Space Perception in Virtual Environments

On how biometric sensing in virtual environments may give architects users's feedback

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This paper focuses on the objective study of emotions, namely, fear induced by architectural spaces, by sensing and statistically analysing some physiological signals of users experiencing Virtual Environments (VE). For this, a virtual building was designed considering the presence of stairs and ramps as architectural elements that could affect users´ physiological states and perception of fear of falling. Thirty-one older persons participated in this study and were assigned to two experimental conditions (i.e., safe and unsafe conditions). Five main locations (beginning of the stairs; neutral room; first descending ramp; ascending ramp; and the middle of ascending ramp) were considered along the participants' path, and heart rate (HR) was collected in the vicinity of those locations. Results shown significant differences in HR activation among neutral, beginning of stairs and middle of ascending ramp. Despite the fact that the effect of condition was not fully verified for HR, participants reported more fear while interacting with the unsafe condition, with significant differences between conditions.

Keywords: *Virtual environments, space perception, biometric sensing, emotion, ambient assisted living, architecture design*

INTRODUCTION

This paper addresses the problem of the objective assessment of emotions induced by architecture spaces in its inhabitants, with an original contribution where we study a single emotion ("fear") sensed by a particular user group (older persons), on a specific condition ("fear of falling"). In our approach, we classify such emotional condition by objectively sensing and statistically analysing some physiological signals of older persons while walking through pre-defined locations in spaces designed for an immersive virtual environment (as opposed to a real space), in a lab setting, and correlate such classification with subjective post-experimental questionnaires.

Our research goes along with the principles set out by Hillier & Hanson (1984) about the existence of a strong link between the constructed environment and human behaviour. Other authors, namely Ferreira et al. (2012), claim that it is possible to design architecture spaces according to the emotions that they can generate in the users and, further argue that this strategy will maximize their psychological well-being. The study reported in this paper follows also on our prior experimental work (Dias et al, 2014), where we´ve shown that physiological measurement of user's perceptions while navigating in Virtual Reality (VR) in a specially designed architectural space, can discriminate well bi-level cases, namely, "negative" spaces (which induce emotions close to fear of heights, claustrophobia, sadness and frustration) from "positive" ones (which generate feelings of happiness, pleasantness and confidence).

This research falls in the broader goal of our group of informing the architectural design process, in its conceptual stages, of the emotions that the designed spaces induce in users. Our team´s intention is to address this problem via objective measurement and statistical analysis of physiological signals while the user experiences VR, from where we can determine the sensed emotion. We believe that this approach enables us to inform better design solutions, since it provides the designer with high-level feedback (physiological response) that s/he can correlate with the users' potential behaviours in space.

In this paper, we address specially the emotion of "fear" for the specific condition "fear of falling", experienced by older people. Our study is being carried out in the context of Ambient Assistive Living (AAL) and by a team interested in technology-based solutions, as serious games and assistive technologies, for older persons and disable citizens, to enable them to live healthier, with more independence, mobility and safety. The presented research is a pilot study in which the measurement of physiological reactions aim to inform the architect's knowledge about users' emotion when confronted with specific building elements and spaces and then bring that information to the design of buildings and other spaces. According to universal design strategies a space that is accessible for older persons and people with disabilities is inherently accessible also to citizens without disabilities, allowing the space to be inclusive and comfortable for all. In this scope testing older persons experiencing a designed space in which architectural elements are part of the accessibility recommendations for buildings will give us the border levels of reactions.

Background: phenomenology, space perception and virtual environments.

Man's level of comfort increases as he controls the environment that surrounds him. In architecture spaces that have the ability to defy our safety state, we have accustomed ourselves to find elements with the aim to restore this protection level. If, for some reason, these elements are not present in a space, our expectation is not confirmed, our conscience of the world that surrounds us is awaken, and our senses and emotions arise (Merleau-Ponty, 1962). Our team recognizes that stairways, ramps and its handrails are architectural spaces and elements that may originate emotions and provoke feelings such as fear, namely, the fear of falling, since they are related to the basic survival instincts and levels of wellbeing regarding man's safety and comfort. Therefore, we took a specific interest in studying the interaction of our targeted users (older persons) with those spaces and elements, in the framework of our VR experiments. In fact, considering older persons, the perception of space may be influenced by their increasingly lack of mobility and walking speed as well as by their degraded sensory skills such as vision, hearing and attention. This leads to the fact that, for older and also for disable people the difficulty to access buildings represent their major limitation (Foster et al., 1998). Falling is the type of accident that occurs more regularly within older people and the fear of falling increases with aging mainly because of the loss of muscle strength (Melo, 2011) as well as leads to a decrease of the quality of life of seniors (Feder et al, 2000). Some architecture elements like ramps and specially stairs, are seen as construction barriers by the seniors which fear to fall in them (Tiedemann et al., 2007).

Emotions, like fear, are studied by several authors who are working on relating them with the physiological system (see Kreibig, 2010). Clearly studying emotions and physiological activity, for the cases addressed in our research, in a real environment seems difficult and risky for older persons. However the use of immersive Virtual Environments (VE), with real time interactive behavior and depicting a real scale experience (Whyte, 2002), enables older persons to visualize and manipulate the real world representations (Aukstakalnis & Blatne, 1992), without compromising their safety. In this context, VR emerge as an applicable computing technology that, by using simulation, interaction, artificiality, immersion and full-body immersion, sense of presence and networking, allows the study of all kind of architectural spaces in a short period of time (Jansen-Osmann 2002). With the access to an immersive VR facility such as a CAVE, the experience of architecture spaces approaches the level of those of the real and physical world. When using a VE to measure user's reaction to architecture spaces we need to ensure that people's behavior in the VE is the same as it would have been if they were in the real space. Studies have been done relating both the interaction in VE and in real space (e.g., Witmer, 1996).

RESEARCH HYPOTHESES

This exploratory research aims to investigate in a quantitative way the influence of architectural elements (i.e., stairs and ramps, with and without handrails) on the comfort of use of a built environment, namely considering the fear of falling reported by older persons while using these architectural elements.

The main hypothesis considered to design this study is that architectural spaces activate emotional reactions in its inhabitants and those reactions may be objectively classified by capturing physiological data (i.e., skin conductance, heart electrical activity). Considering this, we´ve drawn as hypotheses:

H1) Facing selected architectural elements (i.e., stairs and ramps, with and without handrails), within the virtual environment, will trigger a physiological activation that can be measured by sensing the Heart Rate, that is significantly different from the same type of physiological data acquired from neutral parts (i.e., rooms), and that can be related to the emotion of "fear of falling" reported by Tiedemann, Sherrington and Lord (2007);

H2) The physiological activation based in Heart Rate and the fear and anxiety of falling reported by the participants, will be higher for insecure situations (i.e., when the architectural elements are presented without handrail/railings).

Methodology and experimental design

An experimental methodology was adopted with a 2x6 mixed-design was considered to verify the hypotheses: i) A within-subject related to the architectural factor (6 elements: neutral room, stairs, ramp descending, middle of ramp descending, ramp ascending and middle of ramp ascending); ii) A between-subject related to the secure factor (2 experimental conditions called safe and unsafe conditions).

For the safe condition, a safety element (i.e., handrail or railing) was inserted in stairs and ramps presented in the VE. For the unsafe condition, the safety element was not available. The dependent variables were the physiological signals (i.e., heart rate - ECG, from where we derive the Heart Rate - HR) and the perceived fear. The methodology and procedures adopted for this study were in accordance with the approved ethical standards of the responsible committee on human experimentation (ISCTE-IUL Ethics Committee) and with the Helsinki Declaration of 1975, as revised in 2000.

Participants

Participants were recruited at two community centres in Lisbon, as volunteers. However a financial incentive for improvements in the institution was combined. They were selected considering the following admission criteria: i) Having 65 years old, or more; ii) Having normal sight or using corrective lenses; iii) Be able to stand up without support for a long period of time; iv) Do not have pacemakers; v) Do not suffer from claustrophobia; vi) Do not suffer from dizziness.

Before the experimental test, all participants were asked to sign a Term of Consent. Participants' physical or mental conditions that would prevent them from participating in a VR simulation were evaluated through self-report and direct observation by a researcher and by a community centre psychologist.

Thus, thirty-one older persons, between ages 66 and 91 years old (Mean (M) = 78.5; Standard Deviation (SD) = 7.2) participated in this study and were randomly assigned to the two experimental conditions. Due to issues related to data acquired by ECG data sensor, data from ten participants were removed and the final sample was twenty-one older persons between ages 66 and 91 years old (M = 77.6; SD = 7.4), randomly distributed across the experimental conditions.

Designing the virtual environment

For this study, a virtual building was developed in which participants were able to explore and experience the studied architectural elements (i.e., stairs and ramps, with and without handrails). This VE was developed based on requirements defined on systematic brainstorming meetings by the research team. It was established the existence of neutral rooms that would act as stabilizers of the participants' physiological signals, and that served as the baseline for comparisons with participants' physiological signals when facing the studied architectural elements. Thus, the designed VE consisted of: one first room with 30m long by 5.5m wide (neutral room 1 - Fig. 1); two flights of stairs with 12 steps each (0.28x0.18m) and 1.5m wide (Fig.2); one second neutral room (neutral room 2) with the same characteristics of the first neutral room; two flights of ramps with 10m long by 1.5m wide and 20% slope (Fig.3); one horizontal plane with 1.5m wide by 10m long (Fig, 4) and a ramp with the same dimensions and with 40% slope (Fig, 4 and 5); and finally, a third neutral room (neutral room 3) also similar to the first neutral room. Stairs and ramps were designed according to standard construction regulations.

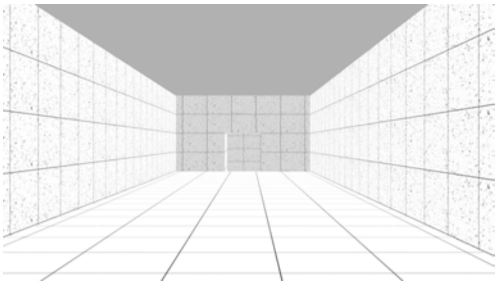


Figure 1
Screenshot from Neutral room

It was decided to use a grey concrete texture for all walls that included a rectangular frame simulating the concrete formwork. All floors had a grey scale as well and a square pattern simulating floor tiles. These finishings were selected to simulate a regular environment. Lighting was also constant for all environment with 5 light points inserted. All of them with the same attenuation factor (linear/quadratic = 0) and falloff distance (25m).

For the unsafe condition, the VE was presented to the participants as described. For the safe condition, handrails were inserted alongside stairs and ramps. Screenshots from the safe and unsafe conditions can be seen at Fig. 2, 3, 4 and 5, respectively left and right.

For training purpose, it was developed another VE, in which two neutral rooms were connected in a "L" shape. The same textures and navigational strategy were used for this training environment so that users were already familiar with the process.

Experimental settings

A semi-immersive VR setup called PocketCave was used for this experiment, in which images were projected on a 4m x 3m screen by a stereoscopic projector (DepthQ HDs3D-1), and visualized with active glasses (nVIDIA® 3DVision(TM)2). The observation distance (i.e. the distance between the observers' eyes and the screen) was 3.50m. The virtual camera had 45° of horizontal field of view (FOV) and 33° of vertical FOV, approximately. Participants could navigate through the virtual environment using a joystick (Logitech Extreme 3D Pro) with a constant displacement speed of 0.82m/s (Patel et al., 2006). Our approach requires the direct access to the software engineering development life-cycle and code (being able to propose and develop handy features and improvements) to serve the requirements of the experiment described in this paper. Therefore, instead of a market-standard software system, we used the CAVE Hollowspace (Soares et al, 2010), fully developed and maintained in-house by our research team.

Instruments for data collection

The data for this experiment was collected using the following objective and subjective assessment instruments.

Objective assessment using non-invasive sensors: Heart Rate - derived from ECG - three electrodes, with 0.8cm of diameter, placed on users' chest with specific gel patches as indicated by Simões et al. (2012). The sensor detects the electrical impulses generated by the polarization and depolarization of the natural heart tissue.

Subjective assessment:

- Participants' Perception - a retrospective questionnaire with images of the virtual environment in selected points (i.e., top of stairs, top of ramp, beginning of the plan and middle of the ascending ramp). A Likert-type scale (Likert, 1932) with seven points (1= nothing; 7=very much) was used to evaluate user's perceptions of fear of falling.
- Sense of Presence - Some items from Presence Questionnaire (Witmer & Singer, 1998) and from SUS questionnaire, based on the authors' research Slater, Usoh & Steed (1994), were applied to evaluate the sense of presence.

Experimental protocol

The experimental session was divided in two parts, prospecting and experiment. For the prospecting part, a researcher went to the community centre to talk with potential participants about the research goals, to collect their signature on the term of consent for the ones that fulfil the admission criteria and ask them to fulfil a demographic questionnaire. The study goals were only partially told to the participants. For them, the main objective was to know their opinion about a new designed building. No reference was made about studying the fear of falling. This omission aimed at preventing any influence on the data collected and related to this variable. This first part occurred one week before the experiment. In the experiment part, the participants were brought to the PocketCAVE room in our lab. The average duration of this second part was approximately 7 minutes for the VR experience and 15 minutes for fulfilling the post-hoc questionnaires. At the beginning of the experiment, the researcher reminded the participant about the study's objectives. Each participant was asked to remain standing in a pre-defined location (approximately 3.5 m away from the projection screen). The ECG sensors were installed on the participant at the same time that the researcher explained that sensors would be used to collect data related to their heart rate.

Participants started with a training session using

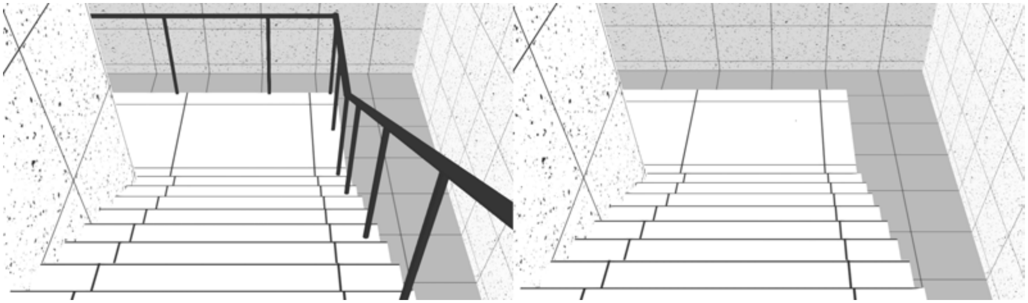


Figure 2
Left image shows a screenshot from the stairs for the safe condition and right image shows the same stair for the unsafe condition.

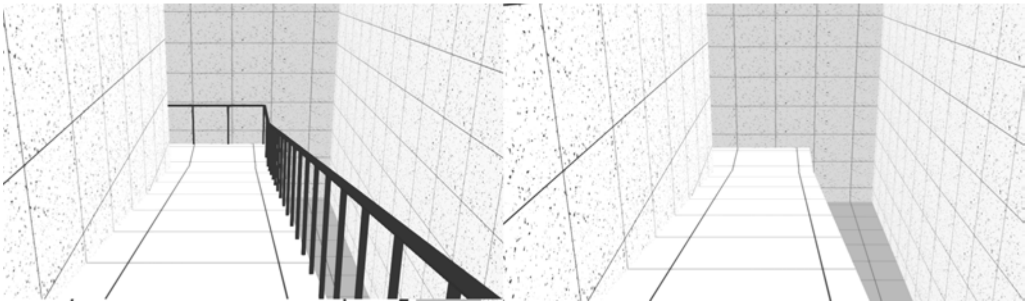


Figure 3
Left image shows a screenshot from the ramps for the safe condition and right image shows the same ramp for the unsafe condition.

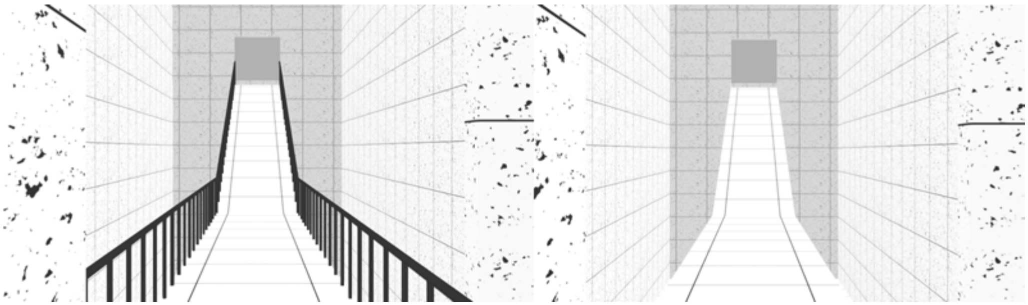
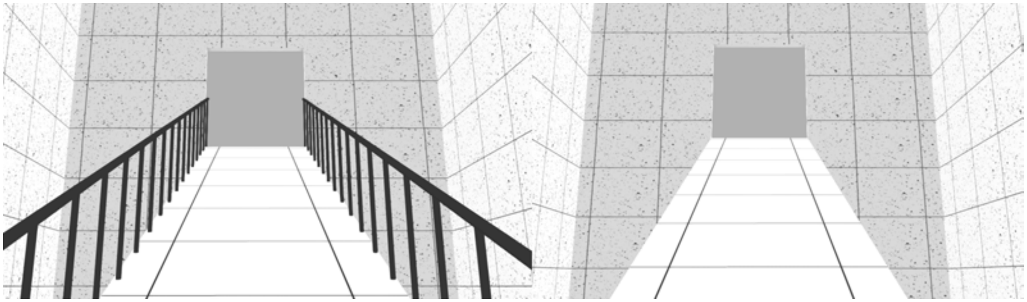


Figure 4
Left image shows a screenshot from the horizontal plane with the ascending ramp for the safe condition and right image shows the same horizontal plane with the ascending ramp for the unsafe condition.

Figure 5
Left image shows a screenshot from the ascending ramp for the safe condition and right image shows the same ascending ramp for the unsafe condition.



the VE developed for this purpose. During the training, some explanations about the experiment and the equipment involved were given. The main objectives of the training session were: 1) familiarize participants with the simulation setup; 2) allow them to practice the use of navigation and visualization devices; and 3) homogenize differences in the participant's performance using a joystick.

For the virtual building experience, participants were randomly signed to one of the two experimental conditions (i.e., safe and unsafe), in a balanced way. Participants were instructed to navigate through the building until reaching the end (as it was a controlled navigation, all participants followed the same path with the same field of view), and that the simulation would automatically stop when it ended. The virtual experience ended when participant reached the third neutral room.

After finishing the VR experience, the participants were taken to a room in which s/he should answer to a post-hoc questionnaire. First, a retrospective experience was made showing screenshots of the VE and questioning about their feelings of fear. After this, the presence questionnaire was applied.

RESULTS AND DISCUSSION

The main dependent variables were the participants' Heart Rate and participant´s declared Perception of Fear of Falling considering the architecture spaces. Only participants with valid data (n = 21) were considered for analysis. All statistical analyses were conducted using the significance level set at .05.

The participants' declared Perception of Fear of Falling was assessed through a 2x4 mixed ANOVA with condition (i.e., safe and unsafe) as the between-subjects variable and, architecture elements (i.e, stairs, ramp descending, ramp ascending and middle of ramp ascending, neutral space), as the within-subjects variable. The results showed significant differences in fear of falling between the two conditions "safe" (M = 1.77; SD = 1.24) and "unsafe" (M=3.27; SD = 2.46). Thus, the ANOVA revealed a significant main effect of condition (F1,19) = 13.062; p = 0.002; η^2=0.41), with participants declaring less fear in architecture spaces with handrails (safe condition). This result may indicate that when controlled process of information (Schneider & Shiffrin, 1977) are active, participants rationalize the information and are able to distinguish between secure and unsecure situations considering the presence of a safety element (handrails or railings). In this way, the presence of a handrail overlap any difference in the perception of fear that could exist among the studied architectural spaces. In fact, results show that users recognize and point out stairs and ramps without handrails as being insecure places to be.

Regarding the objective assessment, HR (Heart Rate) was derived from the ECG, through automatic detection of the heart R peaks and RR (peak to peak) intervals, followed by a manual inspection of the resulting HR signal. The HR was then analysed between conditions (i.e. safe and unsafe) and between several

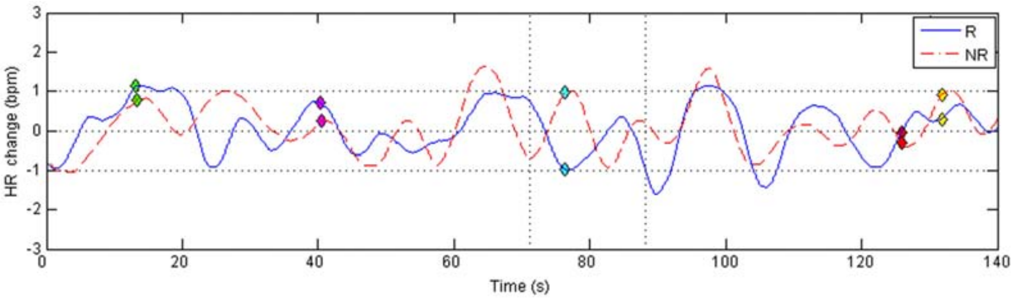


Figure 6
Mean Heart Rate changes for continuous sessions with railings (R) and without railings (NR), during the entire VR experiment. Each marker corresponds an event (architectural location) of interest, respectively and orderly: the beginning of the stairs; the entry to the neutral room; the entry to the first descending ramp; the start of the ascending ramp; and the middle of it. The two vertical dot-lines highlight the precise moments where detected, through our approach, statistical significance between conditions.

events (i.e. triggered at specific architectural locations) marked throughout the VE. A simple one-way ANOVA was performed and we used the HR change (i.e. the difference between HR averaged 5 seconds before one event and the HR averaged 5 seconds after the event), to measure the heart accelerations and decelerations, which are an indicator of arousal.

For the analysis of between-subjects variable (safe/unsafe condition), we compared the 9 valid subjects from the no-railings (unsafe) condition with 9 subjects chosen randomly from 12 valid ones from the railings (safe) condition, for the sake of balanced analysis. Although we have not observed any statistical significant differences between conditions in the precise events of interest, we have detected statistical significance in two moments near those events, by allowing a certain offset: 5 seconds before the entry to the descending ramp ($p = 0.04$), which corresponds to the third marker in Fig.6, where there is a distinct HR deceleration preceding a HR acceleration for the No-railings case; and 12 seconds afterwards ($p = 0.014$) in a corner between two descending ramps, where, in Fig. 6, we observe a distinct HR deceleration, for the railings condition, whereas the HR in the no-railings tends to be constant around this period. In a long time-window analysis (Fig. 6), the mean HR signal from the Railings seems to be out of phase with the one from the no-railings, in several moments of the experience. Therefore there is a distinct HR behaviour between conditions; while in one condition the HR is accelerating the other is decelerating. However, we acknowledge that the statistical significance in these moments is highly sensible to the random selection of subjects for the test sample.

For the analysis of within-subjects variable (i.e., architectural elements events depicted in Fig.7), there is very strong statistical significance ($p<0.01$), in the reported measures. In this case, we neglected the safe/unsafe conditions due to the non-significance mentioned before. Significant high arousal was observed at the beginning of the stairs ($p < 0.01$) and at the middle of the ascending ramp ($p < 0.01$) comparative to the neutral room. In Fig.7, we can visualize consistent HR accelerations in the stairs' event and a slight but steady HR acceleration for both (railings/no railings) conditions.

A Mann-Whitney test was used to verify differences between conditions (safe and unsafe) in the four selected items of Witmer and Singer (1998) questionnaire. No significant differences between conditions for any of the items was found (the degree of naturalness of navigation: M=6.1, SD=1.3, $p=0.460$; rate of adaptation to VR experience: M=5.7, SD=1.5, $p=0.219$; awareness of the presence of devices: M=1.8, SD=1.8, $p=0.062$; distraction caused by control devices: M=1.2, SD=0.9, $p=0.209$), with high levels of presence declared by participants considering naturalness and adaptation to VR. That means the participants had the same degree of presence in both conditions, allowing us to conclude that the VR-setup used for this experiment prevents that the results could be influenced by differences in the sense of presence.

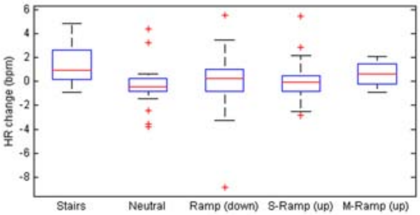


Figure 7
Boxplot of the HR change between the neutral room and locations: the beginning of the stairs; the middle of the neutral room; the entry to the descending ramp (D-Ramp); the beginning of the ascending ramp (A-Ramp 1); and its middle (A-Ramp 2). The outliers plotted individually were properly handled using the winsorising technique.

CONCLUSIONS AND FUTURE WORK

The pilot study aimed at testing the way physiological measuring via Heart Rate analysis, can describe the fear of falling often sensed by older persons in specific architecture spaces (e.g. stairways and ramps). It was hypothesized that when confronted with different architectural spaces and elements, older users would have different physiological activations and perceptions of fear of falling. In this way, objective and subjective assessments were conducted to verify this assumption.

The results discussed in the previous section are in line with psychology literature which elects the use of stairs as one of the most challenging tasks for older users (Tiedemann, 2007). In fact, as verified in this pilot study, the beginning of the stairs and the middle of the ascending ramp presented higher differential arousal (relative to the neutral room) than the other studied architectural locations. When considering the participants' declared perception of fear of falling, significant differences were found considering safe and unsafe situations, with no influence of specific architecture spaces (e.g. stairways and ramps). It could be related with the two types of information process (Schneider & Shiffrin, 1977) and our results are consistent with this theory, since they show that the objective measures detected the most instant and automatic answers and there is no rationalization of the stimulus in the environment. Thus, participants had physiological arousal between architectural elements (stairs, ramps and neutral rooms). However, when participants were asked about their perception of fear, probably they became more conscious about all aspects of the environment, mainly the safety element (the handrail). It could be mediated by the controlled information process, which made them reporting more fear considering the lack of the handrail in whole condition instead of thinking about each architecture space.

These attained results correlating both (objective) biometry and (subjective) declared perception of fear of falling, allow us to conclude that the first hypothesis of this pilot study was partially verified. Results shown that when older users interact with specific architectural elements as ramps and stairs, there was a physiological reaction, reaching levels of arousal with an intensity in the HR signal, that was higher than the ones achieved with the experience of a walk through a regular (neutral) room. The second hypothesis was also partially confirmed since differences were only undoubtedly verified when perception of fear of falling declared by the participants was considered. The objective analysis did show some evidence in the same direction, but we acknowledge that its statistical significance is highly sensible to the random selection of subjects for the test sample and could not be fully confirmed. For older adults, architecture spaces without handrails are perceived as more insecure, which can lead them to avoid this spaces. In this way, we can consider the handrail not only as a physical element for safety, but also as an element that diminishes the fear of falling and increases the self-efficacy, which tends to increase the quality of life (Feder, Cryer, Donovan & Carter, 2000).

Our findings raises several interesting research questions: i) Can the changes of psychological reaction caused by the fear of falling, be measurable by ECG sensors? ii) Is the psychological reaction to fear of falling, influenced by being tested in a VR environment and would it be different if tested in a real environment?

As for i) we do believe we are in the right track and the promising results pave the way for further experiments with a larger sample size. Additionally, complementary data from other physiologic measures (such as from Electrodermal Activation - EDA, Electroencephalogram - EEG, Skin Temperature and Respiration Rate) should be considered, in analysing the same variable (fear of falling), to reinforce the validation of the hypotheses raised in this study, in the line of other research teams (Carey, 2014) [1].

As for question ii), we are convinced that in a real environment users could potentially show a higher physiological activation difference when confronted with the two different conditions (with or without handrails). However, the design of a real-life experiment that observes the "fear of falling", brings ethical and safety challenges and even accident-causing situations that might be difficult to overcome, hence our preference in VE experiments.

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