

DESIGNING BETTER SPACES FOR PEOPLE

Virtual reality and biometric sensing as tools to evaluate space use

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Abstract. We present a pilot study aiming to explore the use of biometrics sensing technology within a semi-immersive VR environment, where users face architectural spaces which induce them sensations close to fear of heights, claustrophobia, frustration and relief. Electrodermal activity was used to detect users' emotional arousal, while navigating in VR. Navigation conditions and participants' expertise with games were controlled. Main results show that physiological measurement of user's perceptions can discriminate well "positive" from "negative" spaces, providing designers with basic information on people's emotional state when using the buildings they design.

Keywords. Virtual reality; computational design; human-computer interaction; space perception; biometrics sensing, electrodermal activity.

1. Introduction

The presented research comes from the premise that user's evaluation of the architectural design is of utmost importance so that buildings and public spaces answer to the real needs of future users. The authors are especially interested in evaluating the usability and impact of architecture space on its inhabitants, by studying their perception, emotional state, empathy and engagement while experiencing the space. Getting such feedback data informs the design process since it directly answers the user's needs and furthermore allows to re-evaluate designs before they get built. The main goal of our research is therefore to improve architectural design by understanding the emotional response to the designed space, of potential inhabitants. To achieve this goal firstly several experiments will be undertaken and the collected data will be analyzed to systematize user's behaviors in architecture spaces and then to infer general and specific design principles. In our approach, the architecture space being studied is represented by means of a semi-immersive Virtual Environment (VE) testbed, where constructive and non-constructive variables (e.g. sound, lighting, shadowing and wind) can be simulated. Users' physiological data from where we derive arousal conditions, is collected through electromyography (EMG) and electrodermal activity (EDA), supplemented by an after experience questionnaire. Our multidisciplinary team gathers 3D Computer Graphics, Virtual Reality, Human-Computer Interaction, Architecture and Psychology researchers, and this work is in the scope of a collaborative initiative which aims at developing Ambient Assistive Living (ALL) technologies for elderly and people with reduced mobility, to enable them to live with more independence, mobility and safety.

This paper is divided in five main sections. In section 1, we provide a context on the related work. In section 2, we define our methodology for the user study. In section 3, we describe the undertaken user experiment in detail. Section 4 presents and discusses the obtained results and finally, in section 5, we draw some conclusions and present some lines for future research.

2. Related Work

When we experience spaces that escape the signs and language system that characterize the cultural spaces to which we are more accustomed to, our conscience of the world that surrounds us is awakened, our senses arouse and emotions take place (Merleau-Ponty 1968). This phenomenon happens e.g. when someone stands before an unknown environment, an organic geometry space, a convergent or divergent space, a narrow space or an unsteady pit, among others, or otherwise spaces that forsake the cultural paradigm that

most fell comfortable with. These spaces may provoke sensations or emotions such as fear, claustrophobia, agoraphobia, vertigo or joy in the seeking of the basic instinct of survival and welfare levels for man's safety and comfort. In this context, Immersive Virtual Reality (IVR) emerge as state-of-the-art technology that, as the literature shows, has been recommended to be integrated in the architectural design process as a useful tool (Kieferle 2001), (Stenson 2012). With the adoption in IVR of physiological sensors, such as EMG, EDA, ECG - Electrocardiogram or EEG Electroencephalogram, it is now possible to perceive the user's emotional state. It has been shown (Bradley et al, 2001) that skin conductance changes and cardiac decelerations are strongly correlated with emotional arousal, whereas facial EMG provides means to identify the specific emotional valence (joy, sadness, anger, fear, disgust, surprise). According to (Ferreira et al. 2012), it is possible to design architecture spaces regarding the emotions that they can generate in the users and this strategy maximizes their psychological well-being, promoting health improvement. Biometric sensing has also been useful in IVR to study phenomena such as presence (Meehan et al 2002) and embodiment (Maselli and Slater 2013). In embodiment experiences, users present physiological reactions, such as, stress, anxiety or fatigue, to arousing situations or threats to the representation of his/her avatar (that is perceived as his/her own body) in the virtual environment. Our approach is to use an IVR system fully developed in-house (Soares et al 2010), since the access to the development lifecycle, allows us the customization of the design, of the visualization process and the incorporation of new natural and multimodal user-interaction paradigms, such as biometric sensing.

3. Methodology of User Study

We conducted a pilot user study whose main goal was to classify the users' response to environmental visual stimuli, by means of biometric sensory data analysis, that considered, as our main hypothesis (H1), that basic user sensations of "comfortable/positive" and "uncomfortable/negative" architectural spaces can be derived through objective measurements of biometric data (i.e., skin conductance, surface electromyography). Two secondary hypothesis were formulated: H2) the navigation condition (free or controlled) will influence the participants' response to the environmental visual stimuli; H3) the participants' expertise in games will influence their response to the environmental visual stimuli. To verify these hypotheses, a VR-based methodology was developed considering four fundamental stages:

1. Identify the architectural elements that are more suitable to induce opposite user sensations, such as of "comfortable space" (or "positive space") and "uncomfortable space" (or "negative space");
2. Design a VE where those elements are the only visual factors of the space;
3. Perform experiments with users interacting with the VEs, while being monitored by EDA and EMG sensors;
4. Process and analyse the sensory data to understand if statistically significant differences can be found in the classification and differentiation between "comfortable – positive" architectural space and a "uncomfortable – negative" one;

4. Experimental Set-up

4.1. The Virtual Environment

A 3D model of an indoor architectural space was designed to be used as the interaction environment, with the aim to create visual stimuli able to induce arousal responses during the users' navigation in the VE, in selected locations where spaces were designed to exceed their neutral reactions. Although these "negative" environments aren't usually created in real architectural design practice, our aim was to observe peak (limit) reactions that would give us a wide scale of physiological measures. The reactions we were looking for, were related to sensations of comfort and discomfort towards space use. The designed spaces explored dizziness and fear (stairs, moats, gaps), claustrophobia (narrow corridors), surprise (large room after a narrow corridor) and disappointment (dead-ends).

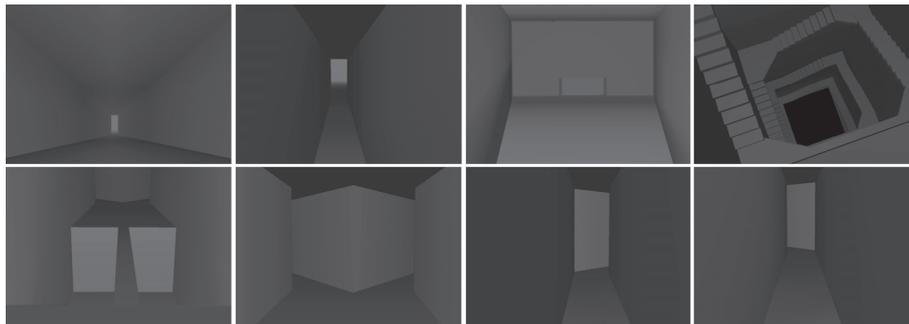


Figure 1. Designed VR Environment, each picture shows one particular space in the visiting order, from left to right, top to bottom: starting hall, passageway, foyer, stairway pit, narrow bridge, bifurcation, first dead end, second dead end.

To provoke limit reactions that could be identified with one particular characteristic of the space, several archetype spaces were chosen and designed for the experiment: a very deep moat around which several flights of stairs

were displaced; a deep gap that users have to overcome through a narrow board; a very narrow corridor; a sequence of spaces inducing an accelerated perspective; a dead-end space (Fig. 1). To minimize the effect of visual stimuli other than the selected ones (i.e., the environmental stimulus), neither objects, nor colours or textures were used in the model, resulting in an illuminated grayscale environment. We used an ambient abstract sound with very few variances and with a constant rhythm, with the purpose of keeping the user focused on the experiment. We believe that the soundscape created was good enough not only to mask distracting sounds but also to reinforce the idea that the user was experiencing an abstract environment.

4.2. EXPERIMENTAL SETTINGS

To simulate our VR environment we used a semi-immersive VR system (referred to as PocketCave), composed by an active stereoscopic projector (DepthQ 3D), with a resolution of 1280x720 pixel at 120 Hz, and a large screen of 320x213 cm. The participants were observing the VE 3.5 m away from the screen, allowing a 50° field-of-view visualization experience. The experiment's participants experienced the VE using active stereoscopy technology granted by a pair of active stereo glasses and an infrared sync device (i.e. NVIDIA 3D Vision). To allow participants interacting with the VE, we set a 5:1 surround sound system and a navigation model based on the Nintendo Wii remote, using the Wii-Nunchuk's accelerometers to control the virtual camera's orientation and the joystick to control the forward/backward navigation movement. In each experimental session, EDA and EMG data were captured using an acquisition system from Plux (2013). All sensors, consisting of bipolar electrodes, were attached to the skin using self-adhesive surfaces. In the case of EDA, a pair of electrodes was attached to the palmar surface of the index and middle finger. Regarding the EMG, 5-pairs of electrodes were placed in the subject's face to explore activity in the main mimic muscles (e.g. Zygomaticus, Corrugator Supercilii, Masseter). Subjects were seated during the experiment, in a resting position. All sensors were connected to an amplifier A/D converter device, which in turn was connected, via Bluetooth, to the computer where the PocketCave was running. This allowed us to know the exact moment in the sensor acquisition stream when the avatar in the VE, entered a virtual location of interest (Fig. 1). Every time the avatar entered such a location, a specific distance-trigger was activated in our system signalling, via shared memory, the application where the sensor data was being captured, thus generating a timestamp of a VR location event. Our aim was to evaluate each subjects' sensations/emotional responses in the vicinity of these locations by selecting only time-samples in the neighbour-

hood of those moments, according to an appropriate time-window. In total, 8 distance-triggers were placed in the 3D scene, one in the beginning of the experiment; one in the entrance of the narrow and claustrophobic passageway; one in the beginning of the foyer; one at the arrival to the stairway pit; one when the avatar passes through the narrow bridge; one when the avatar reaches a bifurcation; one in the right dead-end and one in the left dead-end.

4.3. THE PARTICIPANTS

Eighteen volunteers aged between 21 and 53 (6 male and 12 female) were randomly assigned to the experiments divided in two groups: gamers and non-gamers. Gamers condition reflected the participants' expertise in first person shooter (FPS) games e.g. Counter-Strike, Unreal Tournament, Half-Life, Resident Evil, etc. Non-gamers condition was related to the participants that do not had experience in FPS games or only had an experience on those games several years ago. These conditions were considered because we predicted that a different reaction to the designed environmental stimuli could occur. Gamers could interact with the VE more like a fun and/or unreal experience, diminishing the effect of the environmental stimuli over their perception about the environment. In free navigation conditions these participants were expected to have skills that would allow them to have a deeper sense of presence. On the contrary, non-gamers were expected to have a more immediate and true reaction while navigating through the VE. Non-gamers were expected to introduce "noise" in the captured data if, e.g. they were in stress when controlling the free navigation interface (e.g Wii) within the environment. Participants had normal sight or corrective lenses and reported no physical or mental impairments that would prevent them from participating in the study.

4.4. EXPERIMENT DEVELOPMENT

Experiments undertaken included sessions of about 30 minutes each. Two experimental conditions were defined: participants in controlled navigation (6) and participants in free navigation (12). For the free navigation condition, participants could freely explore the VE, so they could look and move around controlling their motion by themselves. For the controlled navigation condition, a selected path performed by one of the researchers was recorded and presented to the participants. In this condition, participants did not interact actively with the simulation, instead, they experienced VE like a movie. The controlled navigation took 2 minutes. The successful free navigations took an average of 2 minutes and 30 seconds and 3 minutes at most. It was predicted that a free navigation (virtual head and body motion controlled by

the participant) could increase the sense of presence and be closer to a real experience, potentiating their reaction to the environmental stimuli. However, the possibility of having non successful experiments due to the low interaction skills of the participants and lack of control in their point of view in the VE, could difficult robust results and its comparison. A pre-recorded path enables a more controlled and successful experience as it guarantees that all participants have the same viewpoint when facing the selected environmental stimuli, enhancing the validity of the study. However, it could also diminish the immersion as participants could feel as they are only watching a movie. We then decided to test both navigation conditions and try to understand through data analysis, what was to be expected from both approaches.

5. Results and discussion

All types of captured biometric signals, were first visually analysed in search for a common pattern between subjects. As depicted in Fig.2, we observed that there is a clear event-related skin conductance response in most subjects. On the other hand, facial EMG signal proved to be quite variable and requires more research and analysis. Some subjects did not show any muscle activation, possibly as a result of self-inhibition, while others showed strong activation in the Zygomaticus area (lip raiser), around the event timing, but few showed expected muscle activation (e.g. Corrugator supercilii, Masseter, Mentalis) related to expected negative emotions, namely, anger or fear. As described in Section 3.1, samples from EDA data around VR events were compared. Based on a consensus of physiological measures and post-experiment questionnaires, we compared samples from a "positive space" (i.e. foyer) with each of the two spaces ranked as the most "negatives" (i.e. stairway pit and the narrow bridge). In order to compare inter-subjects skin conductance responses (SCR), we first smooth the raw data (Fig. 2), then apply a first derivative and use only the positive derivatives as representative of SCR. This processing sequence results in a signal invariant to the skin conductance level (SCL), natural of each subject. Furthermore, one can observe in Fig. 2, that the SCR amplitude is strongly proportional to the subject's skin conductivity baseline. To deal with this phenomenon, the resulting signal is filtered and finally divided by the correspondent average SCL. We define this last signal as $[C]_+$. The SCR comparison is hence done by subtracting the average $[C]_+$ of one time-window from another. A time-window length of 5 seconds was used for controlled navigation and a length of 10 seconds for free navigation. To check for significant differences, we first transformed the data using a square root function to meet a normal distribution and homogeneity of variance, and then we computed the *p-value* using one-way ANOVA.

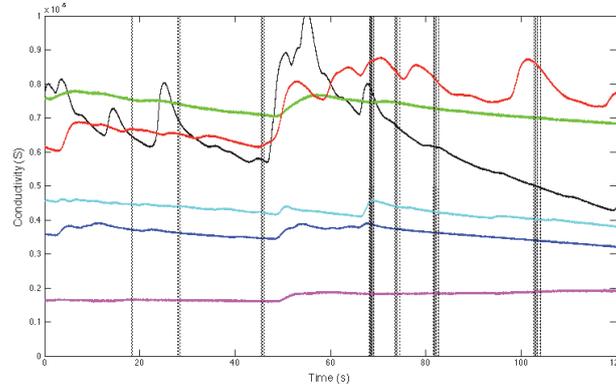


Figure 2: Raw skin conductivity signal (EDA) overlapped for 6 subjects, in controlled navigation experiments. Each vertical line corresponds to one time instance when a trigger-VR event was detected. Rapid changes are visible around trigger 3 and trigger 4 respectively the stairway pit and the narrow bridge. Offsets between the response and the event timing were taken into account when sampling the events.

Table 1: Electrodermal-response significance and mean difference between: stairway pit and foyer; narrow bridge and foyer. Mean $\Delta[C]_+$ is the mean difference of the processed SCR between 2 spaces, for all subjects of the experience. # Negatives is the number of subjects whose $\Delta[C]_+$ is not positive. We consider statistical significance for a p-value below 0.05.

Navigation	Match Up	mean $\Delta[C]_+$	# Subjects	# Negatives	p-value
Controlled	stairway - foyer	28.02	12	0	< 0.001
	bridge - foyer	7.40	11	0	< 0.001
Free	stairway - foyer	2.88	6	1	0.067
	bridge - foyer	4.04	4	1	0.016

As reported in Table 1, the differences in SCR between the VR locations of interest are statistically significant ($p < 0.001$) for all our subjects in the Controlled Navigation. The only condition where significance could not be tenable was between the stairway pit and the foyer ($p > 0.05$) for free navigation. In general, the stairways pit provoked the strongest arousal. However in free navigation, we have observed that subjects avoided facing the pit in the stairway, hence the weak response reported. The unbalanced number of participants per-navigation, was due to users following alternative paths or failing in the VR, which resulted in 6 aborted sessions. We also report for controlled navigation, non-significant differences between gamers and non-gamers ($p \gg 0.05$) for all 3 virtual locations of interest (foyer, stairway pit, bridge).

Each user was asked to fill a survey about the experiment he/she took. This survey enabled us to obtain their subjective perception about the spaces. For each space users had to choose one adjective from the following three

pairs: happy/sad; pleasant/unpleasant; confident/fearful. From the sample of 18 users, 4 were considered invalid because they didn't answer all the questions.

Based on subjective data analysis (Table 2), the foyer is the space most related to positive sensations, followed by the starting hall and the bifurcation. The second dead end is the place mostly related to negative perceptions, followed by the claustrophobic passageway, the first dead end, the narrow bridge and the stairway pit.

Table 2: Surveys' results (percentage). The results are presented individual and grouped. There are two groups: Positive including happy, pleasant and confident and Negative, including sad, unpleasant and fearful. Abstention (total data) - 8,63%

	Happy	Sad	Pleasant	Unpleasant	Confident	Fearful	Positive	Negative
starting hall	12,82	17,95	23,08	12,82	20,51	12,82	56,41	43,59
passageway	5,26	26,32	13,16	23,68	7,89	23,68	26,31	76,39
foyer	27,50	5,00	32,50	2,50	27,50	5,00	87,50	12,50
stairway pit	18,42	13,16	13,16	23,68	2,63	28,95	34,21	65,79
bridge	19,44	11,11	5,56	27,78	5,56	30,56	30,56	69,44
bifurcation	5,41	21,62	18,92	18,92	18,92	16,22	43,25	57,89
1st dead end	5,26	26,32	7,89	26,32	15,79	18,42	28,95	71,05
2nd dead end	0,00	27,78	0,00	36,11	11,11	25,00	11,11	88,89

6. Conclusions and future work

Our experimental results support our basic research hypothesis (H1). Data analysis from EDA sensing in controlled or free navigation, which focused in the observed differences between the foyer and the stairway pit and, the foyer and the narrow bridge, shows that the skin conductance response of all but 1 participants, have statistically significant ($p < 0.05$) differences when they experience a space (foyer) that 87,50% of them consider "positive", where they fell happy, pleasant or confident, relatively to when they experience spaces that 65,79% of them (for stairway pit) or 69,44% of them (for narrow bridge) classify as "negative", with emotions of sadness, unpleasantness or fearfulness. The only condition where statistical significance could not be justifiable, was between the stairway pit and the foyer ($p > 0.05$) in free navigation, most likely because subjects didn't face the pit in the stairway, minimising the visual stimulus. Although the results show that the mean difference of the processed SCR data for all subjects, between "positive" and "negative" spaces, is higher in controlled navigation, we observed also statistical significant differences between foyer and the narrow bridge (for 4 subjects) in free navigation. Therefore our Hypothesis H2 is not verified. This suggests that the illusion of presence and arousal situations can be induced both in controlled and free virtual navigations, although more research is needed to support this assumption in the free navigation condition.

Finally, we also reported, non-statistically significant differences between gamers and non-gamers ($p \gg 0.05$) for all 3 virtual locations of interest (foyer, stairway pit, bridge), therefore discarding our hypothesis H3, which suggests that although gamers are accustomed to VR, this fact do not influence their capacity to feel emotions in such settings. With this work, we've shown that with EDA sensing, we can objectively discriminate arousal responses related to "positive" or "negative" emotions, from the neutral condition, when users are confronted with architectural spaces in VR. On-going research considers less exaggeration on negative design but uses an established range of values that this experiment highlighted. In upcoming VR experiments, we want to resume EMG studies and include Heart Beat Rate (derived from ECG) and EEG, to conclude on the emotions of the user while experiencing an architectural space. Another goal is to record the position of the user and the direction where he/she is looking at, possibly using eye tracking sensing. This data will be used to confront the virtual reality perception of space with space syntax theories on accessibility and visibility.

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