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Assessing Comfort and Safety in Use of Elevators' Human–Machine Interaction Devices

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Abstract: Elevators are essential for accessibility and play a key role in a building's functionality. Normally mass-produced and purchased from catalogs, elevators require thoughtful integration into architectural design to meet ergonomic, aesthetic, and safety standards. Proper design ensures accessibility, comfort, and efficiency for all users. Internal elements, such as the control panel, influence the user experience within the cabin and should be designed for ease of use, particularly for individuals with disabilities. Two experiments were conducted in a static elevator cabin, installed at the University of Bologna to evaluate user interaction. The first experiment assessed user preferences for different control panel layouts, while the second experiment tested emergency procedures, comparing the standard long-press with a double-press method. Both procedures were also tested with participants with hearing impairments to explore accessibility perceptions among disabled users. An urgent need for an alternative emergency procedure, including a double press to initiate the call and a video–textual device for visual–written communication, was identified to ensure both comfort and safety in elevator use.

Keywords: elevator; HMI—human–machine interface; human–machine interface; operating panel; emergency call; hearing impairment; button panel layout

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1. Introduction

1.1. Research Background

Elevators are a fundamental feature in buildings, serving as a crucial element of connection within different floors. Elevators not only facilitate vertical movement but also determine the accessibility and functionality of a building, impacting the flow of people and goods across multiple floors. Elevator technology has been essential for developing multi-story buildings, overcoming height limitations related to comfort and practicality [1]. By optimizing space and improving efficiency, elevators have transformed urban landscapes, making it possible to house more people and businesses in a smaller footprint and significantly shaping the way individuals experience and interact with urban environments.

Elevators are mass-produced yet highly customizable products. As of 2024, estimates suggest that there are about 14 million elevators in the world [2], with China having the highest number. In addition, before the current real estate crisis, the annual installation rate of new elevators approached 1 million. In comparison, Italy and Spain, the second- and third-largest countries by number of elevators, have approximately 1 million each with new installations ranging in the 8 k–12 k figure per year [3].

These numbers are the consequence of estimations available within the industry by comparing different sources. Unlike cars, elevators are unregistered items in almost all countries, and consequently, there are no complete inventories of the number of installed elevators, and how many are still in operation or have been decommissioned.

As mass-produced products, certain design elements are standardized, yet it remains crucial for designers to carefully integrate these systems into the building's architectural and functional framework. This involves considering not only practical aspects but also ergonomic, aesthetic, and safety features that contribute to the overall coherence and operational performance of the building.

Boesso [4] suggested that the elevator car should at least have a modern appearance, given that people tend to trust older-looking elevators less, as they associate them with a higher likelihood of entrapments or accidents. There have been occasional reports of elevator accidents or malfunctions in every country, which can contribute to public safety concerns. Incidents like breakdowns, getting stuck between floors, or door malfunctions may heighten anxiety among users [5]. This is directly connected to the "elevator phobia" [6], a persistent fear of elevators that may stem from a fear of heights (acrophobia) and enclosed spaces (claustrophobia) and that is often associated with panic symptoms [4].

Elevators have been recognized as essential vertical transportation systems and as key in facilitating access, particularly for individuals with varying mobility needs. Marshall et al. [7] emphasize that elevators are integral for designing inclusive and adaptable spaces, ensuring independent and safe navigation in buildings for all users. However, the self-perceived safety of elevators can be a significant concern for some individuals. A previous study by the authors [8] found that nearly half of the deaf and hard-of-hearing individuals who responded to a questionnaire perceived elevator use as unsafe. This sense of insecurity was primarily linked to the risk of getting stuck during an emergency stop and the inability to communicate with the outside.

Safety considerations have also been a focal point of studies analyzing elevator-related accidents and proposing improvements in safety management. Research by Lee et al. [9] reviewed elevator accident cases to strengthen safety management practices, emphasizing the need for enhanced design and maintenance protocols.

A Chinese study [10] examined factors influencing elevator comfort, including operational noise, stability, interior conditions, and ventilation systems. It also discussed integrating sensors to monitor the indoor environment of passenger elevators, aiming to enhance both safety and comfort levels.

Ergonomic considerations in elevator design are vital for promoting comfort, reducing physical strain, and ensuring ease of use for occupants of all ages and abilities. Ergonomic principles in elevator design not only enhance accessibility but also contribute to a building's overall safety and usability by reducing physical barriers. As highlighted by Siikonen [11], well-designed elevators optimize spatial flow and reduce waiting times, which enhances the user experience and supports the efficient movement of people within the building. Therefore, careful thinking about elevator design can bring real improvements to people's lives [12].

As universally relevant elements, elevators must be carefully integrated into building designs, with effective wayfinding playing a crucial role in ensuring users can easily locate them [13]. Clear signage and intuitive layout contribute significantly to the ease of finding elevators, reducing confusion and frustration for occupants [14]. Research has shown that strategically placed directional signage, combined with visual and tactile cues, can greatly enhance wayfinding in complex environments [15]. For instance, color-coded pathways leading to elevators can guide users, while well-placed maps at key decision points allow for quick orientation. Moreover, the visibility of elevators from common areas can further improve their accessibility. The ease of finding elevators is particularly important in high-occupancy buildings, where foot traffic is substantial, and delays in accessing vertical transportation can negatively impact the overall user experience [16].

In addition, using lighting as a wayfinding tool for locating elevators in buildings is an effective design strategy that enhances user experience and accessibility [17]. Thoughtfully designed lighting can create a welcoming atmosphere and guide occupants intuitively toward elevator lobbies. Furthermore, effective lighting design contributes to the overall ambiance and comfort of waiting areas, allowing occupants to navigate easily and safely.

Moving the focus inside the cabin, internal elements—such as the human–machine interface (HMI)—are crucial for a positive user experience. HMI systems in use today are the result of a trend that has progressed during the 160 years of the evolution of elevators. During the first decades after their transformation into an industrial product and application in civil buildings, elevators were controlled by very complex systems of levers that required the presence of specialized human operators. Automatic buttons first appeared in the 1920s, making elevators more affordable and easier to use. This innovation transformed elevators into mass-produced products, facilitating their widespread adoption in ordinary office and residential buildings [18].

Despite the elevator industry proposing highly automated elevators, digitally connected controls, and touchless commands to promote seamless movement inside buildings, such products are tailored for high-end applications due to their high costs [19]. On the contrary, elevators will continue to rely on basic controls in the great majority of buildings for the foreseeable future. Also, existing elevators will likely experience renovations and upgrades, but the fundamental principles of their functioning will not be upgraded as long as they are not decommissioned and changed with completely new installations. Key components of conventional HMI include the control panel, which must feature accessible buttons and clearly labeled warnings and instructions [20].

Inside the cabin, a key element is the control panel containing all the buttons to operate the elevator. The main functions of the panel include a series of buttons representing the floors being served by the elevator and an alarm button. Some elevators may feature two buttons that override the normal operation of the automatic doors: the most frequent one is the one that shortens the delay in the closing of the doors to improve the velocity of the elevator service, while another one is used to stop and delay their automatic closure, for instance, for people inside the cabin to kindly facilitate the entrance of an arriving passenger.

Innovations like touchless controls are also gaining traction, as they reduce surface contact and potential germ transmission. Also, such modern-looking technologies are sought to transmit an idea of modernity and technology to the users [21].

However, it is important to note that while touchless buttons can offer benefits and transmit a positive image, they may represent a barrier for several categories of users such as the elderly or blind users [22]. Blind users may encounter challenges in understanding the system's current state, as they are unable to rely on visual indicators for feedback. A study [23] highlights that while tactile feedback can assist in navigation, some visually impaired individuals may find that tactile buttons, which rely heavily on texture and pressure sensitivity, can lead to confusion, particularly in crowded environments where multiple buttons are present. Instead, clearer auditory signals and well-structured interfaces may enhance the overall experience for users with visual impairments. However, these improvements may not address the needs of deaf or hard-of-hearing individuals. Efforts aimed at benefiting one category of users can sometimes create obstacles for another, highlighting a lack of awareness in the elevator design process regarding the needs of people with impairments.

1.2. Regulatory Framework

HMIs, like all other components of elevators, are standardized by many international standards.

Within the European framework, the main reference standard for elevators is Directive 2014/33/EU [24], which regulates the safety and performance of elevators and their safety components and mentions the need for elevators to be equipped with a two-way communication system. In Europe, elevator components comply with the EN 81 family of technical standards. These standards provide a detailed framework for the features and characteristics of elevator components and are widely recognized as an industry reference, with adoption extending beyond the EU's geographic boundaries in many cases. Furthermore, the standards of EN 81 series ensure compliance with the European Directive. The most relevant of these regarding button panels and accessibility are as follows:

- EN 81-20 [25] sets the general safety requirements for the design, manufacture, and installation of passenger and goods-passenger lifts;
- EN 81-21 [26] applies when installing new lifts in existing buildings, where space constraints may prevent full compliance with EN 81-20;
- EN 81-28 [27] specifies emergency communication requirements for lifts to ensure trapped passengers can call for assistance;
- EN 81-41 [28] applies to vertical lifting platforms designed for persons with reduced mobility, including wheelchair users;
- EN 81-70 [29] defines accessibility requirements for lifts, ensuring they are usable by people with mobility, visual, and hearing impairments.

These standards outline requirements for the design and installation of lifts, focusing on accessibility for all users, including those with disabilities. The standard framework extensively addresses impaired mobility and, to a lesser extent, impaired vision. Specifically, it defines various indicators for control panels, ensuring that buttons are identifiable visually and by touch. The control panel must include features such as tactile elements, contrasting colors, and audible signals to assist users in navigating the elevator system. The design of the control panel must comply with accessibility standards: both the control panels—the cabin control panel and the floor push button panel—must be positioned at a height such that the maximum distance of the buttons is between 900 and 1100 mm from the floor. Additionally, the cabin control panel should be placed on one of the two side walls at a distance of at least 350 mm from the cabin door. Adhering to the above-mentioned standard, the buttons on the control panels must feature raised numbering and inscriptions with Braille translations. Moreover, a recognition plate in Braille characters should be placed alongside each button on the floor panels.

According to the EN 81-28 standard [27], each elevator car shall have one alarm device (two-way communication system) permanently connected to a rescue service. The device shall ensure voice communication in both directions.

EN 81-28 [27] establishes that the alarm system may be designed to filter inadvertent alarm activations by requiring the alarm button to be pressed for a minimum duration, which shall not exceed 3 s.

The above-mentioned standards outline the physical characteristics of the HMI inside an elevator cabin, their position, size, physical appearance, and the operation of the alarm button.

1.3. Aim and Structure of the Research

The present research aimed to test the facility of use of the buttons that are present inside an elevator and the ability of different types of users to operate the cabin during its normal use and in the case of an emergency. A well-designed HMI promotes user comfort and interaction, employing features such as feedback-responsive buttons and auditory confirmation signals [30]. These aspects can provide reassurance to users, making the elevator experience smoother and more intuitive.

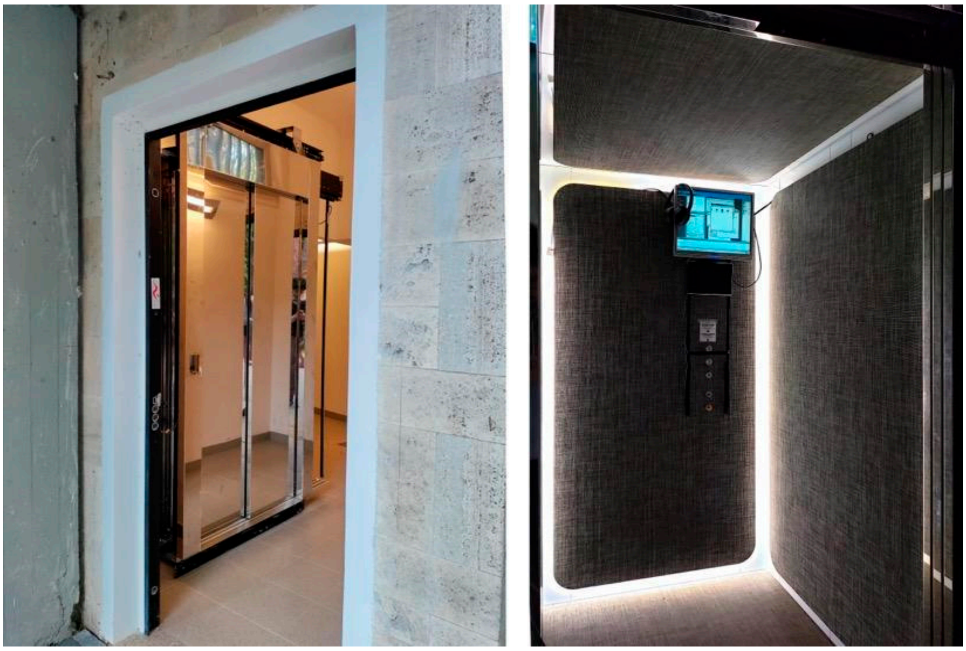
None of the examined standards addresses the needs of individuals with hearing impairments. The EN 81-70 standard contains indications that are voluntarily adopted. This leaves room for significant deviations, such as in the case of touchless controls. On the contrary, as it may lead to potentially serious consequences, the EN 81-28 standard is more rigorously adopted, and the presence of an alarm system is mandatory in all new lifts. According to the EN 81-28 standard, the alarm system consists of vocal communication (through the telephone dialer) that starts after a long press of the alarm button. Operations of visible and audible signals integrate the alarm system. They consist of (1) yellow and audible signals when the communication is established after the filtering, (2) yellow and green signals when the voice communication starts, and (3) just a yellow signal when the voice communication ends.

Since EN 81-70 control panels represent the industry standard for most elevators, this research aimed to verify the suitability of a control panel—proposed in two different layouts—that complies with this norm. It also evaluated users' abilities to operate the elevator correctly and comfortably during both normal and emergency situations.

The paper is organized into three main sections. The first section is organized into several subsections. Firstly, it contains an introduction to the topic, offers a review of the (scarce) scientific literature available, and leads the conversation to the following sections. Secondly, it explores the existing standards framework affecting the HMI in elevators, with a focus on those governing elevator accessibility. European Norms (EN) are used as a reference due to their detailed and comprehensive approach, and they have been adopted in various markets beyond Europe. It then explains the aim and the structure of the research. Lastly, it provides samples and materials used for the research. The second section delves into the methodology employed to evaluate the level of usability of elevator interfaces for generic individuals. This part of the study details the procedural steps undertaken during the research, including the experimental design and data collection methods. The third section discusses the results of the tests and looks at the problem from the particular angle of deaf and hard-of-hearing users describing how such disability may affect the use of elevators. The implications of these findings are discussed in relation to the study aims, and suggestions for future research are provided to further advance the understanding of elevator usability and accessibility for individuals with hearing impairments. The fourth section takes into account the limitations of the study.

1.4. Materials and Sample

The tests were conducted in a real elevator cabin, with the aim of observing users' behavior as they performed the tasks assigned to them by the researcher. The external metal structure of the cabin (Model Rewind Room by NOVA Elevators, Crevalcore-Bologna, Italy), which was installed in the Environmental Psychology Lab at the Department of Psychology of the University of Bologna, measured 1.2 × 1.68 m and stood 2.25 m tall. The cabin provided a free internal space of 1.09 × 1.4 m, with its internal walls covered in textile fabric applied to stainless steel sheets. The cabin was equipped with an automatic sliding door with a free passage width of 0.9 m and a height of 2 m. The elevator was stationary but fully functional regarding doors opening/closing, lighting, audio settings, and electronic devices (Figure 1a). The inbuilt display was covered by a monitor, which was used for presenting the instructions (Figure 1b).



(**a**) (**b**)

Figure 1. The elevator used for the experiments: (**a**) the installed structure; (**b**) the equipment of the cabin.

A microphone and a camera were installed inside the cabin to facilitate communication between the user and the researcher and to monitor the user's behavior. The microphone enabled the user to establish the standard emergency call and to convey any issues or concerns verbally; the camera provided the researcher with a visual feed of the user's interactions and reactions within the cabin environment. This setup enabled real-time monitoring and assessment of the user's experience, ensuring that any difficulties encountered could be addressed promptly and accurately, without causing anxiety or discomfort to participants.

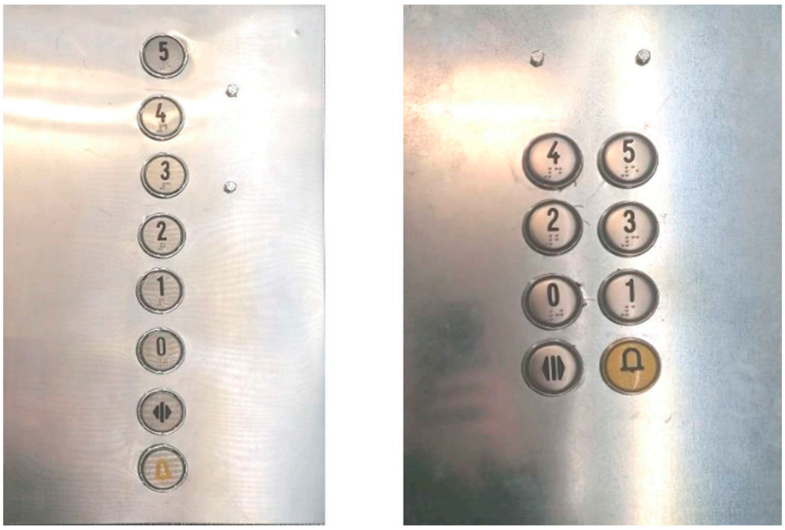
The sample consisted of 47 participants—35 females and 12 males—recruited from university employees, students, and older adults. The average age of the participants was 29.5 years.

2. Methodology

The study was composed of three steps: 1. button panel layout test, 2. emergency-call test, and 3. questionnaire on elevator use. The participants were informed that the study aimed to test different elevator button panel designs. No further information was provided to prevent bias in their responses. The objective related to the emergency procedure was revealed only at the end of the study to ensure that participants interacted with the panels without being influenced by prior knowledge of the emergency focus. No monetary reward was provided for participation.

2.1. Button Panel Layout Test

The first test was conducted by guiding the users in the test cabin installed in the lab and asking participants to use two control panels with different button layouts that were installed alternatively inside the cabin. The panels were constructed on a steel plate covering the cabin's built-in button panel (Figure 2). Adhering to the EN 81-20 standards [25], all the buttons were circular with a diameter of 3 cm. The distance (center to center) between the buttons was 4.5 cm. The research proposed that a vertical layout for the button panel would considerably reduce choice reaction times, as a column arrangement would create a logical connection to the floors, according to Norman [31]. His study, in fact, describes how well the layout of controls corresponds to their function, making it intuitive for the user to understand how to operate them. This layout aligns with the vertical positioning of floors in a multi-story building, promoting stimulus-response compatibility [32], which is suggested to improve usability and performance. Thus, two layouts were provided for the keypad interface: in one case, the buttons were arranged in a 4 × 2 matrix layout (Figure 2a); in the other case, the buttons were aligned on a vertical line at the center of the keypad (Figure 2b).



(**a**) (**b**)

Figure 2. Two layouts of the button panel: (**a**) column layout; (**b**) matrix layout.

The center of the button panel was placed at a height of 105 cm. All the buttons were connected to a PC running a stimulus presentation software with millisecond accuracy (E-prime 2.0) to present the instructions and acquire the button press reaction times.

The order of presentation of the button panels was counterbalanced among participants, and instructions for completing the tasks were displayed on the monitor. The participant was instructed to press a series of specific buttons displayed on the monitor as quickly as possible on the button panel. After completing this task, the second button panel was installed, and the same reaction time procedure was repeated. Reaction times were recorded using E-Prime software (v. 2.0), specifically designed for tracking user performance and measuring response accuracy. The aim was to capture and compare how quickly users interacted with each panel configuration, providing insights into the impact of button arrangement on ergonomics and, consequently, response efficiency.

2.2. Emergency Call Test

Subsequently, a second test involved the simulation of an entrapment situation, in which participants were required to activate the emergency procedure. The participant was instructed to perform the emergency procedure task by following the instructions displayed on the monitor. A message informed the participant that the elevator was stuck due to a malfunction and to call the emergency service to request assistance. Two alternative emergency procedures were conducted: a standard and an experimental one. Building on the results of the aforementioned research [8], the aim was to identify any potential problems associated with the standard emergency procedure while also determining whether the experimental approach could serve as a viable alternative. The study also aims to test the effects of a filtering option as described in the standard EN 81-28 [27]. This option allows the filtering of inadvertent alarm initiations by setting a minimum pressing time of the alarm button that shall not exceed three seconds.

In the STANDARD emergency call procedure, the cabin was equipped with a label stating, "Press the emergency button for at least 3 s to call the emergency service", which was placed at a height of 145 cm, directly above the button panel. This label adheres to the standards and also serves to assess whether it was seen by the user, ensuring that they are aware of the correct procedure for initiating an emergency call. When the emergency button was pressed for time exceeding three seconds, a pre-recorded message assuring the user that the emergency call had been received was played. Then, a call with an operator was activated. The emergency call was classified as successful if the operator received the name and surname of the person in the elevator. The test, in turn, was classified as failed in the following cases: (a) the participant did not press the emergency button for more than 3 s within a 2 min interval; (b) the participant was unable to communicate his/her name to the emergency operator.

In the EXPERIMENTAL procedure, the elevator was equipped with a tablet that was used for establishing audio-visual communication with the emergency service (Figure 3a). In this case, the cabin was equipped with a label stating, "Press the emergency button to call the emergency service. You will be asked to confirm pressing the emergency button a second time", placed at the same height and with the same purpose as in the standard procedure. A research assistant proficient in Italian sign language translated all the instructions when a participant with hearing loss was unable to understand the instructions given through speech (Figure 3b). When the participant was asked to simulate an emergency call, if the emergency button was pressed, regardless of the pressing duration, a message was displayed both visually on the monitor and vocally. The message indicated that the emergency button had been pressed and requested confirmation by pressing the emergency button again. If the emergency button was pressed for confirmation an automatic message was presented in both audio and video, assuring the user that the emergency call had been received. Then, a video call with an operator was activated. The emergency video call was classified as successful if the operator received the name and surname of the person in the elevator, either audibly or via text messages. The call was classified as failed if the participant was unable to communicate his/her name to the emergency operator.

(**a**) (**b**)

Figure 3. Some steps of the procedure with deaf or hard of hearing individuals: (**a**) audiometry test; (**b**) explanation of the test, with an assistant proficient in sign language present.

In both emergency procedures, the press and release times of the emergency button were recorded. At the end of the emergency procedure, the participant was asked to report the content of the pre-recorded message as well as the content of the printed message inside the elevator. This was done to assess whether the participant had understood the pre-recorded message and/or had read the printed message. This investigation aims to determine how button design and layout influence user comprehension and efficiency, particularly in emergency situations. The participants were also asked whether they had noticed the label with instructions or not.

2.3. Emergency Call Test with Hearing-Impaired Participants

To verify the validity of the test, the same set of tests was conducted with a specific category of elevator passengers: deaf and hard-of-hearing users. In fact, as suggested by empirical observations and confirmed by previous research [8], a critical issue in elevator accessibility is that the emergency procedure primarily relies on audio communication. This research originated from what appeared to be a minor issue regarding the accessibility and safety of elevator systems for hard-of-hearing and deaf individuals, focusing specifically on the communication challenges that arise in the event of entrapment. Specifically, 82% of the respondents to the questionnaire that was administered showed a strong demand for the introduction of an interface that would enable visual or textual communication with the operator during an emergency call, overcoming the actual limitations of audio-only communications. This problem strongly hinders people with different levels of hearing loss from using elevators, limiting their access to multi-story buildings and thus restricting their mobility and personal freedom.

Hearing loss or deafness is often considered an invisible disability because it is not outwardly apparent and as a result tends to receive less attention and financial support compared to other forms of disability [33].

Hearing loss is defined as an increase in hearing threshold of at least 20 dB in both ears [34]. This condition is highly prevalent in the population, particularly among older adults. Research [33,35] indicates that hearing loss affects approximately 1 in 4 individuals over the age of 45. More specifically, 27% of men and 24% of women experience some degree of hearing loss. These figures underscore the widespread nature of hearing loss, which can significantly impact the quality of life and communication abilities as people age. Notably, people with partial hearing loss usually communicate through spoken language and benefit from hearing aids, cochlear implants, and other assistive devices. Deaf people mostly have profound hearing loss, which implies little or no hearing. While many deaf individuals use sign language for communication [36], not all rely on it; some may use lip reading, written language, or other forms of communication.

For EN 81-28, which describes the emergency procedure to be adopted in case of entrapment inside the elevator, no visual/textual communication is required, and therefore, the capacity of a deaf or hard-of-hearing user is significantly hindered. The hearing loop, when available, is also signaled by a specific standard symbol [26]. The standard clearly indicates that communication during an alarm relies exclusively on auditory signals, which prevents individuals who are hard of hearing and deaf from effectively communicating with the emergency operator. The only visual feature is the change in the alarm button backlighting once the emergency call is established.

At the international level, the regulatory framework includes specific requirements to accommodate individuals with hearing impairments when using elevators. This is, for instance, exemplified by the 2018 version of the International Building Code [37], which includes provisions for emergency communication systems, ensuring that elevators are equipped with visual alarms and other communication methods that can effectively alert individuals who are deaf or hard of hearing in case of an emergency. In 2022, the ASME A17.1/CSA B44 code [38] was updated to provide specific requirements for elevators, mandating emergency communication options including text display screens and visual alarm systems.

Consequently, an additional test was carried out to evaluate different aspects of deaf users' interaction with the HMI in elevators, involving a group composed of deaf or hard-of-hearing individuals. The group consisted of 33 participants (17 females and 16 males) across a range of ages (40.6 years on average) and levels of hearing loss, ensuring a comprehensive understanding of their unique experiences and needs. Participants with hearing loss were recruited with the collaboration of local associations for deaf people (ENS—Ente Nazionale Sordi, both Sezione Regionale Veneto e Sezione Provinciale di Bologna, FIADDA Bologna, Fondazione Gualandi). A keyboard was added to the first cabin configuration, allowing users to send text messages if they could not communicate with the emergency operator. The methodology adopted for the additional test replicates the one previously described with a significant variation: an oral level test, to assess oral communication proficiency, and an audiometry test, to assess the level of hearing loss, were conducted on all participants. The researcher first rated the participants' level of oral communication on a 1–5 Likert scale, where 1 indicated the lowest level of communication and 5 the highest. Mean level of oral communication was 2.27. In this group, 18 used hearing aids (assistive listening devices). Additionally, four individuals had cochlear implants.

After obtaining informed consent, each participant was guided into the elevator. The hearing level was assessed for all participants by instrumental pure-tone audiometry on both left and right ears wearing headphones inside the cabin (Figure 3), where the doors were closed to create a controlled environment. The hearing level was assessed with the hearing aid active if the participant had one. The audiometry test reported an average −77.58 dB for the left ear and −78.45 dB for the right ear. The group composed of deaf and hard-of-hearing users tested the two control panels using the same procedure as the normal-hearing group by receiving written instructions on the screen installed inside the cabin.

2.4. Questionnaire

The procedure ended with a questionnaire with questions asking to rate, using a Likert scale, (1) the ease of activating the emergency call (from 1—extremely difficult to 5—extremely easy); (2) the quality of communication with the emergency operator (from 1—extremely low to 5—extremely high); and (3) the level of anxiety experienced using the elevator during the emergency test (from "Not at all" to "Extremely elevated"). The questionnaire also asked about the frequency of elevator use by the participants and whether they had ever initiated an alarm procedure during the use of an elevator before.

3. Results

3.1. Button Panel Layout—Reaction Times

A significant main effect of button panel layout on reaction times was found. On average, responses were 17% faster for the matrix layout (with an average of 1140 ms, standard deviation of 105 ms) compared to the column layout (1367 ms on average, standard deviation of 220 ms), indicating a preference for the matrix arrangement of buttons (Figure 4). This result can be explained by the fact that the matrix layout minimizes the distances between buttons, offering a more spatially compact design. This configuration reduces the visual scanning path and time, as well as arm and hand movements. As predicted by Fitts' law [39], the time required to reach a target area is a function of the ratio between the distance to the target and the width of the target. In this case, with the width of the target remaining constant, the matrix layout, with its significantly reduced distance between buttons, resulted in faster reaction times.

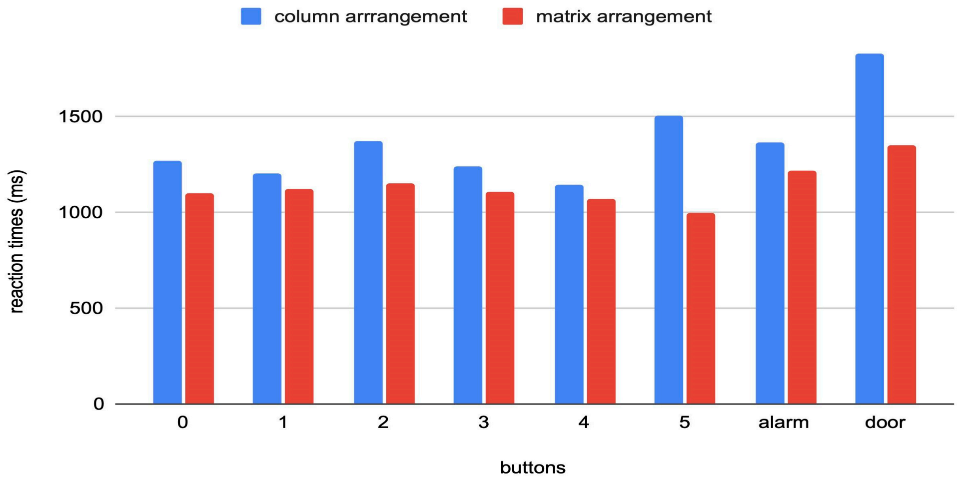


Figure 4. Reaction times for each button in the two different configurations, for the sample of general users.

The interaction between the button panel layout and the hearing situation was significant. In fact, the group of deaf or hard-of-hearing individuals confirmed a slight preference (only 6% on average) for the matrix layout, with respect to the column arrangement. This group reported higher reaction times for each button but the slower response rate may be attributed to other factors not directly connected with the hearing impairment; notably, the matrix layout resulted in a 52% slower response time (1729 ms on average, standard deviation of 348 ms), while the column layout led to a 35% higher time (1842 ms on average, standard deviation 500 of ms).

The fastest reactions were recorded for button 4 in the column layout and button 5 in the matrix layout, across both groups. They are, in fact, placed high in both layouts. Conversely, the slowest reactions were consistently associated with the door-opening button, except in the matrix layout for deaf individuals, where the alarm button was reported as the slowest (Figure 5). These results are likely due to a lack of familiarity with, and the infrequent use of, the door-opening and alarm buttons.

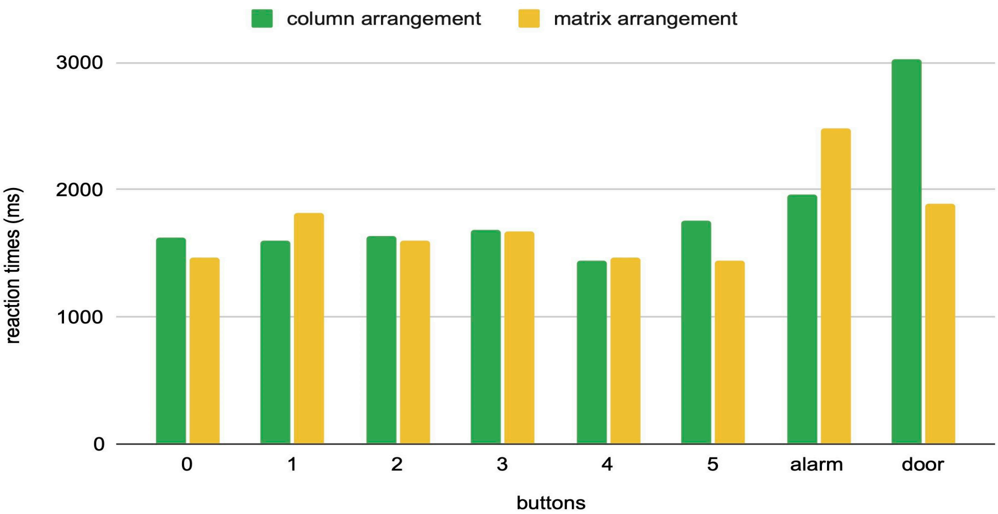


Figure 5. Reaction times for each button in the two different configurations, for the deaf and hard-of-hearing individuals.

These results are presumably due to the position of the buttons, which, in the case of buttons 4 and 5, are the closest to the eye level of an average tall person. This peripheric and prominent position may explain why the buttons are located and pressed more quickly by participants in both groups.

3.2. Emergency Call Test—Success Rate

For the standard procedure, in ten cases among the control generic sample (21%), the participant was not able to issue the alarm call since the alarm button was not pressed for at least three seconds within the two-minute interval. In three of these ten cases, the alarm button was pressed 8, 9, and even 14 times, demonstrating how such a procedure can make the user very anxious. This can also be attributed to the fact that many believe pressing the button multiple times will speed up the opening or closing of the doors [40]. In the remaining 79% of cases, the participant successfully issued the alarm call but with a mean number of presses of 2.21. Considering participants with hearing deficits, only 14 participants succeeded in initiating the alarm call with a single button press. In 23 cases, the alarm button was pressed multiple times (from two to six presses) until a continuous three-second press was achieved. All participants who successfully issued the alarm call were subsequently able to communicate with the voice operator. Only 27 (57.4%) out of 47 participants had noticed the label with instructions.

In the group of deaf individuals, only 12 participants (36%) successfully activated the alarm with a single press lasting longer than 3 s. In 12 instances, the participant failed to issue the alarm call, never pressing the alarm button for more than 3 s. In the remaining nine cases, the alarm call was successful but required an average of three presses, with some reaching up to five presses. Notably, people with disabilities may be more prone to experiencing the above-mentioned "elevator phobia" [6], as the prospect of being trapped in an elevator can represent a greater physical and psychological challenge for them [41]. Only 14 participants who successfully pressed the alarm call were later able to establish oral communication, comprehend the operator's voice message, and respond to his questions. Only nine participants (27%) had noticed the label with instructions.

In summary, for the standard procedure, the success of the emergency call was reported in 79% of participants of the generic control group, while only 43% of participants with hearing loss succeeded (Figure 6). This occurrence highlights the findings of the above-mentioned study [8], which showed hard-of-hearing and deaf individuals experience difficulties during an elevator emergency stop, potentially leading them to avoid using it altogether.

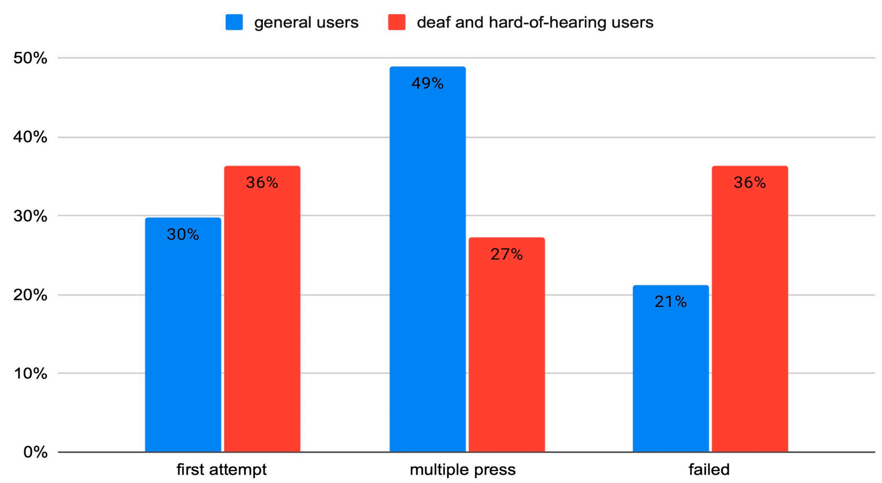


Figure 6. Success rate in issuing the alarm call with a three-second press, for both groups.

This suggests that in emergency conditions where behaviors tend to be more impulsive [42], requiring a long-press action for the alarm button should be avoided. Inadvertent alarms should be managed through more intuitive and straightforward methods that align with instinctive actions taken during high-stress situations.

In contrast with the current emergence process, the experimental procedure—two button presses without time press limits, with the second press serving as confirmation—resulted in 100% success in initiating the alarm call for both groups (Figure 7). Thus, incorporating a second button press for confirmation, similar to practices in software design aimed at preventing inadvertent key presses, could enhance reliability and ensure that emergency calls are initiated deliberately, thereby minimizing accidental activations. All participants from both groups successfully communicated their names to the emergency operator during the video call, either vocally or through text messages using the keyboard.

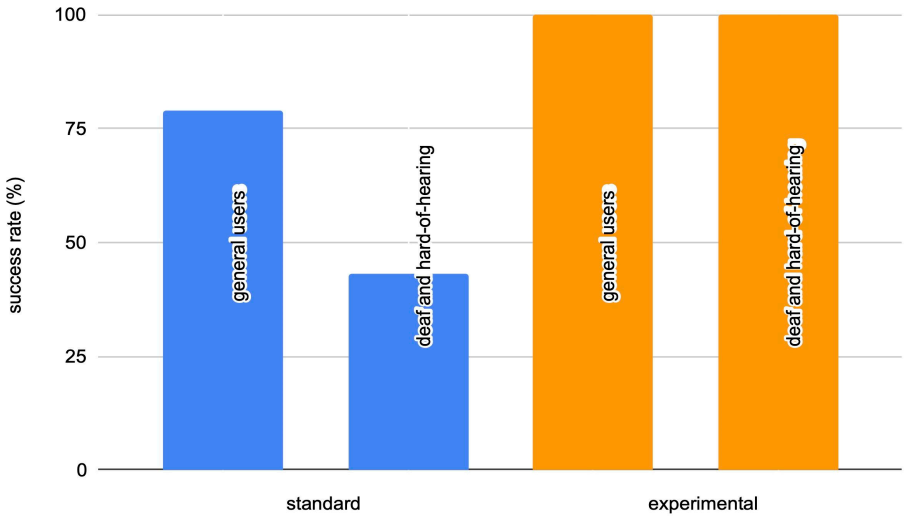


Figure 7. Success rate for both groups in the two emergency procedures.

3.3. Questionnaire on Elevator Use

The ease of use perceived during the test varied significantly between the two groups. The mean ease of use, in fact, was rated at 4.30 in the control sample and 3.39 in the hearing loss group, further highlighting the issues faced by the latter (Figure 8).

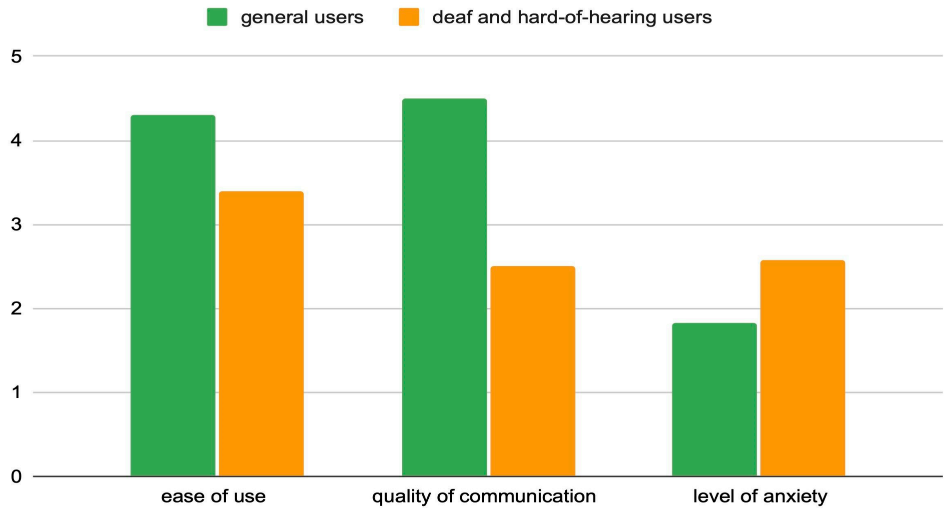


Figure 8. Answers to the questionnaire on elevator use.

Quality of communication with the emergency operator was significantly affected by the hearing condition of the respondent, specifically regarding the standard procedure. While the control sample reported an average rating of almost 4.5 for both the standard and experimental procedures, the sample of hard-of-hearing and deaf people's ratings were 2.5 on average for the standard procedure and 4.3 for the experimental procedure.

As expected, responses to the question "the level of anxiety experienced using the elevator (from "Not at all" to "Extremely elevated")" reported significant differences between the two groups. The hearing loss group experienced more anxiety (with an average of 2.58) than the normal-hearing group (average of 1.83) when using the elevator. This highlights the difficulties an individual with deafness or hearing loss can face when using an elevator, to the point of refraining from using it altogether.

3.4. Summary of Experimental Results

The results of the experiment offer significant insights. These findings demonstrate a preference for the matrix arrangement while highlighting that the traditional emergency procedure poses challenges to users, certainly for deaf and hard-of-hearing individuals.

Below are the key findings from the experiment on button panel layout:

- A preference for the matrix layout was observed in both the general and deaf and hard-of-hearing samples, with an average response time of 17% faster;
- The deaf and hard-of-hearing group reported slower responses (43% slower on average) compared to the general group, primarily due to anxiety, as indicated in their responses on the subsequent questionnaire.

Below are the key findings from the experiment on emergency call initiation using the standard emergency procedure, which requires a press lasting longer than 3 s:

- The general sample reported a 79% success rate, with an average of 2.21 presses. The remaining 21% were unable to initiate the call, and in three cases, users pressed the button 8, 9, and 14 times, respectively. Only 27 out of 47 participants had noticed the label with instructions;
- The group of deaf and hard-of-hearing individuals reported a 43% success rate. Notably, only 12 out of 33 participants successfully initiated the call. In nine other cases, an average of three presses was required to initiate the call, while 12 individuals failed to initiate the alarm. Additionally, only 14 out of 24 participants who managed to initiate the call were able to respond to the operator's questions. Furthermore, only nine participants noticed the label with instructions.

The experiment on emergency call initiation using the experimental emergency procedure, which requires a double press and establishes video communication, yielded the following key findings:

- Both groups reported a 100% success rate, with all participants able to communicate their name either vocally or through text messages using the keyboard.

From the questionnaire administered at the end of the experiment, it was evident that:

- Deaf and hard-of-hearing individuals, compared to general users, reported, on average, lower levels of ease of use and quality of communication, as well as higher levels of anxiety during the emergency simulation.

4. Limitations of the Study

Some research [43,44] highlights the limitations of laboratory experiments in capturing the complexities of real-world scenarios, emphasizing the need for studies that consider the ecological context of tasks. Notably, in this laboratory-based experiment, the use of a monitor covering the in-built display may pose a challenge in reflecting the real-world dynamics of an emergency stop. Additionally, the flow between commands should be improved to prevent interruptions that distinguish simulated environments from real-world settings [45,46]. Participants were not informed in advance about the emergency stop simulation; however, some degree of behavioral alteration [47] can still be expected.

The results of this research could be limited to the six-floor simulation used. Future studies should explore whether the same conclusions apply to panels with a greater or fewer number of buttons, as suggested by research on touchscreens [48].

In this study, only selected ergonomic aspects were assessed. However, other factors that may significantly affect the comfort and safety of users, such as the size of labels, font type, and the height of the control panel, were not considered. These elements warrant further exploration in subsequent phases of the study to gain a more comprehensive understanding of how the human–elevator interface impacts user experience.

Other user groups should be involved in the next phases of the research to fully understand how different impairments impact the comfort and safety of elevator use.

5. Conclusions

The study evaluated the usability of an elevator's human–machine interface under static conditions, focusing on button panel layouts and the emergency call button. Simulated emergency scenarios highlighted the need for modifications to improve user comfort and safety, especially for passengers with hearing impairments. Despite the limitations of the study due to its experimental nature, important results were found, and it is clear that modifications to the emergency procedure are necessary to enhance the comfort and safety of elevator passengers, particularly those with hearing impairments.

The button panel layout test showed that participants could operate both layouts efficiently, with a slight preference for the matrix layout. However, the minimal differences suggest that either layout would be equally effective in real-life scenarios. The test also evaluated participants' ability to interpret button pictograms, particularly for the alarm and door override buttons, as well as the information label indicating the required press duration for the emergency button. Notably, the majority of participants from both groups did not notice the label.

The emergency call test revealed that the current filtering procedure caused delays and user frustration due to multiple attempts before successfully initiating a call. The requirement for a long press was found to be counterintuitive, as users typically expect buttons to function with a simple press, reserving long presses for critical actions like resets. An alternative procedure, requiring a double press for confirmation, proved more intuitive and achieved a 100% success rate, improving activation efficiency and user response in emergencies.

The alarm/emergency button should be unique, reachable by anyone, always ready, prominent, safe for kids, and easy to understand [4]. Multisensory feedback is essential to confirm whether a button press was successful. To ensure safety for children, the button should not activate the alarm on quick presses to prevent accidental activation. Both emergency procedures were guided by labels inside the cabin. However, since only half of the participants noticed the labels, they should be redesigned and repositioned to better align with the interface and button panel.

Full success was achieved thanks to an innovative approach that incorporated an audio-video connection to emergency services, enabling bidirectional text communication between the user and the emergency operator. Infotainment screens, commonly used in modern elevators, are not yet utilized for visual communication with operators. These screens have significant potential to enhance emergency communication when integrated thoughtfully, offering information, entertainment, and visual contact without obstructing the control panel. Ergonomic research suggests that strategically placed screens can reduce perceived wait times, improving passenger satisfaction [49]. Proper placement is crucial to ensure they enhance engagement without obstructing movement, contributing to more efficient traffic flow.

Our society often relies on auditory communication in settings like schools, public transportation, and entertainment, leaving individuals with hearing impairments feeling isolated. In emergencies such as entrapments, prompt rescue is crucial, and this is even more critical for deaf users who face communication barriers. Multiple communication options, such as a reliable internet connection and a direct line to support, can enhance the response time and reassure passengers. Research [4] shows that people feel significantly better knowing someone is aware of their situation, as it alleviates the discomfort of being alone in an entrapment.

Modern elevators with user-friendly interfaces, clear signage, and interactive support screens can significantly improve communication during emergencies. These screens, which are often used for advertisements, could be repurposed to provide support information.

A building's design should be inclusive, considering the diverse needs of people with disabilities. However, there is often a gap in understanding disability and addressing the specific requirements necessary for accessible built environments [12].

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