Psychological and physiological human responses to simulated and real environments: A comparison between Photographs, 360° Panoramas, and Virtual Reality

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1. Introduction

Environmental simulations acquire a relevant role in environmental psychology as they allow us to recreate and study in isolation and in a controlled way the effects of space on human experience (Sheppard and Salter, 2004). The validity of these simulations is related to its capacity of evoking a participant's response similar to the one that the space it is simulating would (Rohrmann and Bishop, 2002). This logic is based on 'behavioural realism': the context in which an environmental simulation is better the more similar the user will respond to it compared to the represented environment (Freeman et al., 2000). In this sense, new environmental representation technologies address this issue through the improvement of the sense of presence, (Sanchez-Vives and Slater, 2005), the visual experience (Lovett et al., 2015), and the interaction with the represented spaces, allowing users to freely act within them (Appleton et al., 2002).

Overall published validity results show that simulations tend to evoke a user's response similar to those for physical environments (Villa and Labayrade, 2012). However, these studies have some limitations, being one of the main ones obsolescence of the studied systems: the constant proliferation and iteration of these technologies (Rohrmann and Bishop, 2002) reveal the importance of critically and comparatively updating the validity of the main formats for the most common current platforms (de Kort et al., 2003). Another serious limitation concerns the neglect of some subjective aspects of user experience: the majority of studies compare responses in terms of preference, without deepening into the set of cognitive-emotional psychological states behind it (Bishop and Rohrmann, 2003). A third limitation stems from the scarcity of studies incorporating the subject's objective response in the validation. Given that most estimation, thought, emotion, and learning are produced at the unconscious level (Zaltman, 2003), validity studies must be performed using new metrics and methods to measure these components (Gill et al., 2013). Thus, traditional scientific measurements may not be sufficient to evaluate new and future platforms (Orland, 2015) and so, any validation of these new systems should address these limitations.

The present work aims to respond to the previously mentioned limitations in order to validate environmental simulation display formats (photograph, 360° panorama, and virtual reality) through subjective judgements (psychological) and objective measures (physiological). Thus, the fundamental goal of the study is to understand which one of the three display formats gives the closest approximation of experience in physical environments by carrying out a comparative validation. Specifically, the questions that we intend to address are twofold: (a) are psychological and physiological responses evoked to the simulations similar to those resulting from exposure to physical environment? and (b) are these simulations capable of generating a strong sense of presence? These results may be of interest to researchers using environmental-simulation technologies currently available to replicate the experience of physical environments.

1.1. Background Research

1.1.1. Simulated environments display formats

Simulation tools are becoming rapidly incorporated into human factors fields (like military training, medical education and improvement of the industrial processes) because of their scientific and commercial possibilities through a combination of new platforms and formats (Lange, 2001). The most used formats in environmental simulations are photography and Virtual Reality (VR).

Photography captures physical-world images using light. Within this format one must differentiate between photograph and 360º panorama. The former is the most widely used because of its visual realism capabilities and ease of use. The validity of this format has also been extensively explored (Stamps III, 1990), especially in landscape studies (Hull IV and

Stewart, 1992), in which strong correlation has been identified between psychological responses and physical environments. This format, typically displayed by means of printed images and more and more often by means of screens, represents a possible limitation: the distortion of the user's response because of the effect of certain environmental factors such as noise or visual distractions. Nowadays there exist display systems which eliminate this effect, such as the head-mounted display (HMD). This is a fully-immersive system which allows us to isolate the user's senses from the external world. A higher degree of immersion provokes a greater sense of presence, understood as a perceptual illusion of non-mediation, only quantifiable by the user experiencing it (Baños et al., 2004; Diemer et al., 2015). Despite HMD has been designed to visualize other types of formats, such as 360º panorama or VR, also allows to visualize photographs. 360º panorama is currently widespread in environmental simulation (Jacobs, 2004) and allows interesting syncretism between photographic techniques and VR (such as Google Street View), making them more interactive, and even immersive when combined with a HMD. However, regarding its validity, no research analogues have yet been developed and so it has only been assessed in terms of spatial knowledge acquisition by using desktop and HMD simulations (Napieralski et al., 2014).

VR offers the possibility of generating computer representations which give the feeling of 'being there' (Steuer, 1992) in an interactive environment which overrides the other sensory information the user receives. In this way, VR acquires a relevant role in certain fields in which the interaction is important, such as medicine (Jack et al., 2001), product design (Ye et al., 2007), environment design (Frost and Warren, 2000) or education (Germani et al., 2012). However, despite its increasing implementation in different fields, the studies which mention its validity are still scarce: for example, studies focusing on projection platforms (de Kort et al., 2003), qualitative research at the behavioural level using a desktop platform (Murray et al., 2000), and although not interactively, work on computer-generated videos (Bishop and Rohrmann, 2003). Another interesting studied effect in this validation of the VR is the possible effect between environment and presentation order (Kuliga et al., 2015). In general, the results show that there are no significant differences in psychological user's responses compared to those evoked by physical environments, although further research is still required (Lange, 2011). At another level, we also found studies comparing features of VR-based set-ups: screen size, stereoscopy, and field of view, etc., in terms of their effects on understanding and presence (Zikic, 2007), the level of detail or realism in spatial understanding (Nikolic, 2007) or the comparison between different set-ups based on a set of metric performances for mechanical design learning (Mengoni et al., 2011).

1.1.2. Psychological human response

Within the psychological measurements, the Küller and Mehrabian–Russell models stand out; these describe the affective and emotional states related to the impact the environment has on individuals. On the one hand, there are eight Küller dimensions: affection, complexity, enclosedness, originality, pleasantness, potency, social status, and unity (called "SMB", from Swedish "Semantisk Miljö Beskrivning" meaning semantic environmental scale; for further description see: Küller, 1991, 1980). These dimensions have been used for very different purposes, such as analysing diverse workspaces (Janssens and Küller, 1989), evaluating the effect of colour in these spaces (Mikellides, 1989), or comparison of different traditional environmental simulation set-ups during planning and design (Janssens and Küller, 1986). On the other hand, there are three Russell–Mehrabian emotional dimensions: pleasure, arousal, and dominance (called "PAD" emotional state model, for a more complete description see: Mehrabian, 1989). These currently form part of a widely accepted conceptual framework on emotion (Plutchik and Kellerman, 1980). The first applications of these dimensions were in environmental psychology, and they have been widely accepted in architecture studies

(Gifford et al., 2000; Higuera-Trujillo et al., 2017). Moreover, they have been extended to applications such as the design of avatars in the VR field (Zhang et al., 2007) and the creation of virtual spaces capable of evoking emotional states in a controlled way (McCall et al., 2016). Therefore, both models are fundamental for assessing psychological judgments of spaces.

Another issue for the psychological analysis of simulated-environments is presence, which is usually measured via post-activity questionnaires (Slater and Wilbur, 1997). While there are other means to measure this aspect such as psychophysical or qualitative methods, questionnaires are the most commonly used because of the advantages they present: validity, low cost, and ease of management and analysis. One of the most widely used is the SUS questionnaire (after Slater, Usoh, and Steed; for further description see: Slater et al., 1994) which measures the extent of three aspects: the participant's sense of being inside the simulated environment, the degree to which the environmental simulation is considered the dominant reality, and how far the simulated environment is remembered as a place (Usoh et al., 2000). The current version of the questionnaire consists of six items rated on a Likert scale of 1 to 7, and the final score is taken as the absolute number of items which scored 6 or 7 (i.e. score range 0-6). This questionnaire has been used in studies on the relationship between presence and performance in VR (Youngblut and Perrin, 2002) and in comparisons between the level of immersion using different platforms (Juan and Pérez, 2009; Slater et al., 2000).

1.1.3. Physiological human response

Knowledge of the human response to the environment can be completed by using physicological measurements (Reinerman-Jones et al., 2013). In this regard, Izar (1992) argues that cognitive-emotional states are characterised by both psychological and physiological responses. This registration capability is especially relevant when considering that going beyond concious control (Winkielman et al., 2001) is more objective than self-reporting (Reinerman-Jones et al., 2010). There are different techniques for registering this response which cover the central, autonomous, and somatic nervous systems (Bagozzi, 1991).

In our case, we decided to study the autonomous nervous system, and specifically electrodermal activity (EDA) and electrocardiogram (ECG) measurements, because, besides being able to capture response patterns in emotion (Kreibig, 2010), they have other greater advantages for the purposes of studying validity. In particular, these techniques can register measurements through portable and minimally-invasive devices, and altogether they quantitatively record sympathetic and parasympathetic nervous system activity related to the generation of states of activation and relaxation, respectively (McCorry, 2007).

EDA measures variation in electrodermal properties resulting from sweat generation (Boucsein, 2012). Although sudomotor activity plays an important role in other bodily processes, it is also related to sympathetic activity (Dawson et al., 2007). Its analysis allows us to break it down into: slowly-varying *tonic* activity, which refers to the basal level of conductance; and fast-varying *phasic* activity, concerning responses to stimuli. Among previously published work using this terminology, some studies have identified an increase in tonic (Ritz et al., 2000) and phasic activity (Blechert et al., 2006) when users were presented aspects related to arousal, with phasic activity sometimes receiving greater interest (Braithwaite et al., 2013). In contrast, ECGs are the graphic representations of electrical heart activity (Goldman, 1976). Heart Rate Variability (HRV) can be calculated from this data, and the analysis of the frequency domain can be broken down into two subsets: high frequency or HF (0.15-0.4 Hz), widely accepted as being related to parasympathetic nervous system activity, and low frequency or LF (0.04-0.15 Hz), which, although more complex, is related to the sympathetic nervous system (Berntson et al., 1997). This recording system has previously been used to observe responses to the valence of certain stimuli (Rantanen et al.,

2013) and aspects related to arousal, resulting in a relationship being identified between increased Heart Rate (HR) (Adsett et al., 1962) and LF domain (Murakami and Ohira, 2007). However, to date, neither EDA nor HRV have been used to study the validity of environmental simulations, they have been used in VR studies. Thus, EDA has been used as a metric to examine the effect of certain affective states in generating the feeling of presence (Felnhofer et al., 2015), and HRV has been used to study the influence of virtual- or physical-category stimuli in generating stress (Kothgassner et al., 2016). Given that registry of these responses is compatible with those offered by traditional metrics (Reimann et al., 2010), there is reason to believe that they could provide deeper insight in validation studies.

2. Materials and Methods

The experiment was conducted in a single session and aimed to uncover the extent to which different display formats produce the same user response as a physical environment. Table 1 presents a summary of the experiment divided into two phases, each one corresponding to a different objective. Phase 1 is focused on the analysis of the psychological and physiological responses. For this purpose, we used SMB and PAD psychological models, and EDA and HRV physiological measurements. Phase 2 comprises the analysis of presence by means of SUS presence questionnaire. For the development of the experience four environmental set-ups were generated (physical environment, photograph, 360° panorama, and VR). A display system compatible with the three display formats to be compared with the physical environment was selected: head-mounted display.

2.1. Environment Set-Ups

We selected an interior shopping environment, because previous work has already evaluated the realism of this type of environment and the employed questionnaires had already been validated (Machleit and Eroglu, 2000; Stone and Congdon, 2007). This environment is also sufficiently complex to evaluate spatial features, and its dimensions and characteristics make it ideal for generating a virtual environment.

Hereunder we describe the fundamental characteristics of the different environment set-ups used, being set-up understood as the group of technological devices, display format and interaction modality forming each experience.

- Physical environment set-up: a physical mock-up of the environment was built in our research space; this comprised a 4.5m × 4.5m white room with a door, a window, and two sales shelves opposite to each other containing several beer brands. Participants walked freely all over the physical environment.
- Photograph environment set-up (Figure 1A): a monoscopic digital photograph with a resolution of 1280 × 720 pixels, taken with a GoPro Hero3+Silver camera. The shot was taken in the centre of the mock-up room at a height of 165 cm to simulate eye level. As technological device, a Samsung Gear VR HMD was used. Due to the fact that the ability of traditional photography to capture the entire environment and to interact is limited, the most representative viewpoint was chosen (Hetherington et al., 1993).
- 360º panorama environment set-up (Figure 1B): a 360° × 180° equirectangular monoscopic photograph with a total resolution of 4096 × 2048 pixels, based on photographs taken with seven GoPro Hero 3+Silver cameras coupled to a stationary base for panoramic recording. Shot was taken in the same position and height as the one used for the standard photograph. As technological device, a Samsung Gear VR HMD was used. The participant's interaction consisted on the tracking of the head orientation by means of the gyroscopes and accelerometers of this device.

- VR environment set-up (Figure 1C): an interactive tridimensional simulation developed by means of the Unity game engine (Unity3D 5.1; https://unity3d.com/). The model was generated in SketchUp 2015 (http://www.sketchup.com), and the textures were extracted from the physical environment to achieve maximum realism. The designed environment contained 15.546 polygons and 112 textures. As technological device, a Samsung Gear VR HMD was used. Participant's interaction consisted on the tracking of the head orientation of this device, and the navigation all over the environment using a wireless joystick.

As it has already been mentioned, a HMD was used in these experiments. It is a fully-immersive virtual environment, following Rangaraju and Terk's classification (2001), which isolates the user's senses from the external world, generating the greatest sense of presence and immersion in the user. This display system has rapidly evolved in the last few years, being no longer difficult to control nor expensive devices (Parsons, 2015). This explains why HMDs are becoming protagonists in the ongoing emergence of several different applications (Javidi and Tekalp, 2017). In this study, the main advantage is that they enable us to comparatively validate three display formats regarding the physical environment, as it they homogenize the experience with regard to the display system used. Specifically, as technological device a Samsung Gear VR was used because of its portability. It consistes of a mobile VR headset with a stereoscopic screen (1280 × 1440 pixels per eye), 96° field of view, supported by a Samsung Note 4 mobile telephone with a 2.7GHz quad-core processor and 3GB of RAM.

2.2. Dependent Variables

Different sets of variables were assessed within each phase and they were evaluated in the same sequence for the four set-ups (three format displays and physical environment), except the presence analysis, which was not employed in the evaluation of the physical environment. A summary of the questions asked for each phase of the experiment is presented in Table 2.

2.2.1. Phase 1. Analysis of the Psychological and Physiological responses

a. Analysis of the psychological response

A questionnaire was designed to collect two data sets on a 7-point Likert scale: the first consisted of the eight affective appraisal dimensions from the SMB scale, and the second comprised the three dimensions from the PAD emotional state model.

b. *Analysis of the physiological response*

We measured EDA and HR signals in this experiment by using a portable physiological wristband device (E4 wristband, Empatica; www.empatica.com). EDA data was sampled at 4Hz (0.001-100 μS) and HR was acquired at 64Hz by photoplethysmography.

2.2.2. Phase 2. Analysis of Presence

The validated SUS presence questionnaire consisted of six items on a 7-point Likert scale and it was used to assess the participants' sense of presence in each display format.

2.3. Participants

One hundred individuals took part in the study; the participants were balanced in terms of age (23-51 years, $\mu = 32.68$, $\sigma = 7.00$) and gender (54% male, 46% female). The required number of participants was determined using statistical methods (Faul et al., 2007), calculations indicating that 25 respondents per stimuli would be sufficient to achieve the desired alpha and beta error levels. In this way, a group of 25 different subjects was set to evaluate every set-up.

The selection criteria were that participants must not be familiar with the scenes or suffer from claustrophobia, epilepsy, or nausea because three-dimensional immersion technologies can be harmful in such cases (Sharples et al., 2008). During the physiological signal acquisition, some data were lost (because of participant movement or wristband failure) resulting in a lower final sample number.

2.4. Procedure

The individuals were given a brief explanation of the experiment and signed their informed consent to participate. They were then instructed on how to use the technology, and those assigned to the VR format practised moving through the virtual 3D environment (a room without furniture or decorations specifically designed for this training) so they could get used to navigate it before starting the experiment.

At the beginning of the study, each participant sat down, put on the E4 wristband, switched it on, and listened to a two-minute relaxing audio through headphones to create a common state of baseline calm. When the audio ended, the subjects stood up and they were shown the assigned scenario (either they were placed the HMD in case of photograph, 360º panorama and VR, or they were accompanied to an adjoining room where the physical set-up was located). In any case the subject was standing during the assessment of the set-up.

The stimulus was always starting at the same point and angle of vision, and the participants examined the environment in detail for three minutes. During this time, the subject explored the space on unconstrained gaze and movement, taking into account the possibilities offered by the set-up to be evaluated. In this manner, the subjects evaluating the photograph could only visualize; the ones evaluating the 360º panorama could visualize other angles from the same point of view; the ones evaluating VR could navigate all over the environment; and the ones evaluating the physical environment walked freely all over the space.

Finally, after three minutes and while the subject was still looking at the stimulus, the researcher orally asked the questions on the questionnaire.

2.5. Data analysis

2.5.1. Psychophysiological data pre-processing

For each participant, the raw EDA and HR data were gathered both during the relaxing audio (baseline) and stimuli visualisation.

The EDA signals were pre-processed and analysed with an EDA analysis toolbox (Ledalab® V3.4.8, www.ledalab.de), run in Matlab (2012a; www.mathworks.com). Pre-processing consisted on a visual diagnostic of artefacts and their corrections. Continuous Decomposition Analysis (Benedek and Kaernbach, 2010) was used applied to the cleaned signal to extract the phasic component. Data was exported into Matlab for each participant and condition (baseline and stimuli) to calculate the means and standard deviations. To reduce inter-subject differences all the values were standardised using an adaptation of the Venables and Christie formula "y = log(1+|x|)·sign(x)" (Venables and Christie, 1980).

HR signals were pre-processed and analysed using a HRV analysis toolbox (HRVAS V2014-03-21), run in Matlab. The Welch method for frequency analysis (Welch, 1967) was used to calculate the absolute values for each participant and condition for the HF (0.15-0.4 Hz) HRV band, expressed in normalised HF (nHF) units (Camm and Malik, 1996) which are correlated with parasympathetic activity (Berntson and Cacioppo, 2004).

Once that Phasic-EDA and nHF-HRV mean values were computed for each participant and condition (1. baseline and 2. stimuli), every stimulus value was standardised over its previous baseline value to acquire individual *within subject* variations that could be exported to our statistical software package. The final values for each participant are:

- Phasic-EDA = (mean Phasic-EDA stimuli / mean Phasic-EDA baseline)
- nHF-HRV = (mean nHF-HRV stimuli / mean nHF-HRV baseline)

Therefore, these two variables represent the response before application of the stimulus in proportion to the pre-stimulus baseline.

2.5.2. *Statistical analysis*

Both the questionnaire and pre-processed psychophysiological data were imported into SPSS (v.22) for statistical analysis.

For Phase 1, average dependent variable values were standardised over “physical” stimuli values to simplify the comparison between different display formats. In this way, these measurements show if the dependent variables for each display format are rated over or under the physical environment. Furthermore, the average of these values was obtained in absolute value, to indicate global accuracy (the more accurate the format, the closer it is to 0). This value was labelled as “closeness”.

Non-parametric Mann–Whitney U tests were carried out to identify any statistically significant differences between each pair of simulation and “physical” condition data. Finally, partial correlation, controlling for the “stimuli” variable, was executed to examine possible relationships between the psychological and physiological responses.

For Phase 2, presence data were treated according to the Slater, Usoh and Steed methodology: the “SUS presence” score is taken as the absolute number of answers that have a score of 6 or 7 (from six questions rated from 1 to 7), to produce a final score ranging from 0 to 6 which was standardised to a 0-1 range. In addition, because the SUS presence score manipulates data in a non-linear way, in order to examine correlations with it, a direct score (presence) was recorded by summing all values from the presence questionnaire (ranging from 6 to 42) and standardising them to a 0-1 range.

3. Results

3.1. Phase 1. Comparison of Psychological and Physiological Responses to the Physical Environment

3.1.1. *Analysis of psychological responses*

Figure 2 shows the means for each variable (eight affective attributes and three emotional factors) and format analysed in relation to 'physical' environment (all values were standardised to the "physical" values: mean = 0 and SD = 1). Overall, the 360° panorama tends to slightly overestimate values for the physical environment (the 'potency' and 'originality' values stand out) while VR and, especially, the photograph, tends to underestimate them. Moreover, all the formats clearly overestimated 'arousal' and underestimated "dominance" compared to the values for the physical environment. The 'closeness' score was 0.38 for the 360° panorama, 0.53 for VR, and 0.93 for the photograph, which gives the accuracy rank in relation to the physical environment.

The paired Mann–Whitney U tests also found statistically significant differences in two out of eleven factors for the 360° panorama, four for VR, and eight for the photograph (Table 3). Thus, regarding affective attributes, participants' responses significantly differed from that evoked by the physical environment only in 'Originality' for the 360° panorama, 'Unity' and 'Enclosedness' for VR, and 'Pleasantness', 'Unity', 'Enclosedness', 'Potency', and 'Affection' for the photograph. In relation to emotional factors, participants' responses significantly differed from that produced by the physical environment only in 'Dominance' for the 360° panorama, 'Arousal' and 'Dominance' for VR, and 'Pleasure', 'Unity', 'Arousal', and 'Dominance' for the photograph.

3.1.2. Analysis of physiological responses

Figure 3 shows the means for the Phasic-EDA and nHF-HRV for every format analysed in relation to the 'physical' environment (all values were standardised to the 'physical' values: mean = 0 and SD = 1). The 'closeness' score was 0.08 for VR, 0.36 for the 360° panorama, and 0.46 for the photograph, which gives the accuracy rank in relation to physical environment.

The paired Mann–Whitney U tests (Table 4) also found a statistically significant difference between the photograph and physical environment in the Phasic-EDA component.

3.1.3. Analysis of the relationship between psychological and physiological responses

Partial correlation between the psychological and physiological responses, controlling for the "stimuli" variable (Table 5), identified relationships between Phasic-EDA and 'pleasantness' ($\rho = 0.426$, $\alpha = 0.002$), "enclosedness" ($\rho = -0.331$, $\alpha = 0.016$), and 'pleasure' ($\rho = 0.314$, $\alpha = 0.023$). No correlations were found for nHF-HRV.

3.2. Phase 2. Analysis of Presence

Figure 4 presents the unitarized means (the sum of the answers to the six questions) for 'presence' and the 'SUS presence' (the absolute number of answers with a score of 6 or 7). The 360° panorama produced the highest sense of presence, closely followed by VR, and finally, by the photograph which had an extremely low score.

The partial correlation test (Table 6) also identified relationships between 'presence' and SMB scale 'pleasantness' ($\rho = 0.333$, $\alpha = 0.016$), 'potency' ($\rho = 0.348$, $\alpha = 0.011$), 'social status' ($\rho = 0.278$, $\alpha = 0.046$), and 'originality' ($\rho = 0.448$, $\alpha = 0.001$), as well as an inverted correlation between 'presence' and physiological nHF-HRV ($\rho = -0.348$, $\alpha = 0.012$).

4. Discussion

The purpose of this research was to comparatively validate three of the most common traditional and current environmental-simulation display formats: photograph, 360° panorama, and VR via an innovative HMD. With this aim in mind, we designed this study to assess both psychological and physiological human responses to environmental simulations compared to physical environments, and the sense of presence felt in these environments.

Psychology research into human factors frequently uses simulations instead of physical environments to assess psychological and physiological responses to environments. Although no platform or format can exactly reproduce physical environment (Moscoso et al., 2015), these environmental simulations have clear advantages for scientific purposes in controlled conditions. The validity of these simulations depends on the similarity of their results to those acquired by physical environment. Although there are many studies comparing display formats and systems, i.e. traditional vs. rendered images (Bates-Brkljac, 2009), images vs. videos (Stamps III, 2007), videos vs. virtual environments (Conniff et al., 2010), videos vs. physical experiences (Bishop and Rohrmann, 2003), or even different factors from a particular system such as screen size, stereoscopy, field of view (Zikic, 2007), level of detail, or realism (Nikolic, 2007), we could not find any studies that compare the generated response by the same simulated environment by means of different formats. Moreover, simultaneously recording both psychological and physiological responses, a fundamental aspect of studying the relationship between people and their environments (Küller, 1991), has not been seen previously used in this type of validation study. Thus, the fundamental contribution of this work lies in its combined technological and methodological innovations.

Specifically, the findings of this study are outlined in the following three main outcomes:

Firstly, we note that the 360° panorama and VR formats more closely approach the physical environment, both in terms of psychological and physiological responses, compared to the photograph. This may be because the participants could look around these environments, thus increasing their sense of presence (Alshaer et al., 2017). Regarding the psychological responses, 360° panorama led to the most accurate outcomes; this may be also linked to increased participants' presence, because it has previously been related to deeper emotional response (Riva et al., 2007). Concerning physiological responses, the VR format reached the closest approximation to physical life conditions, which may be due to the influence that interactivity has on the sense of presence (Haans and Ijsselsteijn, 2012), as there have been proven effects of free navigation at a neurophysiological level (Clemente et al., 2014).

Therefore, VR appears to be the most appropriate display when trying to evoke physiological responses in environmental studies (Rodríguez et al., 2015). Finally, the photograph format is the farthest from physical environment; although it is the most widely used format in environment-behaviour studies, it currently seems to be the least appropriate display option available. This brings the interesting possibility of replicating previous work which used photograph, using 360° panorama or VR formats, depending on the nature of the response to be studied.

Secondly, certain formats present a marked deviation from the physical environment in terms of some psychological responses. More specifically: in the case of the 360° panorama format, some dimensions, especially ‘originality’ and ‘potency’ tend to be overestimated; in the case of photograph, some dimensions are underestimated, such as ‘affection’, ‘unity’, ‘pleasantness’ and ‘pleasure’. Overestimation in the 360° panorama format may be because the platform-format combination (HMD - 360° panorama) produces a particularly polished experience which guides the user towards valuing the uniqueness of the experience more than their own environment, known as the ‘novelty effect’ (Bardo et al., 1996). Of special interest are the high scores in the ‘arousal’ dimension, especially in the VR format. This may be due to the format’s stereoscopy (Cho et al., 2014), or by motion sickness which can be provoked by navigation in this format (Reason and Brand, 1975). Conversely, it is worth highlighting the ‘dominance’ dimension, which presented significantly negative values in all three formats. This factor, which is related to safety or control of the subject in the environment, might have been negatively affected by a technological component, by the use of the HMD system, as well as methodological. The subject sees a displayed stimulus while receiving oral instructions from a researcher who they cannot see, which thus generates a lack of dominance. We must take into account that the received experience is a mixture of the simulated environment and the rest of the stimuli from the space where it is located (Loomis, 1992). On the other hand, in general, we observed a greater sense of presence, the higher the physiological response to the approximation was. This is consistent with certain authors who have indicated that presence is not only the feeling of 'being there' but also requires the users to act as if they were there (Sanchez-Vives and Slater, 2005), in such a way that the higher the users' feeling of presence, the closer their behaviour is to that in the physical environment (Kober et al., 2012).

Finally, with regard to the physiological measurement, two contributions must be highlighted. The first of them is the use of portable and minimally-invasive physiological recording technologies. This devices are increasingly improving: smaller, autonomous, inexpensive, and user-friendly, while remaining highly accurate and reliable (McCann and Bryson, 2009); leading to the current rapid applications in the area of human factors (Axisa et al., 2004). Secondly, it is worth noting the results provided by this physiological measurement tool and its significant correlation with some psychological responses. Importantly, its correlations with the 'pleasure' dimension and the feeling of presence especially stand out. Regarding the former is observable both in the Phasic-EDA and the nHF-HRV data, while the latter nearly reaches a significant level. This is consistent with other studies reporting HR deceleration (Christie and Friedman, 2004; Palomba et al., 2000; Schwartz et al., 1981) in response to visual stimuli aimed at generating contentment, and agrees with studies indicating an increase in the Phasic-EDA in response to amusement (Britton et al., 2006) or a state mixture of joy and pride (van Reekum et al., 2004). Regarding the feeling of presence, it correlates significantly and negatively with the normalised values of the nHF-HRV. Thus, our results coincide with previous studies which found a decrease in nHF-HRV as realism increased (Slater et al., 2009), and may replicate those described by Meehan, Insko, Whitton and Brooks (Meehan et al., 2002) which detected a correlation between an increase in HR and the feeling of presence. However, the results we present here differ from this latter study which found a correlation between EDA and the feeling of presence, albeit with certain limitations. This discrepancy might be due to the stressful nature of the stimulus used in the aforementioned study (a pit). Regardless of this, it is possible that these differences also partly resulted from the use of different systems to evaluate these metrics, and the complexity of defining and measuring the feeling of presence (Lombard and Ditton, 1997). Together, these correlations suggest that it is possible to develop models that can predict these psychological responses via EDA and HRV measurements (Dillon et al., 2002; Lee et al., 2006). Thus, an interdisciplinary research field that integrates neurophysiological bases with design and technology (Parasuraman and Rizzo, 2008) to improve the interface between humans and machines in different application domains is emerging (Liu et al., 2011).

In parallel, some limitations must also be considered, in particular, the restrictions of using a HMD platform and the study of a specific environment. Regarding the former, it was considered relevant homogenize the experience regarding the display system used for the evaluation of the three formats. It is possible that the results might differ if another display system or even another technological device were used. For example, if the 360º panorama had been visualized by means of a screen, it is likely that the previously mentioned 'novelty effect' would have been lost, minimizing the impact in the 'originality' dimension. On the other hand, if the VR experience had been developed in a cave automatic virtual environment (CAVE), it is possible that the observed lack of dominance while using this display would have been reduced, given the fact that the subject has greater control over the physical space around him. In another vein, it should be noted that when comparing the three formats we must consider that the photograph and 360° panorama formats are both photographs of real scenes, while VR is a modelled simulation whose level of realism is lower. Nevertheless, it is possible that at the current rate of progress VR will soon achieve a high level of photorealism (Lovett et al., 2009). On the other hand, it is possible that the obtained results are conditioned by the specific studied environment, so that when altering spatial properties or analysing a different space the results would be modified. There are scenarios that may seem singular in some of the dimensions of the study (for example 'originality'), and they are not adequately captured by a specific display format (for example by means of photograph). In future works, it would be interesting to replicate this study using different display set-ups or environments. Thus, for example, Augmented Reality is becoming increasingly significant and it is foreseeable its greater incorporation into studies analysing behaviour-experience-environment relationship. On the other hand, other neuroscientific methods such as electroencephalographic (EEG) would allow to expand the study of objective responses.

5. Conclusions

We presented a methodology for validating existing simulation-environment display formats (photograph, 360° panorama, and VR) using psychological and physiological human responses. The results suggest that 360° panoramas tend to obtain the best psychological outcome scores while VR scored the best for physiological measurements. In addition, we also found some correlations between psychological and physiological responses and the sense of presence. Specifically, we were able to predict the participants' pleasure experienced using the Phasic-EDA, and the feeling of presence using nHF-HRV. Our methodological contribution lies in the simultaneous measurement of the participants' psychological and physiological responses in such a way that the validation addresses the different aspects involved in the overall experience. Our results may also be of interest to researchers looking forward to take advantage of the visualisation technologies currently available to replicate the experience of physical environments in an investigative context.

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7. Conflicts of interest statement

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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TABLE LEGENDS

Table 1. Summary of the experiment.

Table 2. Summary of the questions posed in different phases of the dependant variable assessment.

Table 3. Differences between the psychological responses to the photograph, 360° panorama, and virtual reality set-ups compared the response evoked by the physical environment set-up.

Table 4. Differences between physiological responses to the photograph, 360° panorama, and virtual reality set-ups compared to the responses evoked by the physical environment set-up

Table 5. Correlations between the psychological and physiological responses, identified by partial correlation analysis, controlling for the “stimuli” variable.

Table 6. Correlations between presence and SMD-PAD and EDA-HRV responses identified using a partial correlation test.

FIGURE LEGENDS

Figure 1. Views from A) Photograph, B) 360º Panorama, and C) Virtual Reality scenarios.

Figure 2. Psychological responses to the Photograph, 360° Panorama, and Virtual Reality set-ups based on the SMB and PAD. Means standardised in relation to physical environment in which mean = 0 and SD = 1.

Figure 3. Physiological responses to the Photograph, 360° Panorama, and Virtual Reality set-ups. Means are standardised in relation to the responses evoked by the physical environment in which mean = 0 and SD = 1.

Figure 4. Mean Presence for the Photograph, 360° Panorama, and Virtual Reality set-ups, as measured on the SUS (after Slater, Usoh and Steed) scale.

Figure 1
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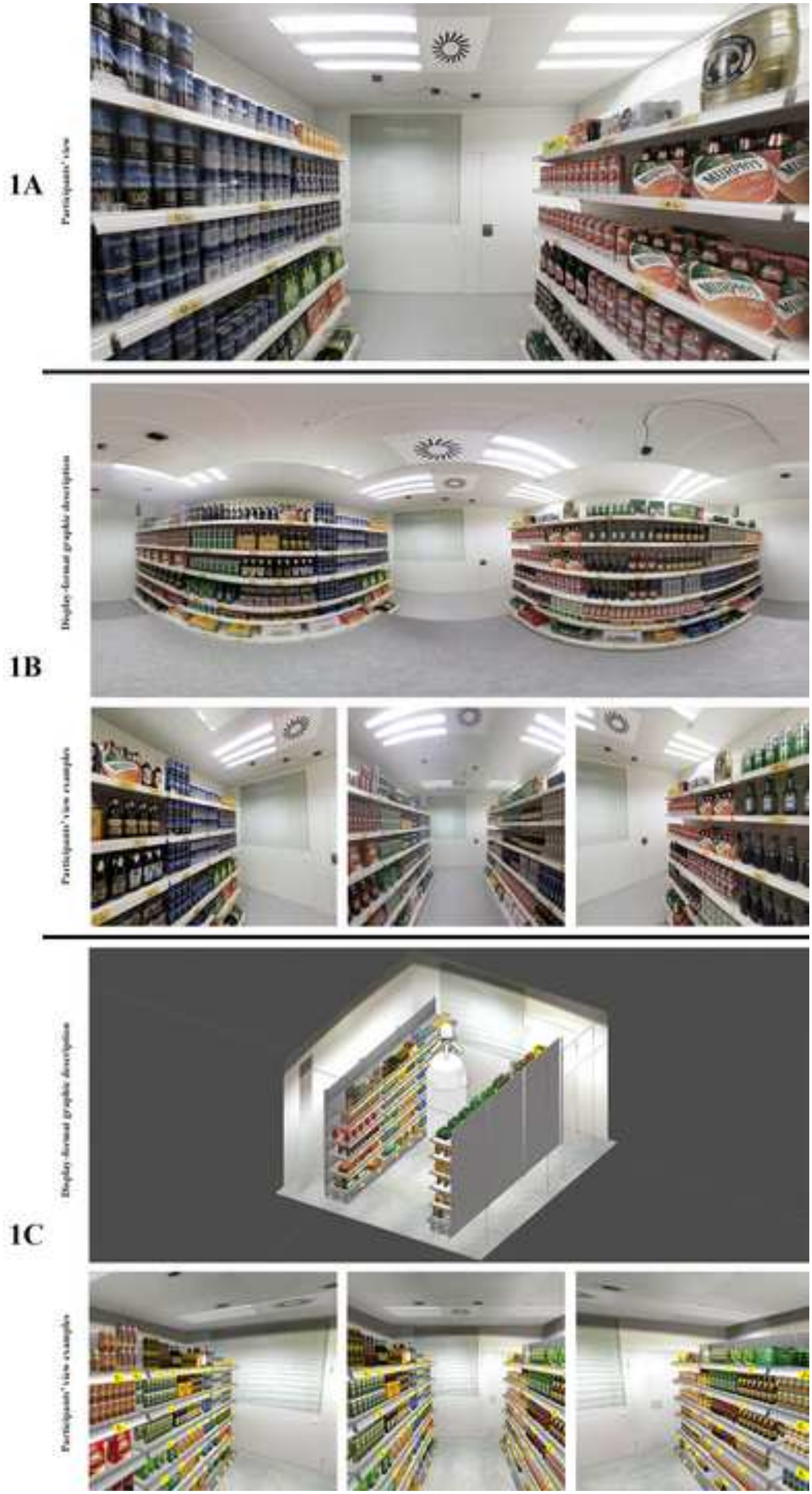

Figure 2
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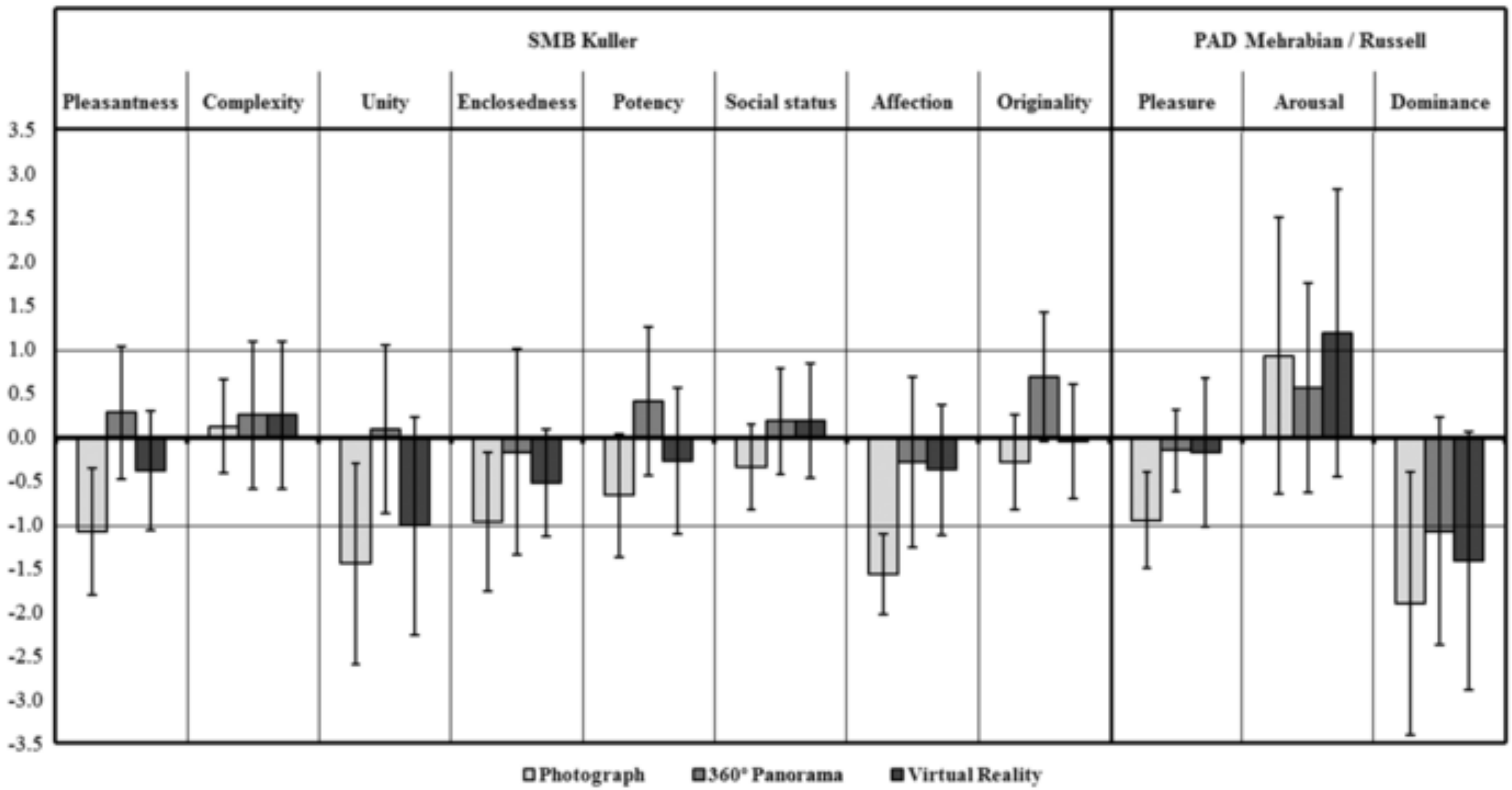

Figure 3
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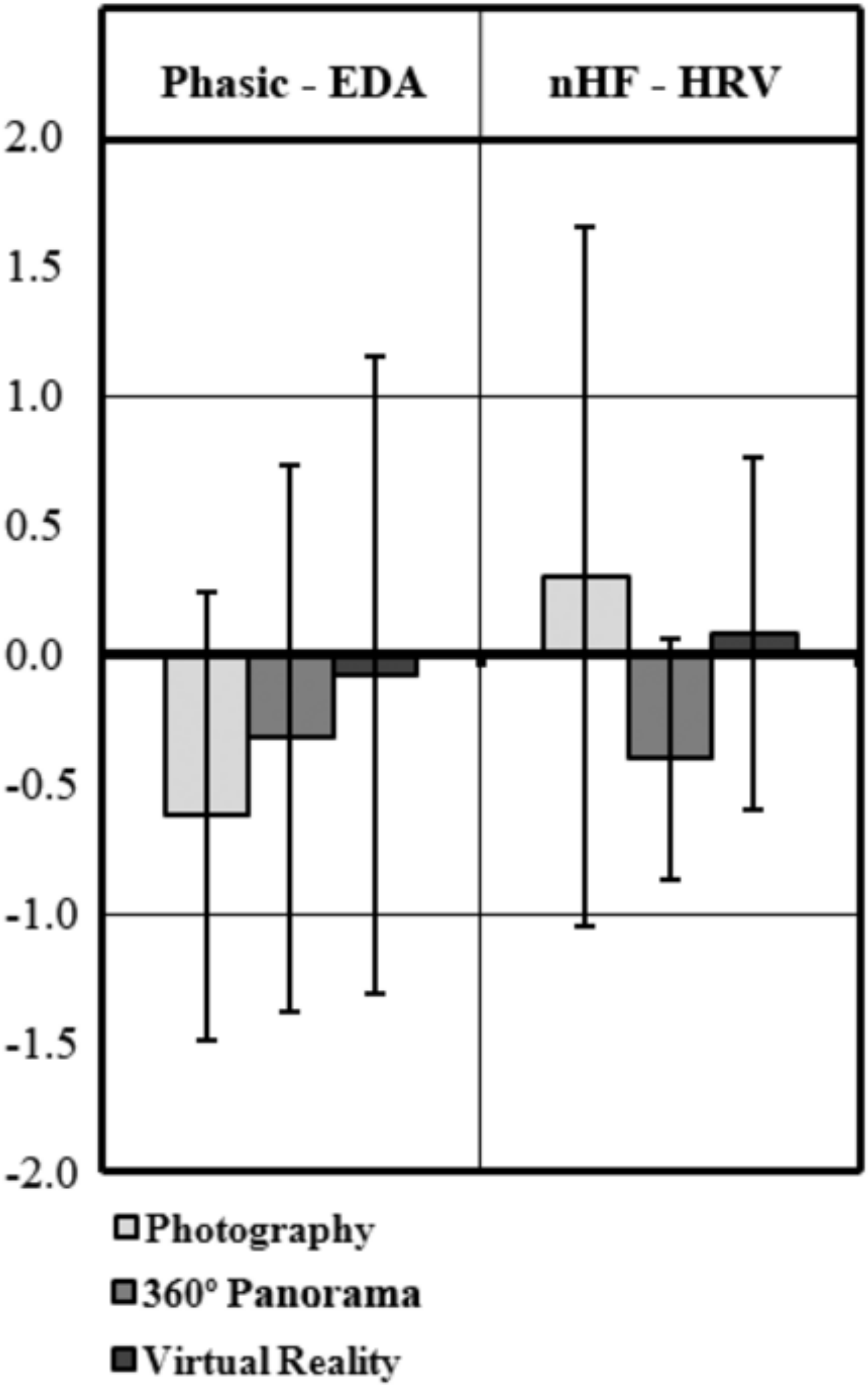

Figure 4
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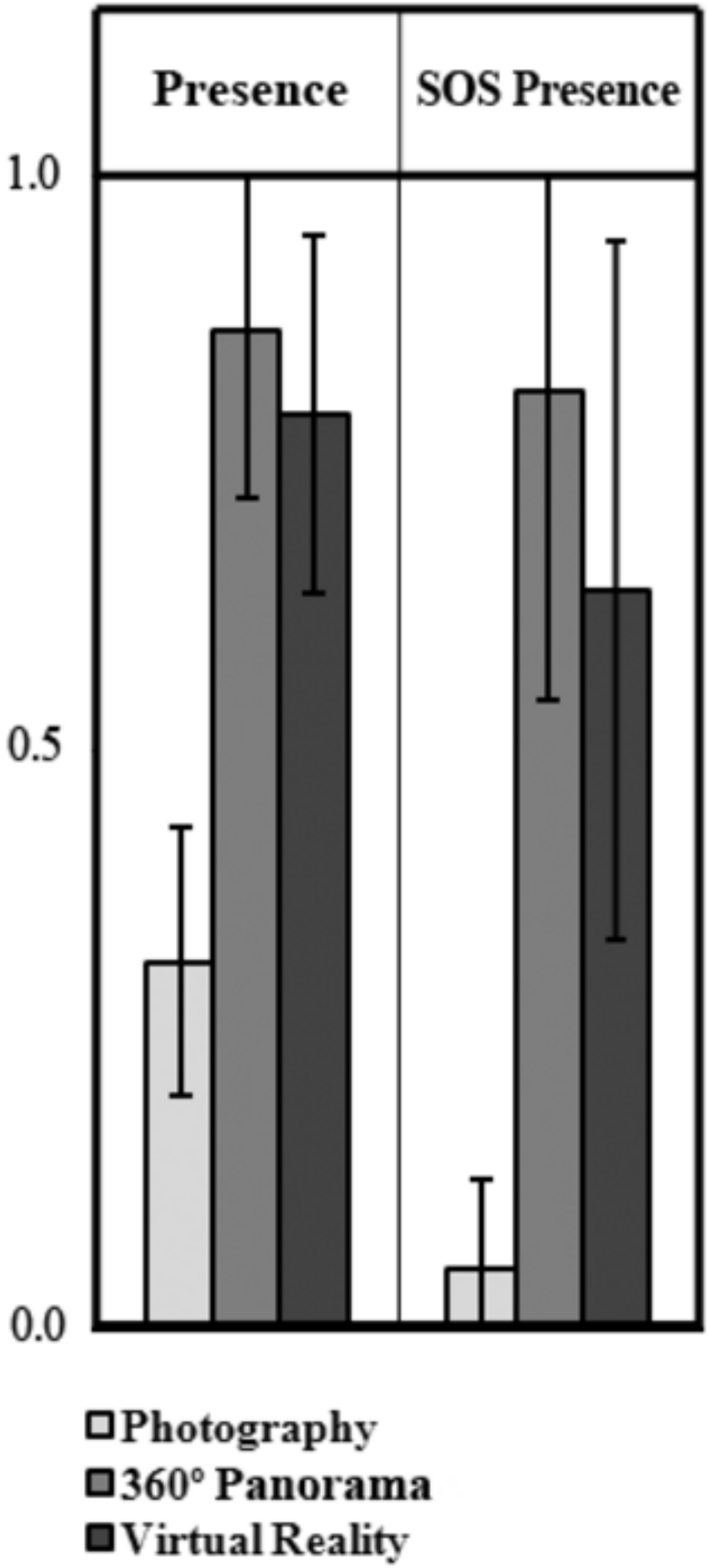

Table 1

Phase	Phase 1. Are responses to the simulations similar to those evoked when exposed to physical environment?			Phase 2. Presence
	a. Are subjective responses to the simulations similar to those evoked when exposed to physical environment?	b. Are objective responses to the simulations similar to those evoked when exposed to physical environment?	c. Are physiological responses capable of predicting psychometric responses?	Are simulated environments capable of generating a level of Presence similar to the physical environment?
Stimuli	Shopping Environment			
Display Format	Physical Environment / Photograph / 360° Panorama / Virtual Reality			
Display System	Samsung Gear VR Head-Mounted Display			
Dependent Variables	SMB PAD	Electrodermal Activity Heart Rate Variability	Correlation of EDA and HRV to the SMB and PAD	SUS Presence Test
Material	Survey	Empatica E4 wristband		Survey
Analysis	Mean analysis Mann–Whitney U test	Mean analysis Mann–Whitney U test	Partial correlation	Mean analysis Partial correlation

Table 1. Summary of the experiment.

Table 2

SMB scale for environmental assessment *(photograph, 360º, VR, physical env.)*		Rate the shopping space in terms of:
	1	Pleasantness: The environmental quality of being pleasant, beautiful and secure
	2	Complexity: The degree of variation or, more specifically, intensity, contrast, and abundance
	3	Unity: How well all the various parts of the environment fit together into a coherent and functional whole
	4	Enclosedness: A sense of spatial enclosure and demarcation
	5	Potency: An expression of power in the environment and its various parts
	6	Social Status: An evaluation of the built environment in socioeconomic terms
	7	Affection: The quality of recognition giving rise to a sense of familiarity
	8	Originality: The unusual and surprising in the environment
PAD emotional state model *(photograph, 360º, VR, physical env.)*		Rate your state in terms of:
	1	Pleasure: how pleasant or unpleasant you feel about the space
	2	Arousal: how energized or soporific you feel due to the space
	3	Dominance: How controlling versus controlled you feel due to the space
SUS Presence questionnaire *(photograph, 360º, VR)*		Rate:
	1	Your sense of being in the space, being 1. Not at all ... 7. Very much
	2	To what extent were there times during the experience when the shopping space was the reality for you? being 1. At no time ... 7. Almost all the time
	3	When you think back about your experience, do you think of the shopping space more as images that you saw, or more as somewhere that you visited?, being 1. Images that I saw ... 7. Somewhere that I visited
	4	During the time of the experience, which was strongest on the whole, your sense of being in the shopping space, or of being elsewhere? being 1. Being elsewhere ... 7. Being in the shopping space
	5	Consider your memory of being in the shopping space. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? being 1. Not at all ... 7. Very much so
	6	During the time of the experience, did you often think to yourself that you were actually in the shopping space? being 1. Not very often ... 7. Very much so

Table 2. Summary of the questions posed in different phases of the dependant variable assessment.

Table 3

		SMB								PAD		
		Pleasantness	Complexity	Unity	Enclosedness	Potency	Social status	Affection	Originality	Pleasure	Arousal	Dominance
Photograph vs Physical env.	U - Mann–Whitney	117.00	248.00	111.00	150.00	197.00	266.00	49.00	293.00	126.00	*201.00*	87.00
	W - Wilcoxon	442.00	573.00	436.00	475.00	522.00	591.00	374.00	618.00	451.00	*526.00*	412.00
	Z	-3.89	-1.30	-4.06	-3.29	-2.31	-0.95	-5.20	-0.39	-3.70	*-2.31*	-4.51
	Significance	0.00	0.19	0.00	0.00	0.02	0.34	0.00	0.69	0.00	0.02	0.00
360° Panorama vs Physical env.	U - Mann–Whitney	261.50	246.50	300.00	294.50	224.50	247.50	252.50	179.50	285.00	*224.5*	175.50
	W - Wilcoxon	586.50	571.50	625.00	619.50	549.50	572.50	577.50	504.50	610.00	*549.5*	500.50
	Z	-1.02	-1.32	-0.26	-0.36	-1.74	-1.29	-1.21	-2.62	-0.56	*-1.82*	-2.77
	Significance	0.31	0.19	0.79	0.72	0.08	0.20	0.23	0.01	0.58	0.07	0.01
Virtual Reality vs Physical env.	U - Mann–Whitney	234.00	249.50	171.50	208.50	280.00	246.00	226.50	294.50	284.50	*170.0*	135.00
	W - Wilcoxon	559.00	574.50	496.50	533.50	605.00	571.00	551.50	619.50	609.50	*495.0*	460.00
	Z	-1.58	-1.25	-2.87	-2.14	-0.65	-1.33	-1.72	-0.36	-0.56	*-2.89*	-3.55
	Significance	0.11	0.21	0.00	0.03	0.52	0.18	0.09	0.72	0.58	0.00	0.00

Table 3. Differences between the psychological responses to the photograph, 360° panorama, and virtual reality set-ups compared the response evoked by the physical environment set-up.

Table 4

		EDA Phasic	HRV nHF
Photograph vs Physical env.	U - Mann–Whitney	152.50	117.50
	W - Wilcoxon	405.50	237.50
	Z	-2.45	-0.63
	Significance	0.01	0.53
360° Panorama vs Physical env.	U - Mann–Whitney	216.00	113.00
	W - Wilcoxon	541.00	303.00
	Z	-1.68	-1.02
	Significance	0.09	0.31
Virtual Reality vs Physical env.	U - Mann–Whitney	275.50	114.00
	W - Wilcoxon	600.50	234.00
	Z	-0.49	-0.51
	Significance	0.62	0.61

Table 4. Differences between physiological responses to the photograph, 360° panorama, and virtual reality set-ups compared to the responses evoked by the physical environment set-up.

Table 5

		SMB								PAD		
		Pleasantness	Complexity	Unity	Enclosedness	Potency	Social Status	Affection	Originality	Pleasure	Arousal	Dominance
Phasic EDA	Coef.	0.426	-0.038	-0.092	-0.331	0.040	0.034	0.057	0.207	0.314	-0.031	-0.064
	Sig.	0.002	0.789	.0518	0.016	0.781	0.810	0.688	0.141	0.023	0.826	0.650
nHF HRV	Coef.	0.155	-0.045	-0.237	-0.178	0.034	0.073	-0.031	-0.126	0.268	0.027	0.050
	Sig.	0.273	0.754	0.091	0.207	0.809	0.606	0.829	0.372	0.055	0.847	0.726

Table 5. Correlations between the psychological and physiological responses, identified by partial correlation analysis, controlling for the "stimuli" variable.

Table 6

Presence	Psycometric											Physiological	
	SMB								PAD			EDA	HRV
	Pleasantness	Complexity	Unity	Enclosedness	Potency	Social Status	Affection	Originality	Pleasure	Arousal	Dominance	Phasic	nHF
Coef.	0.333	0.153	0.255	0.175	0.348	0.278	0.216	0.448	0.021	-0.120	0.014	0.123	-0.348
Sig.	0.016	0.280	0.068	0.216	0.011	0.046	0.124	0.001	0.882	0.398	0.923	0.383	0.012

Table 6. Correlations between presence and SMD-PAD and EDA-HRV responses identified using a partial correlation test.