Examining Whether Secondary Effects of Temperature-Associated Virtual Stimuli Influence Subjective Perception of Duration

Austin Erickson* Gerd Bruder† Pamela J. Wisniewski‡ Gregory F. Welch§

University of Central Florida

Abstract

Past work in augmented reality has shown that temperature-associated AR stimuli can induce warming and cooling sensations in the user, and prior work in psychology suggests that a person's body temperature can influence that person's sense of subjective perception of duration. In this paper, we present a user study to evaluate the relationship between temperature-associated virtual stimuli presented on an AR-HMD and the user's sense of subjective perception of duration and temperature. In particular, we investigate two independent variables: the apparent temperature of the virtual stimuli presented to the participant, which could be hot or cold, and the location of the stimuli, which could be in direct contact with the user, in indirect contact with the user, or both in direct and indirect contact simultaneously. We investigate how these variables affect the users' perception of duration and perception of body and environment temperature by having participants make prospective time estimations while observing the virtual stimulus and answering subjective questions regarding their body and environment temperatures. Our work confirms that temperature-associated virtual stimuli are capable of having significant effects on the users' perception of temperature, and highlights a possible limitation in the current augmented reality technology in that no secondary effects on the users' perception of duration were observed.

Index Terms: Computer graphics—Graphics systems and interfaces—Virtual reality; Human-centered computing—Interaction paradigms—Virtual reality

1 Introduction

As augmented reality head-mounted displays (AR-HMDs) become more ubiquitous in our daily life, we have an increasing opportunity to use these devices to alter and enhance the perception of their users [13, 32]. These devices have already been used to give users access to 'superhuman' senses by allowing them to perceive portions of the electromagnetic spectrum that are outside the range of visible light, and have even been used to give users the ability to see through walls, as well as to extend and augment social cues among collaborating users [7, 8, 19, 22, 24]. While the research mentioned above has been focused on augmenting and enhancing human visual perception, other primary or secondary senses such as sense of temperature can be augmented or enhanced in a similar fashion and offer interesting benefits to the user.

Past research has shown that people are influenced by a phenomenon known as *visual dominance*, where in the presence of stimuli across multiple different sensory inputs, the visual stimulus can drown out other senses or even cause *virtual synesthesia*, where a person perceives stimuli from another sense that is not actually occurring [28, 29]. These phenomena have been used in augmented reality research to influence a user's perception of temperature, such as previous work by Weir et al. and Hoffman et al. where they showed that some users perceived warming or cooling sensations when viewing dynamic fire and icy-fog effects on an AR-HMD, even though no such temperature changes were actually occurring [12, 31]. Erickson et al. additionally showed that these sensations can occur when stimuli are presented directly in contact with the user or when stimuli are presented indirectly in the user's environment [8]. Since significant direct effects on users' temperature perception were achieved multiple times in the past by the above-mentioned studies, it is possible that secondary effects on human perception can also occur from similar stimuli. In other words, can AR stimuli directly affect one aspect on human perception, which in turn triggers secondary effects on other aspects of human perception, such as sense of duration?

As humans, we are inherently good at perceiving events as they happen around us. When a sequence of events unfolds, we naturally observe the order of the events and can remember which event came first, second, and so on, however we are not as good at examining the duration of times that lay between these events. It is largely believed that the perception of passing time, or *subjective duration*, is subjective and may differ from person to person depending on many variables, such as body temperature and emotional state [20, 25, 30]. Extensive past research has shown that changes in body temperature can cause a person to over-estimate or under-estimate durations of events that they are being exposed to [30]. Such an effect is interesting, because it implies that a person's sense of duration can be changed through physical or psychological means. Since there is this direct link between body temperature and subjective duration, and several past research studies have shown significant effects on users' perception of temperature, we propose the following research questions:

- **RQ1:** Does virtual temperature-associated stimuli have secondary effects on the observer's sense of subjective duration?
- **RQ2:** How do different locations virtual stimuli impact the user's sense of subjective duration?
- **RQ3:** Does multiple stimuli presented simultaneously in the user's environment and on their body have stronger effects on subjective duration and/or sense of temperature than either location alone?

If virtual stimuli are capable of inducing secondary effects on other aspects of human perception, it could open many avenues for extending or augmenting our perception and may lead to interesting general discoveries into the nature of human perception. On the other hand, if such secondary effects are not possible, then this is a limitation in using AR technology to extend and enhance perception.

In this paper, we present a human-subjects user study that examines the relationship between virtual temperature-associated stimuli presented on an AR-HMD, and user perception of subjective duration and temperature. We evaluate this relationship through hot or cold virtual stimuli that are presented to the user in three different

*e-mail: ericksona@knights.ucf.edu
†e-mail: bruder@ucf.edu
‡e-mail: pamela.wisniewski@ucf.edu
§e-mail: welch@ucf.edu

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manners: in direct contact with the user's hand, indirectly placed in the environment around the user, and both direct and indirect conditions simultaneously. It was our hypothesis that, similar to past work in psychology that physically changed participants' body temperatures, virtual temperature-associated effects will have secondary impacts on the participants' perception of subjective duration, where hot stimuli such as flames will cause the user to under-estimate time durations and cold stimuli such as snow and fog will cause the user to over-estimate time durations [30]. Our results confirm that temperature-associated virtual stimuli have significant direct effects on users' perception of temperature, however they go against our hypothesis in that there does not seem to be a secondary effect on participants' perception of duration. These findings possibly indicate limitations to using AR technology to enhance and extend human perception.

The remainder of this paper is structured as follows: Section 2 examines prior work in subjective perception of time, extended and enhanced perception, and subjective duration in combination with augmented or virtual reality. Section 3 proposes a human-subjects user study and the methodology behind it. Section 4 explains the results of the user study. Section 5 discusses the results and how they fit within the context of other work in the field. Section 6 concludes the paper.

2 Related Work

In this section, we present an overview of prior work related to human perception and AR-HMDs. Specifically, we examine works that involve subjective perception of time, extended and enhanced perception, and subjective duration in combination with augmented/virtual reality.

2.1 Subjective Perception of Time

Past work in the field of psychology has suggested that perception of time is subjective, and can be different from person to person depending on factors related to the person's physical state, emotional state, or the state of their environment [1, 3, 20, 30]. One such factor is the body temperature of the person making the observation, where past work has shown that increasing the body temperature of a person tends to make them experience a dilated perception of time and perceive durations as occurring for longer than they actually did, which leads them to make under-estimates of time durations [30]. Other studies have also indicated that decreasing body temperature has the opposite effect, causing participants to experience a condensed perception of time which leads them to make over-estimate of time durations [30]. Such works often refer to a chemical or biological 'internal clock' that is affected by these temperature changes and yields inaccurate duration measurements when compared with mechanical or digital clocks [5, 11, 18]. While the mechanism behind the effect is still not entirely understood, the literature review by Wearden and Penton-Voak shows that this effect consistently appears across many different research studies where the body temperature of the subject was physically changed for the experiment [30].

Whereas the work gathered and presented in the literature review by Wearden and Penton-Voak involved making physical changes to the subjects body temperature, past work in AR and VR suggests that warming and cooling sensations can be induced in the user through observation of hot or cold associated stimulus. Our work presented in section 3 is designed to induce warming and cooling sensations that imply to the user that their body temperature is changing and in turn induce secondary effects on the users' perception of duration in a similar manner.

2.2 Extended and Enhanced Perception

As mentioned in the introduction, several recent publications have examined how a user's visual perception can be directly extended or enhanced through the use of augmented reality devices. Integrating additional sensors onto AR-HMDs which translate inaccessible sensory information into sensory cues for the user are a common way of providing this extended and enhanced visual perception. For example, in work by Orlosky et al. a prototype video see-through AR system was developed that allowed a user to view stereoscopic thermal infrared information that was registered one to one with the user's environment [22]. There are many applications where having access to an extended range of visual perception may be very useful. For example, several works have shown that infrared sensors can be integrated into the helmets of firefighters to give them better ability to navigate smoke filled environments [2, 27]. Other applications include building inspection, where having access to thermal infrared information can allow the user to identify flaws in the structure or efficiency of buildings [16]. The US military is also interested in this technology, and has invested heavily in purchasing Integrated Visual Augmentation System (IVAS) AR-HMDs for the US Army that include integrated infrared cameras that can highlight hidden people in the view of the device based on their body temperature [9].

While the above examples have involved directly extending and enhancing visual perception, additional research has involved other senses such as the sense of pain, or sense of temperature. Studies using these sensory channels typically involve visual dominance, or the Colovita effect, where visual stimuli dominates and sometimes drowns out other sensory signals [6]. This effect is has been shown to be useful for medical scenarios, where Hoffman et al. showed that visual dominance can have the effect of reducing the amount of pain that is being experienced by patients such as burn victims when patients are put into an immersive virtual environment [12].

Weir et al. noticed a similar effect in their work BurnAR, when a subset of the participants of their demo, which involved displaying dynamic flames over the user's outstretched hand, noticed that they felt as though their hand was warming in responses to the virtual fire [31]. As the visual stimulus of the flame appeared over their hands, it seemed as though visual dominance led a portion of the participants to experience what is known as virtual synesthesia, where sensory stimulation across one pathway causes an involuntary reaction along a different pathway, in this case visual stimulus affecting perception of temperature. Ho et al. showed similar results, in that the color of a physical stimulus and light projections that change the appearance of users' hand can have significant effects on perception of temperature [10]. Rosa et al. later showed that visual cues in VR can have impacts on how participants interpret other physical sensations such as haptic vibrations, and can affect user perception of what they are interacting with [23]. Other works examining virtual synesthesia in AR have shown that virtual stimuli are capable of inducing both warming and cooling sensations, and that the effect can be achieved either by displaying the stimuli in direct contact with the user (such as displaying fire on a user's hand) or through indirect contact with the user (such as the user being in the same environment, but not touching, as a virtual flame) [8].

Since prior work in augmented reality and virtual reality has successfully used visual dominance and virtual synesthesia to induce perceptual responses from the user on other sensory channels such as sense of temperature, our work investigates if these effects can be chained to induce secondary effects on the users' perception of duration.

2.3 Subjective Perception of Duration and Augmented/Virtual Reality

Several research publications have been in the intersection of virtual or augmented reality and subjective perception of duration. For example, Schneider et al. evaluated the effects of virtual reality immersion on patients perception of time and found that it had the effect of compressing time for the patients and allowed them to more comfortably sit through chemotherapy treatments [26]. Other

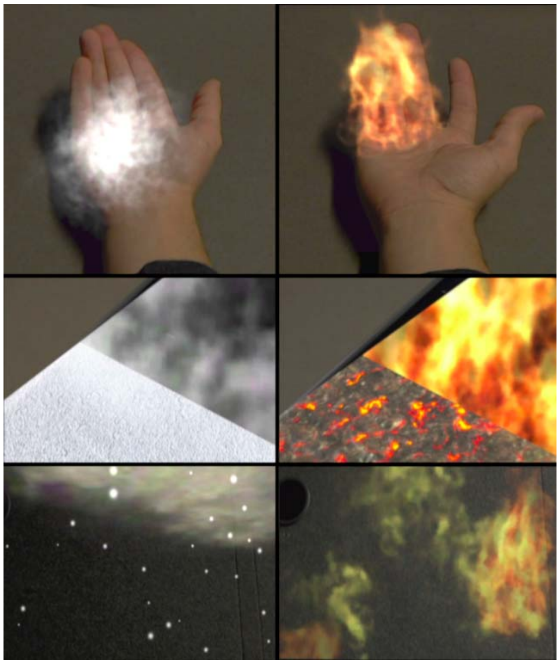

Figure 1: Screenshots of the four visual stimuli used in the study. *Top-Left:* direct contact cold condition. A user holds icy fog. *Top-Right:* direct contact hot condition. A user holds hot flames. *Middle-Left and Bottom-Left:* indirect contact cold condition. The floor of the isolation booth is covered in snow and icy fog, and snow falls from a cloud above the user's head. *Middle-Right and Bottom-Right:* indirect contact hot condition. The floor of the isolation booth is covered in lava and flames, and fire spreads along the walls of the isolation booth.

effects on time perception have been noted in work by Bruder and Steinicke, where participants wearing a virtual reality HMD generally over-estimated the amount of time spent moving through an immersive virtual environment [4]. This is interesting, as the results of Schneider et al.'s study suggest immersion in a VR environment can have the effect of making the user feel as though time has passed by more quickly than usual, whereas the results from Bruder and Steinicke suggest that the user felt as though time had passed by slightly slower than usual. This discrepancy may have come from the difference in the demographics of the participants in the two studies, where in former they were patients undergoing uncomfortable medical treatment and in the latter they were otherwise healthy. It may have also come from the difference in task between each of the studies, where Bruder and Steinicke incorporated a locomotion task where participants actually moved in their physical environment, Schneider et al.'s participants remained physically stationary while being able to traverse the virtual environment using input devices.

While the above studies involved participants viewing fixed virtual stimuli for the duration of the study conditions, we investigated how different types of virtual stimuli affected the participants' sense of temperature and duration.

3 Experiment

In this section, we present a 2×3 factorial within subjects user study that evaluated the relationship between temperature-associated visual stimuli and participants' perception of temperature and duration.

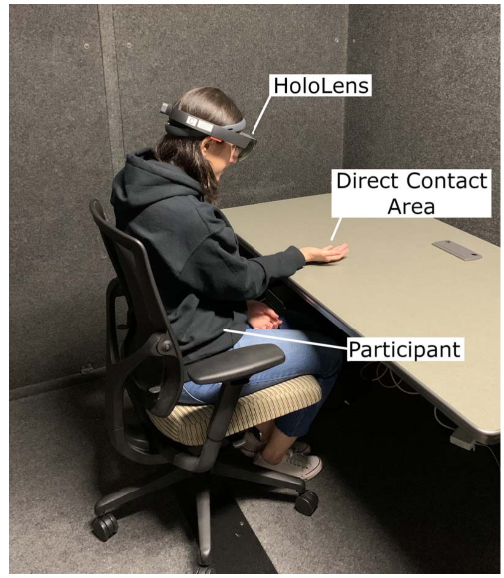

Figure 2: The testing environment for the study. This figure shows a participant observing stimuli in direct contact with her hand.

3.1 Participants

We recruited 18 participants (7 female, 11 male, age $18-31$, average 23.78, standard deviation 3.64) from the graduate and undergraduate population of our university. The protocol for our experiment was reviewed and approved by the institutional review board (IRB) of our university. All participants indicated normal hearing and normal/corrected vision, and exclusion criteria included pregnancy, history of seizures or epilepsy, and neurological or motor impairments. Before the experiment, we asked our participants to use a 5-point Likert scale (1 = novice/unfamiliar, 5 = expert/familiar) to rate their familiarity with AR and found that they had an average familiarity of 3.17.

3.2 Material

We used the Microsoft HoloLens AR-HMD to display all visual and auditory stimuli to the participant. The HoloLens provided a convenient way of presenting visual and auditory cues to the user in a controlled manner. The nature of the optical see-through HMD allowed us to present 3D fire and icy fog effects over the participant's outstretched hand so we could augment the user's view of the real world with virtual effects without immersing them in a virtual environment, as they would be if a video see-through or virtual reality HMD was used. This allowed us to display virtual effects that appear to come in direct contact with the body of the user.

The fire and icy-fog effects were implemented and streamed to the HoloLens using the built-in particle effects of the Unity engine in Holographic Remoting mode. The Holographic Remoting mode of the Unity engine allowed for the study moderator to control the sequencing of the appearance of the 3D effects via the keyboard and mouse, and has the added benefit of not requiring a separate client-server networked implementation to control what the user sees on the HoloLens.

3.3 Methods

The study consisted of a 2×3 factorial design with the following two independent variables:

- **Simulated Temperature:** *(cold or hot)* - The dynamic 3D stimulus that will be displayed to the user on the HoloLens. This stimulus took the form of fire or a ball of icy fog for direct contact stimulus, a room full of fire and smoke for the indirect hot stimulus, and a room full of icy fog and snow for the indirect cold stimulus (see figure 1).

- **Location of Effect:** *(direct contact, indirect contact, or both)* - The location of effect will determine whether the virtual stimulus is presented in direct contact with the user's hand, in indirect contact by placement in the environment near the user, or both in direct contact and indirect contact simultaneously.

These variables made for a total of six conditions of stimuli that were presented to the participants in a counterbalanced order through the use of a Latin Square.

3.4 Measures

This section presents the objective and subjective measures that were gathered from the participants during the course of the study.

3.4.1 Time Estimate

Time estimates were gathered from the participants using prospective estimations, where participants were aware ahead of time that they were going to be making estimates of time intervals. During each condition, participants observed a start signal, then verbally announced when they believed a duration of 30 seconds had passed since the start signal was given. On their response, the study moderator stopped a timer, which was started at the display of the start signal, and the actual amount of time that had elapsed was recorded. The discrepancy between the estimated duration (30 seconds) and the actual duration was examined to determine if the participant's perception of time was affected by exposure to the condition. In this manner, a result that was over-estimated appeared as a time of greater than 30 seconds on the moderator-controlled timer, and a result that was under-estimated appeared as a time of less than 30 seconds on the moderator-controlled timer. The participants were free to use any strategy they desired for keeping time, but were prevented from using timers, watches, or clocks during the study. These time estimates were repeated three times per condition.

3.4.2 Temperature Estimates

After each condition of the study, participants were asked to respond to the following statements:

- Please rate how you perceived the temperature of your body during the last condition.

- Please rate how you perceived the temperature of your environment during the last condition.

These responses were reported using the 7-point ASHRAE-55 standard scale with the following levels: 1 - Cold, 2 - Cool, 3 - Slightly Cool, 4 - Neutral, 5 - Slightly Warm, 6 - Warm, 7 - Hot [21]. Note that the environment temperature was kept consistent at 22.2 degrees Celsius throughout the course of the study.

3.4.3 Subjective Descriptions and Survey

Participants filled out a post-questionnaire after experiencing all study conditions that gathered their descriptions of any sensations noticed during the course of the experiment as well as presented several multiple choice questions. These questions asked about whether the participants had experienced any warming/cooling sensations, asked about which conditions they experienced sensations in, gathered demographics data, and allowed participants to note any additional feedback and comments.

3.5 Procedure

Participants were asked to give their informed consent to participate in the study after given time to read through the consent form. The study moderator then explained the study procedure in detail and answered any questions that the participant had. Following this, the participant was instructed on how to adjust the HoloLens to fit comfortably for the duration of the experiment, as well as how to safely put on and take off the HMD.

Once the participant was comfortable, he or she put on the HoloLens and verified that they were able to see a virtual object placed on the desk near them, as well as hear a repeated tone that is playing through the device speakers. Once this was confirmed, the visual stimulus disappeared and the auditory stimulus stopped. The participant was then asked to place their right arm palm-up onto a fixed position on the desk in front of them. The participant then made three sequential time estimates in a manner as described in section 3.4.1, and then responded to the two temperature statements described in section 3.4.2. These measures were referred to as the training phase and were recorded as a baseline for comparison with their responses that were gathered later in the study.

After the training phase measurements were gathered, the visual stimuli associated with the first condition were presented to the participant. This stimuli were displayed over their outstretched palm and/or in the room around them for a duration of 15 seconds, after which the participant made three sequential time estimates (as described in section 3.4.1) with five second gaps in between estimations. After this, the participant responded to the two temperature statements (as described in section 3.4.2). This timing task was repeated two additional times, so that the participant made three time estimates per condition, and following this the participant answered the same two statements about the temperature of their body and environment as described above. This process was repeated for each of the six total conditions.

Once all conditions were completed, the participant removed the HMD and completed a survey that gathered subjective descriptions of any temperature changes they experienced as well as demographic information. Participants were then compensated for their time.

3.6 Hypothesis

After reviewing the background literature in computer science and psychology, we had the following hypothesis:

- **H1** Participants will report warmer perceptions of their *body* temperature when experiencing hot virtual stimuli, and colder perceptions of their *body* temperature when experiencing cold virtual stimuli.

- **H2** Participants will report warmer perceptions of their *environment* temperature when experiencing hot virtual stimuli, and colder perceptions of their *environment* temperature when experiencing cold virtual stimuli.

- **H3** Participants will over-estimate durations in which they are presented with cold virtual stimuli and under-estimate durations in which they are presented with hot virtual stimuli.

- **H4** The effects of H1-H3 will be stronger when participants experience direct contact and indirect contact stimuli simultaneously, than they will be when experiencing direct contact or indirect contact stimuli individually.

4 Results

In this section we present the analysis and results of our user study, which are broken down in to sections based on the different measures described in section 3. In general, we used parametric statistical tests in order to analyze the results following the ongoing discussion in the field, which indicates that parametric statistics can be a valid and informative method for analysis of combined experimental questionnaire scales with individual ordinal data points measured either through questionnaires or coded behaviors [14, 15]. We analyzed the data with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We confirmed the normality with Shapiro-Wilk tests at the 5% level and QQ plots. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

4.1 Time Estimates

We analyzed the time estimate data by averaging the three time estimates that were gathered per condition and performing a repeated measures ANOVA on the averaged data. We did not find statistically significant results for either the location of the stimuli on the time estimates, nor the simulated temperature on the time estimates.

Time estimates in general were consistently over-estimated, as shown in figure 3 and table 1. The average time estimate for all participants gathered during the training phase of the experiment, in which no stimulus was presented to the participants, came out to be 33.809 seconds, and the average time estimates during the study conditions were between 35.183 seconds and 37.539 seconds. This indicated over-estimates with a range between 4.06% and 11.03% when comparing the time estimates of the conditions to the estimates from the training phase.

Temp.	**Loc.**	Mean Time Est.	Std. Dev.	% Dif.
Training	-	33.809	7.815	-
Cold	Direct	35.282	9.493	4.36%
Hot	Direct	35.577	10.030	5.23%
Cold	Indirect	37.539	11.401	11.03%
Hot	Indirect	36.284	11.219	7.32%
Cold	Both	35.183	9.880	4.06%
Hot	Both	37.158	16.147	9.91%

Table 1: This table shows the mean time estimates, standard deviations, and percent change from the training phase for all study conditions.

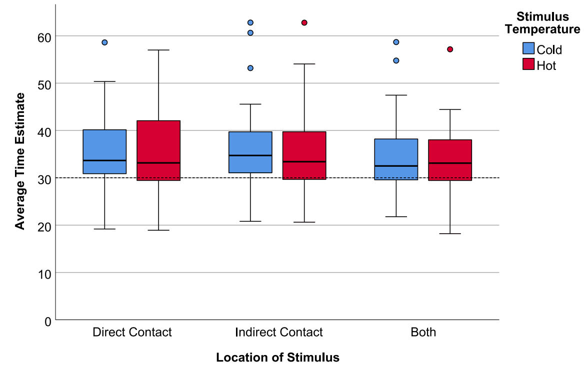

Figure 3: This figure shows the mean duration of users' 30 second time estimates.

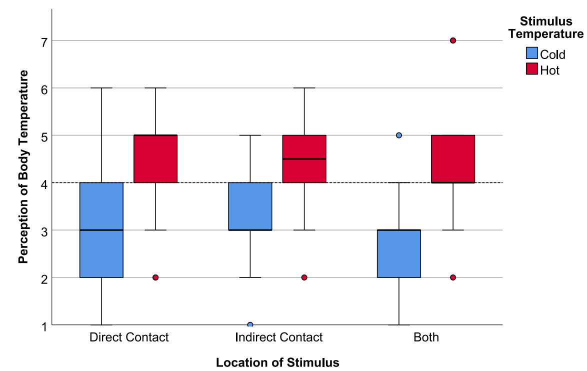

Figure 4: This figure shows the mean of users' body temperature estimates.

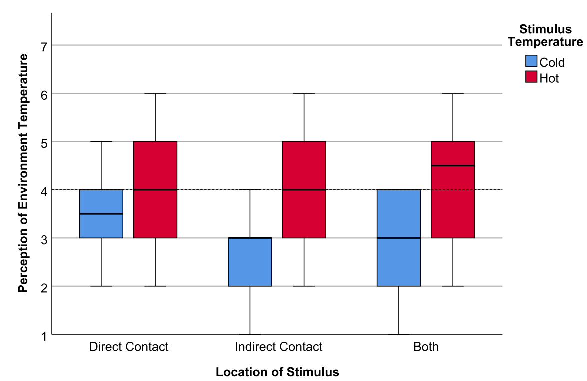

Figure 5: This figure shows the mean of users' environment temperature estimates.

4.2 Temperature Estimates

We found a significant main effect of simulated temperature on the users' body temperature estimates, F(1,17) = 33.936, $\mathbf{p} < \mathbf{0.001}$, $\eta^2 = 0.666$, indicating higher temperature estimates with hot stimuli and lower temperature estimates with cold stimuli.

We found a significant main effect of simulated temperature on the users' environment temperature estimates, F(1,17) = 16.991, **p = 0.001**, $\eta^2 = 0.499$, indicating higher temperature estimates with hot stimuli and lower temperature estimates with cold stimuli.

We additionally found an interaction effect between the location of stimulus and simulated temperature on the users' environment temperature estimates, F(2,34) = 3.730, **p = 0.034**, $\eta^2 = 0.180$.

4.3 Subjective Responses

Participants filled out a post-questionnaire with various questions regarding their experience during the study. We analyzed the yes or no responses of participants in the survey with a two-tailed binomial test with a test value of 0.5 and 95% confidence intervals, and found the following. 72.2% of participants reported feeling a warming sensation during at least one of the conditions of the study ($p = 0.096$), indicating a strong trend. 88.9% of participants reported feeling a cooling sensation during at least one of the conditions of the study ($p = 0.001$), indicating a significant result. 44.4% of participants reported that they felt as though the temperature in the testing environment was being manipulated between conditions during the course of the study ($p = 0.815$), indicating a non-significant result.

5 Discussion

In this section, we discuss the results shown in section 4 and their implications.

5.1 AR Stimuli Do Not Have Significant Effect on Perception of Time

As shown in figure 3, time estimates gathered from participants were fairly consistent on average between data gathered during the study conditions and the training phase data. While there were slight deviations of the results between conditions, the most noticeable effect in the data is that users on average overestimated their times for each of the conditions.

This general over-estimation across all training data and conditions could imply that users were in general feeling cold throughout the entire duration of the study. This is possible, as the testing environment was slightly below room temperature at 22.2 degrees Celsius. Another unlikely explanation for these over-estimates may be due to the emotional state of the users, which would imply that in general the users were in a decreased emotional state throughout their time in the study. While we did not gather any data on the participants' emotional states in the form of surveys, we can say that in general, participants seemed to be excited about getting to use the AR-HMD and participate in the study. It is also possible that the over-estimates come from the users being distracted by the AR stimuli while they are supposed to be keeping track of how much time has elapsed. For instance, if the user was counting seconds in their head and got distracted, this would lead to a slight pause between numbers, which would result in an over-estimate of the duration. In examining table 1, we see that the mean time estimates for indirect located stimuli and for simultaneously located stimuli have higher over-estimates than that of the direct located stimuli (except for the simultaneously located cold condition). These conditions are the ones that consisted of the highest amount of virtual effects being displayed in the environment around the user, which gives the user the most effects to be distracted by. While this is a possibility, these differences in times were not statistically significant, so it is unlikely that this is the sole reason for the general over-estimations. This leads us to believe that the temperature of the testing environment was at least partially responsible for these over-estimations.

Regardless of the general over-estimation, if the conditions were affecting the users' sense of duration as laid out in **H3**, then we should see smaller over-estimations on the hot conditions and larger over-estimations on the cold conditions, however this is not the case. In this study we knew that the stimuli could have a direct effect on the users' sense of temperature and we thought that, due to the link between body temperature and time perception, that this in turn would trigger a secondary effect on the users' perception of duration. It seems that even though the users experienced significant temperature perception effects and experienced hot and cold sensations during the study, these effects do not carry over to achieve the secondary effect on their perception of duration. While other avenues of inducing similar effects on perception of time should be investigated, these results seem to support the theory in psychology of an internal biochemical clock that can be affected by physical changes to the system [11, 18, 30].

This is an interesting finding which could indicate that secondary effects on perception of duration are difficult or not possible to induce through observation of virtual stimuli. Such a general conclusion would require investigation in future research. However, to support our results we performed an additional a priori power analysis on the time estimate ANOVA results, following guidelines by Lakens [17] (parameters $\alpha = 0.05$, power = 0.8). The effect size f values for the *location of effect* and *simulated temperature* were calculated using G*Power using the η^2 values from the ANOVA analysis discussed in section 4.1, which were found to be 0.037 (medium-small effect) and 0.005 (very small effect), respectively. The results of the power analysis suggested that a sample size of 29 participants would be sufficient to find a significant main effect of the location of effect on user perception of duration, and that a sample size of 214 participants would be required to achieve a significant effect of the simulated temperature of the stimulus on user perception of duration. These results support the above-mentioned theory that the amount of stimuli presented simultaneously to the user may have impacts on their perception of time, therefore this should be examined further in future work. The results also seem to support our conclusion that the apparent temperature of the stimuli has little to no effect on user perception of duration.

These findings could be indicative of a more general conclusion that secondary perceptual effects are not possible to induce through observation of virtual stimuli, although a significant amount of research into the combination of AR/VR technology and human perception would be necessary to support such a broad conclusion. Because of this, future work involving human perception and AR/VR should continue to investigate similar secondary effects on user perception to see if the work presented here is indicative of a more general limitation of the technology.

5.2 AR Stimuli Affect Perception of Temperature

As shown in figures 4 and 5, we found significant effects of the augmented reality stimuli on the participants' perceptions of their own body temperature and the temperature of their environment. These results are largely in line with prior work by Weir et al. Erickson et al. and Hoffman et al. where they showed that AR virtual stimuli can induce warming and cooling sensations in participants using stimuli placed in direct contact with the user or stimuli placed in the users' surroundings [8, 12, 31]. As expected, these results confirm hypotheses **H1** and **H2**.

When examining figures 4 and 5 and comparing the results gathered at different locations of effect, we can see several interesting findings. For the body temperature estimates, it appears as though direct contact located conditions yielded the strongest temperature scores from the users. This makes sense, as the effect is displayed as being physically in contact with the hand of the user in this type of condition, which makes the user focus their attention on this singular point. Users know by association that they would feel hot when interacting with real fire and cold when interacting with fog or snow, so observing this type of visual stimulus seems to have the strongest effect on the participants' perception of their body temperature.

We had hypothesized in **H4** that the effects on perception of temperature would be the strongest when stimuli were displayed simultaneously in direct contact with the user and indirect contact with the user, however in the case of the body temperature data, this does not appear to be true. We believe that this may be in part due to the limited field of view of the HoloLens AR-HMD, because in the direct contact based conditions, the user is able to see the whole visual stimulus on the screen at once without having to move their head around to see everything, whereas in the case of the other two locations of effect the user must move their head in order to see the effects that are displayed around them. In the case of environment temperature, it does appear that the simultaneously located hot condition led to the strongest responses, which partially confirms **H4**. The reason for this is likely that the user is more aware of their environment than their body when observing conditions in which virtual effects are displayed in 360 degrees around the user. This shift in awareness from their own body to their environment would mean that the user is less likely to notice any subtle temperature sensations on their hand and body that happen to be occurring at that time.

6 Conclusion

In this paper, we have presented a human-subjects user study that investigated the effects of temperature-associated virtual stimuli on the users' sense of temperature and duration. We have confirmed prior work in the field that has shown that this type of stimuli have significant effects on user perception of temperature, and we have presented the first investigation into whether these stimuli are capable of inducing secondary effects on the users' sense of duration. Future work should continue to investigate whether virtual stimuli are capable of inducing other forms of secondary perceptual effects, or whether the work here is indicative of a more general limitation in the types of perceptual effects that virtual stimuli can have on human perception.

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