Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions

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ABSTRACT
In this paper, we present and evaluate Ambiotherm, a wearable accessory for Head Mounted Displays (HMD) that provides thermal and wind stimuli to simulate real-world environmental conditions, such as ambient temperatures and wind conditions, to enhance the sense of presence in Virtual Reality (VR). Ambiotherm consists of a Ambient Temperature Module that is attached to the user's neck, a Wind Simulation Module focused towards the user's face, and a Control Module utilizing Bluetooth communication. We demonstrate Ambiotherm with two VR environments, a hot desert, and a snowy mountain, to showcase the different types of simulated environmental conditions. We conduct several studies to 1) address design factors of the system and 2) evaluate Ambiotherm's effect on factors related to a user's sense of presence. Our findings show that the addition of wind and thermal stimuli significantly improves sensory and realism factors, contributing towards an enhanced sense of presence when compared to traditional VR experiences.

ACM Classification Keywords
H.5.1. Information Interfaces and Presentation (e.g. HCI): Multimedia Information Systems: Artificial, augmented, and virtual realities

Author Keywords
Presence; Ambient Temperature; Virtual Wind; Virtual Reality; Multimodal Interaction

INTRODUCTION
Simulating environmental conditions by utilizing multisensory stimuli is essential to providing sensory-rich experiences and enhancing immersion in Virtual Reality (VR). However, despite ongoing research and development, the majority of existing VR systems utilize interfaces that do not provide users with multisensory feedback that accurately mirrors their experiences of environmental conditions in the real-world. This lack of additional environmental feedback restricts potential

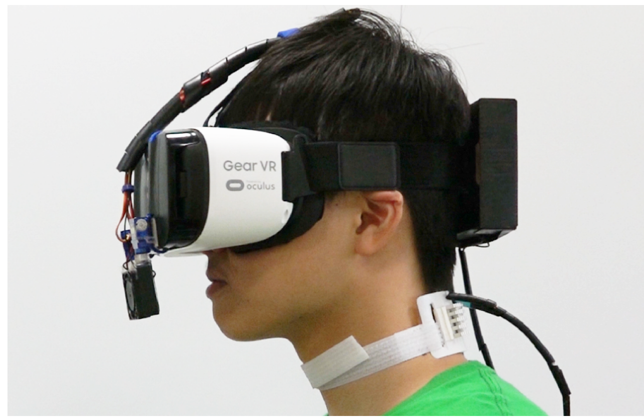

Figure 1. A participant is using the Ambiotherm system with a Samsung™ Gear VR HMD. The control module is attached behind the neck.

immersive features which, in turn, can have severely negative effects on a user's sense of presence within a VR experience and their ability to interact with respective virtual environments [40]. Although the inclusion of visual and auditory stimuli is key to providing users with an enhanced sense of immersion and presence in VR experiences, there are many other forms of multisensory stimuli whose capabilities for conveying environmental factors are yet to be as thoroughly investigated in the same context.

For example, several research works in human-environment psychology have suggested that both thermal and wind stimuli can have strong impacts on the way in which people perceive their environmental surroundings [2, 3, 23, 36]. Whilst there has been a relatively limited amount of research performed regarding the utilization of thermal and wind feedback, existing studies have suggested that the inclusion of these stimuli within VR applications can provide users with an enhanced sense of presence by enabling greater multisensory engagement and increasing users' perceived immersion and involvement within VR experiences [17, 34]. In addition to these beneficial capabilities, several studies have also highlighted that thermal and wind stimuli can be used as a tool to increase a user's performance during location, orientation and memory-based tasks in VR [8, 9].

In this paper, we present Ambiotherm: a novel accessory for existing VR Head Mounted Displays (HMDs) that incorporates both thermal and wind stimuli into traditional VR experiences. Ambiotherm is a wearable solution that aims to increase

CHI 2017, May 06-11, 2017, Denver, CO, USA

DOI: http://dx.doi.org/10.1145/3025453.3025723

users' sense of immersion and presence in VR experiences by simulating real-world environmental conditions such as ambient temperatures and wind patterns. To achieve this functionality, as shown in Figure 1, the system is equipped with 1) an Ambient Temperature Simulation Module that utilizes Peltier elements to provide heating and cooling sensations (worn on the neck) and 2) a Wind Simulation Module that utilizes multidirectional fans focused towards the user's face.

In summary, the main contributions of this paper are:

- A proof-of-concept prototype of Ambiotherm that provides thermal and wind stimuli, enabling the simulation of real-world environmental conditions within VR experiences.
- A set of preliminary studies that are used to address key design considerations made prior to the implementation of the system. Here, aspects including the location, intensity, duration and relative comfort of stimuli are analyzed.
- A user evaluation that compares key aspects of a user's perceived sense of presence when using a traditional HMD alongside multiple configurations of Ambiotherm. This study suggests that 1) Ambiotherm significantly improves both sensory and realism factors of the VR experience, 2) the addition of thermal and wind stimuli does not have any significant detrimental effects on the control and distraction aspects of the user's experience and 3) wind stimuli, comparative to thermal stimuli, are more easily identified and perceived as realistic environmental sensations.

BACKGROUND AND RELATED WORK

Interdisciplinary by nature, Ambiotherm draws on concepts from several fields including VR, telepresence, and human thermoception. In this section, we first define the meaning of presence in VR and the ways in which this can be enhanced through multisensory stimuli. Following this, we provide a review of related thermal and wind stimuli research to highlight the key capabilities and limitations of existing simulation methods for environmental conditions.

Enhancing Presence in VR

Witmer and Singer [40] define presence as the experience of being in one place or environment, even when one is physically situated in another. In terms of VR, sense of presence occurs when experiencing a computer generated environment as opposed to the physical real-world environment that it represents. As expressed by Sheridan [34], presence is an extremely subjective sensation. Due to the fact that presence in VR is dependent on both the physical interface and the user's individual experience [17], it cannot be easily measured through objective definitions.

Improving a user's sense of presence in VR is an inherently challenging issue due to the multiple factors that can affect a user's perception during a VR experience. In related literature, it is noted that aspects such as the immediacy and mode of control, the presentation and consistency of multimodal information, the user's awareness of the interface device and the personal meaningfulness of the VR experience [11, 17, 25, 34] may have a notable impact on a user's sense of presence.

However, one concept that is consistently predominant in related research is that, in order to achieve an optimum sense of presence in VR, a user must be provided with a broad and coherent range of multisensory stimuli [11, 25, 40]. As described in [37], this is due to the fact that the human perceptual system has been trained for the perception of real-world multisensory stimuli through the process of evolution and that it is crucial to appeal to these perceptual mechanisms. With regards to generating a perceived sense of presence based on multisensory stimuli, both Witmer and Singer [40] and McGreevy [25] share similar arguments in that presence depends on the ability to focus on one meaningful VR stimulus set, where the experience of presence is based on attention to the continuities, connectedness and coherence of the stimulus flow.

Studies in Thermal and Wind Stimulation

In 2009, Gooch [13] developed and tested a device that was able to significantly increase feelings of social presence through thermal feedback. In 2010 Iwasaki [20] et al. constructed a prototype system that uses galvanic skin response (GSR) measurements to detect one user's emotional state and then displays this information to another user via temperature changes on the back panel of a mobile handset. Similarly, Lee & Lim [24] discuss the prospect of using thermal feedback to display information within the context of a messaging platform, highlighting the concepts of using thermal feedback to change user's emotions. In 2015, Song et al. [35], developed a wrist-worn device that provides thermal and pressure cues for the purpose of non-visual notifications. Although pressure cues were easily recognized, thermal cues had a high recognition error rate due to latency and users' thermal sensitivity. In studies by both Hannah et al. [16] and Nakashige et al. [31], a set of visual stimuli were coupled with congruent thermal stimuli (e.g. Images of hot soup and ice cream paired with warm and cold sensations respectively), which, in certain cases, was able to enhance the emotional reactions of users.

As the majority of aforementioned studies are proofs of concept for specific applications of thermal feedback, none of these studies thoroughly investigate the mapping between thermal stimuli and corresponding changes in environmental perception and emotions experienced by the user. Studies by both Wilson et al. [39] and Salminen et al. [33] examined responses to thermal cues using methods such as gathering subjective feedback about the comfort and intensity of thermal sensations and by taking physical measurements of the user's skin conductance response (SCR). Although the findings of these studies indicate that thermal feedback may be used to evoke certain emotions, they only investigate the effects of thermal feedback as an isolated stimulus.

With respect to research on wind stimuli, the majority of existing studies have only focused on the human ability to detect wind speed and direction [1, 32], the types of wind conditions that can affect human motion [19] and the acceptability of wind conditions for human comfort in and around buildings [26]. As is the case with thermal stimuli, this field still lacks research that thoroughly assesses the effects of wind stimuli on human emotions and environmental perception.

Employment of Thermal and Wind Stimuli in VR

Despite there being limited research that explores the direct effects of thermal and wind stimuli on human environmental perceptions, continuous advances in VR technologies have generated increased interest in utilizing wind and thermal stimuli to enhance immersion in VR experiences.

One of the earliest examples of an immersive, multisensory VR system, "Sensorama Simulator" [29], featured wind, vibration and olfactory environmental feedback that was presented alongside stereoscopic film to enhance viewer's sense of presence. In 1997, Dionisio [10] created VR Thermal Kit; a system for simulating environmental thermal conditions by utilizing a set of convectors, infrared lamps and Peltier elements to influence whole-body and localized thermal sensations, respectively. Initial testing of this system suggested that a level of environmental thermal perception was achievable by relatively simple technical means.

More recently, in 2014, Hülsmann et al. [18] performed a comprehensive analysis of software and hardware requirements for simulating wind and warmth sensations for Cave Automatic Virtual Environments (CAVE). Based on this analysis, Hülsmann et al. created a three-sided CAVE system, including projectors, a camera system for user tracking, an 8.1 surround sound speaker configuration and an array of infrared lamps and fans for simulating thermal and wind sensations. Pilot studies of this system suggested that users experienced a strong sense of presence within the VR environment, although the authors recommended further studies to quantify presence and collect significant results.

With regard to the incorporation of wind stimuli in VR systems, attempts to simulate environmental wind conditions can be categorized based on the positioning of stimuli relative to the user. In systems such as WindCube [28], VR Scooter [8] and Verlinden's sailing simulator [38], arrays of static fans are positioned at different angles facing towards the user in order to simulate wind from different directions. In studies performed on these systems, participants reported an increased sense of presence when experiencing wind sensations and, in studies that measured task performance, achieved faster performance times than when performing tasks without wind stimuli. However, similarly to the VR Thermal Kit and Hülsmann's CAVE system, all these systems consist of heavy and expensive equipment that require large operational spaces.

As stated by Minakuchi [27], systems that employ arrays of static fans can suffer from stimuli latency and intensity issues based on the distance between each fan and the user. To address this issue, Cardin et al. [6] developed a head-mounted wind generation system that utilizes a set of 8 fans which are positioned in a ring and worn by the user. Although initial studies of this system suggested that participants were able to correctly detect wind direction and experienced an enhanced sense of presence, stimuli latency and the physical weight of the system were still notable issues that required further study.

Overall, the studies discussed in this section outline 1) the potential for creating more immersive multisensory experiences by simulating thermal and wind sensations as part of existing VR systems and 2) the inherent physical and performance challenges related to developing a system of this manner. By designing Ambiotherm as a wearable multisensory accessory to existing HMD devices, we aim to form a VR system that simultaneously utilizes the immersive capabilities of thermal and wind stimuli whilst countering issues experienced by these reviewed works.

STIMULI DESIGN CONSIDERATIONS

This section discusses key multisensory stimuli design considerations that were identified prior to the implementation of the prototype system. Here, notable design considerations include the delivery method, the location and intensity of thermal and wind stimuli. It should be noted that the points discussed in the following subsections focus on multisensory stimuli design and that many other design aspects such as the device's physical form were also considered during development.

Delivery Method

Similar to [12], we established a set of stimuli requirements to ensure that appropriate environmental sensations were provided within the context of Ambiotherm: 1) not pose any significant safety risks to the user, 2) be controlled in real-time to produce low-latency stimulation, 3) provide multi-directional stimulations of wind, heating, and cooling, and 4) be available in a form that does not affect the portability of the system.

Based on these requirements, Peltier elements were used to generate thermal stimulation. Unlike devices such as radiant heaters or infrared heat lamps [18], Peltier elements are well-suited to this application as they are compact lightweight components that can produce both heating and cooling sensations. As they require direct contact with the skin, Peltier elements avoid some of the thermal latency issues that affect other forms of non-direct thermal stimuli. Due to their capabilities for being controlled with low-latency, the thermal sensations produced by Peltier elements can be easily maintained within a controlled range of temperatures that are safe for contact with human skin.

Wind stimulation is achieved by incorporating two small fans into the system. Unlike air conditioning or large scale fan configurations [28, 8, 38] that are too heavy for portable applications, these compact fans can be fitted to low-power servo motors to facilitate controllable multi-directional wind stimulation. Although using pressurized air can be another low-latency alternative to using fans, incorporating pressurized air storage components into the system would have a detrimental effect on both its safety and portability.

Location, Intensity, and Comfort

Since different parts of the human body have varying levels of thermal and cutaneous wind sensitivity, selecting an appropriate location and respective intensity range for stimuli was crucial for effectively simulating environmental sensations in Ambiotherm. To elicit effective wind perception, two fans are positioned to direct wind onto the user's face, a location with a high density of sensitive somatosensory receptors [14]. Although using a larger array of fans was considered, this type of setup, as stated in [6], can add significant weight to a system and is not effective for users with long hair.

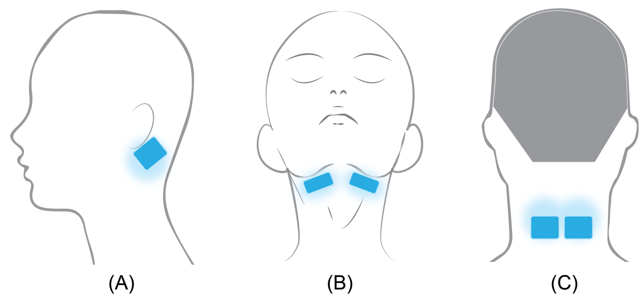

Figure 2. Different locations selected for delivering thermal stimuli: (A) Behind The Ear, (B) On The Throat, and (C) Behind The Neck.

With respect to thermoception, three of the main factors that are known to affect the human ability to detect changes in temperature are the site of stimulated skin, the amplitude of the temperature change and the rate of temperature change [22]. Based on these factors, the following studies were performed to identify the optimum locations and intensities for providing thermal stimulation via Peltier elements. The studies and their findings are discussed in the following subsections.

Selection of Location for Thermal Stimuli

Three locations: 1) Behind The Neck (BTN), 2) On The Throat (OTT) and 3) Behind The Ear (BTE), as shown in Figure 2, were chosen for the study due to their proximity to the thermoregulatory centre of the central nervous system [15]. A user experiment was conducted with 15 participants (12 males and 3 females, average age = 26.4, SD = 3.99) and they were asked to rate the different locations based on sensation of the applied thermal stimuli (HR4, HS10, CR8 and CS10 stimuli as in Table 1). These sensations were recorded on a continuous sensation scale containing intervals ranging from “very cold” to “very hot”, based on an adaptation of the ASHRAE 7-point scale of thermal comfort by Arens et al. [4]. They were subsequently asked to rank the locations based on the degree of comfort. For each participant, the order of the locations was randomized. The study was conducted using Peltier elements in a room with controlled temperature (24°C) and no air circulation.

(i) Selection of Location Based on Sensation:

A repeated measures ANOVA with sphericity-assumed determined that mean sensitivity to heating at the three locations differed statistically significantly ($F_{2,118} = 38.4$, $p < 0.001$). Post hoc tests using the Bonferroni correction further revealed that BTN (M = 0.86, SD = 0.09) was significantly different to OTT (M = 0.73, SD = 0.19) ($p < 0.001$), as well as to BTE (M = 0.63, SD = 0.18) ($p < 0.001$). A significant difference was also observed between OTT and BTE ($p < 0.001$). Therefore, we concluded that BTN is most sensitive to the heating stimuli (Figure 3 (A)). Repeated measures ANOVA with sphericity-assumed determined that mean sensitivity to cooling at the three locations differed statistically significantly ($F_{2,118} = 4.68$, $p < 0.05$). Post hoc tests using the Bonferroni correction further revealed that there was no significant difference between OTT (M = 0.22, SD = 0.17) and BTE (M = 0.2, SD = 0.14) ($p > 0.05$) as well as between OTT and BTN (M = 0.28, SD = 0.20) ($p > 0.05$). However, BTE was significantly different to BTN ($p < 0.05$) with the lowest average thermal score. Therefore, we concluded that BTE was relatively more sensitive to the cooling stimuli (Figure 3 (B)).

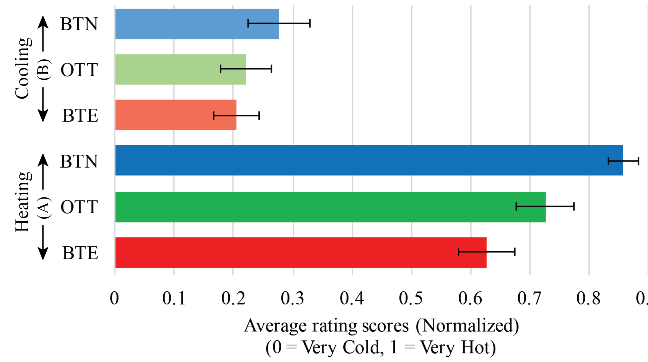

Figure 3. Normalized average rating scores: (A) heating sensation at three locations and (B) cooling sensation at three locations. (Error bars represent 95% CI, n = 15).

(ii) Selection of Location Based on Comfort:

87% of the participants selected BTN as their first preference while 13% chose BTE and 0% chose OTT. 100% of the participants who chose BTE or OTT as their first preference, listed BTN as their second preference.

Although BTN was found to be most sensitive to the heating stimuli, it was not the most sensitive to the cooling stimuli. However, BTN was still selected as the location for thermal stimulation in our system, primarily due to three reasons: 1) high levels of comfort based on participant’s preference, 2) provides a perception of overall temperature change (similar to the effects of induced hypothermia [21]) and, 3) can be used to augment heat loss or heat gain whilst, at the same time, not competing with thermoregulatory needs [30]. Using this location also mirrors the effects of familiar practices, such as wearing a scarf or opening a collar to preserve or release body heat, respectively.

Selection of Thermal Stimuli

The same 15 participants were then asked to rate the different thermal stimuli applied at the BTN location based on sensation. These sensations were recorded on a continuous sensation scale containing intervals ranging from “Very Cold” to “Very Hot”, based on an adaptation of the ASHRAE 7-point scale of thermal comfort by Arens et al. [4]. They were also asked to rate the different stimuli based on comfort, with a continuous comfort scale, ranging from “Very Uncomfortable” to “Very Comfortable”, based on Arens et al. [4]. For each participant, the order of the thermal stimuli presented was randomized. Details of the set of thermal stimuli used are provided in Table 1. This study was also conducted using Peltier elements in a room with controlled temperature (24°C) and no air circulation.

(i) Selection of Stimuli Based on Sensation:

In order to compare the sensation scores of the four heating stimuli (HR2, HR4, HS6, and HS10), a one-way repeated measures ANOVA was conducted with sphericity-assumed. A significant difference in the sensation scores of the four heating stimuli ($F_{3,42} = 8.6$, $p < 0.001$) was observed. Post

Label	Type	Mode	Duration (seconds)	Approximate Temperature Change (°C)
HR2	Heating	Rapid	2	+2
HR4	Heating	Rapid	4	+4
HS6	Heating	Slow	6	+3
HS10	Heating	Slow	10	+5
CR4	Cooling	Rapid	4	-3
CR8	Cooling	Rapid	8	-6
CS5	Cooling	Slow	5	-2.25
CS10	Cooling	Slow	10	-4.5

Table 1. Details of the set of thermal stimuli used in the study.

hoc tests using the Bonferroni correction revealed that HR4 (M = 0.93, SD = 0.08) was significantly different to HR2 (M = 0.8, SD = 0.09) ($p < 0.005$) as well as to HS6 (M = 0.83, SD = 0.08) ($p < 0.001$). No significant difference was observed between: 1) HR4 and HS10 (M = 0.87, SD = 0.1) ($p > 0.05$), 2) HR2 and HS6 ($p > 0.05$), 3) HR2 and HS10 ($p > 0.05$) and 4) HS6 and HS10 ($p > 0.05$) (Figure 4 (A): sensation scores). Participant's comments, as well as prior studies, indicate that a rapid change in temperature can generate a sense of pain and may, in turn, affect the degree of immersion [7]. Hence, HR4 was not selected as a potential heating stimulus.

Similarly, to compare the sensation scores of the four cooling stimuli (CR4, CR8, CS5, and CS10), a one-way repeated measures ANOVA was conducted with sphericity-assumed. A significant difference in the sensation scores of the four cooling stimuli ($F_{3,42} = 5.2$, $p < 0.01$) was observed. Post hoc tests using the Bonferroni correction revealed that CR8 (M = 0.18, SD = 0.21) was significantly different to CS5 (M = 0.37, SD = 0.15) ($p < 0.05$). No significant difference was observed between: 1) CR4 (M = 0.24, SD = 0.24) and CS10 (M = 0.32, SD = 0.17) ($p > 0.05$), 2) CR4 and CS5 ($p > 0.05$), 3) CR4 and CR8 ($p > 0.05$), 4) CR8 and CS10 ($p > 0.05$) and 5) CS5 and CS10 ($p > 0.05$) (Figure 4 (B): sensation scores). Due to the aforementioned effects of pain produced by rapid temperature changes, CR8 was not selected for further analysis or as a potential cooling stimulus.

(ii) Selection of Stimuli Based on Comfort:
A one-way repeated measures ANOVA with sphericity-assumed was conducted to compare the comfort scores of the four heating stimuli (HR2, HR4, HS6, and HS10). A significant difference in the sensation scores of the four heating stimuli ($F_{3,42} = 12.68$, $p < 0.001$) was observed. Post hoc tests using the Bonferroni correction revealed that HR4 (M = 0.29, SD = 0.27) was significantly different to HR2 (M = 0.68, SD = 0.2) ($p < 0.05$) as well as to HS6 (M = 0.6, SD = 0.23) ($p < 0.05$). No significant difference was observed between: 1) HR4 and HS10 (M = 0.52, SD = 0.2) ($p > 0.05$), 2) HS6 and HS10 ($p > 0.05$), 3) HR2 and HS10 ($p > 0.05$) and 4) HS6 and HS10 ($p > 0.05$) (Figure 4 (A): comfort scores). Confirming previous findings, HR4 was found to be the most uncomfortable stimulus with the lowest average score.

Similarly, to compare the comfort scores of the four cooling stimuli (CR4, CR8, CS5, and CS10), a one-way repeated

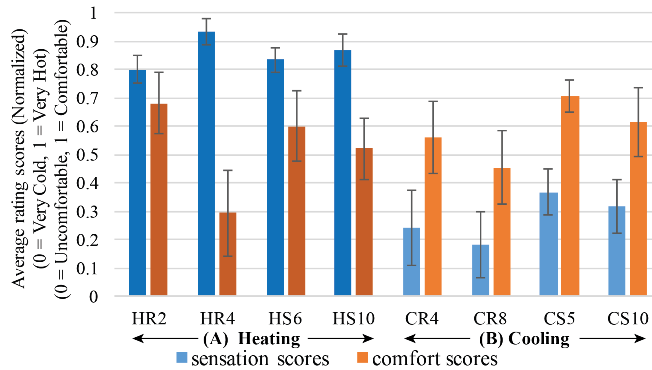

Figure 4. Normalized average sensation and comfort scores: (A) four heating stimuli and (B) four cooling stimuli. (Error bars represent 95% CI, n = 15).

measures ANOVA was conducted with sphericity-assumed. A statistically significant difference in the sensation scores of the four cooling stimuli ($F_{3,42} = 4.93$, $p < 0.01$) was observed. Post hoc tests using the Bonferroni correction revealed that CR8 (M = 0.45, SD = 0.23) was significantly different to CS5 (M = 0.7, SD = 0.1) ($p < 0.05$). No significant difference was observed between: 1) CR4 (M = 0.56, SD = 0.23) and CS10 (M = 0.61, SD = 0.22) ($p > 0.05$), 2) CR4 and CS5 ($p > 0.05$), 3) CR4 and CR8 ($p > 0.05$), 4) CR8 and CR10 ($p > 0.05$) and 5) CS5 and CS10 ($p > 0.05$) (Figure 4 (B): comfort scores). Again, confirming previous findings, CR8 was found to be the most uncomfortable stimulus with the lowest average score.

These studies indicate that there is no statistically significant difference based on sensation as well as comfort between the three heating stimuli HR2, HS6 and HS10 and also between the three cooling stimuli CR4, CS5 and CS10. The results of these user studies allow us to choose either of the stimuli from the respective groups without affecting the degree of sensation or comfort. Based on our application to simulate environmental conditions of real-world, stimuli HS10 and CS10 were chosen for heating and cooling respectively to ensure a subtle and continuous change in temperature.

SYSTEM IMPLEMENTATION

As shown in Figures 5 and 6, the system consists of three primary modules: 1) Head Mounted Display (HMD), 2) Control Module and 3) Environment Simulation Module. The Environment Simulation Module comprises of 3a) Wind Simulation Module and 3b) Ambient Temperature Module.

Head Mounted Display (HMD)

Both the Control Module and Environment Simulation Modules were mounted on the Samsung Gear VR[1] HMD, and an application for VR simulation was built on Unity 3D using Unity's Android SDK. In order to connect the VR application with the Control Module, we developed a separate API that triggers and controls wind and thermal stimuli. Based on the VR environment, the application wirelessly triggers stimuli and controls parameters such as direction, speed, and sweep speed for wind stimuli, and type, intensity, and duration

[1] Consumer Edition SM-R322

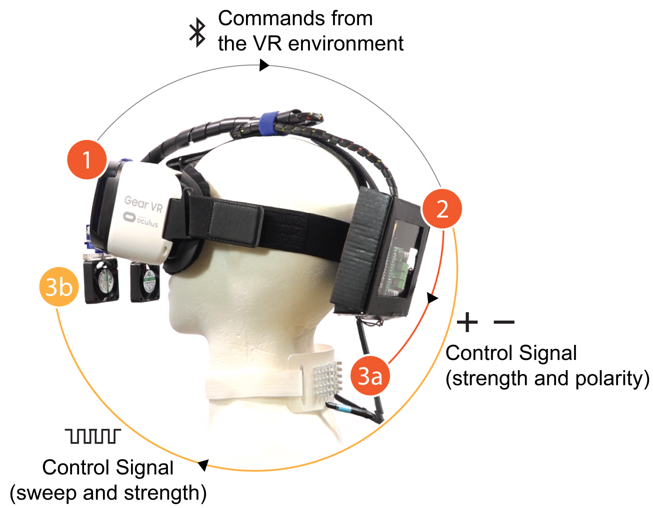

Figure 5. Operational procedure of Ambiotherm: (1) VR environment (Android Application) sends commands to (2) control module that actives (3a) thermal module and (3b) wind module.

for thermal stimuli. These commands are sent to the control module via Bluetooth using the developed Ambiotherm serial command protocol.

Control Module

A DFRobot Bluno Nano BLE-enabled microcontroller connected to the Samsung Galaxy Note 5 of the HMD interprets the received commands and generates control signals in real-time. It drives the Wind Simulation Module using the technique of Pulse Width Modulation (PWM), and controls factors such as wind intensity and wind direction (using the servo motors) in accordance with the VR environmental conditions. Similarly, thermal stimuli factors such as type, intensity and duration are controlled by varying the magnitude and polarity of the current supplied to the Ambient Temperature Module using PWM via a full H-Bridge MC33926 motor driver carrier, capable of delivering up to 3A of current continuously.

Environment Simulation Module

The Wind Simulation Module, mounted on the HMD panel, consists of two 5V fans (each of dimensions 40 x 40 x 10 mm) mounted on micro servo motors facing the user's cheeks. The Ambient Temperature Module, worn on the neck of the user, consists of two Peltier elements that draw up to 13W and are mounted on heatsinks for efficient temperature control.

EVALUATION

We developed two distinct VR environments (as an Android application) to showcase Ambiotherm's capabilities for simulating real-world environmental conditions within VR experiences. Here, the user experiences a desert environment (Figure 7 (A)) and a snowy mountain environment (Figure 7 (B)) for 30 seconds each, presented in a randomized order. The user follows the virtual guide on her path and is provided with a first-person view of the virtual environment. The user is also provided with auditory feedback that represents the virtual guide's footsteps and the wind blowing. Although the user is able to look around the 3D virtual environment using

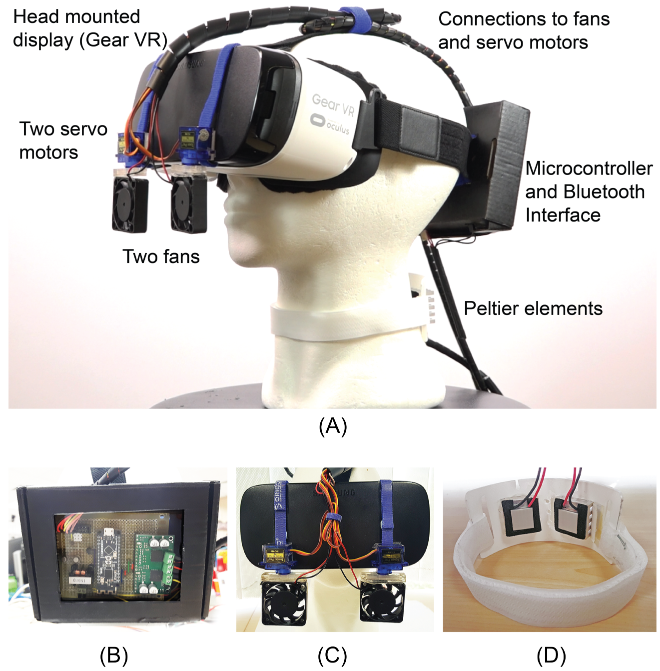

Figure 6. Ambiotherm: (A) Main components, (B) Control Module, (C) Wind Simulation Module, and (D) Ambient Temperature Module.

the HMD's head-tracking system, no additional interactions were added to this version as interactive factors were not the main focus of this study.

Instrumentation

The HMD that was used in this study was a Samsung Gear VR with a Samsung Galaxy Note 5 mobile phone running the demo application. To provide auditory feedback from the mobile device, a pair of Samsung Wired earphones[2] were used. The following section describes a pre-study experiment that was performed to prevent any detrimental impacts of stimuli latency on the users' experience by ensuring that wind and thermal stimuli were correctly synchronized with visual and auditory stimuli from the VR HMD.

Synchronization of Thermal and Wind Stimuli with Visual and Auditory Stimuli

By applying randomized heating and cooling thermal stimuli, mentioned in Table 1, to 10 participants (5 males and 5 females, average age = 24.4, SD = 1.17) via Peltier elements behind the neck, it was indicated that the average time to perceive the selected heating stimuli was 3 seconds, and the average time to perceive selected cooling stimuli was 2 seconds.

Based on these response times, the following thermal and wind synchronization timings were chosen to be examined with respect to the timings of visual and auditory stimuli produced by the demo application running on the HMD:

- Thermal: Cooling stimuli triggered 2 seconds before scene starts (C-2), triggered simultaneously with scene start (C0), and triggered 2 seconds after scene starts (C+2). Heating

[2]Model No: HS3303

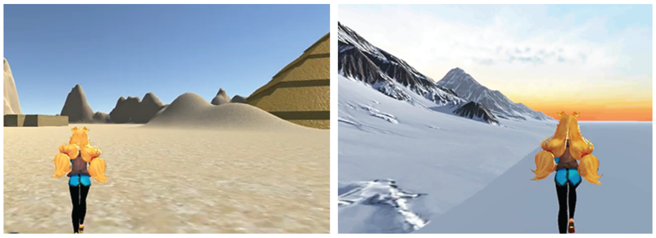

Figure 7. User's first-person view following the virtual guide in (A) the hot desert and (B) the snowy mountain virtual environments.

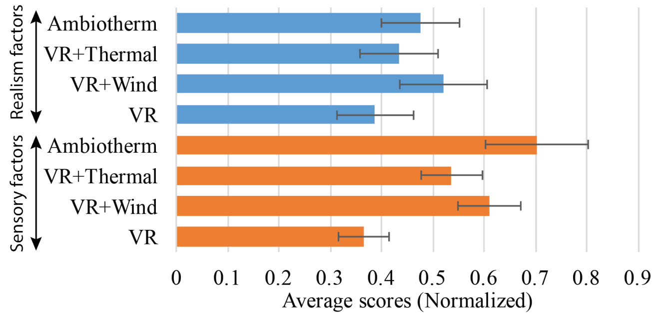

Figure 8. Normalized average Sensory and Realism Factors scores for four stimuli configurations (Error bars represent 95% CI, n = 20).

stimuli triggered 3 seconds before scene starts (H-3), triggered simultaneously with scene start (H0), and triggered 3 seconds after scene starts (H+3).

- Wind: Wind stimuli triggered 2 seconds before wind audio (W-2), triggered simultaneously with wind audio (W0), and triggered 2 seconds after wind audio (W+2).

Again, 10 participants (5 males and 5 females, average age = 24, SD = 1.24) were randomly selected and asked to rate how much they felt that these stimuli configurations (randomized) were disconnected with their respective visual or auditory stimuli. These ratings were recorded on a continuous scale ranging from "Strongly Disagree" to "Strongly Agree". The results of a one-way repeated measures ANOVA with sphericity-assumed indicated that the conditions C-2, C0 and C+2 have no significant difference ($F_{2,18} = 0.66$, $p > 0.05$) with 76% of participants not feeling any disconnect with respective visual and auditory stimuli across the three conditions. However, results of a one-way repeated measures ANOVA with sphericity-assumed indicated that the conditions H-3, H0 and H+3 have a significant difference ($F_{2,18} = 4.73$, $p < 0.05$). Post hoc tests using the Bonferroni correction further revealed that H+3 (M = 0.55, SD = 0.23) was significantly different to H0 (M = 0.8, SD = 0.16) ($p < 0.05$). No significant difference was observed between: 1) H+3 and H-3 (M = 0.8, SD = 0.26) ($p > 0.05$) and 2) H0 and H-3 ($p > 0.05$). Further confirming these statistical findings, 30% of participants reported a disconnect with H+3 and the audio-visual stimuli, 10% of participants reported a disconnect with H-3 and 0% with H0. The results of a one-way repeated measures ANOVA with Greenhouse-Geisser correction indicated that the disconnect between wind and auditory stimuli within conditions W-2, W0 and W+2 have no significant difference ($F_{1.15,10.36} = 1.64$, $p > 0.05$). Based on these results, conditions C0, H0 and W0 were chosen for the user study that is described in the following sections.

Procedure

20 participants (11 males, 9 females, average age = 25.45, SD = 4.98) were recruited for this study. All 20 participants had experienced VR systems prior to the study and were aware of HMD and VR technology. Prior to each new participant using the system in this study, earphones used to provide auditory stimuli were sanitized using alcohol swabs and the straps of the HMD were tightened to ensure that the device was both secure and comfortable on the participant. Before using the system, participants were also asked to provide basic demographic information (gender and age).

During the study, participants were asked to experience the demo application with four different system configurations: 1) via the HMD without the addition of thermal or wind stimuli (VR only), 2) via the HMD with only thermal stimuli (VR+Thermal), 3) via the HMD with only wind stimuli (VR+Wind), and 4) via the HMD with both thermal and wind stimuli (VR+Wind+Thermal = Ambiotherm). For each participant, the order of the four trials (aforementioned configurations) was randomized to avoid any effects that may occur from a set sequence of experiences.

Following each trial with the system, participants were asked to complete a questionnaire evaluating different aspects of their experience with respect to their sense of presence in the virtual environment. This questionnaire consisted of 21 questions that were adapted from Witmer and Singer's [40] presence questionnaire. As stated in [40], these questions each focused on one of four presence related factors; sensory factors, control factors, realism factors and distraction factors.

As user interactions and user-specific tasks were not the focus of this study, questions that relate to interaction and task-based aspects from Witmer and Singer's Presence Questionnaire were not included. Furthermore, questions pertaining to involvement were adapted to assess both thermal and wind aspects of the system.

Here, each question was answered on a continuous scale based on the semantic differential principle, adapted from [5], where each item is anchored at the ends by opposing descriptors. By doing so, data sets were collected that represent sensory, control, realism and distraction factors for each configuration of Ambiotherm compared to that of a standard HMD experience. The overall time taken by each participant per session, including instructions and completing all four questionnaires, was approximately 20 minutes. This study was conducted in an air conditioned room (24°C) with no air circulation.

Results

In this section, we present and discuss the results from the analysis of the user studies in terms of sensory, realism, distraction and control factors, all of which are associated with sense of presence within the VR experience [40].

Evaluation of Sensory Factors

A one-way repeated measures ANOVA, with Greenhouse-Geisser correction was conducted using the average sensory

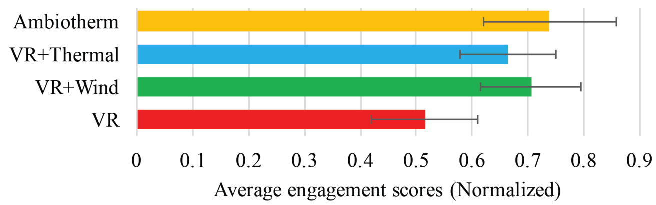

Figure 9. Normalized average engagement scores for four stimuli configurations (Error bars represent 95% CI, n = 20).

factor scores given for each of the four stimuli configurations (VR, VR+Wind, VR+Thermal, and Ambiotherm). There was a significant difference in the scores ($F_{1.7,32.44} = 27.1$, $p < 0.001$) with Ambiotherm having the highest average score (M = 0.70, SD = 0.21), as seen in Figure 8. Post hoc tests using the Bonferroni correction revealed that Ambiotherm (M = 0.7, SD = 0.21) was significantly different to: 1) VR (M = 0.37, SD = 0.11) ($p < 0.05$) and 2) VR+Thermal (M = 0.54, SD = 0.13) ($p < 0.05$), but not to VR+Wind (M = 0.61, SD = 0.13) ($p > 0.05$). Also, significant differences were observed between: 1) VR+Thermal and VR ($p < 0.05$) and 2) VR+Wind and VR ($p < 0.05$), but not between VR+Wind and VR+Thermal ($p > 0.05$). Following are the summarized results:

i) A significant difference was observed in the engagement scores of the four setups (Greenhouse-Geisser correction, $F_{2.15,40.97} = 6.07$, $p < 0.005$) with Ambiotherm having the highest engagement, as seen in Figure 9. Post hoc tests using the Bonferroni correction revealed that Ambiotherm (M = 0.74, SD = 0.26) was significantly different to VR (M = 0.51, SD = 0.2) ($p < 0.05$) but not to 1) VR+Wind (M = 0.71, SD = 0.19) ($p > 0.05$) or 2) VR+Thermal (M = 0.66, SD = 0.19) ($p > 0.05$). Also, a significant difference was observed between: 1) VR+Thermal and VR ($p < 0.05$) and 2) VR+Wind and VR ($p < 0.05$). However, no significant difference was observed between VR+Wind and VR+Thermal ($p > 0.05$).

ii) As expected, no significant difference was observed in the involvement due to visual aspects (Greenhouse-Geisser correction, $F_{1.72,32.76} = 2.32$, $p > 0.05$) and auditory aspects (Greenhouse-Geisser correction, $F_{2.1,39.88} = 0.83$, $p > 0.05$), as these were identical across the four configurations.

iii) A significant difference was seen in the involvement scores due to the thermal aspects (sphericity-assumed, $F_{3,57} = 36.76$, $p < 0.001$), where, as expected, Ambiotherm and VR+Thermal had higher scores (as shown in Figure 10). Post hoc tests using the Bonferroni correction revealed that Ambiotherm (M = 0.64, SD = 0.28) was significantly different to: 1) VR (M = 0.07, SD = 0.17) ($p < 0.05$) and 2) VR+Wind (M = 0.24, SD = 0.32) ($p < 0.05$), but not to VR+Thermal (M = 0.65, SD = 0.24) ($p > 0.05$). Also, statistically significant difference was observed between: 1) VR+Thermal and VR ($p < 0.05$) and 2) VR+Thermal and VR+Wind ($p < 0.05$), but no significant difference was observed between VR+Wind and VR ($p > 0.05$).

iv) Similarly, a significant difference was noted in the involvement scores due to the wind aspects (sphericity-assumed, $F_{3,57} = 31.67$, $p < 0.001$) with Ambiotherm and VR+Wind having higher scores as seen in Figure 10. Post hoc tests using the

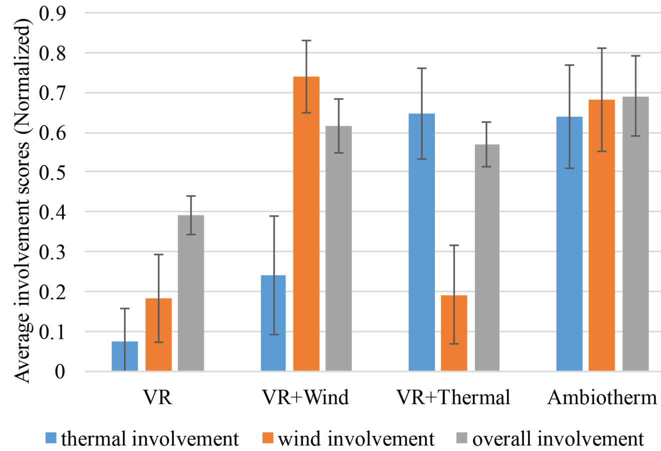

Figure 10. Normalized average thermal, wind, and overall Involvement scores for four stimuli configurations (Error bars represent 95% CI, n = 20).

Bonferroni correction revealed that Ambiotherm (M = 0.68, SD = 0.28) was significantly different to: 1) VR (M = 0.18, SD = 0.23) ($p < 0.05$) and 2) VR+Thermal (M = 0.19, SD = 0.27) ($p < 0.05$), but not to VR+Wind (M = 0.74, SD = 0.2) ($p > 0.05$). Also, a significant difference was observed between: 1) VR+Wind and VR ($p < 0.05$) and 2) VR+Wind and VR+Thermal ($p < 0.05$), but no significant difference was observed between VR+Thermal and VR ($p > 0.05$).

v) A significant difference was observed in the overall involvement (visual, auditory, thermal and wind stimuli combined) scores (Greenhouse-Geisser correction, $F_{1.75,33.25} = 17.85$, $p < 0.001$) with a notable improvement in Ambiotherm from the traditional VR experience, as seen in Figure 10. Post hoc tests using the Bonferroni correction revealed that Ambiotherm (M = 0.69, SD = 0.22) was significantly different to VR (M = 0.39, SD = 0.1) ($p < 0.05$), but not to 1) VR+Wind (M = 0.62, SD = 0.14) ($p > 0.05$) and 2) VR+Thermal (M = 0.57, SD = 0.12) ($p > 0.05$). Also, a significant difference was observed between: 1) VR+Wind and VR ($p < 0.05$) and 2) VR+Thermal and VR ($p < 0.05$), but no significant difference was observed between VR+Wind and VR+Thermal ($p > 0.05$).

vi) Lastly, even with the addition of extra multisensory stimuli, no significant difference in the delay between the modalities was noticed (Greenhouse-Geisser correction, $F_{2.07,39.23} = 0.61$, $p > 0.05$), thereby validating selected synchronization settings.

This study also revealed that 95% of the participants were able to identify the thermal stimuli delivered using Ambiotherm, of which, 73% perceived the thermal sensation as part of the ambient environment. However, only 50% of these participants perceived the thermal sensation as an overall body experience. This highlights a potential limitation of the system and suggests that methods to decrease this localized perception of thermal stimuli should be explored in future work. Furthermore, 90% of the participants were able to identify the wind stimuli delivered using Ambiotherm, out of which 94% perceived the wind sensation as part of the ambient environment. Additionally, a paired-samples t-test, conducted to compare the degree to which the sense of moving was compelling, re-

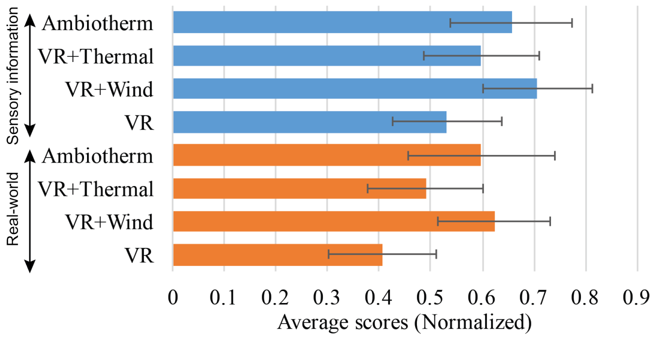

Figure 11. Normalized average consistency scores of VR Environment compared to Real-World and consistency scores for sensory information for four stimuli configurations (Error bars represent 95% CI, n = 20).

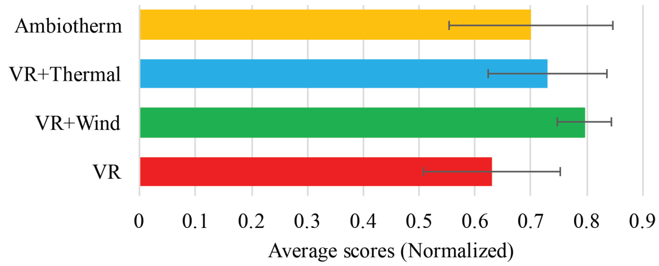

Figure 12. Normalized average scores assessing the quickness to adjust to the VR Environment with four stimuli configurations (Error bars represent 95% CI, n = 20).

vealed a significant improvement (t(19)=-4.16, $p < 0.05$) in Ambiotherm (M = 0.72, SD = 0.23) when compared to the traditional VR experience (M = 0.55, SD = 0.19).

Evaluation of Realism Factors

A one-way repeated measures ANOVA, with Greenhouse-Geisser correction was conducted using the average realism factor scores given for each of the four stimuli configurations. There was a significant difference in the scores ($F_{2.07,39.4}$ = 6.53, $p < 0.05$) with Ambiotherm having an average score significantly higher than the traditional VR experience, as shown in Figure 8. Post hoc tests using the Bonferroni correction revealed that Ambiotherm (M = 0.48, SD = 0.16) was significantly different to VR (M = 0.39, SD = 0.16) ($p < 0.05$) but not to 1) VR+Wind (M = 0.52, SD = 0.18) ($p > 0.05$) or 2) VR+Thermal (M = 0.43, SD = 0.16) ($p > 0.05$). Also, a significant difference was observed between VR+Wind and VR ($p < 0.05$), but no significant difference was observed between 1) VR+Thermal and VR ($p > 0.05$) or 2) VR+Wind and VR+Thermal ($p > 0.05$). Although there was no significant difference in the realism factor scores between Ambiotherm and VR+Wind, we believe that the difference in score may be due to the relatively localized nature of thermal stimuli which are present in the Ambiotherm configuration.

A one-way repeated measures ANOVA, with sphericity-assumed, was conducted to compare how consistent the VR environment was in comparison with the participants' experiences of the real-world. Results for the four stimuli configurations revealed a significant difference in scores ($F_{3,57}$ = 8.26, $p < 0.001$), with Ambiotherm (M = 0.6, SD = 0.3) and the VR+Wind (M = 0.62, SD = 0.23) having higher average scores, as shown in Figure 11. Post hoc tests using the Bonferroni correction revealed that Ambiotherm was significantly different to VR (M = 0.4, SD = 0.22) ($p < 0.05$) but not to 1) VR+Wind ($p > 0.05$) or 2) VR+Thermal (M = 0.49, SD = 0.23) ($p > 0.05$). Also, a significant difference was observed between VR+Wind and VR ($p < 0.05$), but no significant difference was observed between 1) VR+Thermal and VR ($p > 0.05$) or 2) VR+Wind and VR+Thermal ($p > 0.05$). Similarly, results of a one-way repeated measures ANOVA, with sphericity-assumed, indicate a significant difference in the scores for consistency of information coming from the various senses ($F_{3,57}$ = 4.19, $p < 0.05$), where Ambiotherm and VR+Wind have higher average scores, as seen in Figure 11. Post hoc tests using the Bonferroni correction revealed no significant difference between: 1) Ambiotherm (M = 0.66, SD = 0.26) and VR (M = 0.53, SD = 0.23) ($p > 0.05$), 2) Ambiotherm and VR+Wind (M = 0.70 SD = 0.23) ($p > 0.05$), 3) Ambiotherm and VR+Thermal (M = 0.6, SD = 0.24) ($p > 0.05$), 4) VR+Wind and VR+Thermal ($p > 0.05$) and 5) VR+Thermal and VR ($p > 0.05$), however a significant difference was observed between VR+Wind and VR ($p < 0.05$). Furthermore, the participants indicated that they did not feel disoriented after any trials during the study.

Evaluation of Control Factors

On conducting a one-way repeated measures ANOVA, with Greenhouse-Geisser correction, no significant difference in the control factor scores for the four different stimuli configurations was found ($F_{2.13,40.55}$ = 1.01, $p > 0.05$). These results matched our expectations, as the developed VR environments in the demo application did not include any responsive interactions other than changes in visual stimuli based on head-tracking. Interestingly, a significant difference was observed from the results of a one-way repeated measures ANOVA, with sphericity-assumed, in the rate of adjustment to the VR environment in the four configurations ($F_{3,57}$ = 4.8, $p < 0.05$) with VR+Wind being found to have an average score (M = 0.79, SD = 0.10) higher than the other three configurations as shown in Figure 12. Post hoc tests using the Bonferroni correction revealed no significant difference between: 1) Ambiotherm (M = 0.73, SD = 0.25) and VR (M = 0.63, SD = 0.26) ($p > 0.05$), 2) Ambiotherm and VR+Wind (M = 0.79, SD = 0.1) ($p > 0.05$), 3) Ambiotherm and VR+Thermal (M = 0.73, SD = 0.23) ($p > 0.05$), 4) VR+Wind and VR+Thermal ($p > 0.05$) and 5) VR+Thermal and VR ($p > 0.05$), however a significant difference was observed between VR+Wind and VR ($p < 0.05$).

Evaluation of Distraction Factors

The results of a one-way repeated measures ANOVA, with sphericity assumed, indicates no significant difference in the scores of distraction factors for the four different stimuli configurations ($F_{3,57}$ = 1.18, $p > 0.05$). This validates the settings of the selected thermal and wind stimuli as they do not cause any additional notable distractions to the user's experience in the VR environment. However, it should be noted that Ambiotherm was unable to address the distractions caused due to real-world conditions and the physical device, such as its weight, which remain a common issue with all existing HMDs.

DISCUSSION AND FUTURE WORK

This work was our first attempt to understand how a combination of wind and thermal stimuli can be utilized to enhance the sense of presence in VR. The study also explored several aspects of human multisensory perception, utilizing information from visual, auditory, and haptic sensations, and addressed several issues including design factors for multisensory stimuli. Here, we discuss a number of interesting findings from our studies, highlighting limitations and proposing further studies of this technology in the future.

Within this study, one of our primary observations is that, despite both performing equally well in many aspects, Ambiotherm outperformed VR+Wind in terms of thermal involvement. We speculate that, due to the relatively localized nature of the thermal stimuli presented by Ambiotherm, a marginal drop in scores was observed for aspects such as consistency in sensory information (Realism Factor) and speed of adjustment to the VR environment (Control Factor), when compared to VR+Wind. Another notable observation is that VR+Wind consistently outperformed VR+Thermal in nearly all recorded aspects. We speculate that this may be due to differences in the raw impact of the two stimuli. Unlike the relatively subtle thermal stimuli behind the neck, the wind stimuli on the face were perceived more intensely due to the number of somatosensory receptors within the face (physiologically), and as humans are generally more aware of activities occurring near the face (psychologically).

Future implementations of Ambiotherm may be improved by integrating heating and cooling mechanisms within the fans, with the aim of controlling the temperature of the wind stimuli. We also believe that developing this functionality may provide additional benefits as this will 1) form a single module that can generate both thermal and wind stimuli, 2) enable Ambiotherm to more accurately simulate real-world environmental conditions and 3) enable thermal stimulation to be applied in multiple locations (both on the face and back of the neck). Furthermore, additional modalities such as smell as well as other haptic sensations, including vibration and humidity (vaporized water), will be integrated in the future to simulate additional environmental conditions.

Besides multisensory stimuli considerations, there are several other aspects that may be improved in future work. For example, this study does not include interactions between the user and the virtual environment. As stated by Witmer and Singer [40], interaction is a key factor that can affect the sense of presence, thus, we intend to extend our studies to compare the passive and interactive VR experiences. In addition, when using a questionnaire to evaluate a subjective experience such as the sense of presence, participants tend to interpret each question differently, based on prior experiences. In future research, other objective physiological measurements, for example, participant's heart rate and skin responses will also be incorporated into our studies. Furthermore while conducting the analysis, we observed that some datasets, such as degree of sensation to thermal stimuli, had high variances, suggesting a need for larger sample sizes in future studies.

Through the synchronization study we observed that the overall latency of stimuli perception is reduced when all modalities of Ambiotherm are combined. We believe that, by engaging multiple modalities, Ambiotherm appeals to many of the same perceptual mechanisms that a user employs when experiencing the real-world, in turn, potentially enabling users to process multisensory stimuli more efficiently than in traditional VR experiences [37].

Moreover, as an extension of the synchronization study, potential cross-modal effects between stimuli should be explored in future work. Results from these studies will further help to refine the stimuli design and protocol to facilitate the creation of more compelling virtual experiences. Although the stimuli used during this study had consistent characteristics for all user experiences, future work may also look towards developing individual calibration methods that alter stimuli parameters based on users' sensitivity or preferences.

Aside from making the electronics more compact and enhancing the system's power efficiency, we are developing Ambiotherm as a platform that is integrated with VR development environments, such as Unity, where developers may directly utilize its capabilities. By further studying and refining these multisensory stimuli, a taxonomy may be established for future VR developers.

Finally, as noted by Witmer and Singer [40], it is not clear how appropriate weightage can be assigned to signify the influence of each factor on the overall sense of presence. This is mainly due to the fact that the concept of sense of presence is both multi-faceted and subjective. Due to this, we have presented the results of our analysis, and our conclusions, under these separate factors without constructing an overall score to compare the four different system configurations.

CONCLUSION

We have developed the Ambiotherm system to simulate the sensory aspects of different environmental conditions such as wind and ambient temperature in VR environments, with the aim of enhancing the users' sense of presence within VR experiences. We have conducted multiple experiments to optimize fundamental aspects such as location, level of comfort and intensity of stimuli. Furthermore, a formal study was conducted to evaluate the effectiveness of the prototype system. In summary, a significant improvement in scores for sensory and realism factors of the VR experience was observed in Ambiotherm when compared to a traditional VR configuration. Secondly, the addition of thermal and wind stimuli via Ambiotherm did not cause notable distractions during the users' VR experiences. Lastly, compared to the relatively localized thermal stimuli, the wind stimuli had a more significant effect on users' sense of presence when simulating realistic environmental wind conditions.

ACKNOWLEDGMENTS

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its International Research Centres in Singapore Funding Initiative.

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