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Can active and passive wayfinding systems support fire evacuation in buildings? Insights from a virtual reality-based experiment

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ABSTRACT

Occupant safety in case of building fires depends on the selection of proper evacuation routes. Today, several passive and active Emergency Wayfinding Systems (EWSs) have been proposed to support occupant route choices. Nevertheless, their effectiveness should be accurately assessed before being manufactured and used. In this sense, Virtual Reality (VR) could support the design and preliminary evaluation phases, using the Theory of Affordances to quantitatively verify if the EWSs are correctly visible, understood, and able to support users in fulfilling the evacuation goal. This work hence aims at comparing the efficiency of different EWSs in terms of the Theory of Affordances through a VR experiment involving more than 70 volunteers of different ages. The experimental setup focuses on three types of EWSs (punctual and photoluminescent; passive, continuous and photoluminescent; continuous and active) and lights-on, lights-off and smoke conditions in an educational building. Results mainly indicate that the passive EWSs receive a higher rating while supporting the direction selection, while the active EWS is more effective along mono-directional paths. The work also confirms the capabilities of the proposed combined affordances-based and VR-based approach, boosting future works and suggesting additional comparisons between real-world and VR experiments on emergency wayfinding tasks and systems.

1. Introduction

Wayfinding is an essential task in case of building fires, since it allows occupants to move towards proper evacuation routes and to successfully leave the fire-affected scenario [1–4]. In fact, previous accidents showed that a non-efficient use of routes could lead to losses in human lives [5–7]. In public buildings, poor individuals' familiarity with the architectural layout and low level of occupants' safety training can reduce the possibility of selecting the most appropriate route and so create congestion on main exits [4,8–12]. This phenomenon was theorised by Sime in the ‘80, and it is known as affiliative theory [13]. This has been observed in real emergencies, evacuation drills and laboratory experiments over the last decades [1,5,14–16]. Further social interactions could lead occupants to follow each other along the same paths by provoking overcrowding, required egress time increase, or even the use of unsafe routes [1,14,17,18].

As such, it is fundamental that a new generation of codes and building design move toward more performing Evacuation Wayfinding Systems (EWSs), providing evacuees with clear instructions on where to go during an emergency [19–25]. Nevertheless, they should be designed according to a “behavioural design” approach [19], that is, by considering the effective occupant-signage interactions and by configuring EWSs on the occupant needs during the evacuation according to experimental results [26,27]. Comparing

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and raking the efficacy of EWSs according to this “behavioural design” approach are useful tasks to select the best strategies, and Virtual Reality (VR) tests could efficiently support these actions since they allow to implement of different scenarios conditions in a quick and sustainable manner, and also to work as training tools for the participants [24,28–31].

This work aims at investigating the Theory of Affordances to compare the efficacy of different types of EWS using VR experiments. In particular, the Theory of Affordances is innovatively used for efficiency comparison since it can take into account the main behavioural issues in occupant-EWS interactions in wayfinding tasks [23,32]. The proposed experiment involved both passive and active EWSs, to mainly compare the main current solutions adopted in common fire safety regulations, e.g. see Refs. [33,34], and innovative, intelligent building components that are not yet recognised by most of the building regulations [24,35]. Different scenario conditions (i.e., lights-on, lights-off, smokes) were considered. These systems were applied to a part of a public building, i.e., a university building in Italy, focusing on a simple but effective building layout configuration to compare the EWSs. Furthermore, motion sickness issues were also analysed to fully evaluate the experimental protocols.

2. Related works

2.1. Evacuation Wayfinding Systems (EWSs)

According to national and international regulations such as ISO 16069:2017, NFPA 101, UNI EN ISO 7010:2012, BS 5499 Series, and International Building Code (IBC),[1] [36], EWSs should be composed of easily identifiable signs visible from different locations within each neighbouring area and route, to provide occupants with the range of available evacuation paths beyond the familiar ones. Moreover, EWSs can also be combined with staff members' support.

The distance between signs, the typology, the location and the position along the evacuation route is defined according to occupant typologies and visual capabilities, and high-contrast colours should be preferred [19,37–39]. In such a way, autonomous occupant motion could be supported by these systems by allowing rescuers and safety staff to help disabled and/or injured people. Symbols to be used for EWS signs have also been widely addressed [39,40].

In view of the above, EWSs can be mainly distinguished in terms of:

- Location: high-level (generally placed above the door level) and low-level (are located on the lower part of walls, e.g. within 455 mm of the floor according to NFPA 101, or on the floor). In particular, low-level signs reduce possible interferences with smoke [19,38,40–42];
- Illumination: internal (including electrically-powered, self-luminous and photoluminescent ones) and external (such as reflective ones). In particular, EWSs equipped with internal illumination can avoid disruptions while following a path [21,38,41,43–45];
- Distance between the signs: punctual (mainly placed at intersections, exits, additional route variations and depending on the sign listed viewing distance) and continuous (at least one directional sign per 5 m of a route). In particular, continuous EWSs could be more effective since they allow a constant spatial description of the evacuation path [19,38,42].

Moreover, according to their functioning, they could also be distinguished between passive and active or, rather, dynamic and variable) EWSs [21,22,25,27,37,43,45–47]. In passive EWSs, the displayed directional information does not change over time. In active EWSs (, real-time change in direction information is possible depending on data collected about the building status, the fire spreading and the evacuation process. Some commercial systems have also been developed.[2] Finally, some efforts have also been devoted to developing real-time solutions using Augmented Reality (AR), so as to support each occupant via personal devices [25].

2.2. Virtual Reality (VR) for EWSs testing

According to the “behavioural design” approach [19], EWSs should be well perceived, understood and used by evacuees, and experiments in real-world or VR scenarios are useful to support the comparison of EWSs' efficacy and the design of new solutions. The assessment of the ecological validity of VR studies for evacuation is an open topic in the scientific literature, as highlighted in many recent works [48,49].

Nevertheless, besides real-world and full-scale experiments [21,22,43], previous studies have illustrated how immersive and non-immersive VR presents a valuable solution [1,24,26,28,30,31,44,46,50]. Previous validation studies have shown that VR setups involving a Head-Mounted Display (HMD) seem to reliably reproduce the data obtained in a physical environment [28,51,52]. In detail, such experiments are shown validity in the data collected using this type of setup while investigating exit and route choices and pre-evacuation behaviours. Although such results seem to encourage the use of immersive VR for comparing EWSs effectiveness, only a limited number of studies deeply investigated wayfinding tasks depending on different EWSs systems [24,44]. In this sense, this work would like to move towards such activities, focusing on public buildings in view of the general issues discussed in Section 1 and Section 2.1.

VR techniques, and in particular immersive ones such as those of HMD-based solutions, also allow monitoring of additional parameters during the test [53,54], combining the possibility to define different scenarios to the limitation of additional negative effects of real-world applications (e.g. biases due to users' movement or environmental conditions).

[1] https://codes.iccsafe.org/content/IBC2018P6/chapter-10-means-of-egress#IBC2018P6_Ch10_Sec1013 (last access: 01/03/2023).

[2] e.g. https://www.eaton.com/gb/en-gb/markets/buildings/how-we-drive-building-efficiency-and-safety/safe-evacuation/adaptive-evacuation.html; https://www.evaclite.com/(last access: 29/08/2022).

Nevertheless, some limitations exist depending on the adopted VR environment. It is worthy of notice that navigation issues in VR could affect microscopic issues in the motion, such as trajectories [55], and the possibility of suffering from motion sickness [56–58]. In particular, motion sickness used to be associated with low frame rates in earlier versions of VR applications when graphic cards generated several limitations for VR experiences. Nevertheless, VR sickness seems to rarely affect the experimental results, while specific procedures could be adopted to limit their arising [1]. Today, sickness is mainly linked to the type of navigation used in the VR experience [57,59].

2.3. Behavioural approaches for EWSs testing: the Theory of Affordances

Results from VR tests can then be analysed according to the Theory of Affordances, which argues that the individual perception of a given object in the built environment depends on "what it offers or affords the individual" [23]. Thus, object Affordance depends on the support the object can give to individuals to achieve their goals.

Four Affordances categories [23,32,37,60] can be identified as follows and used to assess the EWSs efficacy:

- *Sensory Affordance* relates to "sensing or seeing". In respect of an EWS, it evaluates if and how the individual can effectively see the EWS;
- *Cognitive Affordance* relates to "understanding". In respect of an EWS, it evaluates if and how the individual can effectively understand the evacuation direction displayed by signs;
- *Functional Affordance* relates to the "fulfilment of the individual goal". In respect of an EWS, it evaluates if the EWS fulfils the proper exit choice selection, thus becoming the main affordance for the EWSs effectiveness comparisons;
- *Physical Affordance* relates to "physically doing or using something". This affordance is not pertinent to the purposes of the EWS assessment since the EWS does not imply physical use during the evacuation.

This theory has been used so far in several physical and virtual experiments only to assess tunnel and underground evacuation systems [23,32], and in a study assessing dissuasive exit signs [37]. This research uses the Theory of Affordances for evaluating different EWS strategies by also using VR environments. However, to the best of our knowledge, previous studies did not investigate how this theory can also be applied to assess and compare EWSs. As such, this work represents one of the first in its kind as it applies this theory to compare different EWSs using an immersive virtual reality experiment. Finally, previous studies were also limited by two additional issues. On one side, many existing studies (as the ones illustrated in Section 2.2 and above about the application of the Theory of Affordance in a wider way) mainly used students as participants for VR experiments, and so possible scalability of results could be argued. On the other side, people were asked to assess the Functional Affordance by asking people to answer a Likert-scale question. In this work, we measure this affordance by observing the behaviour of the different typologies of participants (i.e. by age) using a binary variable to assess if the participants used the information provided by the EWSs correctly or not.

3. Research methodology

This work aims at comparing different active and passive Evacuation Wayfinding Systems (EWSs) using immersive VR experiments and the Theory of Affordance. Fig. 1 resumes the workflow of this research to reach this goal and the correlation with the related sections in which each phase is described.

In the first phase, the virtual experimental scene and the experimental design have been defined by identifying the EWSs to test, the scenario conditions (in terms of illumination and smoke conditions) and the building layout (Section 3.1). In the second phase, experiments were carried out by involving volunteers (Section 3.2). Tests are performed according to the selected experimental procedure and by using an immersive VR apparatus (Section 3.3). Finally, in the third phase, experimental results were analysed to evaluate the EWSs' effectiveness according to the Theory of Affordances, as well as to preliminary analyse the influence of specific volunteers' and testing conditions on the experimental results (Section 3.4).

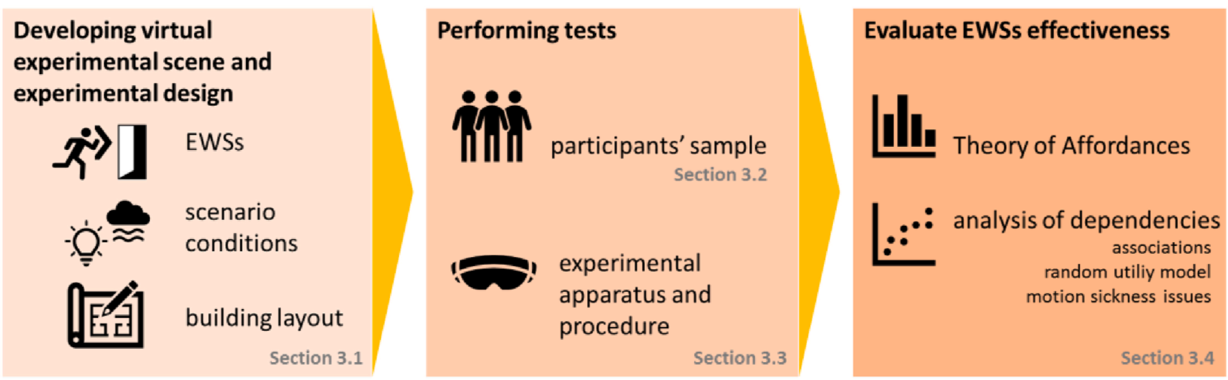


Fig. 1. Workflow of the research, including main references to the following methodological sections.

3.1. Virtual experimental scene and experimental design: EWSs, scenario conditions and building layout

Table 1 shows the main features of the three EWSs tested in this study, corresponding to different levels of support to evacuees during wayfinding tasks, including the rationale behind their selection (and the related references), a view of the EWSs implementation in the VR environment and the assumed testing conditions.

EWSs 0, 1 and 2 are passive EWSs using photoluminescent materials based on previous works [61–63]. EWS0 is characterised by a punctual layout of signs, corresponding to minimum support level as in common fire safety regulations and common implementation in real-world environments, e.g. see Refs. [33,34]. On the contrary, EWSs 1 and 2 are characterised by a continuous layout of signs corresponding to continuous support in the path identification and that were previously included in fire safety guidelines and market proposals [42,64,65]. EWSs 0, 1 and 2 are characterised by the same RGB colour coordinates: [0, 132, 58] for the sign green background; [190, 210, 190] for photoluminescent elements.

EWS3 is a continuous and active EWS, and it has been developed by Ref. [43]. The directional information is composed of electrically-illuminated signs (based on strip LED), which are green arrows placed along the corridors and strips portal placed at the doors (red for the unavailable exit, green for the available exit). When a path is considered as unavailable, the directional information displayed by the system changes. EWS 3 has already been tested in a full-scale experiment, demonstrating the positive impact of the system on occupant wayfinding support [43].

Different lighting and smoke conditions were tested to compare extreme EWSs visibility conditions [38]: best for lights-on; worst for lights-off and smokes. EWS0 was tested in both visibility conditions as a common reference system implemented in real-world scenarios. EWS1 and EWS2 were tested in light-off and smoke conditions to focus on their capability to spatially describe the built environment in critical visibility conditions [42,61,65]. EWS3 was tested in both light-off and smoke conditions in view of the novelty of the system and its potential significant illuminance level also in lights-on the scene [43,63].

The geometry layout for the virtual building is a part of the spaces of the DICEA department in the buildings of the Università Politecnica delle Marche in Ancona, Italy (Fig. 2). The 3D digital environment was built by using Revit 2019 and Unity 2019.1, using a 1:1 scale representation of the space. An overall Unity view of the virtual environment is illustrated in Fig. 2-B. Fig. 3 shows some views of the tested scenarios and how the EWSs were blended in the virtual building.

All the tested scenarios had the same starting position (red “start” label in Fig. 2-A), and the participants concluded the experiment when they reached one of the two exits (green “exit” labels in Fig. 2-A). This geometry was selected because it allows testing the affordance-based assessment:

- in a common scenario composed of a mono-directional L-shaped corridor to make people confident with EWSs);
- in a T-shaped intersection, to include a decision point where volunteers can decide the evacuation direction depending on EWS directional information.

From the starting point, the overall routes shown in Fig. 2-A are about 33 m long for the left exit and about 28 m long for the right exit. In the real-world environment, there is only one direction arrow because there is only one evacuation route for the considered area (the right exit in Fig. 2-A). In the experiments, we replicated this condition by simply varying the direction of the directional arrows of the EWSs, but only a safe exit has been still identified. Indeed, the “wrong” exit position was changed between the different tests so as to limit the memory effects by participants. Fig. 2-C shows the correct evacuation paths for each EWSs. Passive EWSs did not change during the experiment time. On the contrary, EWS3 was changed during the test to determine if the participants reacted to the addressed route variation. EWS3 initially pointed towards the left exit, and then the displayed direction automatically changed towards the right exit when the individual was 8 m–9 m distant from the left exit (within the yellow area schematised in Fig. 2-C for EWS3). This length has been chosen just for the immersive VR-based EWS comparison purposes, to be comparable with the length of the final corridor reaching the exit (compare with Fig. 2). As a consequence, the experiment considers that EWS3 changes its direction when the participant is still moving near the corridor's intersection.

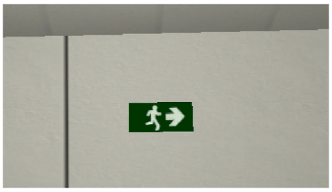
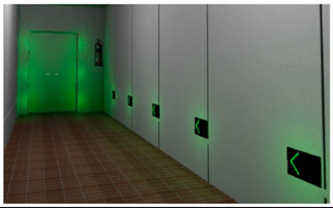
Smoke and visibility conditions in the VR environment considered in Table 1 were simulated by using particle systems from the Procedural Fire Package[3] and the native lighting setting in Unity. The visibility distance of opaque objects was calibrated by modifying the *ambient colour* and *intensity multiplier* of the Unity scene, while the particle system supported the creation of a sense of dynamic smoke in the scene. Furthermore, a virtual fire was replicated in the VR environment beside the “wrong” exit (thus not visible from the corridors) to make people aware of their “wrong” evacuation exit selection. According to the “wrong” exit randomisation defined above, Fig. 2-B just shows an example view of a tested scenario where the “wrong” exit is the left one, and thus the fire is replicated beside it. The controller of movement in the VR environment was enabled by touchpads, allowing participants to move forward in the direction they were looking at. Colliders were used in Unity to avoid participants could navigate through walls. Videotapes examples for passive and active EWSs are available in the video materials attached to this manuscript (see supplementary data).

3.2. Participants

The participants in VR experiments were composed of 71 volunteers (35 females and 36 males) who had no previous experience with the architectural layout of the building virtually reproduced. According to other works methods [1], they were required to have no visual impairments, no wrist/hand injuries and no heart-related illness. According to other similar studies also performed by our research group and involving VR tests at the Università Politecnica delle Marche - DICEA department [43,63], the ethical issues included the necessity to properly and fully inform volunteers about the experiment procedures and the analysed data. No sensitive in-

[3] https://assetstore.unity.com/packages/vfx/particles/fire-explosions/procedural-fire-141496 (last access: 22/02/2022).

Table 1
Description of main factors characterising the evacuation wayfinding signage systems tested in this work and related scenario application conditions in the architectural layout.

EWS CODE	Characterisation and positions of the elements (Reference)	Reference view	Testing condition(s): SCENARIO CODE(s)
0	Passive punctual photoluminescent evacuation signs with a directional arrow and running man (dimension: 350 × 150mm), placed at directional changes or maximum distances of 10 m, and hung on the wall at 2.10 m from the floor [34,61,66].		0A: lights-on; 0B: lights-off with smoke
1	Passive low-located (height from the floor: 40 cm) continuous photoluminescent evacuation signs composed of direction arrows (5 elements per meter; height: 5 cm) plus directional arrow and running man (dimension: 240 × 100mm) placed at directional changes or at a maximum distance of 5 m [61,65]		lights-off with smoke
2	Passive low-located (height from the floor: 40 cm) continuous photoluminescent evacuation signs composed of guidance line (height: 5 cm) plus directional arrow and running man (dimension: 240 × 100mm) placed at directional changes or at a maximum distance of 5 m [61,65]		lights-off with smoke
3	Active low-located (height from the floor: 40 cm) continuous evacuation system composed of electrically illuminated led (RGB LED strips, Lm/LED: 12, Lm/m:800, 60 LED/m) signs (distance between consecutive elements: 150 cm; dimension: 300 × 170mm) which can change the displayed direction (by a green colour arrow on black background) plus LED strip with red (exit unavailable) or green (exit available) status [43]		3A: lights-on; 3B: lights-off with smoke

formation was collected, and all the data were anonymised. According to national regulations and university rules, all the participants (or, in the case of minors, their parents or guardian) signed a waiver before the tests giving consent to the research group.

Fig. 4 shows the age distribution of the sample, which is close to the Italian National Statistics [67] within the range 11–66 years. 77% of the participants had previous experience with evacuation drills, but only 4% had experienced immersive VR applications before.

Each participant went through 3 tests having different EWSs shown in Table 1: one test with the passive, punctual and photoluminescent layout; one test with one of the two passive, continuous and photoluminescent layouts; and one test with the active, continuous and active layout. The criteria used to assign participants to each EWS scenario were defined to ensure similar samples and limit "learning" effects for the whole testing sample [19]. In particular, we ensured a minimum of 35 volunteers for each EWS by recreating similar age conditions with respect to the original sample and maintaining the percentage of female participants in a range from about 45% to 55% (average of about 49% as in the whole sample). Nevertheless, the order of the EWSs scenario for each participant has been randomised to introduce stochastic effects, and the effects of randomisation was studied according to Section 3.4.2 methods.

3.3. Experimental apparatus and procedure

In view of the capabilities of HDM VR tests [1,28], the hardware used for VR experiments was through the HTC Corporation VIVE PRO Eye (1440 × 1600 resolution image per eye), as shown in Fig. 5, using SteamVR plugin.[4] Before wearing the HMD, the distance between the lenses of the headset was adjusted, depending on the interpupillary distance of the volunteer (measured using a ruler), so as to improve the sharpness of images.

Each volunteer was involved in a preliminary training activity using a separate VR scenario to test how to move in the VR space by using the locomotion system. After the training, the participants who experienced no motion sickness were placed at the starting point of the test (Fig. 2-A), waiting in a fictitious room. No information about the EWSs and the architectural layout was provided to

[4] The plugin can be retrieved at https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647 (last access: 29/08/2022).

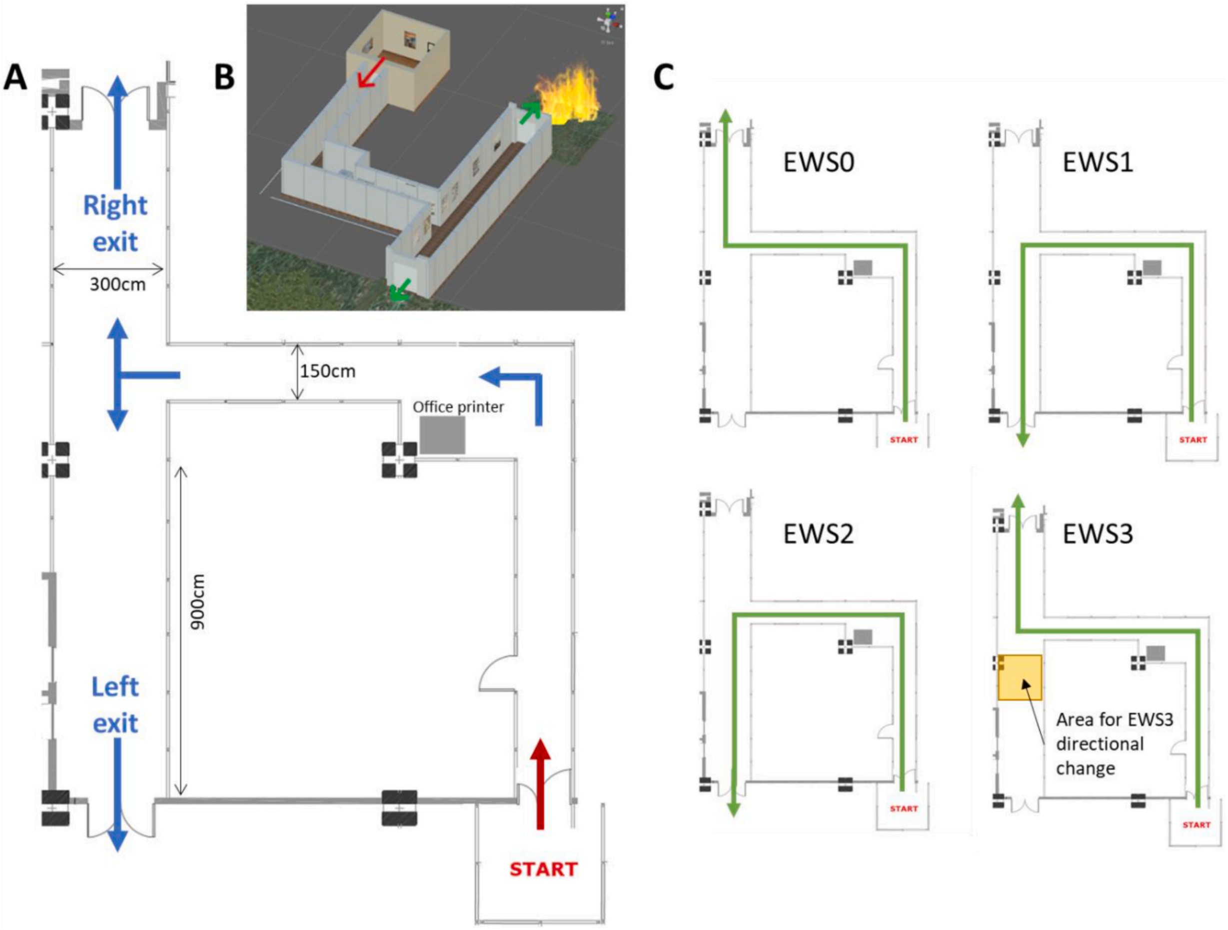


Fig. 2. The overall architectural layout plan reproduced in VR by pointing out the start and possible endpoints (exits) for the experiments (A). An example of a Unity 3D view from the right exit is shown, considering that, in this case, the correct exit is the right one, while the fire on the left exit is reproduced as the "wrong" exit (B).Specific "wrong" (in red) and "correct" (in green) exits are also identified in each tested EWS scenario (C). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

participants before the test. After the evacuation alarm rang,[5] they were asked to enter the corridor of Fig. 2 and to move towards the exit by using the implemented EWS. The evacuation ended when the participant reached one of the exits in Fig. 2-A. The volunteer's VR trajectories were also recorded during each test to evaluate the presence of specific exit choice behaviours at the T-intersection point, i.e. in view of EWS3 direction change. Once the participant completed each scenario, they were asked Affordance-based questions based on the concepts of Section 2.3 (see Section 3.4.2).

As long as each volunteer was involved in more than 1 test, he/she was given a 1-min break between two consecutive experiments, while the overall test duration was limited to less than 15 min to avoid heavy motion sickness effects according to literature procedures [58].

At the end of the whole VR experience, the participants were asked to fill out a survey form, including if they experienced motion sickness (by mainly distinguishing between nausea, oculomotor and disorientation issues) during the test [56,58], and a free-form interview was performed on the experience and EWSs.

3.4. Criteria for EWSs evaluation

EWSs are first evaluated by using the criteria given by the Theory of Affordances (Section 3.4.1). Then, an analysis of dependencies between experimental data has also been performed to evaluate if specific conditions concerning the volunteers and the experimental procedure could affect the result (Section 3.4.2).

3.4.1. EWSs evaluation according to the Theory of Affordances

Affordances were assessed by:

[5] The alarm continued ringing during the whole experiment.

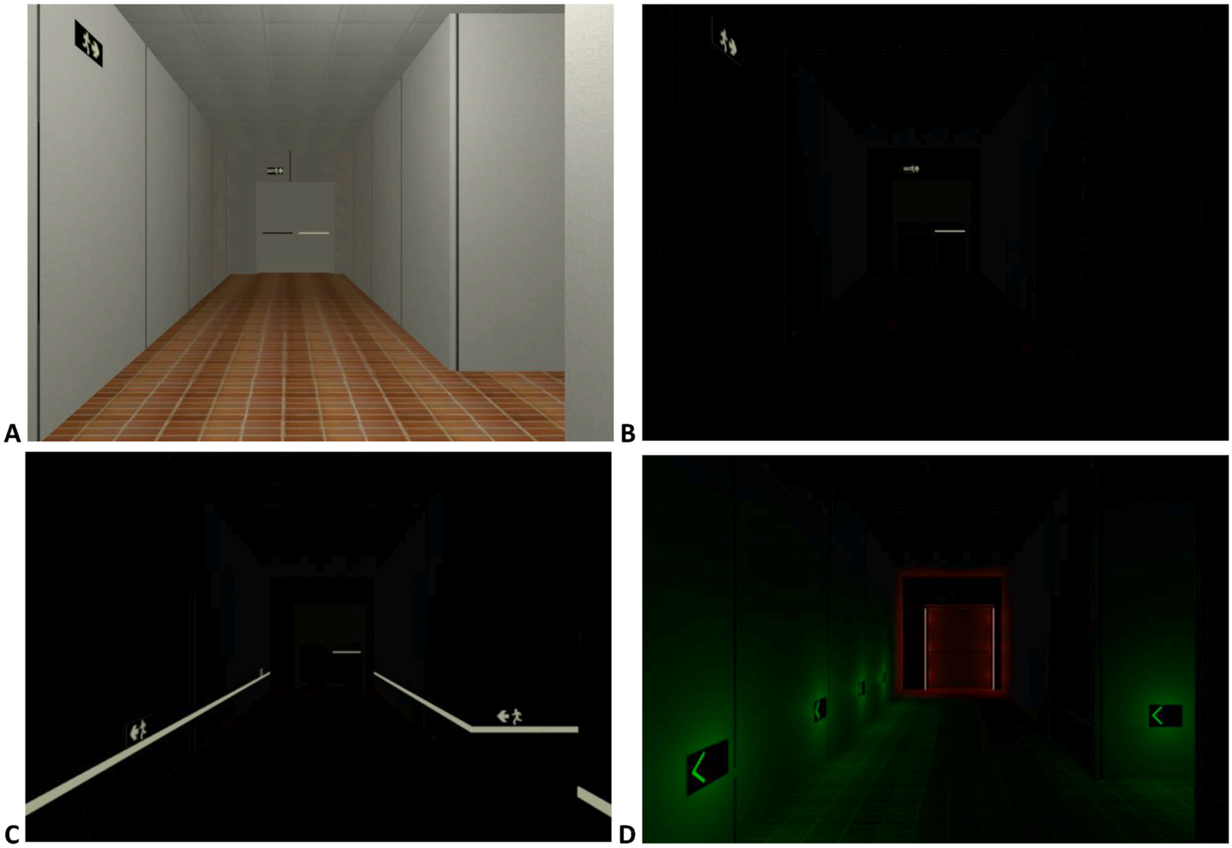


Fig. 3. Example VR views of the simulated scenario (the view of the corridor from the left exit towards the right exit as in the scheme of Fig. 2) for: A-test 0A; B-test 0B; C-test 2; D-test 3B.

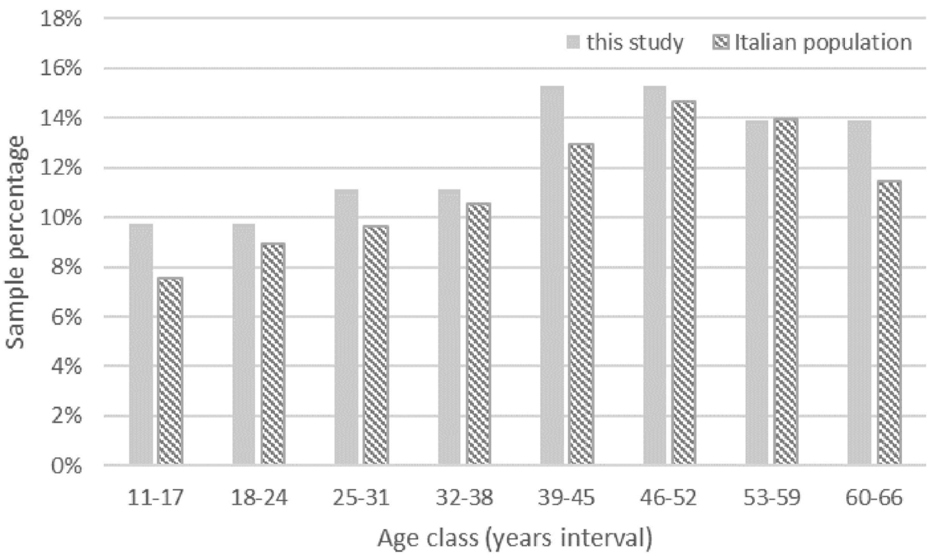


Fig. 4. Age distribution by comparing this study sample and Italian statistics.

A. Asking each volunteer to answer "Was the sign clearly visible?" using a Likert scale 1 (not visible) to 5 (immediately/completely visible), for the Sensory Affordance;
B. Asking each volunteer to answer "Was the directional information reported by the sign easy to be understood?" using a Likert scale 1 (not visible) to 5 (immediately/completely understandable), for the Cognitive Affordance;
C. Assessing the final selection of the correct (1) or wrong (0) exit by each volunteer for Functional Affordance.

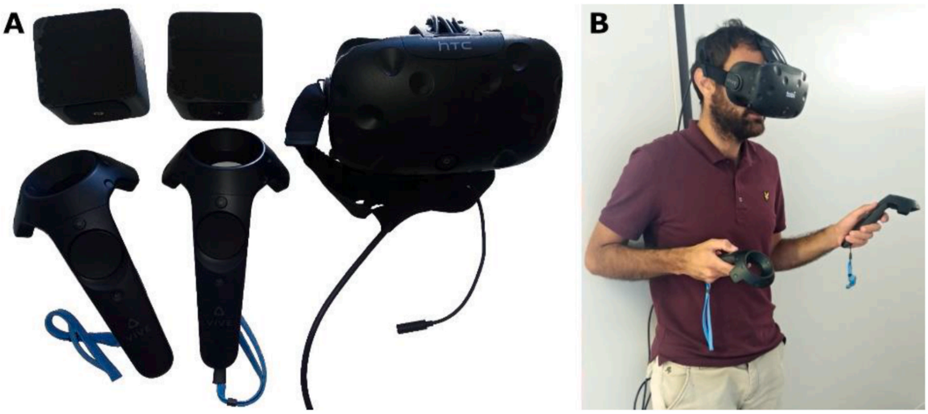


Fig. 5. VIVE PRO Eye headset components (A) and worn by a participant (B).

The approach of point C ensured to point out the existence of differences between Sensory/Cognitive Affordances and Functional Affordance, in terms of the final achieved goal (select or not the “safe” exit), limiting the individual opinion on the system. The number of wrong evacuation choices within the sample was pointed out, thus becoming the main affordance for the EWSs effectiveness comparisons [23,37]. The functional affordance is also scaled up to 5 (100%), thus being comparable with sensory and cognitive affordances. Mean Affordances have been calculated along with their standard deviation for Sensory and Cognitive Affordances as a result of the assessment process.

Furthermore, Functional Affordance values along the initial mono-directional L-shaped path (from the test start point to the decision point, as in Fig. 2) were assessed to verify if the volunteers were confident with the base configuration of the systems. In particular, in this part of the path, EWS3 directional information did not change over time. Then, Functional Affordance values along the path placed from the decision point to the exit were assessed to verify the volunteers' response to the displayed directional information and, in particular, to EWS3 directional information change.

3.4.2. Analysis of dependencies between experimental data

Association tests [68] were performed to trace dependencies between data collected in this experiment. Such data concern:

- the volunteer's features, considered as input conditions for the tests, and classified as continuous (i.e. age), ordinal (i.e. the order of the tests, which were ordered from 1 to 3 to trace a level of familiarity with the VR environment) and nominal (i.e. gender, experiencing motion sickness effects);
- results from VR experiment, considered as outputs of the tests and classified as ordinal (i.e. sensory and cognitive affordance) and nominal (i.e. functional affordance, in a binary scale).

The following tests [68] were performed between X and Y variables in pairs shown in Table 2: (1) for Continuous-ordinal, the Spearman's test; (2) for Continuous-nominal and Ordinal-nominal, the Pearson's test, since the nominal classes included two levels; and (3) for Nominal-nominal, the two-by-two contingency table applying Fisher's Exact test in view of the limited dataset dimension. Such association results are used to highlight if some input conditions could define specific trends in output data and if the specific affordances could be dependent or not. In particular, the associations between the order of the test and affordances have been provided to verify if “learning” and “memory” effects affected or not the VR experiment results.

Additional analysis has been performed to understand how Sensory and Cognitive Affordances can affect Functional Affordance and to identify why an evacuation signal is working or not. Random utility models have been used by previous works to investigate the impact of Sensory and Cognitive Affordances on Functional Affordance [69], showing that there is a statistically significant influ-

Table 2
Association tests: “all” means that the test was performed for each EWS; “between tested EWS” means that the test was performed considering the specific EWSs tested by the individual. In columns and rows, Continuous (C), Ordinal (O) and Nominal (N) variables have been identified.

X:	Y: VR experiment results		
	Sensory (O)	Cognitive (O)	Functional (N)
Sample characterisation			
Age (C)	all	all	only on EWS3
Gender (N)	all	all	only on EWS3
Order of the test (O)	all	all	only on EWS3
Motion sickness (N)	all	all	only on EWS3
VR experiment results			
Sensory (O)	between tested EWSs	between tested EWSs	only on EWS3
Cognitive (O)	between tested EWSs	between tested EWSs	only on EWS3

ence of both affordances. Thus, the Sensory and Cognitive Affordances are the independent variables, while the binary variable measuring the Functional Affordance is the dependent variable. The data collected in this research can help identify if these findings are consistent by estimating a new random utility model and confirming if Sensory and Cognitive Affordances have a great impact on Functional Affordance.

Finally, the percentage of individuals experiencing motion sickness effects was assessed by also taking into account gender and age issues to compare results with previous works outcomes [58]. Such kind of analysis has been devoted to understanding if the experimental procedure could mitigate literature-based impacts of motion sickness on the volunteers. The specific issues in affordance due to motion sickness were also investigated, as also pointed out by the association tests described in Table 2. Matlab R2016b was used to perform all the statistical analyses (https://it.mathworks.com/help/doc-archives.html; last access: 20/12/2020).

4. Results

This section provides the results of the experiments. The results focusing on the Affordances are proposed in Section 4.1, according to the methods shown in Section 3.4.1. Concerning the analysis of dependencies between the experimental data according to the methods discussed in Section 3.4.2, Section 4.2 shows the association results, while Section 4.3 resumes the random utility model results and, finally, the analysis of the data related to motion sickness issues is reported in Section 4.4.

4.1. EWSs effectiveness evaluation results according to the Theory of Affordances

Fig. 6 summarises the Affordances results for the EWSs in the VR. It distinguishes the functional affordance along the mono-direction L-shaped path (before the decision point) and from the decision point to the exit. The distribution of Sensory and Cognitive affordance pairs, in terms of probability, is shown in Fig. 7 by considering the whole sample and in Fig. 8 by considering only volunteers who selected the wrong exit (thus, being characterised by Functional Affordance = 0).

From a general point of view, Functional Affordance along the mono-direction L-shaped path is always maximum for all the tested EWSs, as expected. On the contrary, considering the path from the decision point to the exit, passive EWSs are characterised by the maximum Functional Affordance values, while the active EWS shows lower Functional Affordance values in comparison to EWSs 0, 1 and 2 for both lights-on (scenario 3A) and lights-off with smoke (scenario 3B) conditions.

Participants taking the wrong evacuation direction for EWSs 0 and 1 declared lower Sensory and Cognitive affordance pairs (see Fig. 8) than the whole sample (compare with Fig. 7), and they also reported being unable to properly see and understand the signs while moving. On the contrary, according to the interviews after the VR experiments, in scenarios 3A and 3B, participants who selected the wrong exit generally pointed out that they did not understand the meaning of the change of displayed direction by EWS3.

Nevertheless, uncertainties in exit selection were also detected for participants who perceived EWS3 and then responded to the stimulus by changing their evacuation route. Fig. 9 shows the trajectories for EWS3 experiments in terms of absolute frequencies of the VR spaces used with a discretisation of 50 cm (equal to the avatar size), referring to participants who selected the correct evacuation direction. According to Fig. 9, participants generally modified their trajectory after the active EWS changed the direction information, but some of them continued moving towards the initially selected door and then delayed their path change. Individuals were not aware or trained about EWS3 functioning, thus affecting this result. It is worth noticing that participants, who took the wrong evacuation direction while using EWS3, still generally pointed out a high satisfaction in Sensory and Cognitive Affordance (see Fig. 8). According to the post-test free-form interview, they seemed to particularly appreciate the guidance offered before the displayed direction change in EWS3, as remarked by Sensory and Cognitive Affordances (Fig. 6).

Additional remarks can be pointed out on sensory affordances. Affordances values in Fig. 6 and the related Sensory-Cognitive Affordances pairs in Fig. 7 could be mainly affected by the higher perceived luminance visibility for 3A and 3B, especially considering the contrast in respect of the background conditions (i.e. for 3B). As expected, the sensory affordance seems to decrease when the per-

Affordance	Scenarios 0A	0B	1	2	3A	3B
Functional, along the mono-directional path	5.00	5.00	5.00	5.00	5.00	5.00
(percentage of correct choices)	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*	*(100%)*
Functional, from the decision point to the exit	5.00	4.85	5.00	4.85	3.45	3.20
(percentage of correct choices)	*(100%)*	*(97%)*	*(100%)*	*(97%)*	*(69%)*	*(64%)*
Sensory	4.29	3.65	4.28	4.28	4.72	4.83
(st. dev.)	*(1.11)*	*(1.42)*	*(0.80)*	*(0.96)*	*(0.77)*	*(0.44)*
Cognitive	4.57	4.32	4.50	4.47	4.69	4.44
(st. dev.)	*(0.96)*	*(1.14)*	*(0.93)*	*(0.83)*	*(0.97)*	*(0.86)*

Fig. 6. Affordances comparison for the tested EWSs in the considered scenarios. Numerical data are combined with a colour scale, one by line, to graphically show better and worst performances of the EWSs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

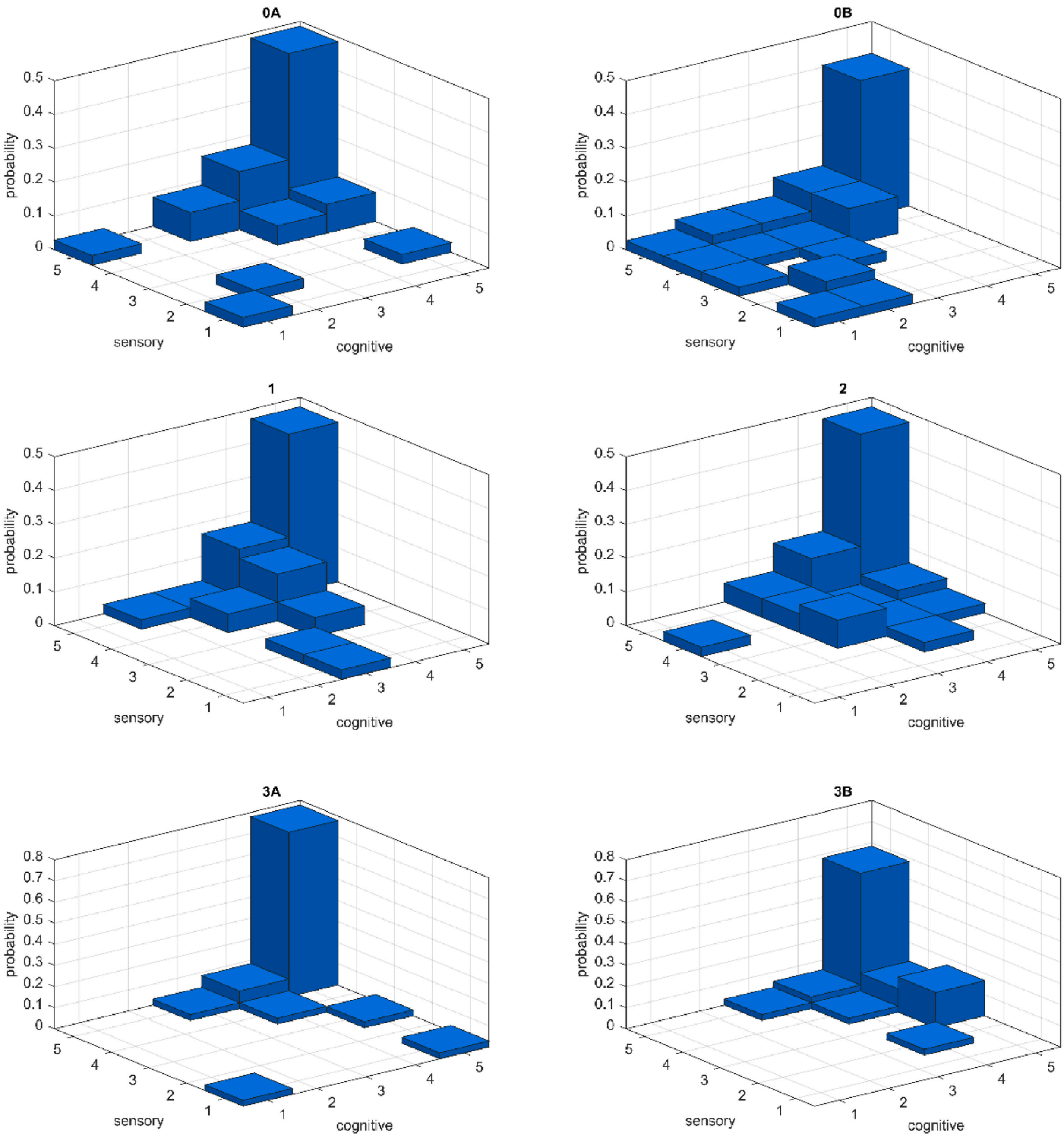


Fig. 7. Sensory and Cognitive Affordances pairs distribution (in terms of probability) by EWS, considering the whole sample.

ceived visibility decreases, maybe because of the luminance difference between the background, the additional conditions (e.g. smokes) and the signage elements. In this sense, it can be noticed that:

- Scenario 3B represents the best visibility scenario because of the high luminance and contrast with the background given by the directional signs;
- Scenarios 1 and 2 can be characterised by quite similar intermediate conditions;
- the scenario 0B represents the worst conditions because of the small dimension, punctual localisation and lower luminance and contrast with the background given by the direction signs.

4.2. Associations results

All the association results are provided in supplementary material S1, while this section only provides data on weak and moderate associations and discusses results by remarking on specific cases in which significant associations fail.

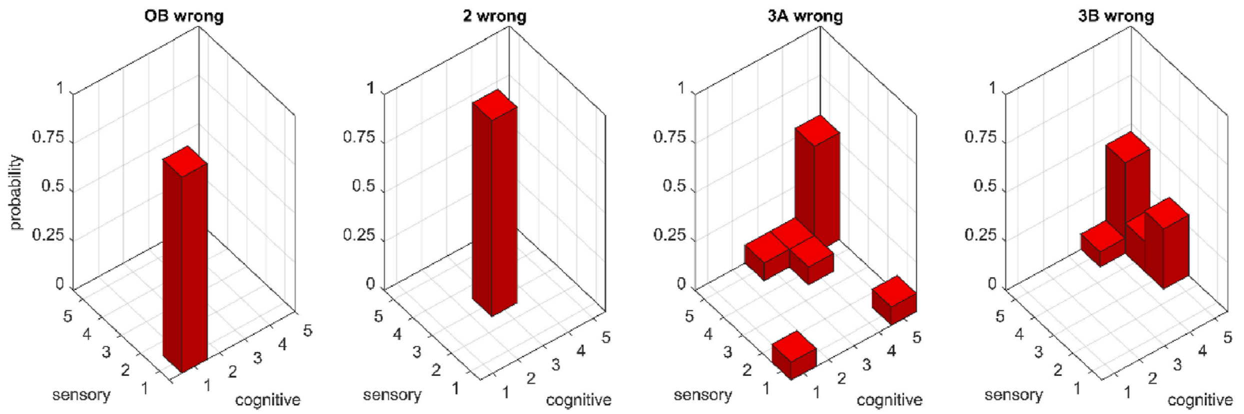


Fig. 8. Sensory and Cognitive Affordances pairs distribution (in terms of probability) by EWS, considering only people who selected the wrong evacuation path (functional affordance was not reached).

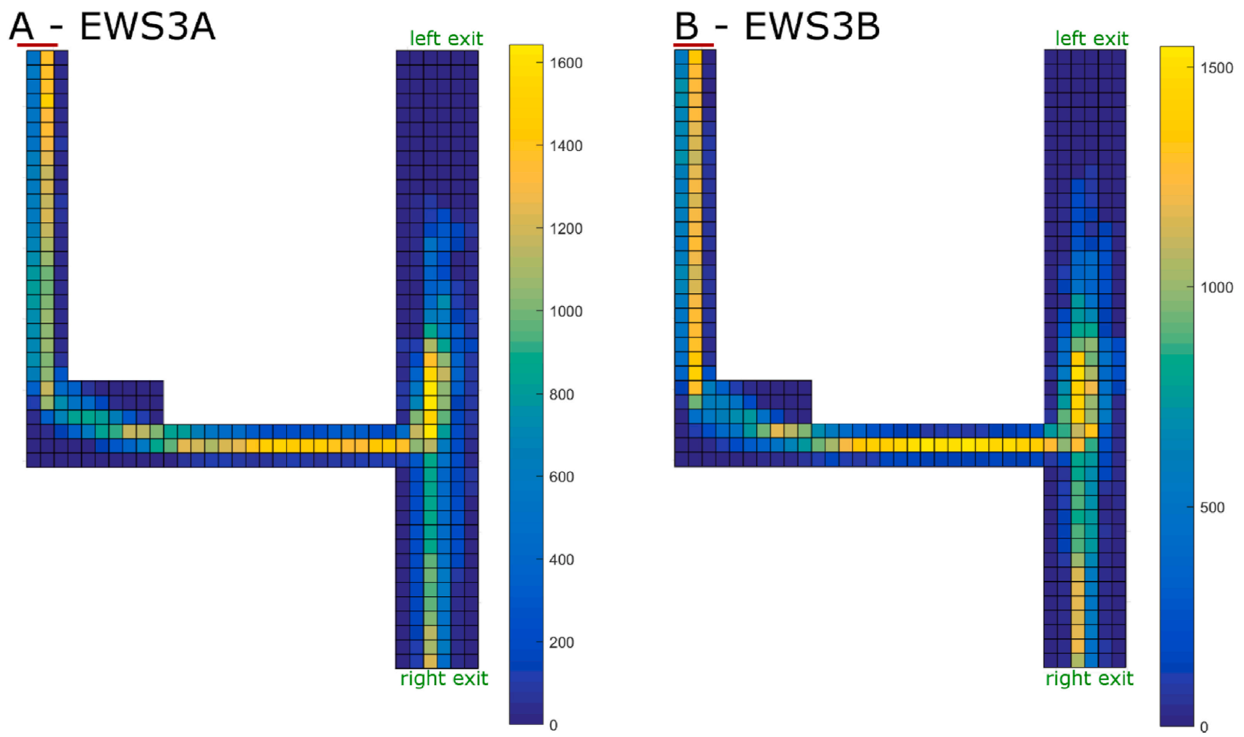


Fig. 9. Trajectories of the individuals in the VR experiments: A- for scenario 3A; B- for scenario 3B. Only people who selected the correct evacuation direction were considered. The colour of the cells (50 × 50cm) is expressed in the number of items (colour bar on the right of each figure panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Considering associations between the sample characteristics and the VR experiment, the Spearman's rank test suggests a weak positive association between age and sensory affordance for EWS3B (r-value: 0.403, p-value: $0.015 < 0.05$), maybe because the ageing of sensory systems could affect the subjects but does not directly lead to visual impairments [70].

In general terms, the order of the test seems to not affect the Affordances results. The only case in which a weak association is shown refers to the association between the order of the test and the Sensory Affordance in scenario 3B (r-value: 0.205, p-value: < 0.001).

Furthermore, no association between motion sickness issues and Affordances values seem to appear in the experiment, thus confirming previous insights into VR sickness on the experimental results [1].

Concerning the associations between the VR experiment results, according to Spearman's rank test, sensory and cognitive affordances seem to be generally positively associated, as expected. In particular, a moderate positive association seems to be shown for scenarios 0B (r-value: 0.643, p-value: < 0.001) and 1 (r-value: 0.615, p-value: < 0.001), while a weak positive association seem to be shown for scenarios EWS2 (r-value: 0.496, p-value: $0.002 < 0.05$) and 3A (r-value: 0.330, p-value: $0.049 < 0.05$). On the contrary, no association is retrieved for scenario 3B.

As expected, in scenario 3A, the Pearson test shows a weak positive association between the functional and the sensory affordances (r-value: 0.388, p-value: $0.019 < 0.05$) and the functional and the cognitive affordances (r-value: 0.352, p-value: 0.035 < 0.05). On the contrary, no association between sensory/cognitive and functional affordances were retrieved for scenario 3B.

Finally, additional insights on associations underline similarities between the perceived affordances while dealing with passive EWSs. The Spearman's rank test reveals a moderate positive association between cognitive affordances in EWS0B and EWS1 tests (r-value: 0.639, p-value: $0.019 < 0.05$). Both the EWSs are based on the use of similar arrows as the main directional signs, and thus people can understand the direction information in a similar manner, although signs have different dimensions.

4.3. Random utility model

A random utility model has been developed to assess if/how the Sensory and Cognitive Affordances affected Functional Affordance. This analysis is done only for EWS3 data (i.e., 3A and 3B), given the high variance of participants selecting the correct and wrong options (see Section 4.1). The results of the logit model predicting the binary Functional Affordance (i.e. 1 = correct exit and 0 = wrong exit) are reported in Table 3.

The proposed model shows that Cognitive Affordance is the only significant variable. Given the specification of the Functional Affordance, a positive value of the parameters of the model indicates that the independent variable increases the probability of a participant selecting the correct exit (i.e. Functional Affordance = 1). As such, the results indicate that a high level of Cognitive Affordance increases the level of Functional Affordance. This is in line with the results published in previous studies [23,69]. However, in these previous studies, Sensory Affordance had a significant impact on Functional Affordance. This trend is not observed in this work model, essentially because of the relatively small sample size for the regression model and the significant correlation between Cognitive and Sensory Affordances ($p\text{-value} < 0.05$), which is a limitation of the specific dataset used in this work. On the other hand, the fitting results indicate that the proposed model is capable of providing almost 70% of the correct classification of the binary dependent variable.

4.4. Motion sickness

In this experiment, we observed a significant difference in the motion sickness occurrence comparing it with previous studies.

In our study, only 11% of the individuals experienced such phenomena (mainly, Disorientation-Vertigo) using the navigation system described in Section 3.3. This number is lower than the statistics (up to about 22%) reported in previous works using (1) immersive VR with mounted displays and (2) navigation via a handheld controller or joystick for translational components, plus head movements for rotational components [56,58]. Sickness phenomena were seen only in the first part of the tests, that is, during the training. Only in 3 cases the volunteers decided to end the test in this training phase. The protocol used in the VR experiment (including the training environment activities and the rest-time) could have supported these results. Furthermore, as remarked in Section 4.2, no association between motion sickness and Affordances values were highlighted by the association analysis (compare supplementary material S1). Nevertheless, it is worthy of notice that the navigation system could affect the occurrence of motion sickness effects [57]. Solutions based on a handheld controller or joystick can generally reduce negative effects also because of the easiness of interaction with respect to other systems (e.g. walking-in-place systems, which can cause cognitive dissonance). Similarly, CAVE-based systems for VR could additionally reduce sickness as the participants score the system without navigating in the space [23,55,71], although some limitations in replicating real-world results could exist in respect of HMD solutions [28].

5. Discussion

This work represents one of the first attempts at using Affordance-based methods for EWS effectiveness assessment by involving a volunteer sample composed of people of different ages, thus overcoming the limitations of previous work. Furthermore, this is one of the first experiments involving a great variety of different EWSs, including an active EWS. Therefore, the results of this work provide significant findings on the capability of the Theory of Affordance to this end, as well as remarks on the application of VR experiments to this end which also prepare the basis for further activities.

From a general point of view, considering the EWSs investigated in this work, the results point out that:

Table 3
Logit model results for EWS3.

Fitting Results			
N = 73 observations Cox & Snell R Square = 0.08 Nagelkerke R Square = 0.11 Correct Classification = 69%			
Variable	**Parameter**	**Stand. Error**	**p-value**
Cognitive Affordance	0.57	0.30	0.05
Sensory Affordance	0.41	0.50	0.42
Constant	−3.86	2.69	0.15

- the simpler the EWS and the higher the individual's familiarity with it, the higher its effectiveness, as pointed out by the values referring to Functional Affordances from the decision point to the exit (i.e. EWS0 in lights-on conditions; EWS1);
- the brighter the EWS, the higher its effectiveness in terms of Sensory Affordance, especially for electrically-illuminated signs (i.e. EWS3);
- considering lights-off scenarios, continuous EWSs implementing arrows as directional signs are the most effective (i.e. EWS1);
- Affordance values on scenarios with smoke are quite similar to those without smoke, maybe because of the limited intensity of simulated smoke.

Results also suggest that passive EWS1 is the best system in lights-off and smoke conditions, thus confirming previous real-world experiment results since it offers continuous guidance, directional information repetition (by using arrows) and spatial description to the occupants [19]. Furthermore, the best system along mono-directional paths is EWS3, which is electrically illuminated and continuous, using arrows to point out the direction to be followed. However, it fails when the decision point is reached, in view of its functioning complexity, as shown by the EWS3 low Functional Affordance values along the path from the decision point to the exit. In this sense, these research outcomes suggest that training on active EWSs should be given to individuals to make them confident with its possible directional change. Furthermore, at the end of the test, most of the participants suggested introducing sound alarms at the directional changes or using flashing lights to better stress the directional change of EWS3, thus confirming results from previous works [37]. Nevertheless, these work results are different from the key findings noticed in real-world experiments concerning the same EWS3 [43], which suggest significant support of such signs in evacuation guidance also at the decision points. Differences could be due to group effects in evacuation, noticed in real-world experiments: occupants who properly understand the EWS3 system could guide the others along the correct evacuation path selection according to the EWS3 directional information. On the contrary, this work experiment is related to isolated occupant motion, thus highlighting individual Functional Affordance differences. Further efforts should be hence devoted to the implementation of virtual crowd flow in such contexts [1].

This work has some limitations that need to be discussed. The results seem to point out an apparent ceiling effect observed in almost all of the Affordances, which offer very similar results for the different tested EWSs. This effect confirms previous research outcomes, but it does not affect the possibility of using the Theory of Affordances and the “behavioural design” approach to provide useful comparisons between EWSs during the design and implementation phase [19,23]. In this sense, future works should move towards the development of overall ranking methods for Affordances evaluation to merge the different issues and stress differences between the tested systems.

Further, the VR experiments seem to be a promising way to collect data on EWSs effectiveness comparison before implementing EWSs in real-world environments. Two different kinds of activities are then needed. Although demonstrations of the reliability of VR tests in respect of data obtained in a physical environment [28,51,52], more validations work is required in the future to fully assess the capability of VR for evacuation investigations by comparing results in real-world scenarios and using virtual models replicating them in VR environments, using different apparatus and procedures. Second, the motion sickness results show how employing simple and safe protocols for tests could reduce the negative effects on the people, but different navigation (e.g. walking-in-place) and apparatus (e.g. CAVEs) should be tested to find the most effective equipment set up to be used [1,23,55,57,71]. Similar tasks are required for scaling the VR environment towards real contexts, e.g. by verifying identification distances for the EWS signs, also in relation to their position, colour and typology [39,63].

Following the outcomes of previous research [28], further activities are needed to understand the reasons for differences in the individuals' response to EWS3 between real-world and VR conditions. In fact, in previous full-scale works related to the same EWS3, all the people directly understood EWS3 functioning without hesitation while moving in groups [43]. This result could be affected by social dynamics which are not included in this VR experiment setup, thus highlighting the importance of including additional avatars to replicate more complex and crowded scenarios for active EWS testing.

Thus, future challenges involve the combination between such social dynamics analysis (through the use of other non-players or players' characters), the aforementioned definition of other immersive VR solutions, including navigation-related ones, and the quality of the multimodal experience offered to the participants. This work provides a first step in the affordance-based analysis of such EWSs, thus limiting the additional sensory issues which can affect the individual response. From a multimodal perspective, additional feedback could be introduced too, for instance, relating to audio stimuli (i.e. merging the emergency sounds with additional background noises), heat stimuli or other sensory feedback, like smells. From this point of view, future research steps can also take into account the use of sensors to detect physiological measures, such as electroencephalographic and eye-tracking sensors to assess visual/audio stimuli perception, or even signals of heart rate, galvanic skin response, skin conductance level, respiration, and salivary cortisol to measure engagement and feelings of participants, especially in immersive VR experiences [10,40,53,63,72].

The aforementioned combined guidance effects in such multidomain conditions should be also assessed in complex scenarios to extend the validity of this work results. This research focuses on floor-related scenarios, which are more relevant than monodirectional spaces (e.g. stairs) for the investigation of EWS using virtual reality since directional changes can exist and wayfinding is hence a primary task. Nevertheless, multi-storey buildings can represent examples of critical buildings open to the public (such as universities, libraries and malls) that should be investigated by future experiments. In this sense, future dynamic wayfinding systems, such as the EWS3 in our study, could be activated in the future based on the congestion conditions on the stairs. In this regard, previous works were devoted to the real-world analysis of the system in a part of a multi-storey building, demonstrating the capabilities of the general guidance approach [43]. At the same time, we believe that the analysis of single-floor evacuation still represents an interesting scenario when progressive horizontal evacuation strategies are applied [73]. These evacuation strategies aim at limiting evacuee cowards on the main stairs of a building by redirecting people toward closer and less familiar stairs. As such, dynamic EWSs can play a key role in this regard.

Finally, the proposed regression model illustrates that only Cognitive Affordance is significantly affecting Functional Affordance while Sensory Affordance does not seem to have an impact. This result is different from the finding of the previous studies [23,69] where the authors found that both Sensory and Cognitive Affordances significantly affect Functional Affordance. However, the proposed results can be related to the specific data set used in this work. In fact, the two independent variables in the model (i.e., sensory and cognitive affordances) are strongly correlated with each other, given the limitation of the specific dataset used in this work. This violates one of the key assumptions of multivariate analysis [74]. Further, the model is capable of predicting almost 70% of the data. While this is a relatively high level of accuracy, this indicates that there are other factors which might have affected the decision-making process that needs to be investigated in future works.

6. Conclusions

This work demonstrated that the Theory of Affordance can be used to compare the effectiveness of passive and active Emergency Wayfinding Systems (EWSs). Virtual Reality (VR) tests involving isolated occupant motion were used to this end, thus focusing on the direct occupant-EWSs interaction. VR experiments were preferred because of the possibility of easily replicating different scenarios and increasing the number of tested conditions and EWSs in the same architectural layout. EWSs performances in terms of sensory (the EWS signs are clearly visible), cognitive (the EWS signs are easy to be understood) and functional (the EWS leads people to select the proper route) Affordances were investigated.

According to the affordance-based results, continuous EWSs implementing signs with arrows, and placed near the floor level, should be preferred to punctual solutions. Some difficulties in the correct understanding of active and continuous EWSs functioning are remarked on because this technology is not currently implemented in buildings, and occupants have limited familiarity with them. In fact, the tested active EWS shows good results in mono-directional paths, in view of the implementation of electrically-illuminated signs, which are well visible, but many participants were not able to select the proper evacuation path when its directional information changed. Thus, better training of the occupants in the EWS is encouraged as well as the EWS implementation with additional supplies (i.e. sound alarms and flashing lights). Moreover, it is worth noticing that efforts in active EWSs' technological equipment and supply are needed, especially when applying them in existing contexts.

Finally, the results also stress how VR experiments could be used to assess EWSs effectiveness when specific protocols are adopted to reduce motion sickness effects. The authors are aware that further studies should primarily enrich the participants' sample dimension, also moving towards the involvement of specific typologies of occupants, including the most vulnerable ones (e.g. elderly, children, occupants with motion or visual impairments). The generalised validity of results should be improved by using different architectural layout configurations, while additional comparisons with real-world scenarios are encouraged to fully validate the proposed affordance and VR-based approach. The methodology and the results could be directly employed by designers to preliminary test the best EWS configuration in existing or new buildings before its implementation. Experiments including additional disaster-induced effects during the time as well as the extension to other kinds of emergencies (e.g. earthquakes) could also be provided by future activities to fully evaluate the EWS capabilities under different scenarios.

Ethical approval

According to other similar studies also performed by our research group [43,63] and involving VR tests at the Università Politecnica delle Marche - DICEA department, the ethical issues included the necessity to properly and fully inform volunteers about the experiment procedures and the analysed data. No sensitive information was collected, and data were anonymised. All the participants then signed a waiver before the tests giving consent to the research group.

Availability of data and materials

Data from the experiments are included in this article and its supplementary materials. Additional raw datasets generated during the experiment are available from the corresponding author upon reasonable request.

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Authorship contributions

Gabriele Bernardini: Conception and design of study; acquisition of data; analysis and/or interpretation of data; drafting the manuscript; revising the manuscript.

Ruggiero Lovreglio: Conception and design of study; analysis and/or interpretation of data; drafting the manuscript; revising the manuscript.

Enrico Quagliarini: Conception and design of study; acquisition of data; analysis and/or interpretation of data; revising the manuscript; funding acquisition.

Marco D'Orazio: Conception and design of study; analysis and/or interpretation of data; revising the manuscript; funding acquisition.

Declaration of competing interest

No potential competing interest was reported by the authors.

Data availability

Data are included in this article and its supplementary materials. Additional raw datasets generated during the experiment are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.106778.

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