Psychophysical Effects of Experiencing Burning Hands in Augmented Reality

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Abstract. Can interactive Augmented Reality (AR) experiences induce involuntary sensations through additional modalities? In this paper we report on our AR experience that enables users to see and hear their own hands burning while looking through a Video See-Through Head-Mounted Display (VST-HMD). In an exploratory study (n = 12, within-subject design), we investigated whether this will lead to an involuntary heat sensation based on visual and auditory stimuli. A think-aloud-protocol and an AR presence questionnaire indicated that six out of twelve participants experienced an involuntary heat sensation on their hands. Despite no significant change of perceived anxiety, we found a significant increase in skin conductance during the experiment for all participants; participants who reported an involuntary heat sensation had higher skin conductance responses than participants who did not report a heat sensation. Our results support our initial hypothesis as we found evidence of cross-modal audiovisual-to-thermal transfers. This is an example of virtual synaesthesia, a sensation occurring when single-modal (or multi-modal) stimulus sets off the simultaneous sensation over other senses—involuntarily and automatically. We believe that our results contribute to the scientific understanding of AR induced synaesthesia as well as inform practical applications.

1 Introduction

Augmented Reality (AR) systems supplement the real world with virtual objects that appear to coexist in the same space as the real world [1]. The character Morpheus in the movie The Matrix (1999) posed the following questions: *"What is real? How do you define real?"*. These are simple yet profound questions. Recent technological advances have enabled content developers to create photorealistic graphics, making these questions increasingly important. In the near future, virtual objects in AR experiences may become barely distinguishable from real ones [35]. Already, AR experiences can induce significant feelings of presence, making people respond as they would in relation to real stimuli [38].

We hypothesize that AR experiences have the potential to fool various senses. Inspired by BurnAR by Weir et al. [42]; we set out to explore more deeply how

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AR experiences create involuntary sensations in alternate pathways. This is a form of synaesthesia—an individual sensation, occurring when a stimulus creates a simultaneous sensation on other sensory modalities [31]. The experiment described in this paper is creating virtual synaesthesia, which is induced by experiencing realistically burning hands in AR.

Our contribution is to show the physiological and psychological stress response of user's experiencing their own hands burning in AR. We are reporting about an exploratory user study that supports our initial hypothesis as we found some evidence of cross-modal audiovisual-to-thermal illusion. In spite of no significant change of perceived anxiety, we found a significant increase in skin conductance during the experiment. Moreover, participants who experienced involuntary heat sensations had a higher skin conductance response.

Insights from our experiment may be of significance in a neuroscientific or clinical context, as we were able to demonstrate a cross-modal audiovisual-to-thermal transfer using AR technology. This allows insights into the perceptual and cognitive effects of AR experiences. Significant work in this area has been previously done in the framework of VR, using avatars to provide a virtual proxy representation of the user's body. Our experiment departs from that research in that the AR setup integrates the real body into the experience.

2 Related Work

In this section, we summarize existing works that report on the induction of sensations (e.g., temperature, touch, smell, taste, sound) as a result of stimulation of the visual and auditory senses.

Cytowic [7] defined synaesthesia as an involuntary joining of the senses in which the real information of one sense is accompanied by a (virtual) perception in another sense. In addition to being involuntary, this additional perception is regarded by the synaesthete (a person experiencing synaesthesia) as real, often outside the body, instead of imagined in the mind's eye.

There has been several works reporting the occurrence of synaesthesia, sometimes called cross-modal illusions in virtual environments: Visual-to-haptic illusions in VR have been observed in psychological experiments [2,24]. An AR system called Hand-displacEMent-based Pseudo-haptics (HEMP) induces haptic sensations from purely visual input, using a VST-HMD to displace the visual representation of the user's hand dynamically [30]. Similar results from other research into cross-modal sensory illusions involve the visual, olfactory, and gustatory senses [27,28].

A more related approach is to present objects or effects which humans associate with ambient temperatures or thermal sensations: In a variation of the classic Rubber Hand Illusion, the rubber hand was hit with a strong light beam, resulting in thermal sensations of the participant's real hand [11]. Hoffman et al. [17] placed patients in a virtual environment depicting snow and ice and gave them the task of throwing snowballs when undergoing usually painful treatment for burn injuries. They could prove that this strategy significantly reduces pain-related brain activity.

This paper is a spiritual successor to BurnAR from Weir et al. [42]. In their demonstration the user can experience the illusion of seeing their own hands burning by looking through a VST-HMD. In a questionnaire-based user study, some of the participants reported an involuntary heat sensation in their hands. Several studies have used VR experiences to treat anxiety disorders in the form of VR Exposure Therapy (VRET) [23]. The immersive nature of the VR and AR [22] experiences can induce measurable stress responses. The main differences of our current paper are a more sophisticated experimental platform, as well as additional measurements of physiological effects (skin conductance) and psychological effects (perceived anxiety).

Several studies indicate that participants react to virtual stressors as if they were real [12]. Martens et al. [26] found that exposure to a realistic stressful situation in a VR elevator could increase physiological and subjective stress responses. Yeh et al. compared the VR and AR on induced anxiety using heart rate and skin conductance as indicators of anxiety. They found a significant increase in skin conductance and heart rate, but not in subjective anxiety [44].

The majority of publications investigates the sense of presence and immersion with VR systems [5,34,36,45]. Very few investigations have been done on AR systems, and even fewer on AR systems using VST-HMDs. Slater [38] proposed two orthogonal components that contribute to realistic responses in immersive VR systems: **(1)** "Being there", often called "presence", the quality of having a sensation of being in a real place. We call this place illusion (PI). **(2)** Plausibility illusion (PSI) refers to the illusion that the scenario being depicted is actually occurring. Place illusion/presence is an illusion that the user is located inside the rendered virtual environment. In the literature, this illusion has been referred to as the "sense of being there" in a virtual environment [34]. PSI is determined by the extent to which the system can produce events that directly relate to the participant, the overall credibility of the scenario being depicted in comparison with expectations. In the context of Slater's definition of presence, place illusion (PI), initially defined for VR systems, is not an illusion in AR. Thus, what remains to be satisfied for presence is the plausibility illusion to achieve presence. Previous work has demonstrated that the degree of presence is increased by using audio to enhance visual perception [8], and hence adding to the feeling of presence. Gandy et al. [14] investigated whether the findings from VR presence studies can be transferred to AR, as Slater's definitions of presence (PI, PSI) are initially defined for VR systems. They discuss a crucial difference between AR systems and VR systems: the ability of the participant to observe their own body and its movement in real-time, which is not available in VR. This results in a much stronger sense of "being there". Their work highlighted the differences in AR systems that need to be considered, from the use of physiological measures to the design of questionnaires to assess the participant's level of presence. Our work builds on the previous experiment by Weir et al. and demonstrates that increased realism alone can significantly heighten the synaesthetic experience, providing much more insight into the cross-modal illusions induced by AR experiences [43].

3 Experiment

We performed an exploratory study, that addresses the following three research questions: **RQ1:** Can the observation of virtual flames result in an involuntary heat sensation? **RQ2:** Do participants exhibit stress responses during the observation of virtual flames using subjective self-report and different physiological measures (skin conductance or heart rate)? **RQ3:** Do participants who report an involuntary heat sensation experience a higher level of presence and stress responses compared to participants who do not report it?

System Design. Our AR system will alter the perception of the user's body. Therefore, it needs to be capable of precise body tracking and recreating its volumetric representations in real-time. For this experiment, we only need to create volumetric representations of the user's hand, which we achieved with the Leap Motion sensor together with its SDK. The sensor was mounted on the headset (See Fig. 1 a)). The volumetric representation of the hand will be fed into our fire simulation software based on nVidia GameWorks nvflow, a voxel-based fluid simulation capable of creating a realistic interactive fire and smoke simulation. The nvflow-SDK was integrated into a custom-built version of the Unreal Engine. This simulation was later fine-tuned to provide a system response time of 11.1 ms (equals one frame in a 90fps system). The AR experience provides multiple sensory stimuli. To play auditory cues, we used the spatial audio system of the Unreal Engine for playing fire sound effects.

We use an HTC Vive Pro as a VST-HMD. The display has a resolution of 1440×1600 pixels, a refresh rate 90 Hz, and a field of view of 110°. The dual front-facing cameras of the Vive Pro have a resolution of 480p at 90fps [18]. The Valve Lighthouse tracking system was used to track the headset. To achieve a video see-through mode, we used the HTC Vive SRWorks SDK.

Participants. We recruited twelve participants (six female, six male) from the staff and student population of the City University of Hong Kong. All participants were in the range of 20–32 years, with a mean age of 28.25 ± 3.7. The experiment had the approval of the ethics committee at our university.

Measures. We gathered stress responses of participants, both subjective (self-report) and objective (physiological measurements).

The state version of the State-Trait Anxiety Inventory (S-STAI) was used to measure perceived anxiety. This questionnaire consists of 20 items using a 4-point Likert scale [37]. A higher score represents a higher level of perceived anxiety. We deployed the questionnaire before and after the AR experience to assess a change of perceived anxiety.

Regarding the physiological level, the central part is the interaction between the sympathetic and parasympathetic branches in the autonomic nervous system. The most immediate stress response is related to the activation of the sympathetic branch and inhibition of the parasympathetic branch, which represents the 'fight or flight' mechanism obtained from human evolution [29]. The skin conductance level (SCL) is a good indicator of sympathetic activity [20]. It has been also shown, that it increases in response to psychological stress [20].

We used the BitAlino to measure physiological data[16]. We connected the BitAlino through electrodes to the participant. The device was mounted on an armband attached to the participant's left arm (See Fig. 1). We started logging three minutes before the experiment and stopped logging five minutes after the end of the experiment.

Questionnaires. To measure the level of presence and immersion, we have employed a customized questionnaire based on the AR presence questionnaire from Gandy et al. [14]. The presence questionnaire consists of 7 questions (e.g., "How natural did the fire appear on your left hand?") on a 7-point Likert scale (See Table 1). We added one question, where we asked the participant how strong they felt a heat sensation. For this questionnaire, the internal consistency was satisfactory, Cronbach's $\alpha = 0.78$, McDonald's $\omega = 0.78$. After the experiment, we collected basic demographic data, including gender and age.

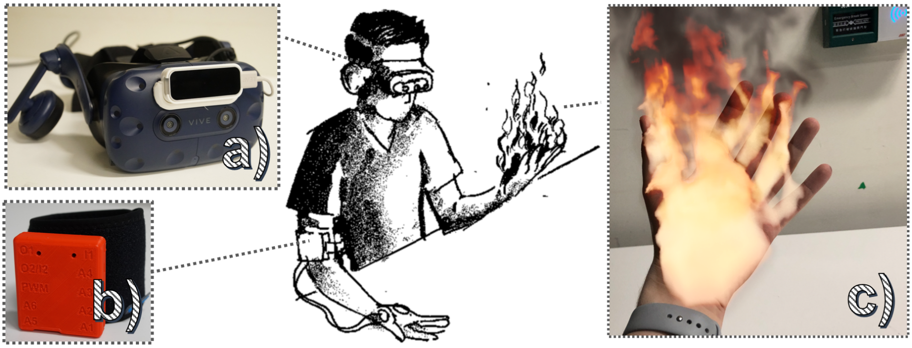

Fig. 1. Experimental platform. **a)** HTC Vive Pro, a VST-HMD, with attached Leap Motion. **b)** BitAlino, measuring various bio-markers, worn by the participant on an armband. The device measures biomarkers through electrodes placed on the participant's hand. **c)** The fire as a visual stimuli appearing in the participants hand.

Procedures. Before the experiment began, all participants were provided with information sheets and consent forms, containing basic information about the experiment. However, we never mentioned that they would see a virtual fire on their left hand, as we did not want to influence the outcome.

The data collection for the questionnaires was divided into two parts, i.e, before and after the AR experience. Physiological data (HR and GSR) was recorded continuously. We recorded for an additional three minutes after the participants put on their headset to take a baseline, as putting up a headset might result in techno-stress [32].

These self-report questionnaires are needed to determine the influence of the burning hand experiment on the participant's subjective anxiety level. Before the start of the experiment, the first set of questionnaires was given to the participant (demographic, S-STAI). After the participant gave consent and filled all questionnaires, the experimenter set up all devices for collecting the physiological measurements. During the experiment, the participants were seated at a table, which would allow them to rest their arm. The experimenter helped the participant to put on the HMD. The participants were asked to sit still, but were allowed to move their left hand as long as it stayed in the field of view of the HMD. A camera started recording after correct placement of the headset. After three minutes of baseline recording the virtual fire appeared on the participant's left hand. The fire stopped five minutes later, and the experience ended. The headset was removed, and all connected devices detached. After that, participants filled out a second S-STAI and the AR presence questionnaire.

4 Results

We observed that six out of 12 participants reported a strong involuntary heat sensation on their left hand in the self-report questionnaire. We counted a value higher than five as a positive heat sensation. We divided the participants into two groups based on their responses using the method of median split [19]: **Group A**, in which participants have felt an involuntary heat-sensation on their left hand during the AR experience; **Group B** in which participants did not feel a heat sensation on their left hand.

We processed electrodermal activity (EDA) and the electrocardiogram (ECG) signals using NeuroKit [25]. Due to noisy measurements, we decided to rely solely on SCL signals for our analysis and conclusions. EDA signals contain two components: a tonic component, the SCL, which varies slowly in time, and a shorter phasic component, called the skin conductance response (SCR), which changes quickly over time [9]. According to Braithwaite [3], averaging across the whole signal will over-estimate the SCL. One solution is subtracting the amplitudes of SCRs from the tonic signal and then establishing a true score of SCL. Hence, we used the cvxEDA algorithm proposed by Greco et al. [15] to decompose the signal to the tonic (SCLl) and phasic (SCR) components.

The following time windows were considered: the baseline time (30s after setting up the headset and before the virtual fire appeared); three intervals during the AR experience: the first third of the total time (early stage), the second third of the total time (middle stage), and the third of the total time (late stage). We normalized the score using a log transformation and then averaged only the SCL scores within each time window.

In the following we present both descriptive and inferential statistical analysis based on our research questions. As this is an exploratory study, we did not conduct a priori power analysis to analyze the sample size. Both statistic tests were carried out using the open source statistics software JASP [21].

Table 1. Results of our AR Presence questionnaire.

Questions	Group A Mean	Group B Mean	All participants Mean	Min	Max
1. In the application, did you feel like an observer or a participant?	5.83 ± 0.98	5.83 ± 0.98	5.83 ± 0.94	4	7
2. How natural did the fire appear on your left hand?	5.33 ± 0.52	5.17 ± 1.33	5.25 ± 0.97	3	7
3. How aware were you of events occurring in the real world around you?	4.00 ± 1.41	4.50 ± 2.17	4.25 ± 1.76	1	7
4. How comfortable did you feel interacting with the fire?	5.67 ± 1.21	6.00 ± 0.89	5.83 ± 1.03	4	7
5. How much did the visual display quality interfere or distract you from interacting with the fire?	3.33 ± 1.86	3.83 ± 2.48	3.58 ± 2.11	1	7
6. How much delay did you experience between your actions and expected outcomes?	3.33 ± 0.82	2.50 ± 1.87	2.92 ± 1.44	1	6
7. Was the information provided through sight consistent with your other senses?	5.50 ± 0.55	5.17 ± 1.72	5.33 ± 1.23	2	7

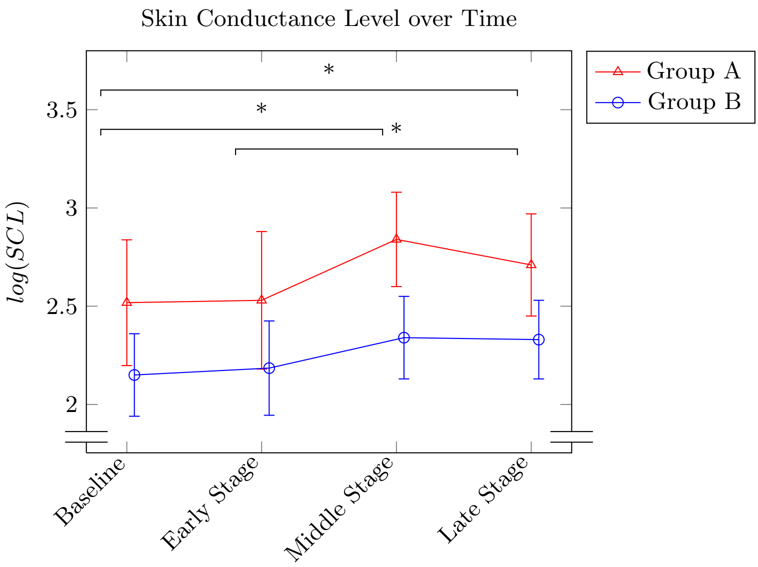

Fig. 2. Log transformed SCL of Group A (reported a heat sensation) and Group B (no heat sensation) over time. Error bars denote the standard error. Connected bars represent significant differences ($p < 0.001$).

4.1 Analysis

Skin Conductance Level. We processed the EDA signals using the NeuroKit package in Python [25]. We used the cvxEDA algorithm proposed by Greco et al. [15] to decompose the signal to the tonic (SCL) and phasic (skin conductance response SCR) components.

We examined the SCL at baseline, early stage, middle stage, and late-stage using a repeated-measures analysis of variance (RM-ANOVA) with time as a within-subject factor. For the frequentist RM-ANOVA, the Greenhouse-Geisser correction was used due to the violation of sphericity ($\chi 2(5) = 18.46, p = .003$). The result showed a significant within-subject effect of time, ($F(1.35, 15.56) = 9.11, p = .005, \eta 2p = 0.45$). A high Bayes factor ($BF10 = 145.55$) also decisively supports this outcome using Bayesian RM-ANOVA. This results shows a changing of SCL between different time points.

In post hoc tests with an applied Bonferroni correction, we found significant differences between the baseline and the middle stage, ($t(11) = 4.36, p < .001$), between the baseline and late stage, ($t(11) = 3.21, p = .018$) and between the early stage and middle stage, ($t(11) = 3.98, p < .002$). The Bayes factor showed strongly ($BF10 = 30.96$) substantial ($BF10 = 8.06$ and $BF10 = 5.39$) support, respectively. In general, these results showed an increase of the SCL from baseline to the middle stage. Notably, the difference between early stage and late stage is just significant, ($t(11) = 2.83, p = .047$), while the Bayes factor only indicates an small evidence to support, ($BF10 = 1.63$). In contrast, despite the lack of statistical significance ($t(11) = -1.15, p = .275$), the Bayes Factor nearly substantial supported a decrease of the SCL from the middle stage to late stage, ($BF01 = 2.38$). This results suggest a descending trend back to the early stage of the SCL over time when participants became used to the exposure.

A mixed-ANOVA test with the within-subjects factor time and the between-subjects factor heat sensation was conducted (see Fig. 2). We used the Greenhouse-Geisser correction to adjust the biased result because of the violation of sphericity ($\chi^2(5) = 19.93, p = .001$). We found the main effect of within-subjects factor time was also significant, ($F(1.35, 13.51) = 8.88, p = .007, \eta 2p = 0.30$) and a decisive evidence-based the Bayesian statistics, ($BF10 = 145.55$). In contrast to the result in descriptive statistic, the interaction effect between the within-subjects factor time and the between-subjects factor heat sensation was non-significant, ($F(1.35, 13.51) = 0.71, p = .45$). However, the Bayes factor based on the model comparison just showed slightly over substantial evidence to the null hypothesis (without this interaction), ($BF10 = 0.25, BF01 = 4.08$). Furthermore, we compared the SCL in the middle stage using an independent t-test. The results show a non-significant higher score in Group A, ($t(10) = 1.55, p = .15$, $BF10 = 0.96, BF01 = 1.04$). No significant differences were found for age and gender.

Presence. In order to test if there was a significant difference between the two groups in terms of presence, we used an independent t-test that contrasted the summed score of presence and immersion between Group A and B. The questions and results are shown in Table 1. Because of the violation of equality of variance,

($F(1, 2) = 11.92, p = .006$), the result was reported using Welch's correction: We found a non-significant difference between the two groups, ($t(6.14) = 0.18, p = .864$). However, the Bayes factor gave an anecdotal support to no difference, ($BF10 = 0.47, BF01 = 2.12$).

Subjective Level of Stress Response. Overall, a paired t-test revealed no significant differences ($p = 0.08$) in self-reported anxiety through the S-STAI questionnaire before and after the experiment.

5 Discussion

Our exploratory study has produced three key findings: **1)** Half of the participants report a cross-modal heat illusion: they experienced heat on their left hand, induced through purely visual and acoustic stimuli from our AR experience in the absence of a real heat source. **2)** In spite of no significant change of perceived anxiety at subjective level, we discovered a significant increase in skin conductance when the participants observed their left hand burning in our AR experience. **3)** Participants who reported experiencing this illusion had a higher skin conductance response compared to the participants who did not report experiencing it. The following three paragraphs discuss our hypothesis in light of these results.

RQ1: Can the observation of virtual flames result in an involuntary heat sensation? We observed that six out of twelve participants reported an involuntary heat sensation in the form of cross-modal audiovisual-to-thermal transfers. However, it is still unknown which variables are responsible for inducing cross-modal illusions in Augmented Reality. One of the external factors could have been the high plausibility, as we designed the fire simulation to make it look, behave and sound as realistic as possible. But we are unsure how much that contributed to the cross-modal illusion. Would an unrealistic fire also induce heat sensations? Other external factors might involve the technical aspects of the AR system, for example, it might be harder to induce cross-modal illusions if the headset would feature a high latency or low resolution. Other than the AR system and the plausibility of the simulation, we hypothesize that various internal factors of the participant's personality play an important role. Personality traits already have been shown to have a significant impact on presence and immersion [33,41] and sense of embodiment [10].

RQ2: Do participants exhibit stress responses during the observation of virtual flames using subjective self-report and different physiological measures (skin conductance or heart rate)? We found a significant increase in participant's skin conductance observing their hands burning in our AR experience. The systematical change of skin conductance shows evidence of a real stress response induced by our experiment. In other words, this result shows that participant's reaction elicit physiological mechanisms similar to those engaged when exposed to real world stressors. However, we did not find a significant change of perceived anxiety or stress at the subjective level. This result matches the study by Yeh et al. [44], but not the results of [12,26]. One possible explanation is that stress response is not regarded as a unitary construct in the field of psychophysiology; instead, it includes multiple interacting components [40]—subjective, physiological, and behavioral effects of threat and challenge appraisal [39]. So a dissociation between the subjective emotional component and physiological component is possible, thus making these results not directly comparable.

RQ3: Do participants who report an involuntary heat sensation experience a higher level of presence and stress responses compared to participants who do not report it? Overall, based on our AR presence questionnaire (See Table 1), the level of presence did not correlate to the intensity of the observed cross-modal illusion. Since we observed a high level of presence through all participants, we believe that our AR system, especially our tracking and fire simulation, leads to an illusion experienced as highly plausible. Some participants noted the high realism and fidelity of our fire simulation. Moreover, participants who experienced an involuntary heat sensation had a higher skin conductance response. One possible reason is the small sample size in our study, making it difficult to find significant results due to the lack of statistical power [13].

6 Conclusions and Future Work

This paper describes the design, implementation, and evaluation of an AR experience that enables users to see their own hands burning. We showed in an exploratory user study that it is possible to use AR to induce an involuntary cross-modal sensation in some individuals, without direct sensory stimulation. We also discovered that participants that experienced an involuntary cross-modal sensation in our AR experience, had a higher skin conductance response than participants who did not.

We suggest that in a future user study, the plausibility of the AR experience could be made an independent, controlled variable. This could be the control of the level of realism of the fire (e.g., color, level of interaction) or external factors of the AR system (e.g., system latency, display refresh rate, resolution ..). As audio can enhance the immersion in VR or plausibility in AR [8], we will look into ways to integrate real-time fire-like sound synthesis (such as [4]) into our system. Our experimental setup did not allow the participants a huge degree of freedom due to the reliance of electrodes. We recommend that in future studies, more non-invasive ways to measure biometric data to be used. For example, Collins et al. used a wristband to measure SCL and ECG data, allowing participants to move freely [6]. We chose to use AR for this experiment, as there already have been a big number of experiments conducted using VR to examine presence, embodiment and cross-modal illusions. However, it is still not clear, whether this experiment would lead to the same results in VR. This could be examined in a future study. To further answer the question of why only some participants experience a thermal sensation from the audiovisual input provided by our system, we want to additionally explore how important personality traits are in explaining the emergence and strength of these AR-based cross-modal illusions.

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