MULTISENSORY DESIGN IN VR

Implementing Digital Smell Technologies for Architecture

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Abstract. Although the potential of VR for studying human-environment interactions is well-established, the scope has mostly been limited to audiovisual sensory feedback, where the other senses were conceived as secondary. This paper develops a novel method for evaluating human responses to multisensory environmental stimuli, including visual, auditory, and olfactory, using VR. An innovative approach is adopted to implement digital smell technologies for architecture. The proposed method provides dynamic interactions with the sensory environments and, in return, collects an extensive range of data streams regarding user experiences. The effectiveness of this method was tested through a proof-of-concept study assessing user responses to a private office involving multisensory modalities. The proposed methodological approach can be further applied to the research and practice of multisensory environmental stimuli.

Keywords. Immersive Virtual Reality, Multisensory Evaluations, Smell, Olfactory, Human Experience, Built Environment.

1. Introduction

The way we perceive and react to environmental exposure relies on the entire spectrum of multisensory information, including visual, auditory, olfactory, and haptic (Schreuder et al., 2016). Although the olfactory stimuli have mostly been ignored in human-environment interactions, odors have a significant impact on daily life domains, including emotions, behaviors, memories, mood, stress, and cognition (Brianza et al., 2022). In the context of architecture, the design of environments and buildings is primarily dominated by only one sense - the visual, neglecting other sensory domains, including the sense of smell (Pallasmaa, 1994). However, in order to promote the health, well-being, and productivity of inhabitants, it is necessary to take into account the multisensory nature of our daily life experiences in the practice of architectural and

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urban design (Spence, 2020). Over the past two decades, there has been a growing interest in the intricate connections between humans, olfaction, and built/natural environments, especially in the fields of urban planning (urban smellscape), landscape design, marketing, tourism, and indoor environmental comfort (Henshaw, 2013).

Several methodological challenges related to internal validity, ecological validity, and required resources (e.g., time, effort, expertise, expenses) exist in evaluating human responses to environmental exposure with multisensory modalities, which are mostly conducted in controlled laboratories or in actual buildings (Andrade, 2018). The use of Virtual Reality (VR) technology to carry out similar research is becoming more prevalent in recent literature (Alamirah et al., 2022). VR has a lot of potential as an empirical research tool for simulating real-world environments in controlled settings. Despite the indisputable potential of multisensory VR to provide more immersive experiences leading to a greater sense of presence and realism (Martin et al., 2022), studies exploiting multisensory aspects of VR systems are still in their infancy (Lyu et al., 2023). Although visual rendering and audio in VR have witnessed substantial progress, the development of other sensory simulations pertaining to olfaction, tactile feedback, thermoception, and taste lags behind (Melo et al., 2020). The literature shows that integrating olfactory stimuli into VR systems can enrich our digital experiences from the aspects of increased realism, immersion, sense of presence, and memory (Baus and Bouchard, 2017). There have been some attempts to provide olfactory experiences in VR applications, ranging from using simple air diffusers (Serrano et al., 2016) and wearable devices (Wang and Li, 2022) to room-scale installations (Maggioni et al., 2020).

In the context of human-built environment interactions, although the effectiveness of VR is well-recognized, only a limited number of studies have employed digital smell technologies (Shin et al., 2022; Sona et al., 2019). For instance, Hedblom et al. (2019) investigated the role that multisensory aspects (visual, auditory, and olfactory) of green spaces (parks and forests) along with urban environments play in reducing physiological stress levels using a computer-controlled olfactometer. Overall, there are considerable barriers to incorporating the sense of smell in VR applications. Implementing olfactory experience in VR often requires significant time and expense commitments (Melo et al., 2020). The development of custom-built scent devices requires a considerable level of expertise. Furthermore, the majority of published studies provided a low level of interactions with the olfactory environment and overlooked the dynamic nature of scents and odors. Finally, the data regarding participants' responses to the olfactory content of human-built environment interactions has been mostly limited to subjective evaluations. Research exploring the physiological, psychological, and cognitive implications of olfactory environments is rare. This research aims to develop a novel method to assess multisensory human experiences, including visual, auditory, and olfactory cues, in the built environment using VR technology. This paper specifically presents an innovative approach for incorporating the sense of smell in VR applications in human-built environment interactions. The proposed method leverages a commercially available scent device – OVR ION2 (Olfactory Virtual Reality Technology, 2024) to create an alternative approach for implementing olfactory experiences in VR that takes significantly less time and expertise. This paper reports the practical implementation of the proposed approach, development pipeline, user testing procedure, and preliminary results.

2. Methodology

The conceptual overview of the proposed approach is shown in Figure 1. The proposed methodology for the development of a multisensory VR system facilitates a high level of interactions with the sensory environments; visual, auditory, and olfactory, and encompasses an extensive range of data collection methods, providing quantitative and qualitative evidence. In order to demonstrate the capabilities and potential of the proposed development pipeline, a proof-of-concept study was conducted. This study was based on a real private office room situated at the University of Sydney Law School, Sydney, Australia. In this study, the restorative benefits of multisensory nature experiences in workplaces, and the roles played by different sensory modalities were investigated. A detailed description of the study design, experimental setup, and data collection methods are presented in the following sections.

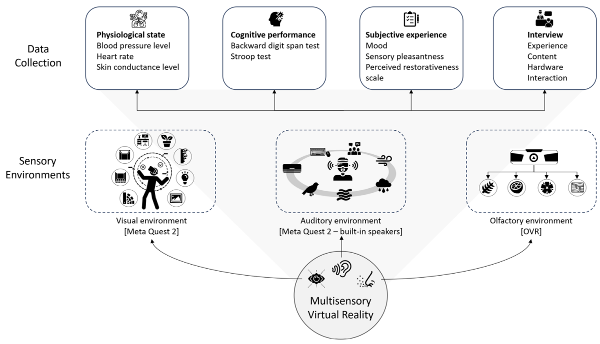

Figure 1. Conceptual overview of the methodology

2.1. STUDY DESIGN

We used a within-subject design for this study, in which the sensory input acted as a within-subject factor with two levels (control vs. multisensory). In detail, we labeled and defined the two conditions as follows: (1) non-biophilic workplace without nature exposure; (2) multisensory biophilic workplace with visual, auditory, and olfactory experiences of nature. A total of thirty-two participants (16 male subjects and 16 female subjects) with an average age of 29.2 ± 6.2 were recruited through poster flyers and email invitations. In order to assess the restorative benefits gained through exposure to both conditions, a pretest-posttest experimental design was employed. The order of two sessions was randomized and counterbalanced to eliminate the possible effects of repeated measures. Figure 2. illustrates the timeline of the experimental procedure.

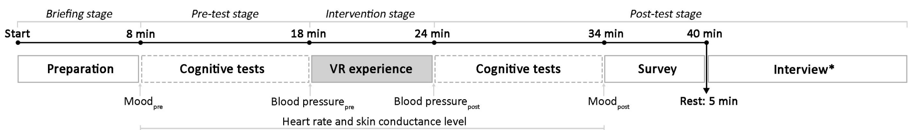

Figure 2. Timeline of the experimental procedure. *Interview was only conducted at the end of the second session.

At the beginning of the experiment, subjects were informed regarding the research and experimental procedure and asked to read and sign the consent form. Participants then completed a pre-experiment questionnaire about demographic information, including age, gender, occupation, cultural background, and VR experience. After that, the experimental equipment, including the VR headset, the smell device, and wearable sensors, were set up. During the pre-test stage, participants first described their current mood, followed by the completion of two cognitive tests. Next, participants' pre-test blood pressure levels were collected. Before the intervention stage, participants were first randomly assigned to one of the two experimental conditions. Following a brief induction to the VR system, they were exposed to the VR workplace settings for six minutes, consisting of 4-minute standing and 2-minute sitting. They were asked to freely explore the environment. Immediately after the VR immersion, subjects' post-test blood pressure levels were collected. Participants then performed another round of cognitive tests as their post-test cognitive performance. Following this, their post-test mood was evaluated. Lastly, a survey was administered regarding the participants' subjective experience of the workplace settings. A 5-minute break was taken between the two sessions. After the end of the second session, an interview was conducted about the design and experience of the VR prototype.

2.2. EXPERIMENTAL SETUP

The experiment was conducted in an indoor setting located at the School of Architecture, Design, and Planning, at the University of Sydney. A multisensory VR system was developed to simulate the conditions of the indoor workplace environment, see Figure 3. An overview of each sensory environment is presented below.

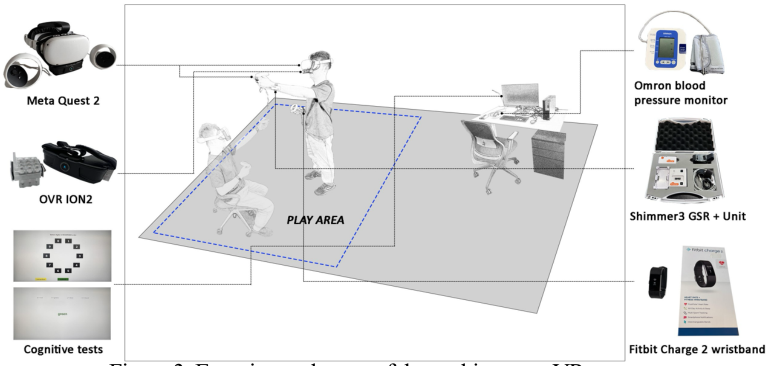

Figure 3. Experimental setup of the multisensory VR system

The three-dimensional (3D) model of the virtual environment was realized using Rhino3D and then transferred to Unity to build the VR scene, including materials, textures, lighting, and interactions. The visual environment was delivered to subjects using Meta Quest 2 HMD (top left of Figure 3.). Two virtual scenes were developed to depict the conditions of non-biophilic and multisensory biophilic scenarios (Figure 4). For the biophilic environment with multisensory experiences, subjects were provided with the opportunity to freely customize the visual components of the virtual environment, including indoor greenery, outdoor greenery, lighting, decoration, wall, floor, ceiling, and furniture.

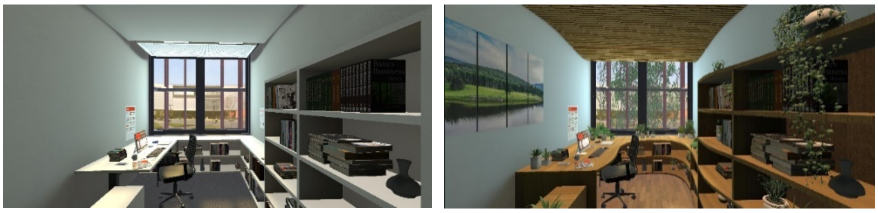

Figure 4. Simulation of non-biophilic scenario (left) and multisensory biophilic scenario (right)

The auditory environment consisted of ambient noises, including people talking, typing, printers, air conditioning, and computer fans for the non-biophilic workplace scenario and ambient noises overlaid with nature sounds for the multisensory biophilic workplace scenario. In the biophilic setting featuring multisensory experiences, subjects were given the chance to modify the type (birds, wind, rain, and ocean) and volume of the nature sound options. The auditory component of the virtual environment was presented to subjects through the built-in speakers available in the VR headset (top left of Figure 3.). The sense of smell was introduced to the multisensory biophilic scenario by using an OVR ION2 clip-on mask, which is an add-on scent device compatible with all HMDs (middle left of Figure 3.). OVR ION2 features scentware cartridges containing 9 distinct aromas. We employed the nature scent pack, which encompasses the smell of the beach, flowers, earthy dirt, pine forest, ocean breeze, wood, citrus, ozone, and fern grass. In this study, scents of fern grass, citrus, flowers, and wood were selected to align the olfactory experience with the visual elements within the virtual environment. Spatial and positional information of the user and objects were used to deliver an immersive smellscape experience.

2.3. EVALUATION CRITERIA

2.3.1. Physiological state

We used physiological measures of blood pressure (BP), heart rate (HR), and skin conductance level (SCL) as an indication of acute stress reaction. Omron 10 Series wireless upper arm blood pressure monitor (top right of Figure 3.) was used to measure systolic and diastolic blood pressures (mmHg). BP was measured at two different time points: before and after VR exposures. Furthermore, participants' heart rate was continuously monitored throughout the experiment using a Fitbit Charge 2 (bottom right of Figure 3.) that was attached to the right wrist of each participant. The measurements of HR were performed every 5 s. Finally, Shimmer3 GSR + Unit (middle right of Figure 3.) was used with a sampling frequency of 20 hz to continuously measure participants' SCLs (μS) during the experiment.

2.3.2. Cognitive performance

Backward digit span test: Backward digit span test has been widely used to assess short-term working memory. This test requires participants to repeat a sequence of numbers starting at a length of 2 in a reversed order (bottom left of Figure 3.). If the answer is correct, the number of digits increases. If the subject responds incorrectly on two occasions at a span length, the length of the number sequence decreases by one. Mean span reflecting the sum of the average performance of each sequence length during 14 trials was used as a test score for performance analysis. Stroop test: Stroop test is a commonly used basic task to measure attentional capacity. This test consists of congruent and incongruent color-word stimuli in a randomized order (bottom left of Figure 3.). Some colored words are displayed with inconsistent color ink. For instance, the word "blue" is inked with red. The test requires participants to identify the ink color of the displayed words. In this study, the overall proportion and overall mean latency of all correct trials were used as the performance metrics.

2.3.3. Subjective experience

Participants' emotional states were evaluated using a self-reported measure of affect. The five-point bipolar scale questionnaire is composed of ten items divided into five items for positive feelings and five items for negative feelings (depressed-elated, unsure-confident, grouchy-good-natured, anxious-relaxed, fatigued-energetic). Moreover, perceived sensory pleasantness of the visual, auditory, and olfactory environments was assessed using a seven-point Likert scale rating system, from 1 - very unpleasant to 7 – very pleasant. The short version of the perceived restorativeness scale with five components (fascination, being-away, scope, coherence, compatibility) of restorative environments was also used. Finally, the quality of virtual environments was evaluated for the items of system usability, engagement, and presence based on five- and seven-point Likert scale questionnaires.

2.3.4. Interview

Before finishing the experiment, a short interview was carried out about the design and quality of the developed multisensory VR prototype to find out the areas that are open for improvement in terms of content, hardware, and interaction.

3. Initial Results

3.1. QUANTITATIVE DATA ANALYSIS

A repeated measure ANOVA was performed to compare the changes in heart rate and skin conductance levels between the two scenarios. A comparative analysis of the restorative effects between non-biophilic scenario and multisensory biophilic scenario was conducted using pairwise t-tests, including blood pressure, cognitive performance (backward digit span test, Stroop test), and subjective experience (mood, sensory pleasantness, perceived restorativeness, system usability, presence, engagement). IBM SPSS Statistics was used to carry out the statistical analysis. The significance value was set to 0.05 ($p<0.05$) for all statistical tests.

Physiological state: Figure 5. indicates that participants' heart rate (HR) and skin conductance level (SCL) declined during exposure to both non-biophilic and multisensory biophilic scenarios. There was no statistically significant interaction between time and condition for both HR ($p>0.05$) and SCL ($p>0.05$).

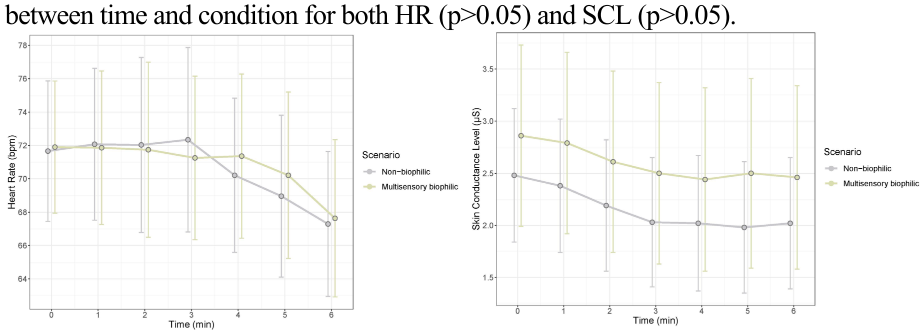

Figure 5. HR (left) and SCL (right) change during the VR exposures

Cognitive performance: Figure 6. shows that while subjects' mean span scores from the pre-test to the post-test decreased for the non-biophilic scenario, there was a statistically significant improvement in mean span scores for the multisensory biophilic scenario (Mean Difference = 0.75, 95% CI [0.43, 1.07], p<0.001). This suggests that digit span performance is positively associated with multisensory nature experiences in indoor workplace environments.

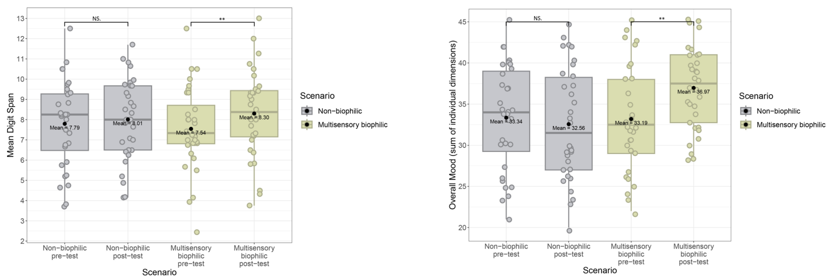

Figure 6. Backward digit span performance (left) and overall mood (right) for non-biophilic and multisensory biophilic scenarios (NS. non-significant * p<0.05 **p<0.001)

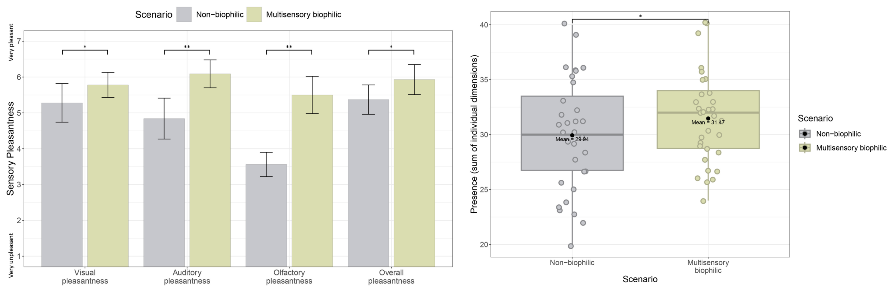

Figure 7. Sensory pleasantness votes (left) and engagement ratings (right) for non-biophilic and multisensory biophilic scenarios (NS. non-significant *p<0.05 **p<0.001)

Subjective experience: The results demonstrated that there was a statistically significant improvement in participants' overall mood (sum of individual dimensions) from the pre-test to the post-test for the multisensory biophilic scenario (Mean Difference = 3.78, 95% CI [2.07, 5.48], p<0.001) (Figure 6.). Figure 7. shows that sensory pleasantness votes (visual, auditory, olfactory, overall) statistically significantly increased over the multisensory biophilic scenario. Regarding the presence ratings, the multisensory biophilic scenario achieved a greater sense of presence compared to the non-biophilic scenario (Figure 7.).

3.2. QUALITATIVE DATA ANALYSIS

The interviews were recorded and transcribed for further qualitative analysis. NVivo was used to organize and structure the data. Participants' responses were categorized under the following subheadings according to their frequency of use:

Multisensory biophilic scenario: The user feedback suggests that integrating sound and smell into the VR system and providing the ability to manipulate the environment substantially improved their experience in terms of level of engagement, sense of presence, immersion, and perceived realism. For example, participant 17 indicated that *"The smell and sound did make me feel relaxed. It definitely added to the immersion of it, and I didn't want to leave the environment. I had the smells, and I could see the plants. The office was beautiful, and it just felt really nice in there."*. Another important point is that most of the participants mentioned that they were feeling more relaxed, calmed, and focused after the multisensory scene. For instance, participant 16 said, *"After the first one (multisensory condition), I found myself more focused when I was doing the cognitive tests. I think this is probably due to the sound, the smell, and the environment as I was able to modify it based on my preference. There's a certain level of autonomy involved while modifying the VR environment."*.

Olfactory environment: Participants mentioned that having a sense of smell in VR changed their whole experience. They found it impressive and inspiring. It was highlighted that the smell played a significant role in transporting the users into the VR environment. The reason olfactory input positively impacted the perception of the space and user experience could be explained by its seamless integration into the environment. For example, participant 5 said that *"I think the smell is pretty reliable as it is not very strong, and after a while, I noticed that I was not aware of the fact that there was a smell. So, it's like well-integrated into this. It's very subtle and embedded into the environment very well. So that actually reminds me of the reality."*. There were also negative comments about the olfactory environment. Some participants found the scents strong, artificial, and synthetic. *For instance, participant 18 mentioned that "The smell is too strong. So, that's why it makes you feel like the smell is artificial and not natural, because in the real world, if you smell a flower or a plant, even if you are very close, the smell is very slight."*. Another important point is that some participants did not respond positively to the olfactory stimuli, primarily because their preferred scents were not present in the environment, or the sense of smell was not strongly related to their personal experience in a space.

Improvement strategies: Participants were asked if they would like to add more components to the multisensory information they receive from the VR environment. The majority of participants tend to favor having thermal feedback based on the environmental conditions of the VR scene. For example, participant 27 said, *"I think the temperature would make the experience totally different because if we're thinking about workspace, I'd like to have it. This would be a bit too cold for me, and also, what I was imagining in the VR world was a warm space. So, I think the temperature would affect it."*. Furthermore, some participants exhibited a preference for incorporating tactile input into their VR experience. For instance, participant 12 stated that *"Touching* *experience would be really nice, because you're sitting there at the table. So, if you can change the material of the table like wood or other style and if is touchable, I feel like I would be more engaged in it, and it would be more realistic.".*

4. Discussion and future studies

This paper presents a novel methodology for the implementation of VR in exploring human experiences under multimodal conditions, including visual, auditory, and olfactory. This paper particularly proposes an innovative approach that leverages a commercially available scent device to incorporate olfactory stimuli in VR experiences. The proposed multisensory VR simulation process takes significantly less time, effort, and expense commitments. The method described here captures the dynamic nature of olfactory conditions and facilitates automated interactions with them, which has rarely been achieved in the current development of smell technologies in VR. Furthermore, the proposed methodology introduces a comprehensive data set regarding human responses to multisensory stimuli. Examining the association between multisensory environmental factors and psychological, physiological, and cognitive dimensions provides a holistic understanding of human-environment interactions.

The proposed methodological approach in this paper can potentially promote multisensory environmental research and practice. The results from the current experiment suggest that multisensory experiences in the built environment are strongly associated with a range of restorative benefits, including improved cognitive performance, reduced stress levels, and enhanced mood. This suggests that considering the multisensory aspects of spaces in the design, planning, and evaluation of the built environment can have significant health, well-being, economic, and social implications for society at large. This research particularly introduces a tool to integrate the sense of smell into VR under controlled and realistic conditions that can pave the way for smellscape research. This, in the long run, can promote incorporating smell into decision-making processes of built environment design.

While the method presented in this paper shows considerable promise and offers a feasible, practical, and cost-effective workflow for exploring multisensory experiences in VR, it is important to acknowledge and address some limitations. For example, the scent device used in this research, OVR ION2, is currently out of the market, limiting its usage in future applications. Furthermore, the device does not provide the ability to map a diverse range of scents in the same VR experience, as the cartridges only allow the dispersion of 9 digital aromas and require the swap of the scent pack for further olfactory experiences. Although the majority of participants found the olfactory experience realistic and natural, some complained about the accuracy and intensity of the smells. Therefore, future VR applications should consider an olfactory experience that exactly replicates the physical world. Another limitation was that the proposed method did not provide thermal and tactile feedback. Exploring the possibility of incorporating haptic experience into VR deserves further attention since the human experience of a place is usually based on inputs from the entire spectrum of senses. Finally, leveraging wearable brain activity devices, as well as eye and facial tracking technologies, can provide further insights into the user experience in VR.

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