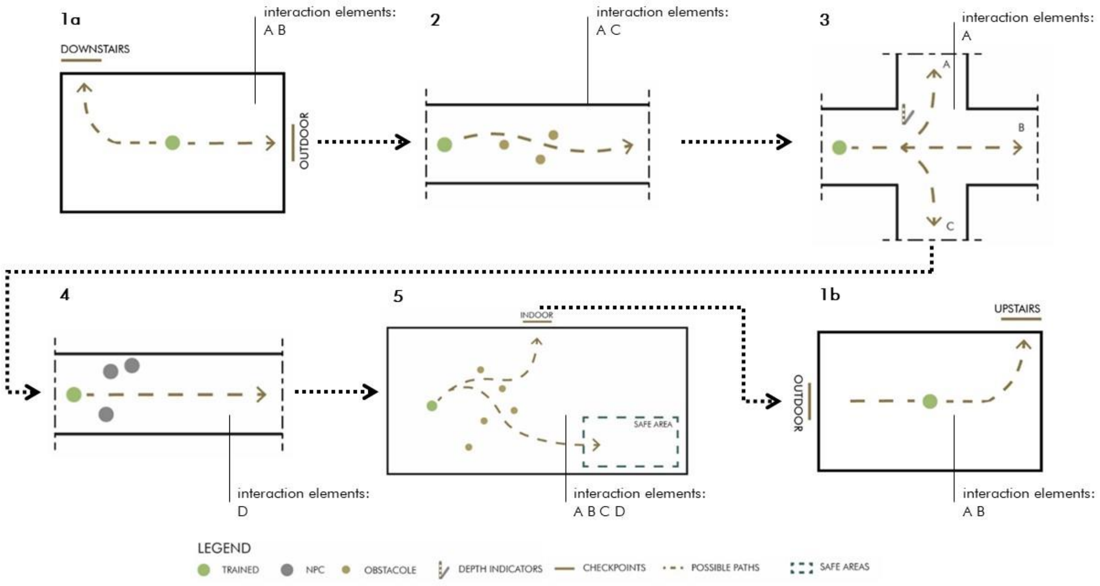

Figure 1. Tested storyline: for each story module, the related behavioural interaction elements are provided according to the codes in the main text.

2.2. Testing methods and verification criteria

Tests used non-immersive VR and First-Person Movement, ensuring a quick replication of the experiments but a reliable perspective of movement for the volunteers. The navigation was then performed through keyboard and mouse as locomotion methods, thus using a common approach and familiar devices to the volunteers [28].

In each test, the participant was preliminary "trained" on how to use such navigation controls in a specific environment having similar layout features to the testing one but no floodwaters and a significant abstraction level. Then, the volunteer was "teleported" inside the room at the ground floor of a building in the historical UBE. Then, each volunteer moved in the scenario according to the storyline in Figure 1. Comments to volunteers' reasons for specific behavioural interactions according to the "story modules" were also collected at the end of the test.

For each volunteer, trajectories in VR environment were recorded in an anonymous manner. Then, the whole volunteers' sample trajectories were merged to estimate the usage levels of the historical UBE spaces during the test by distinguishing data for each of the story modules in Figure 1. In particular, this work focused on the outdoor public spaces according to Section 1 literature overview and research aims. The outdoor public space has been discretized according to a 1m x 1m grid to detect discrete trajectories in respect of the ranges of distances between pedestrians and fixed objects [15].

Trajectory analyses were used for verifying common behaviour interactions according to the story module purposes for evaluating if common trends are shared in the VR and real-world evacuation conditions. Beside such interactions, trends in the volunteers' position in outdoor public spaces were discussed with respect to the fixed obstacles to investigate locomotion-related issues between VR and real-world scenarios [15,28,29]. Finally, the percentage of volunteers completing their evacuation in each safe area or in a "game over" condition was assessed. Matlab R2021b was used to perform these analyses (www.mathworks.com/downloads, last access: 12/07/2022).

2.3. Application scenario and involved sample

The historical UBE investigated in the tests is a typological context of a historical riverine city, outlined and investigated by previous works [1]. Figure 2A shows that the layout represents a typical regular urban fabric, as in a Cardo-Decumano configuration, with streets width equal to 4m for those parallel to the river and to 6m for those orthogonal to the river. Figure 2A also shows the excerpt of the layout where tests were performed by identifying the position of the spaces according to the related "story module" code (compare with Figure 1), the main path connecting the "story modules" themselves (continuous orange line) and the position of safe areas, namely RSA as Raised Safe Area (placed in a raised platform in the square) and ISA as Indoor Safe Area (placed at upstairs in "story module" 1b). Figure 2A also traces outdoor paths leading to "game over" conditions (dashed blue line), which refer to the river direction (for "story module" 2), and the wrong crossroad direction (for "story module" 3). Figure 2B and Figure 2C respectively show views of a street and of the square in the VR UBE.

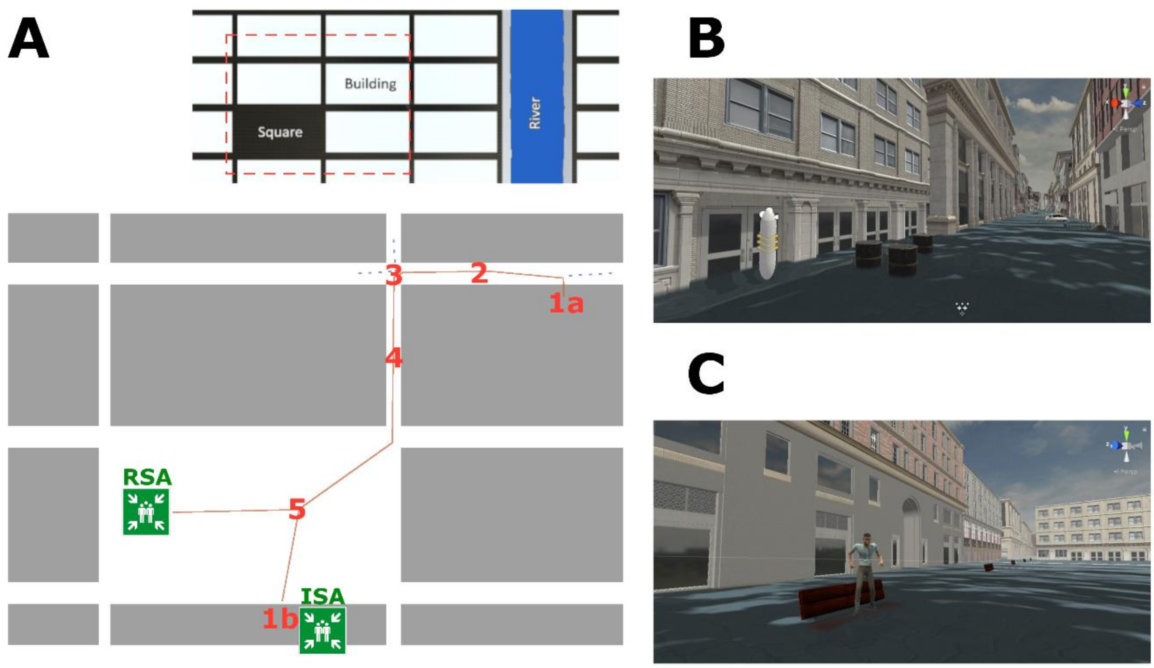

Figure 2. Historical Urban Built Environment scenario implemented in the VR-SG tool and used for verification tests: 8A) overall plan view in terms of the urban fabric scheme (top; the limits of the specific area for the tests is enclosed in the dashed red rectangle) and the specific area for the tests (bottom; including story modules as in Figure 1, ideal connecting path in continuous orange line, and "game over" paths in dashed blue line, and position of the safe areas); (B) a street view; (C) a square view.

106 tests were performed in this scenario involving volunteers coming from riverine and coastal cities in the Marche Region, Italy. Tests were carried out by also involving students in the last year of local high schools. Their age ranged from 18 to 68 years, with an average age of 27,56. About half of them were female. About a third of volunteers said they do not

use virtual reality games at least once a year. Finally, less than 10% of volunteers stated to be involved in flood evacuation, but more than half of them were aware that such situations could lead to critical safety conditions in historical UBEs.

3. Results and discussion

Figure 3, Figure 4 and Figure 5 show the trajectories according to the 1m x 1m grid, respectively, for the 3 outdoor public spaces in the VR historical UBE, that are the streets ("story modules" 2 and 4), the crossroad ("story module" 3) and the square ("Story module" 5). They also include the positions of the main obstacles along the paths and of other NPCs. From a general point of view, real flood behaviours are confirmed.

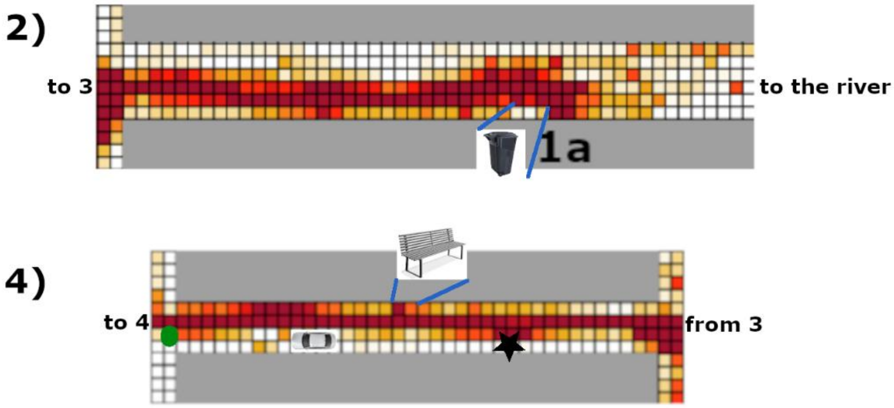

Figure 3. Pedestrian trajectories in the VR environment for the streets, that are "story modules" 2 and 4, according to the 1m x 1m grid. Each cell describes the frequency of use, ranging from 0 (white) to >1000(dark red). The positions of cars, benches, trash bins, rescuers (green circle) and other pedestrians (black star) as main reference elements in the UBE are shown. The starting point for the test ("story module" 1a) is also shown.

18% of volunteers immediately ended their evacuation in the downstairs "game over" before exiting from "story module" 1a, because of a misunderstanding of the role of stairs in the building. Along the streets, people prefer to move close to buildings, being about 1m to 2m far from them, in both "story modules" 2 and 4, as shown in Figure 3. In "story module" 2, repulsive phenomena due to the fear of movable obstacles (i.e. trash bins dragged by floods) were noticed, while, in "story module" 4, pedestrian trajectories were attracted by the bench, the group of NPCs and the rescuer simulated along the street. The car in "story module" 4 was avoided since it was perceived as a possible movable element. All these trends confirm previous works' results on protective behaviours in the UBE [8,9,12,15].

In addition, in the street of "story module" 2, volunteers explored the outdoor area in front of the initial building exit to collect data on where to go and on the floodwater levels. In this sense, this is a hazardous behaviour since it induces volunteers to remain in their initial unsafe position before selecting the proper evacuation path, but negative effects are mitigated by the proper selection of the evacuation path thanks to collected information (i.e. estimated floodwater height and speed due to dragged bins; urban wayfinding signs pointing out the river direction). In fact, no volunteer moved toward the river in "game over" conditions. This result confirms real-world interactions with surrounding UBE and flood conditions and wayfinding elements [8,16].

A similar behavioural interaction is shown by "story module" 3 analysis in Figure 4. Most of the volunteers select the correct path by taking advantage of elements with known dimensions, such as cars and street poles and urban wayfinding signs indicating the square position. Only 7% of them failed in selecting the proper evacuation path at the crossroad because they were not able to properly recognize floodwater levels. The dark red colour of some cells in Figure 4 is essentially due to the fact that volunteers spent time evaluating floodwaters' conditions while remaining close to the same position. The same desire to collect risk-related information is confirmed by literature for floods and other kinds of emergencies [8,12,16]. Nevertheless, the VR environment could have increased the time spent in an unsafe position in respect of real-world conditions because of no direct perception of risk due to direct floodwater sensation on the human body. Also, in this case, the trajectory was essentially 1m or 2m far from the buildings.

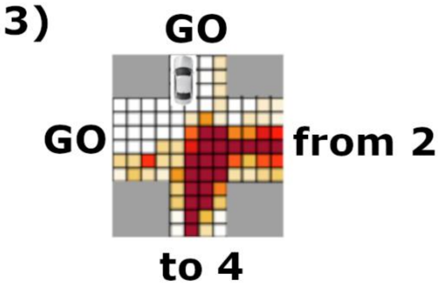

Figure 4. Pedestrian trajectories in the VR environment for the crossroad, that are "story module" 3, according to the 1m x 1m grid. Each cell describes the frequency of use, ranging from 0 (white) to >1000(dark red). The position of cars as main reference elements in the UBE is shown.

Figure 5 shows that the trajectories of 77% of volunteers who reached square ("story module" 5) are quite "scattered". Anyway, some attraction points due to the presence of UBE elements and NPCs seem to influence this result. Volunteers entering the square from "story module" 4 firstly noticed some benches placed on the right, being attracted by them as temporary safe areas where to stop motion. Then, they collected information on the two gathering areas, according to the same approach given by literature works [8,12,16]. The volunteers' final destination was the RSA for 43% of the whole sample and ISA for 34%. While approaching the final destination, their trajectories were attracted by rescuers placed in the square, thus demonstrating the impact of emergency support while moving [8]. Trajectories were also partially attracted by buildings, as for the streets and crossroads scenarios.

Finally, the overall analysis seems to show how differences between the effective VR trajectories and possible real-world ones could be influenced by the growing familiarity with the navigation methods. Despite the volunteers' training before the tests in the VR historical UBE, trajectories seem to become more linear while volunteers continue moving in the test VR environment (e.g. compare the great dispersions of data in "story module" 2 and 4 in Figure 3). Nevertheless, this phenomenon could also be partially affected by the street dimension. On the contrary, in the square of "story module" 5, volunteers' trajectories were mainly not close to the buildings, as can be assessed by real-world observations [15]. According to their comments, collected volunteers generally argued that "moving in a straight line in this open public space was really simple" and that they limitedly "adapted their trajectories to collect additional information on specific local conditions". Thus, the proposed VR approach still seems to succeed in describing local interactions due to specific safety elements such as fixed obstacles and NPCs. At the same time, the importance of locomotion methods is confirmed [28,29].

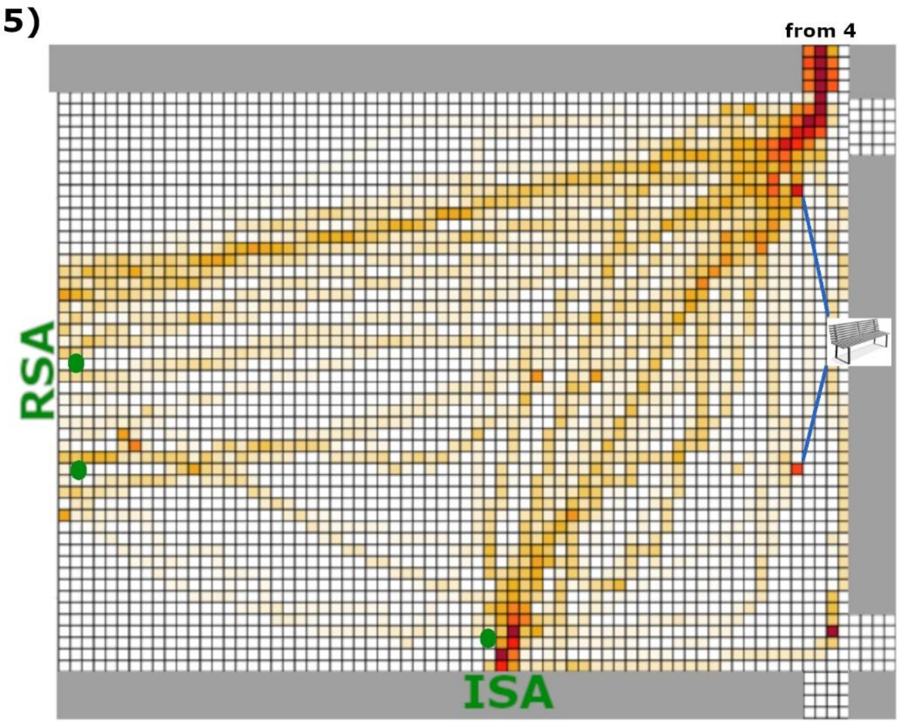

Figure 5. Pedestrian trajectories in the VR environment for the square, that are "story module" 5, according to the 1m x 1m grid. Each cell describes the frequency of use, ranging from 0 (white) to >1000(dark red). The positions of benches, and rescuers (green circle) as main reference elements in the UBE are shown.

4. Conclusions and remarks

Risk-mitigation strategies in historical Urban Built Environments (UBEs) should be designed by taking account of both the historical scenario features (to preserve their fundamental aspects while ensuring good reuse of the Heritage) and the users who live and move in them in case of an emergency. Flood is a critical disaster to be faced in view of the critical characteristics of historical UBEs, and of the direct interferences between the hazard effects, the UBEs and the users' behaviours in emergency conditions (i.e. pedestrian evacuation). This work uses Virtual Reality and Serious Game methods to provide a behavioural-design (BD) approach for risk assessment and risk-mitigation strategies evaluations in such urban scenarios.

This work firstly develops a VR-SG tool and tests it in a significant application context, which is a typical UBE configuration referring to a historical riverine city. Elements characterizing such UBEs are modelled in the VR environment, and tests concerning pedestrian evacuation are carried out involving more than 100 volunteers. These preliminary tests were performed using non-immersive VR to ensure quick replicability of the approach in each context.

This work succeeds in demonstrating how the use of such an approach is valid thanks to the disclosed main behavioural similarities between real-world and VR conditions. Some differences exist indeed, as the VR approach can limit the level of engagement of people in respect of the floodwater conditions and the related realism. Future works should hence improve this aspect, e.g. by using immersive VR in open channels or pools and other locomotion methods (e.g. walking or running in place). Further tests in such conditions should be carried out to evaluate how the approach reliability can be improved by these solutions.

The approach's effectiveness is also shown by its methodological implementation. The structure is composed of "story modules" that can create different storylines for different tests or be improved by additional "modules". Thanks to such a modular perspective in VR-

SG, the approach and the related tools (including its further modifications) will be used to test the behavioural interactions between pedestrian and risk-mitigation strategies in the historical UBEs, such as: (1) the implementation of temporary safe areas on raised elements, including architecturally-integrated benches and outdoor layout elements; (2) the positioning of risk and wayfinding signs devoted to supporting pedestrians during the evacuation process; (3) the optimization in the safe area and rescuers' positioning in respect to the pedestrians' paths and final destination choices in the VR environment. Considering point (2), it is worth noticing that additional tests can be performed by considering a preliminary (pre-emergency) movement of pedestrians in the VR environment, thus evaluating differences due to their familiarity with the UBE. Concerning points (1) and (3), this BD approach can also be exploited to increase pedestrians' awareness in typological and real-world contexts through the SG criteria. Such kinds of tests can increase the preparedness of people to flood emergencies as well as support the dissemination of emergency plans in specific case studies virtually reconstructed through the proposed tools. Such research and practice steps will help decision-makers (i.e. local administrations) and their safety planners in evaluating risks and designing more sustainable solutions to fight floods in historical UBEs.

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