How to Help Elderly in Indoor Evacuation Wayfinding: Design and Test of a Not-Invasive Solution for Reducing Fire Egress Time in Building Heritage Scenarios

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Abstract Population aging increases the importance of emergency safety for elderly, especially in complex and unfamiliar spaces. Individuals who can autonomously move should be encouraged to evacuate by themselves, and adequate help should be provided to them. To this aim, a "behavioral design" approach of these elderly facilities is proposed: understanding behaviors and needs in emergency; designing systems for interacting with them during an emergency; testing solutions in real environment or by using validated simulators. Wayfinding tasks are fundamental aspects in evacuation: elderly have to receive proper information about paths to be used, in the simplest, clearest and most unequivocal way, so as to reduce wrong behavioral choices and building egress time as much as possible. This work proposes a robust wayfinding system based on photoluminescent material (PLM) tiles with continuous applications along paths. Tests concerning a significant case study (an historical theatre) evidence how the proposed system allow to significantly increase elderly evacuation speed (more than 20%) in respect to the traditional system. It could be introduced in other buildings for increasing elderly safety and data are useful to define man-wayfinding systems interactions.

Keywords Elderly safety · Elderly emergency evacuation · Risk-reduction building components for elderly · Wayfinding systems · Historical building safety · Fire evacuation

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1 Introduction

Population aging is going to radically change needs, requirements and scopes of many fields in our society. Only in Italy, more than the 30% of population will be composed by over 65 population in 2065, according to the recent 2015 ISTAT estimations [1]. They will be surely more active and involved in the society than today. For this reason, the environment they will join should be able to host them in an accessible, comfortable and safe way. Solutions for their free use of spaces should be urgently provided, especially for individuals who can autonomously move.

A particular attention should be posed to elderly safety in emergency conditions, such as in case of fire, earthquake, flooding. Elderly represents one of the most vulnerable categories in emergency conditions [2], especially since they move in spaces that are unfamiliar to them or that are not designed to be easy used by them also in ordinary (because, e.g., for the building layout) [3, 4]. In these cases, their safety level could suffer critical choices about what to do and where to move during the evacuation process [5]. Therefore, this occupants' category can suffer secondary higher risks in respect to the other individuals, because of increased egress time and possible interferences with hazardous environmental modifications (e.g.: exposure to smoke or flames in building fire) [2, 3, 6].

Since occupants' safety depends on a rapid building evacuation [7, 8], all occupants should be properly guided during their emergency motion towards proper paths and exits. In particular, people with motion autonomy (and so many of the hosted elderly) should exit the building by themselves: they do not need the intervention of an assistant, but they can be simply helped by proper evacuation facilities, such as wayfinding systems [9].

Our research is aimed at reaching this goal by designing systems that can help these occupants during the whole evacuation procedure, by taking advantages of a "behavioral" point of view [10, 11]. Needed activities are:

1. understanding human behaviors and their needs during the emergency process, and then define behavioral models for representing evacuation interactions;
2. designing systems (mainly, wayfinding systems) for interacting with them during the evacuation;
3. testing the proposed solutions through experiments or behavioral models (and related simulation tools).

Each designed element should be tested about both technological requirements and influence in space perceptions and motion.

Literature demonstrates how wayfinding systems are effectively able to suggest people the evacuation path and then reducing the egress time [12, 13]. However, they should guarantee an immediate identification of directional information in different environmental situations [14]. Wayfinding systems include: reflective signs [15], photoluminescent (PLM) signs [16, 17], electrically-illumined signs [15], interactive systems and portable devices [10, 18, 19]. Their effectiveness is influenced by pedestrians' perception depending on both individuals' characteristics and environmental conditions [13, 20]. According to the interaction level, they can be "active" [21] or "passive" since they are able to suggest the evacuation direction depending on the surrounding environment conditions (e.g.: presence of fire [22] along paths), or not (e.g.: fix arrow direction [12, 23]).

PLM signs systems [24–26] are the most robust ones because they do not need any supply (no interventions on building structure), are easy-to-apply and remove, need a low level of maintenance and are efficient also in black-out or smoke conditions. Identification distances [14, 27], influence on evacuation time and speed [25, 28] and appreciation questionnaires on the involved individuals [12, 23, 29] are performed for system effectiveness assessment. Evacuation drills in different buildings are performed [8, 29, 30], but few studies involve high occupants' number [31, 32]. Current literature generally evidences how the design of the facilities seems to be not properly based on human evacuation needs and behaviors. At the same time, a lack of data about interactions with older adults and most vulnerable people [2], especially in critical environment, is verified.

For these reasons, this study proposes a PLM system (which requirements are based on these occupants' behaviors) and then test it in a critical scenario for elderly safety. Historical buildings [33–35] represents an important location because they are generally characterized by high risk level (because of, e.g., wooden structures), complex layout (with usual difficulties in access by elderly), and contemporary use leading high occupants' densities (such as for cultural activities, e.g.: museums, theatres, concert halls). Related current fire safety regulations are mainly based on dimensional requirements (width, length) of evacuation paths and exits [36–38], but denote a schematic approach in relation to effective human behaviors at all [3], especially about the ones of disabled people and elderly [33]. Hence, these spaces are often unable to supply an adequate safety level to them. Finally, the increasing number of elderly (only for Italy, over the 20% [1] of over 65 usually frequent these spaces) who spends free time in related places suggest the pressing need to provide them a useful help in emergency. In particular, an Italian-style historical theatre is chosen for experiments about the designed PLM guidance system. We evaluate the system effectiveness in terms of evacuation time reduction by focusing on autonomous Elderly evacuation experiments. Our system could be used as a useful support for older adults evacuation in many emergency situations and buildings.

2 Materials and Methods

The work is organized in two phases according to the adopted "behavioral design" approach. The first one involves the definition of the wayfinding system by understanding human behaviors in evacuation and taking advantages of previous literature results. The second phase concerns experimental drills in an historical Italian-style theatre, in order to verify the effectiveness of the system in terms of evacuation speed and egress time.

2.1 Rules for Wayfinding System Definition on Behavioral Bases

The definition of an “efficient” passive wayfinding system is performed by take advantages of main results of previous studies on man-wayfinding systems and man-fire interactions [3, 6, 12]. In particular, limits of current systems and results of previous tests allows to define essential requirements (given the “correct” directional information in a “clear” and “unequivocal” way, especially for vulnerable individuals), in each environmental condition (normal, emergency lightning, smoke and blackout conditions). Regulations about technical requirements and materials characterization are considered [16, 17, 39], by mainly considering Italian regulations and guidelines are because of the application to an Italian case-study. Finally, proposing an easy-to-apply and easy-to-remove system would increase the wayfinding system attractiveness for particular scenarios, such as the historical ones.

2.2 Evacuation Drills

The Italian-style “Gentile da Fabriano” theatre (Fabriano, AN, Italy), built during the second half of the XIX century, was chosen as critical environment. It is a typical horseshoe-shaped theatre with 721 seats (4 tiers and a gallery), as shown by Fig. 1. It respects current Italian regulations about fire safety [38] and a punctual

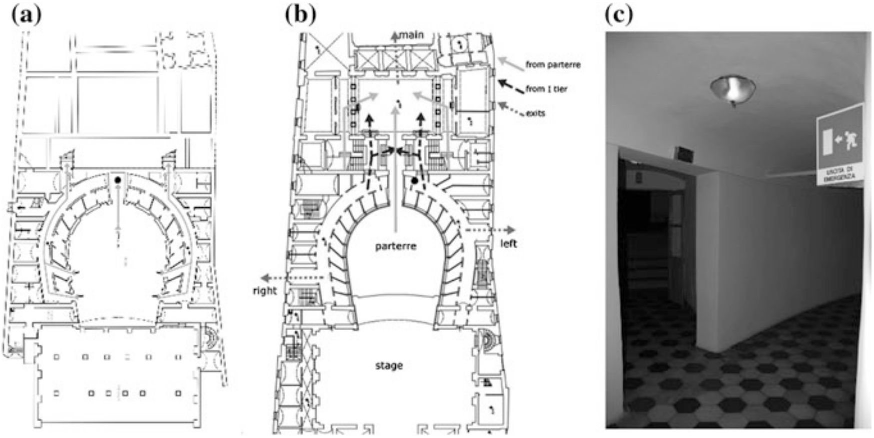

Fig. 1 Theatre layout and actual emergency wayfinding system: **a** the parterre plan with evacuation paths; **b** first order plan including main entrance hall spaces and view of the parterre, including evacuation exits identification; **c** a view of the current punctual wayfinding system placed in the theatre

PLM wayfinding signs system is actually placed in the theatre, as shown by Fig. 1. The existing traditional punctual is composed by standard directional signs (a person running and a triangle with tail) [16, 40], hung at the wall (minimum height from the floor: ≈200 cm) placed at directional intersections. However, it can be useless in case of fire because of smoke rising at the ceiling.

In order to evaluate the system effectiveness by mainly focusing on elderly, individual's and collective drills are performed. 97 individuals take part in experiments; about the 50% of the whole sample was composed by over 55 individuals, while over 65 where about the 20% of it (about the other individuals: 10–25 years-old = 15%; 26–40 years-old = 25%; 40–55 years-old = 10%). No people with motion impairments are involved in the tests. All people confirmed having normal or corrected-to-normal vision. All people confirmed to be unfamiliar with the architectural spaces (or rather, they had no previous experience of the theatre spaces, especially in emergency conditions). Two tests were performed.

2.2.1 Individual's Evacuation

16 individuals in the overall sample is randomly selected, by obtaining a sub-sample with the same age characteristics of the global one. One by one, each person is placed in a theatre box, then he/she is asked to evacuate the building by using the identified evacuation path in emergency (simulated black-out, smoke) conditions. No previous information about the path configuration is given to them. All individuals tested the two escape systems in a random order, so as to avoid errors due to the influences of order of tests. Hence, for 8 individuals, the first test involved the current punctual wayfinding system, and for others by our proposed system. Fixed cameras were placed along the path (at the box door, at directional changes in path configuration, at the emergency exit) in order to evaluate the evacuation time, according to previous studies [23]. Then, speeds were calculated as the ratio between the evacuation path length and the occurred evacuation time.

Average evacuation speeds were analyzed with a particular attention to older adults. In addition, a linear interpolation on experimental data is performed in order to define the tendency of speed against individual's age for each used system. Percentages differences between the two systems, about an evacuation motion quantity dy (e.g.: evacuation time [s], speed [m/s]), are offered according to the following Eq. 1:

$$dy = \frac{y_{trad} - y_{prop}}{y_{trad}} (\%) \tag{1}$$

where *trad* subscript refers to the traditional punctual system, while *prop* to the proposed one. Adopted approximations were 1 s for evacuation times and 0.1 m for path length estimation.

2.2.2 Collective Drill

The proposed evacuation wayfinding system was applied along path on the left part of theatre according to Fig. 1, while the current punctual one involves the right part of it.

The whole sample entered the theatre and occupies seated at the parterre and I tier. Individuals' positions were randomly choices by taking account a homogenous distribution for the two sides (by having similar positions in specular parts).[1] The test was performed during a show in order to reproduce real cases conditions as soon as possible. No previous information about evacuation paths was given to them. Emergency lighting started working, while the fire alarm rang and the voice alarm announced: "Please, the evacuation drill is started. Staff members are invited to activate safety procedures, while the audience is invited to not hurry and to exit the theatre by following the wayfinding systems". The evacuation drill ended when the last occupant exited the theatre. At the end, persons were asked to fill out a questionnaire including aspects on evacuation wayfinding system appreciation (the question is: "Did you find the system helpful in evacuation choices?"). According to Sect. 2.2.1, video cameras were placed at the starting point (one camera on the stage for the parterre; two cameras along the I tier corridor, one for each tier side), at each significant intermediate door and exit. Evacuation path choices, speeds and times were retrieved by videotapes analysis, with a particular attention to older adults, and percentage differences were calculated. The drill was useful in order to quantify both overall evacuation values and data concerning elderly evacuation.

3 Results

Results demonstrates the capabilities of a "behavioral approach" for elderly evacuation facilities.

3.1 Wayfinding System Definition on Behavioral Bases

The first man-environment interaction to be considered while defining this wayfinding system is connected to smoke interferences and signs visibility. Reflective signs could be not visible in case of poor environmental lightning, such as in case of smoke or black-out. Moreover, when PLM signs are placed near to the ceiling (as in current application), they could become useless in a fire, because of the possible rising smoke. On the contrary, PLM floor elements are always visible

[1] In particular, for the parterre, individuals' positions are shown by Fig. 4.

Table 1 PLM characterization according to current guidelines (ISO 16069:2004)

Tested element	Luminance (mcd/m^2) after 2 min	Luminance (mcd/m^2) after 10 min
directional signs	600	400
stripes	500	300

[3, 6, 12]. Hence, PLM are chosen and applied on the floor. Table 1 resumes the characterization of photopic luminance of components according to regulations procedures [17, 41]: luminance conditions are chosen by considering the ideal duration of each test ($\leq$ 10 min). The guidelines minimum value is 20 mcd/m^2 [41].

Wayfinding systems composed by continuous elements seem to increase the evacuation motion [42] and also seem to allow a better perception of architectural spaces where occupants are moving [12], especially when strips are placed at plano-altimetric variations of the path (stair-steps markers, wall corners, handles, doors). A similar requirement is especially needed by vulnerable individuals, including elderly, and when people are not familiar with the architectural spaces.

The dimension of directional elements should be suitable for both occupants' visual features and architectural spaces dimensions: in indoor conditions, a chevron (width: 5.0 cm) can be generally seen from an average distance of about 18 m [14]. Colors of signs should be green for the background and white for the directional symbol [14, 16], so as to guarantee a clearer directional indication. According to these behavioral analysis, shows the proposed continuous PLM wayfinding system, composed by: adhesive round tiles (diameter: 10.0 cm) with directional arrow (chevron with tail, width: 5.0 cm), with 70.0 cm between them, and placed on the floor, at the middle of the evacuation path; adhesive stripes (dimension: 2.5 cm 60.0 cm) placed at each stair-steps. This system is not yet used in buildings and so people, especially older adults, could be not familiar with related signs and information. For this reason, real world evacuation experiments are essential while assessing their effectiveness.

Finally, the system should have a low impact level on the building in terms of application (easy-to-apply and to-remove) and maintenance: hence, adhesive tiles and strips are chosen. In this way, the solution maintains not-invasive features in relation to the application scenario while is able to help people in a more efficient way in respect to current solutions. At the same time, in respect to "active" wayfinding solutions, it does not need any external supply (e.g.: electrical) and could be fully used by occupants also during power outage (Fig. 2).

3.2 Evacuation Drills Results

Individual's and collective drills demonstrates the efficiency of the wayfinding system in helping occupants' during the egress process.

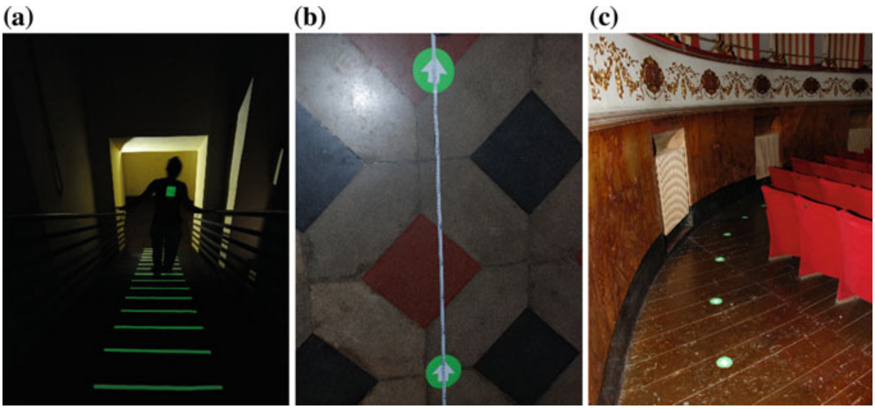

Fig. 2 The proposed system: **a** PLM adhesive strips along the stairs, guarantying the visibility in black-out conditions; **b** the *directional arrows* on the floor; **c** a view of the parterre by focusing on the *directional arrows*

3.2.1 Individual's Evacuation Results

In particular, an overall increasing of evacuation speed for single moving pedestrians is retrieved by individual's tests. In these conditions, people seem to be influenced only by the wayfinding system, because any additional interference due to surrounding individuals is introduced. Then, emergency environmental conditions being equal, percentage differences in motion speeds effectively demonstrate the effectiveness of our system in respect to the traditional punctual one.

While using the traditional wayfinding system, average speed in the sample is about 0.85 m/s with a standard deviation of 0.28 m/s. In particular way, average elderly speed is about 0.51 m/s. On the contrary, while using the proposed wayfinding system, average sample speed is about 0.98 m/s, with 0.28 m/s standard deviation. For elderly, average value is about 0.79 m/s. Our data confirm speeds found in literature by other experiments about PLM systems, by evidencing the same speed ranges (0.64–0.96 m/s) [26, 28].

> An increasing of evacuation speeds equal to +15% is obtained for the whole sample. These data demonstrate how the proposed system can effectively increase the individual's safety level in evacuation: the traditional system seems to introduce behavioral hesitation while moving along spaces, while the proposed one clearly address the correct motion direction and support people in spaces perception also in critical (e.g. smoke) conditions [3, 12]. A similar issue is really relevant for older people, who could generally suffer of these problems while autonomously moving. In fact, elderly evacuation speeds connected to the proposed continuous system grow of about +54%.

Finally, Fig. 3 resumes these evacuation tests results by offering their interpolation (individual's age versus motion speed). Linear regressions show an $R^2 > 0.7$ and then seem to demonstrate a valuable data fitting. Figure 3 also shows

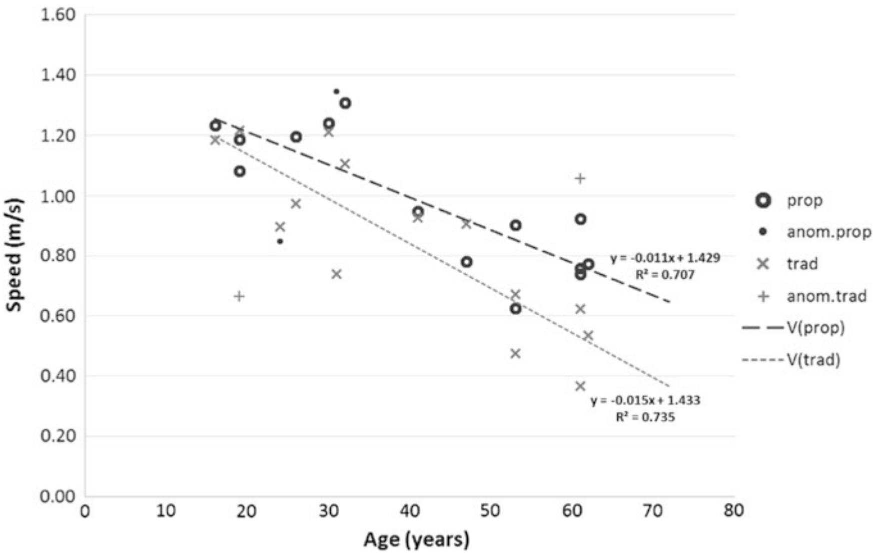

Fig. 3 Individuals' age versus evacuation speed: *prop* refers to the proposed system, while *trad* to the punctual traditional one. Anomalous data are also evidenced (*anom*) and tendency lines (*V*) are shown

the linear regression equations: they could be useful in order to quickly estimate building egress times for single pedestrians.

3.2.2 Collective Drill Results

Collective drills are able to evidence if individuals in "perturbed" conditions (including additional man-man interactions) can correctly perceive the wayfinding system and are able to take advantages of its directional information.

Table 2 resumes an overview of the drill results. In particular, evacuation times for the two samples (using the traditional and the proposed system) demonstrates how the proposed system is able to hasten the egress process (about −26% for the maximum egress time). Reasons are essentially due to the increased use of secondary paths, as also graphically shown by Fig. 4. People using the traditional system generally moves towards the main exit (because of herding behaviors and memory effects [43]). On the contrary, individuals using our proposed system (left theatre side) trust in using secondary path addressed by the continuous PLM signs. They are visible and their information is clearly perceived by occupants, as demonstrated by percentages to related questionnaires answers in Table 2. Thanking to secondary path use, people (and especially elderly), take advantages of avoiding overcrowding conditions along the theatre corridors and could increase their speed of about +30% (+26% for over 65 individuals).

Table 2 Collective drill results distinguished by the used system, and including egress maximum time, evacuation speeds and questionnaire answer about perceived effectiveness of wayfinding systems

Quantity	Traditional	Proposed	Percentage difference (%)
Maximum egress time [s]	167	122	−25
Average egress time [s]			
Overall sample	91	68	−26
Over 65	107	81	−24
Average speed [m/s]			
Overall sample	0.28	0.37	+30
Over 65	0.28	0.35	+25
Signs were useful for path identification [%]			
Overall sample	31	87	+180
Over 65	12	65	+440

Data for elderly are evidenced

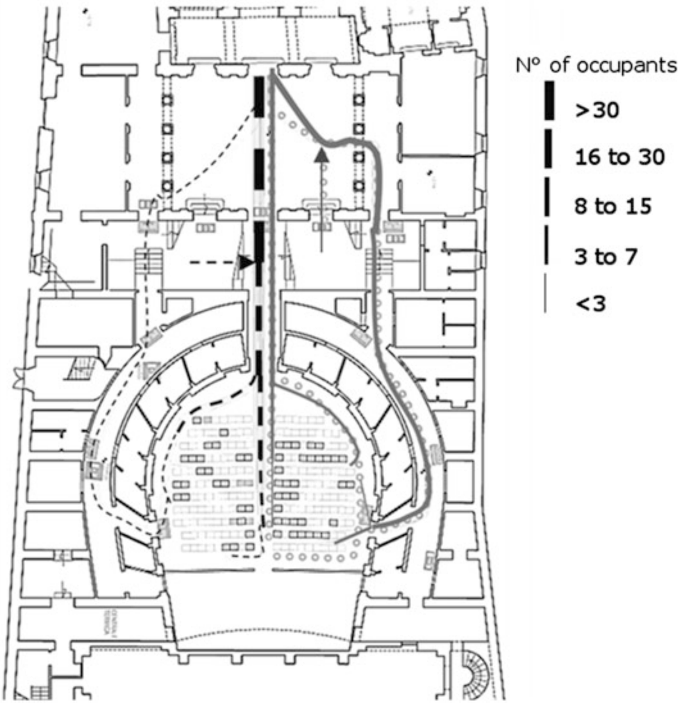

Fig. 4 Individuals' evacuation path during the drill: *dashed lines* refer to the traditional system, while continuous to the proposed one. *Lines thickness* expresses the number of people using the path

4 Conclusion

In case of fire evacuation, people carry out wayfinding activities in order to egress the building. Wayfinding actions are fundamental for individuals who can autonomously reach the building exits. A correct identification of proper evacuation path is able to diminish overall time and so to prevent hazardous conditions to occupants (e.g.: prolonged exposure to toxic smokes; structural failures). This is really relevant in case of vulnerable people, such as elderly. A possible solution is the introduction of efficient wayfinding systems, especially when occupants are not familiar with architectural spaces.

Historical buildings surely represent one of the riskiest environment for elderly, because of the buildings features, their layout, high occupants' density, level of familiarity of people with the spaces. In these scenarios, wayfinding systems should guarantee: a low impact on the original building; an high level of effectiveness on human evacuation behaviors; a clear perception of motion paths; a successful help to all people categories, in all the possible environmental conditions. This study proposes a robust wayfinding system by taking advantages of a "behavioral design" approach: understanding individuals' needs; developing solution to accomplish their requests; testing the solutions by validations activities; defining rules for describing human interactions with the proposed solution, so as to also develop models for their simulation.

The proposed system is based on continuous (placed close to each other along the path) photoluminescent (PLM) signs, because they could give an efficient support to evacuating pedestrians also in low visibility conditions (black-out, smoke presence). The proposed system is also easy-to-apply and remove because composed by adhesive elements. An Italian-style historical theatre is chosen as a representative case study within historical buildings in order to verify the proposed system effectiveness in respect to current punctual exit signs. Results show how evacuation speeds significantly increase in both individuals' and collective drills (up to +50% for over 65) while occupants are guided by the proposed system. Advantages are essentially due to the clear path and spaces identification given by the short distances between two consecutive signs. The same results descend from both motion quantities evaluation and analyses on questionnaires to attendees. Study outcomes suggest how wayfinding systems on existing building should involves a smaller distance between signs in order to help occupants during the evacuation (especially autonomous older ones).

Moreover, relations about evacuation speeds and individuals' age are traced by using experimental values, depending on the tested wayfinding system (traditional or proposed ones). However, further studies should extend the results validity, especially for silver age individuals. At the same time, some possible adaptation of similar systems (in terms of technological requirements and operative definition) could be proposed by adopting requirement analysis coming from some interview with older people. Final outcomes would be useful in defining models for man-environment interactions in emergency conditions, by including specific aspects such as the ones connected to elderly characterization.

The proposed system can be easily introduced in historical building in order to decrease the total evacuation time, and so to increase of the occupants' safety level. At the same time, this system could be extended to all other building characterized by autonomously elderly presence and need of low-impact and reversible interventions. In fact, it does need no supply or physical building modifications for the application.

Future researches should investigate the systems optimization by a deeper analysing the human perception of the wayfinding elements, in order to minimize the signs number. Innovative techniques that directly measure typical individual's quantities about perceptual attention in reference to the signs (e.g.: brain activities, pupils motion) should be employed.

Finally, this study underlines the capabilities of the "behavioural design" approach for elderly safety in critical environment. In this case, we focus the definition on low-impact and passive wayfinding technologies, but they could be enhanced by combining signs systems and sensors-based technologies (both about occupants' behaviours and building response to fire).

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