Investigation of Thermal Perception and Emotional Response in Augmented Reality using Digital Biomarkers: A Pilot Study

Sangjun Eom*
Department of Electrical and Computer Engineering
Duke University

Seijung Kim†
Department of Computer Science
Duke University

Yihang Jiang ‡
Department of Biomedical Engineering
Duke University

Ryan Jay Chen §
Department of Electrical and Computer Engineering
Duke University

Ali R. Roghanizad ¶
Department of Biomedical Engineering
Duke University

M. Zachary Rosenthal ‖
Department of Psychiatry and Behavioral Sciences
Department of Psychology and Neuroscience
Duke University

Jessilyn Dunn **
Department of Biomedical Engineering
Duke University

Maria Gorlatova††
Department of Electrical and Computer Engineering
Duke University

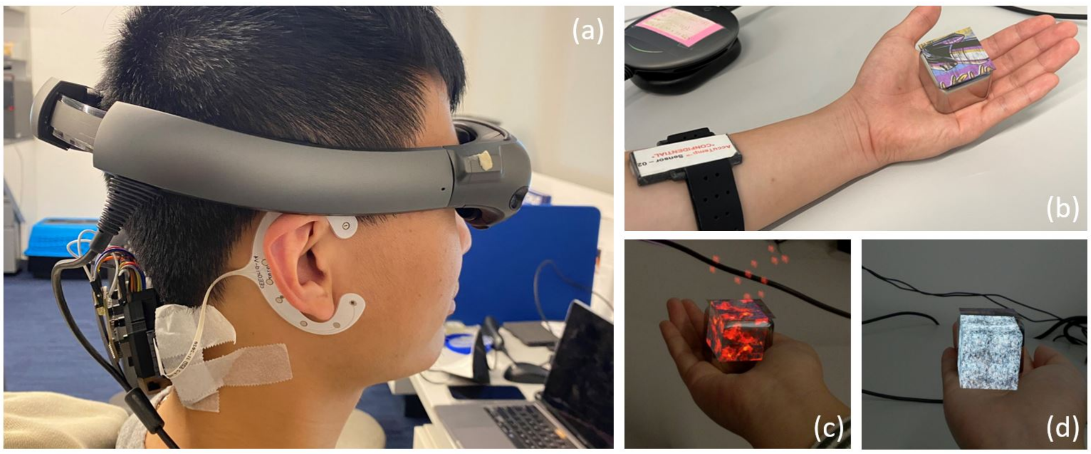

Figure 1: Hardware setup of the user wearing Magic Leap One AR headset and EEG sensor (a), the AccuTemp blood temperature sensor on the left forearm (b), varying thermal perception with holograms to induce warm sensations (c) and cooling sensations (d).

Abstract

Dialectical behavior therapy (DBT) is an evidence-based psychotherapy that helps patients learn skills to regulate emotions as a central strategy to improve life functioning. However, DBT skills require a long-term and consistent commitment, typically to group therapy over the course of months. Patients who might benefit may find this approach undesirable; it can be challenging to transfer learning from therapy sessions to daily life, and there is no way to personalize skills learning based on individualized needs. In this paper we propose the use of Augmented Reality (AR) and digital biomarkers to enhance DBT skill exercises to be more immersive and personalized by using physiological data as real-time feedback. To explore the feasibility of AR-based DBT skill implementation, we developed AR-based DBT skill exercises that manipulate the user's thermal perception by visualizing different thermal information in holograms. We conducted a user study to evaluate the impact of AR in changing the thermal perception and emotional states of the user with an analysis of physiological data collected from wearable devices.

*E-mail: sangjun.eom@duke.edu
†E-mail: seijung.kim@duke.edu
‡E-mail: yihang.jiang@duke.edu
§E-mail: ryan.j.chen@duke.edu
¶E-mail: ali.roghanizad@duke.edu
‖E-mail: mark.rosenthal@duke.edu
**E-mail: jessilyn.dunn@duke.edu
††E-mail: maria.gorlatova@duke.edu

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality;

1 Introduction

Dialectical behavior therapy (DBT) is a type of cognitive behavioral therapy developed to treat complex behaviors associated with emotion dysregulation [7]. DBT is focused on enabling patients to acquire new skills to improve life functioning by learning to regulate emotions effectively. In its conventional form, DBT is a 1-year treatment during which the patients acquire and generalize four sets of skills: *distress tolerance*, *mindfulness*, *emotion regulation*, and *interpersonal effectiveness* [11]. However, the long-term and consistent commitment required in DBT can often be challenging for therapists and patients. Some patients cannot regularly complete the given assignments by transferring their learning from the therapy sessions to their daily life. Furthermore, DBT is based on the individual patient's needs. Therefore, the DBT skill exercises need to be personalized for each patient based on their learning progress and changes in emotional states.

Augmented Reality (AR) and digital biomarkers have the potential to address those challenges by enhancing DBT skill exercises to be more effective and personalized for patients. Digital biomarkers are aggregate metrics from wearable devices that can collect various types of physiological data from patients. These metrics can be calculated in real-time, and such real-time feedback can be used for evaluating and monitoring the changes in users' emotional states to allow the AR system to personalize skills based on their needs. Hence, we propose *the first use of AR and digital biomarkers* for DBT through a pilot study investigating the manipulation and monitoring of thermal perception and emotional arousal.

We developed an AR app for an adaptation of the *emotional regulation* skills, which are the DBT skills that can be practiced by patients to help them regulate their emotional states. Our AR app manipulates the thermal perception of the user by showing different levels of thermal information in holograms. We conduct a user study to investigate 1) the impact of varying thermal information in AR on user's thermal perception and emotional response, and 2) the changes in digital biomarkers using various physiological data including heart rate variability (HRV), electroencephalogram (EEG), electrocardiogram (ECG), electrodermal activity (EDA), and forearm core blood temperature.

2 Related Work

AR and Virtual Reality have the potential to enhance mental health training to be more immersive and interactive for patients. Prior studies have shown that exposure to an augmented environment (e.g., displaying animal holograms for patients with animal phobia [16] or providing guided meditation to patients for emotion regulation [14]) helps the patients embrace certain types of phobias and reduce negative emotions such as anxiety and depression. Similarly, exposure to a virtual environment (e.g., reconstruction of war experiences for post-traumatic stress disorder patients [12], calming environment involving the nature for DBT mindfulness training [6]) helps the patients reduce the level of stress or increase the positive emotions.

Additionally, the use of digital biomarkers has the potential in evaluating patients' emotional responses using quantifiable physiological data. Prior studies show that we can relate physiological data such as HRV, EEG, and EDA to users' emotional responses (e.g., stress or relaxation levels) [9]. From the analysis of the brain waves of gamma, beta, and alpha activities from the EEG data, a reduction in negative moods was found after the AR-based meditation [14]. Similarly, the decreases in both HRV and skin conductance response analyzed from the EDA data correlated with the decrease in self-reported stress levels (e.g., an increase in relaxation was seen after the AR-based meditation exercises [9]). Digital biomarkers provide crucial feedback about users' emotional responses in real-time that enhance the DBT skill exercises to be more personalized for individuals.

The use of AR in manipulating users' thermal perception by displaying thermal information in holograms has been demonstrated by prior studies. Different types of thermal stimuli (e.g., virtual flames and icy fogs [5], flames in red and blue colors [4]) have been used to invoke warming or cooling sensations. Though prior studies have demonstrated that thermal stimuli are effective in manipulating the thermal perception of the user, the implementation of the AR app with thermal stimuli into clinical applications (e.g., helping patients control and reduce pain) still remains as future work.

3 Pilot Study Design

We created an AR app using a Magic Leap One AR headset and Unity 2020.3.14fl. The app consists of two main stimuli: thermal stimuli for visualizing different thermal information and emotional stimuli for visualizing pictures that represent different emotional states as holograms. For collecting physiological data, we used four wearable devices: 1) the Bittium Faros 180, an FDA-approved 3-lead wearable ECG device, 2) an Empatica E4 wristband for collecting HRV and EDA, 3) the OpenBCI Cyton, a 16-channel EEG device with around-the-ear electrodes, and 4) a ThermaSENSE AccuTemp wearable blood temperature sensor. In addition to the physiological data, we collected eye gaze data including gaze fixation and pupil diameter using the Magic Leap One AR headset.

3.1 AR Application

3.1.1 Thermal Stimuli

To manipulate the thermal perception of the user, we show holograms that convey different thermal information to be overlaid on the object placed on the user's left hand. We used a metal cube with a printed image marker attached to the top surface of the cube for overlaying a hologram through Vuforia marker detection. Two different levels of thermal information were displayed in holograms. The hologram for the warm temperature was displayed as a burning coal texture with an animation of fire particles emanating from the cube, as shown in Fig. 1c. The hologram for the cold temperature was displayed as an ice texture and an animation of snowflakes emanating from the cube, as shown in Fig. 1d.

Table 1: Classification of emotion labels associated with valence and arousal ratings [13].

Quadrant	Valence	Arousal	Emotion Labels
LVHA	Low	High	Angry, Distressed, Tense
LVLA	Low	Low	Sad, Depressed, Tired
HVHA	High	High	Excited, Happy, Aroused
HVLA	High	Low	Relaxed, Satisfied, Calm

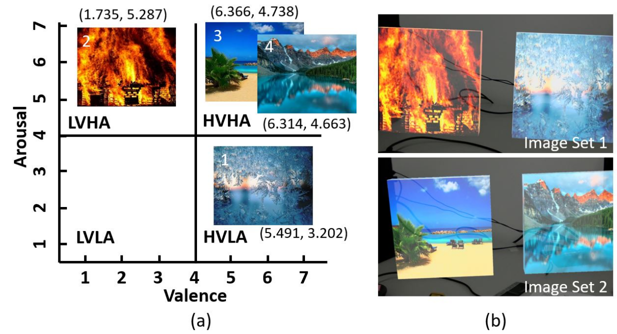

Figure 2: Selection of pictures in emotion classification model (a) and display of these pictures in holograms using Magic Leap One headset for emotional stimuli (b).

3.1.2 Emotional Stimuli

To induce the emotional states of the user, we display pictures that convey different levels of arousal and valence as holograms. Valence is a level of pleasantness that a stimulus generates, ranging from unhappy (i.e., low rating) to happy (i.e., high rating) [15]. Arousal is a level of autonomic activation that a stimulus generates, ranging from calm (i.e., low rating) to excited (i.e., high rating) [15]. Based on the ratings of valence and arousal, emotions can be categorized into four quadrants in the emotion classification model (shown in Fig. 2a) [13]. Table 1 shows the list of emotional labels associated with each quadrant.

We use pictures from the OASIS database [10] that provide normative arousal and valence ratings. Using this database, we create two sets of images, shown in Fig. 2b, as emotional stimuli to induce emotional changes after the thermal perception experiment. The first set comprises two images with one low valence and high arousal image (i.e., a burning fire) and one high valence and low arousal image (i.e., a frozen view with ice particles). These two images are in opposite quadrants in the emotion classification model (shown in Fig. 2a). Alternatively, the second set comprises two images with similar levels of valence and arousal ratings, but the images convey different thermal perception to the user (i.e., a summer beach vs. a winter lake). These two images are in the same quadrant in the emotion classification model. We display each image set as holograms, allowing participants to observe and record their emotional states with valence and arousal ratings on the questionnaire.

3.2 Digital Biomarkers

The four wearable devices used for collecting various types of physiological data in this user study are shown in Fig. 3.

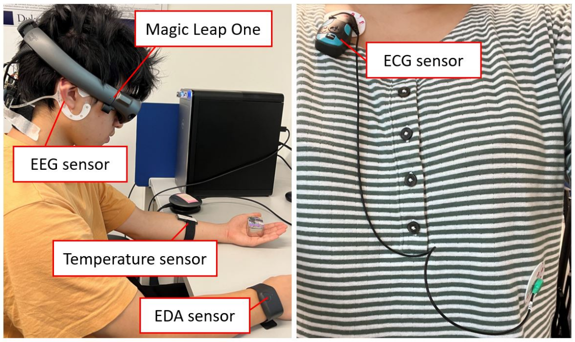

Figure 3: Overall experimental setup including four wearable devices and Magic Leap One AR headset.

3.2.1 EDA Signal Processing

During the experiments, the users wore the Empatica E4 wristband on their right forearms (shown in Fig. 3). The forearm was put at the height of the user's heart. We used the timestamps to select the signals for each experimental step for data processing. From the data collection, we can quantify features that are associated with the level of arousals such as peaks, amplitude, rise time, and recovery time from the EDA data. [2].

3.2.2 ECG Signal Processing

The preprocessing of the ECG data includes signal filtering, peak detection, and metric calculation. The processed data can quantify the heart rate and HRV by calculating the peak-to-peak intervals of the signal. The HRV measurements can induce the level of relaxation (e.g., significant fluctuations in HRV indicates a more relaxed state of the user [1]).

3.2.3 EEG Signal Processing

The EEG data collected during the experiments can quantify the measurements for alpha, beta, and gamma activities. The signals of these activities are related to the level of stress [8] by calculating the alpha/beta ratio that is negatively correlated with the level of stress. The open-source software from OpenBCI provides the analysis of the recorded data from the 16-channel EEG device.

3.2.4 Core Blood Temperature Sensing

The AccuTemp blood temperature sensor, created by ThermaSENSE, worn on the user's forearm (shown in Fig. 3) can directly measure the internal blood temperature response. By using this unique non-invasive sensor instead of a skin temperature sensor, we can more directly quantify the forearm's core blood temperature which can provide information about the user's thermal perception. We hypothesize that the thermal perception of the user induces vasomotor changes in the left forearm which causes localized changes in blood flow and blood temperature. Therefore, changes in the internal blood temperature of the forearm can be affected by the user's thermal perception.

3.3 Experimental Steps

Prior to the trials, the participant put on all wearable devices. The EDA sensor was worn on the right forearm, and the AccuTemp sensor was worn on the left forearm. The two electrodes of the ECG sensor were attached to the right clavicle near the right shoulder and below the pectoral muscles' lower edge of the left rib cage (shown in Fig. 3). The microcontroller of the EEG sensor was attached to the back of the participant's neck and two EEG electrodes were attached to the participant's ears. We started the calibration for 15 minutes to establish the baseline for data collection. Finally, the participant put on the Magic Leap One.

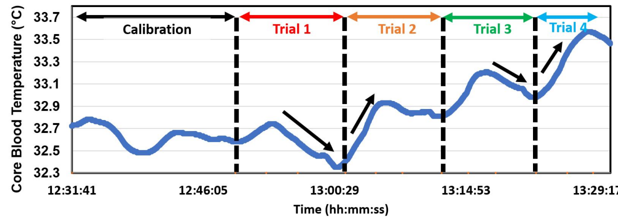

Figure 4: Changes in the core (i.e., internal) blood temperature of one of the user's left forearm.

The participant performed four trials during the study. Each trial consists of 5 minutes for interacting with cubes in different temperature-perceived environments, and 5 minutes each for observing the image sets to stimulate emotions. We created a different thermal perception of the environment by varying the temperature level of the cube and the thermal information of the hologram for each trial. We designed two trials for matching thermal perception between the temperature of the cube and the thermal information of the hologram, and the other two trials for unmatching thermal perception. Four trials were 1) cold cube and ice hologram, 2) warm cube and burning coal hologram, 3) cube at room temperature and ice hologram, and 4) cube at room temperature and burning coal hologram. On the other hand, we used the same two image sets for emotional stimuli for all trials. We recorded the timestamps after each trial for the analysis of the digital biomarker data.

3.4 Survey Questionnaire

In the pre-experiment survey, participants were asked to record self-reported emotional states using the self-assessment manikin (SAM), a clinically validated survey designed for the evaluation of emotions [3]. In the post-experiment survey, participants were asked to record self-reported emotional states and invoked emotions from the image sets using SAM. These self-reported emotional states can be compared to the analysis of digital biomarker data that can quantify the changes in users' emotional states.

4 Preliminary Results

We recruited 6 participants to perform all four trials of AR-based DBT skill exercises while wearing wearable devices. One participant uses the AR headset frequently (i.e., more than once a week); The other five participants have never used it before. This study was approved by the Duke University IRB. In this section, we present the analysis of changes in users' thermal perception and emotional states by processing the data from the AccuTemp blood temperature sensor and survey responses.

4.1 Changes in Forearm Core Blood Temperature

We analyzed the changes in the core blood temperature of the user's left forearm during the trials. Fig. 4 shows the change in the core blood temperature from one of the participants in the study over time. We observed that the core blood temperature of the user's left forearm changed without varying the temperature of the cube. During trials 1 and 2, the core blood temperature changed based on the temperature of the cube placed on the left hand (e.g., the cold cube induced a decrease in temperature due to vasoconstriction, and the warm cube induced an increase in temperature due to vasodilation). However, the core blood temperature of the user still changed when the temperature of the cube was consistent at room temperature. We believe that the changes in the core blood temperature are in response to the perceived temperature of the cube. The results indicate that the thermal perception created by visualizing ice and burning coal holograms affected vasomotor function and induced changes in the core blood temperature of the user's left forearm.

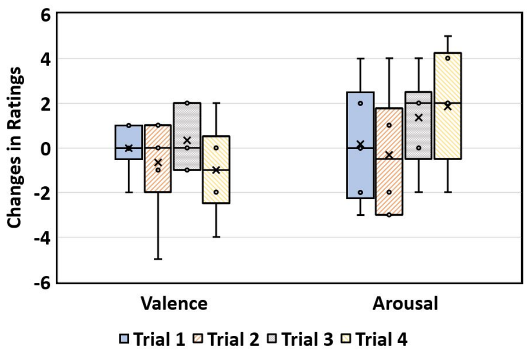

Figure 5: Changes in valence and arousal ratings after each trial.

4.2 Changes in Emotional States

We explored the changes in the emotional states of the user by calculating the difference between the self-reported valence and arousal ratings before and after trials, shown in Fig. 5. We observed that when the temperature of the cube was at room temperature, the use of the burning coal hologram (i.e., trial 4) resulted in a shift towards the HVLA quadrant (i.e., decrease in valence and increase in arousal), while the use of the ice hologram (i.e., trial 3) resulted in a shift towards the HVHA quadrant (i.e., increase in valence and increase in arousal) in the emotion classification model. This indicates that the use of the ice hologram induced emotions such as happiness or pleasantness, while the burning coal hologram induced emotions such as anger or annoyance (Table 1). We hypothesize that this is due to the changes in the user's thermal perception induced by the visualization of different thermal information in holograms. The overlay of the ice hologram on the cube potentially illuded the users to feel the cold temperature which induced them to feel happy and pleasant. This shows that the manipulation of thermal perception through AR has the potential to enhance such DBT skill exercises that are used to help users reduce high emotional states.

5 Discussion and Future Work

In this study we displayed holograms of cubes with burning coal and ice textures to manipulate the user's thermal awareness and perception of the environment. However, the current visualization of holograms is overlaid only on the cube (i.e., a 2cm by 2cm by 2cm dimension), and the hologram animations (i.e., fire and snowflake particles emanating from the texture) were too subtle for users to notice. We plan to improve the visualization by expanding the hologram animations (e.g., snow falling from the sky and accumulating on the floor) and adding more holograms to the surrounding areas (e.g., snow surface on the hand or the table) for a more realistic and immersive environment.

Moreover, we currently analyzed the physiological data collected from the wearable devices after the experiment. However, using the physiological data as real-time feedback to AR can further enhance the AR-based DBT skill exercises to be personalized based on the users' needs during their everyday lives. In our future work, we plan to develop a wireless communication pipeline for our AR system to use physiological data as real-time feedback. We will evaluate this intervention by digital biomarkers in AR by conducting a long-term user study of the daily uses of AR-based DBT skills.

6 Conclusion

This paper presents the first use of AR and digital biomarkers for enhancing DBT skill exercises. We conducted a user study to investigate the impact of AR visualization on the thermal perception and emotional responses of the users. Our results show that the manipulation of the user's thermal awareness and perception by displaying different levels of thermal information in holograms has impacts on the changes in the user's vasomotor function and emotional states. We will further analyze the relationship between the physiological data and the emotional response of the users and evaluate the clinical use of AR-based DBT skill exercises in DBT therapy sessions.

Acknowledgments

This work was supported in part by NSF grants CNS-2112562 and CNS-1908051, NSF CAREER Award IIS-204607, and by a Thomas Lord Educational Innovation Grant.

References

[1] B. M. Appelhans and L. J. Luecken. Heart rate variability as an index of regulated emotional responding. *Review of General Psychology*, 10(3):229–240, 2006.

[2] M. Z. Baig and M. Kavakli. A survey on psycho-physiological analysis & measurement methods in multimodal systems. *Multimodal Technologies and Interaction*, 3(2):37, 2019.

[3] M. M. Bradley and P. J. Lang. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1):49–59, 1994.

[4] D. Eckhoff, C. Sandor, G. L. Cheing, J. Schnupp, and A. Cassinelli. Thermal pain and detection threshold modulation in augmented reality. *Frontiers in Virtual Reality*, p. 130, 2022.

[5] A. Erickson, K. Kim, R. Schubert, G. Bruder, and G. Welch. Is it cold in here or is it just me? Analysis of augmented reality temperature visualization for computer-mediated thermoception. In *Proc. of IEEE ISMAR*, 2019.

[6] J. Gomez, H. G. Hoffman, S. L. Bistricky, M. Gonzalez, L. Rosenberg, M. Sampaio, A. Garcia-Palacios, M. V. Navarro-Haro, W. Alhalabi, M. Rosenberg, et al. The use of virtual reality facilitates dialectical behavior therapy® "observing sounds and visuals" mindfulness skills training exercises for a latino patient with severe burns: A case study. *Frontiers in Psychology*, 8:1611, 2017.

[7] M. Goodman, D. Banthin, N. J. Blair, K. A. Mascitelli, J. Wilsnack, J. Chen, J. W. Messenger, M. M. Perez-Rodriguez, J. Triebwasser, H. W. Koenigsberg, et al. A randomized trial of dialectical behavior therapy in high-risk suicidal veterans. *The Journal of Clinical Psychiatry*, 77(12):4031, 2016.

[8] N. H. A. Hamid, N. Sulaiman, S. A. M. Aris, Z. H. Murat, and M. N. Taib. Evaluation of human stress using EEG power spectrum. In *Proc. of IEEE International Colloquium on Signal Processing & Its Applications*, 2010.

[9] Y. Jiang, W. Wang, T. Scargill, M. Rothman, J. Dunn, and M. Gorlatova. Digital biomarkers reflect stress reduction after augmented reality guided meditation: A feasibility study. In *Proc. of the Workshop on Emerging Devices for Digital Biomarkers*, 2022.

[10] B. Kurdi, S. Lozano, and M. R. Banaji. Introducing the open affective standardized image set (OASIS). *Behavior Research Methods*, 49(2):457–470, 2017.

[11] M. M. Linehan. *Skills Training Manual for Treating Borderline Personality Disorder.* Guilford Press, 1993.

[12] A. Rizzo, B. Newman, T. Parsons, G. Reger, K. Holloway, G. Gahm, B. Rothbaum, J. Difede, R. McLay, S. Johnston, et al. Development and clinical results from the virtual Iraq exposure therapy application for PTSD. In *Proc. of IEEE Virtual Rehabilitation International Conference*, 2009.

[13] J. A. Russell. A circumplex model of affect. *Journal of Personality and Social Psychology*, 39(6):1161, 1980.

[14] J. Viczko, J. Tarrant, and R. Jackson. Effects on mood and EEG states after meditation in augmented reality with and without adjunctive neurofeedback. *Frontiers in Virtual Reality*, 2:618381, 2021.

[15] A. B. Warriner, V. Kuperman, and M. Brysbaert. Norms of valence, arousal, and dominance for 13,915 English lemmas. *Behavior Research Methods*, 45(4):1191–1207, 2013.

[16] M. Wrzesien, M. Alcañiz, C. Botella, J.-M. Burkhardt, J. Bretón-López, M. Ortega, and D. B. Brotons. The therapeutic lamp: Treating small-animal phobias. *IEEE Computer Graphics and Applications*, 33(1):80–86, 2013.