Mid-Air Tactile Stimulation for Pain Distraction

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Abstract—Using the human sense of touch, pain control has been studied for decades. With the rise of Virtual Reality (VR) and haptic technologies, creating VR and haptic sensations provide a unique opportunity for pain distraction. In this paper, we present an experimental study to test whether VR and mid-air ultrasound tactile stimulation reduce perceived pain simulated via the cold pressor test, i.e., submerging a human hand in cold water (2 °C) for as long as the test subject can. Fifty right-handed subjects participated in the study and three tasks were considered: task 1 involved experiencing the cold pressor test with no distraction (considered as the control task), task 2 involved playing a simple VR game with no tactile feedback, and task 3 utilized the same VR game with tactile feedback; tasks 2 and 3 were assigned in random order after task 1. The tolerance time, perceived pain rating, and quality of experience were evaluated and compared for the three tasks. Results demonstrated that when a VR task involves physical (touch) interaction, tactile stimulation plays a significant role in increasing pain tolerance time. Furthermore, the study demonstrated that for high pain tolerance participants, tactile stimulation is more effective for pain distraction compared to low pain tolerance participants. Although there are no significant differences in perceived pain and quality of experience between VR and VR+Tactile tasks, there are significant differences in tolerance time (Wilcox signed rank test, $p < 0.05$). It is presumed that VR and the tactile stimulation induces positive emotions when utilized (for both valence and arousal).

Index Terms—Haptics, tactile, virtual reality, pain distraction, mid-air ultrasound stimulation

1 Introduction

Fear of pain is one of the most common reasons for people to seek consistent, as well as urgent medical care [1]. There are many medical procedures that can cause pain, such as dental procedures and minor surgeries, such as mole removal. Partial anesthesia might still cause discomfort, but full anesthesia might not be necessary due to the short length and pain level of the procedure. Furthermore, some patients might be allergic to the anesthetic substance [2]. Therefore, controlling pain through alternative methods than anesthetics and painkillers is an appealing field of study for scientists, and activities that may distract attention are commonly used for an effective pain control.

It is common knowledge that distracting attention can reduce perceived pain [3], [4], [5]. Early studies examined the effects of affective distraction tasks upon the subjective experience of pain [6]. Participants were exposed to positive, neutral, and negative 2D images from the International Affective Pictures System (IAPS) while his or her hand is immersed in very cold water. Experimental results concluded that pain tolerance scores were directly proportional to picture pleasantness.

More recently, Virtual Reality (VR) has been utilized to manage pain and distress associated with a wide variety of known painful medical procedures [7], [8]. In both clinical and experimental laboratory settings, participants immersed in VR experience reduced levels of pain, general distress/unpleasantness and report a desire to use the technology again during painful medical procedures. VR technology is well studied in medical settings as a means to attenuate pain perception, anxiety, and general distress during painful medical procedures, including wound care [9], chemotherapy [10], dental procedures [11], burn pain [12], and routine medical procedures [13]. In particular, VR has been applied in many studies to reduce the pain in medical treatment for children [14], [15], [16], [17].

Meanwhile, the sense of touch, being intense and emotional, has a vital potential in pain management. Traditional touch therapy techniques such as healing touch, therapeutic touch, and Reiki have been found to be useful in pain relief for adults and children [18]. Results of trials conducted by more experienced practitioners appeared to yield greater effects in pain reduction. The use of haptic technologies seems to be largely unexplored in the field of pain management. A preliminary study assessed the effects of vibrotactile stimulation on experimental pain [19]. Vibrotactile stimulation resulted in a 40 percent decrease in heat pain in all subject groups whereas distraction did not seem to affect experimental pain ratings.

The relationship between tactile stimulation and emotional reactions is widely studied [20]. There are three approaches for tactile stimulation. The first type involves attaching a tactile device (with embedded vibration motors) to the user body, for example, vibrotactile jacket [21], haptic glove [22], or haptic belt [23]. In this approach, the skin and the device are always in physical contact and that might lead to undesired touch feelings. The second approach involves

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controlling the position of the tactile device so that it makes physical contact with the skin only when tactile interaction is required (an example is a master-slave system where force feedback is realized by an exoskeleton master hand [24]). The drawback of this strategy is that it usually required a bulky and expensive robotic arm. The third type is a promising approach for providing tactile feedback in mid-air (examples of this type include ultrasound phased array [25], air-jet stimulation [26], and laser stimulation [27]).

Tactile stimulation patterns that had been previously rated as being positive (continuous tactile stimulation), neutral (discrete stimulation), or negative (simultaneous stimulation) are used in this study. Participants experienced tactile stimulation on their right hand while the left hand is immersed in cold (2 °C) water. Participants will be asked to keep the hand immersed in cold water for as long as possible but to withdraw the hand when it begins to hurt. The question here is whether tactile stimulation, with or without VR, may affect the level of perceived pain.

Three hypotheses are tested in the current study:

- H1: VR reduces the perceived pain during cold pressor test.
- H2: VR along with tactile feedback reduces further the perceived pain compared to only VR.
- H3: VR with tactile feedback enhances the quality of user experience compared to only VR.

The remainder of the paper is organized as follows: Section 2 presents the experimental setup, including an overview of the Haptogram system and the VR task. In Section 3, the experimental design, procedure, measures, analysis, along with the participants information, are introduced. Section 4 presents results regarding the perception of pain (pain tolerance and intensity) and the quality of experience. Section 5 presents a discussion about the findings and limitations of the current study. Finally, Section 6 summarizes the findings of the study and provides perspectives for future work.

2 Experimental Setup

The experimental setup comprises a Haptogram interface [25] for generating tactile sensations at the subject's hand palm, an Oculus Rift Head Mounted Display (HMD) for displaying VR contents, a Leap Motion hand tracker to detect the hand movements, and a cold water bath (12 cm depth of cold water at 2°C). A laptop with the following specification is used in this study: Intel Core i7-6700HQ at 2.60 GHz CPU, 16 GB RAM Memory, GeForce GTX 1060 GPU, with the Windows 10 64-bit Operating System. A snapshot of the experimental setup is shown in Fig. 1.

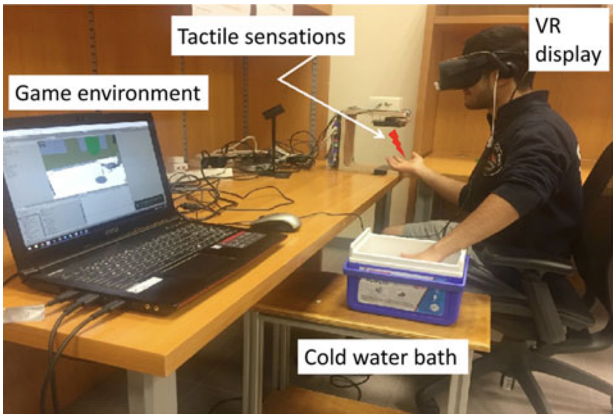

Fig. 1. The experimental setup showing a user performing the experiment.

2.1 Haptogram: Mid-Air Ultrasound Tactile Stimulation

The Haptogram system provides tactile stimulation in mid-air via acoustic pressure. A two dimensional array of ultrasound transducers is used to produce a movable focal point with tangible acoustic pressure in order to create 2D or 3D tactile shapes. As elaborated in our previous work [25], the Haptogram system comprises a software component and a hardware component.

The software component enables users to author and/or select a tactile object, create a point-cloud representation, and generate a sequence of focal points to drive the hardware component. The hardware component comprises a tiled two-dimensional array of ultrasound transducers, each driven by an FPGA. The FPGA receives the position information for a focal point, then loads the phase information for all transducers, and generates the control signals to drive all the transducers together to form this focal point. A driver circuit is also implemented to generate sufficient voltage to drive the actuators.

The Haptogram system renders point-cloud 3D tactile objects by switching focal points at a frequency up to 1.34 KHz. The flowchart that explains the haptic rendering is shown in Fig. 2. First of all, the tile configuration is loaded (N number of tiles, n number of transducers along x-axis, and m number of transducers along y-axis) along with the 3D point cloud file that represents the 3D tactile object to be displayed. Then, for each focal point, the distances between the given focal point and every transducer of the tiled array is calculated; results are saved in the distances array. Next, the timings (phases) needed by each transducer in order to form the focal point of acoustic pressure are calculated; results are stored in the timings array. The timings array is converted to an appropriate HEX memory file that can be uploaded to the FPGAs.

2.2 VR Tasks

Oculus Rift HMD is utilized to immerse the participants in a desktop space with two hands avatars. The virtual environment and the corresponding control logic are developed with the Unity 3D game engine. The 3D environment is a classroom that resembles university surroundings, so the users will feel comfortable and familiar. Unity uses a specific plugin to render this virtual scene stereoscopically in the Oculus device which is connected through HDMI and USB 3.0 cables to the laptop. The users can turn their head around to observe/explore the entire classroom and thus become immersed in the experience.

The hand avatars are animated based on the real hand movements captured by the LEAP motion tracker. Depending on the users gender, a different 3D hand model is chosen by a script to be shown in the scene as the virtual hand that always follows the real hand movements.

The VR-based task is a ball balancing game where the participant sees her/his right hand avatar in virtual environment,

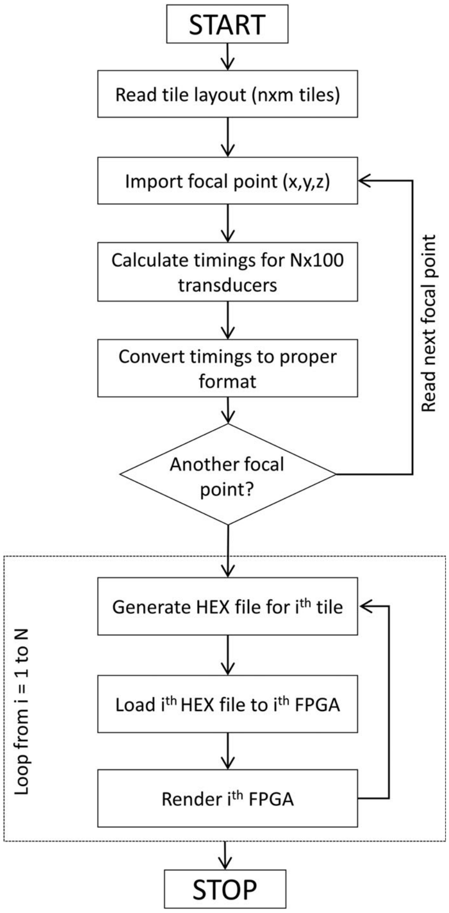

Fig. 2. Tactile rendering algorithm based on 3D point cloud (nxm = 100).

and a ball is dropped from a height to the center of their palm. The ball receives random bursts of energy to fall off the palm in an arbitrary direction and the participant has to respond by balancing his/her palm to bring the ball back to the center of the palm. In the VR-based task with tactile stimulation, the collision between the ball and the palm avatar is tracked in order to provide tactile sensation for the contact between the ball and the palm (using the Haptogram device). A snapshot of the VR task is shown in Fig. 3.

3 Method

This section presents the experimental design, participants information, procedure, measures, analysis and design for the conducted study. A commonly used technique for pain simulation, named the cold pressor test, is utilized to simulate pain on the left hand whereas the right hand is used to interact with the VR game.

3.1 Participants

Fifty right-handed participants with ages ranging between 18 and 25 (23 females and 27 males) took part in the experiment. The participants were students from New York University Abu Dhabi. The experimental procedure and participant recruitment was reviewed and approved by New York University Abu Dhabi Institutional Review Board (IRB #103-2016). Before beginning the experiment, all participants were given a self-report checklist to indicate whether they had any health problems that might make it dangerous for them to participate or bias the results. The

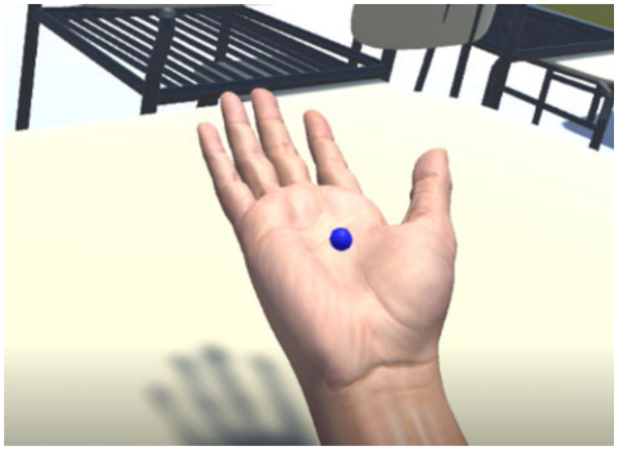

Fig. 3. VR image of ball balancing task. Blue ball indicates the mid-air ultrasound stimulation point.

participant agreement form specifically asked about circulatory problems, skin problems, painful conditions or serious health problems. Participants who have had any of these problems were excluded from the experiment.

3.2 Procedure

The experiment comprised three tasks. Task 1 required that the participant submerge his/her left hand up to the wrist in cold water and receive no distraction for a maximum of 2 minutes or until the participant decided to withdraw their hand. The participant was asked to wear the Oculus Rift HMD with black screen and white noise audio to avoid any distractive visual/auditory feedback from the ambient environment. The tolerance time was recorded and the participant rated his/her pain and quality of experience by completing a questionnaire. Afterwards, he/she was provided with paper towels to wipe his/her hands and, upon request, was given a scarf to wrap around the hand, to help with warming it back up after each task. The room temperature was kept constant at 21 °C.

In task 2, the participant was introduced to the VR game and allowed to practice using the game to familiarize themselves with the setup. Once comfortable with the setup, the participant started playing the game and immediately the participant's left hand was submerged into the water bath, while continuing to play. Once the participant removed his/her hand from the water bath, the tolerance time was recorded and the participant was asked to complete a questionnaire about his/her perceived pain and quality of experience. Finally, in task 3, the participant conducted the same VR game experiment augmented with tactile feedback and completed a third questionnaire related to the tactile experience. The participant was debriefed for further feedback about the entire experimental experience. All participants were instructed to start with no distraction, and assigned the two other tasks in random order (25 participants started with VR game without tactile feedback as the second task whereas the other 25 participants started with VR with tactile feedback as the second task).

3.3 Measures

In order to evaluate the user experience, two types of measures are considered: the cold pressor test and the quality of

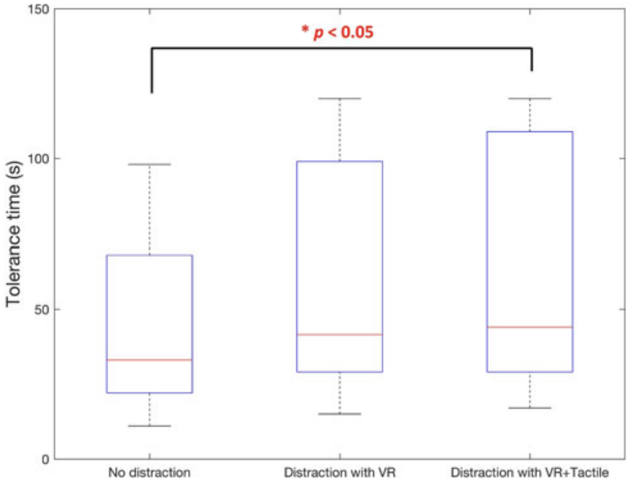

Fig. 4. Tolerance time based on distraction method (N=50). Box plots show the median and distribution of tolerance time. Kruskal-Wallis test, $^{*}p < 0.05$.

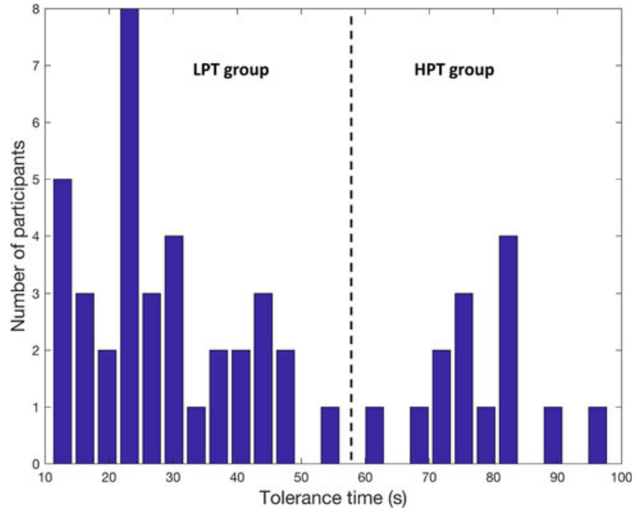

Fig. 5. Histogram of the participants with no distraction (N=50). LPT and HPT indicate low and high pain tolerance groups.

experience questionnaire. The former simulates and measures pain experience whereas the latter captures the subjective quality of experience (including emotional reactions).

The cold pressor test is a commonly used model to trigger pain without the confounding of baroreflex activation [28]. An optical sensor is used to record how long participants left their hand submerged from entry to withdrawal (usually known as the tolerance time). There was an upper limit of 2 min after which the participant was asked to remove her/his hand from the cold water. Furthermore, after each task, participants used the Visual Analogue Scales (VAS) to quantify the intensity of perceived pain [29]. The VAS scale is a straight horizontal line of fixed length (usually 100 mm) where the ends are defined as the extreme limits of perceived pain, oriented from the right (100 mm or worst imaginable pain) to the left (0 mm or no pain). The VAS scale provides superior metrical characteristics than discrete scales (such as Likert scale), thus a wider range of statistical methods can be applied to the measurements [30].

At the end of the second and third tasks (VR game with and without tactile feedback), the participants were asked to answer a modified version of the Igroup Presence Questionnaire (IPQ) a scale created by Schubert, Friedmann and Regenbrecht to measure the sense of presence experienced in virtual environments [31]. The questionnaire covered four parameters: valence, arousal, realism (hand avatars and tactile stimulation), and performance (perceived pain). Answers were given on 9-Likert scale for pleasantness and excitement, and a 7-Likert scale for realism.

3.4 Design and Analysis

As for the pain reduction rate, an average of the perceived pain was calculated for each participant for the three tasks: no distraction, distraction with VR and no tactile feedback, and distraction with VR and tactile feedback (VR+Tactile). In order to test if the efficacy of the tactile feedback was significant, ANOVA was used for comparison among three tasks, however Kruskal-Wallis test was used when data is not required to fit a normal distribution. When the ANOVA or the Kruskal-Wallis test indicated an effect of condition, pairwise comparisons were performed to identify significant differences. Furthermore, two-sided Wilcoxon signed-rank test [32] is utilized for the VR and VR+Tactile tasks since single-scale Likert ratings is questionable due to the non-parametric nature of the data.

4 Results

4.1 Pain Tolerance

The tolerance time is measured and compared for the three tasks. There is a significant difference in tolerance time between the distraction with VR+Tactile and the no distraction groups, as shown in Fig. 4 (Kruskal-Wallis test, X2(2)=7.96, $p < 0.05$; post-hoc, Tukey-Kramer). However, there is no significant differences between the distraction with VR and the no distraction tasks. This implies that the tactile stimulation has played a crucial role in increasing the tolerance time and thus in enhancing the distraction level.

It is worth mentioning that the tolerance times were drastically different across the subjects. While some subjects were only able to keep their hand in for a few seconds, some had no issues with the ice cold water for up to two minutes and later reported relatively lower pain levels. This led to plotting the data histogram in order to explore potential distributions across the participants (Fig. 5). It became evident that the data did not exactly follow a normal distribution but rather is a bimodal distribution, suggesting two groups of participants with low and high pain tolerance. As such, the entire population is divided into two groups: High Pain Tolerance (HPT) group and Low Pain Tolerance (LPT) group. In the following, the analysis will be conducted per each of these groups.

Figs. 6 and. 7 report the tolerance time for the LPT group and the HPT group over the three distraction conditions, respectively. For the HPT group, the Wilcox signed rank test showed significant differences between the distraction with VR and distraction with VR+Tactile tasks ($p < 0.05$). Both distraction methods reported significant differences compared to the no pain distraction condition (Kruskal-Wallis test, X2(2)=21.26, $p < 0.01$; post-hoc, Tukey-Kramer). These results suggest that for high pain tolerance participants, tactile stimulation has improved even further the tolerance time and eventually enhanced the level of pain distraction.

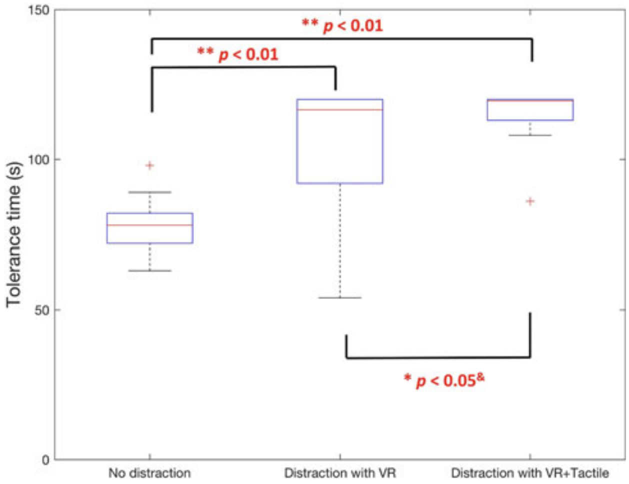

Fig. 6. Tolerance time for the HPT group (N=14). Box plots show the median and distribution of tolerance time. Kruskal-Wallis test, $^{**}p < 0.01$. $^{\&}$Wilcoxon signed rank test, $^{*}p < 0.05$.

On the other hand, the differences in LPT group (Fig. 7) are observed between no distraction and distraction with VR, and no distraction and distraction with VR+Tactile stimulation. The Kruskal-Wallis test demonstrated that there are significant differences between these groups (Kruskal-Wallis test, X2(2)=8.75, $p < 0.05$; post-hoc, Tukey-Kramer). However, the Wilcox signed rank test reported no significant differences between distraction with VR and distraction with VR+Tactile tasks.

This study has also explored the role of gender on pain tolerance. An ANOVA analysis as well as a Wilcox signed rank test reported no significant differences between male and female participants in relation to pain tolerance across the no pain distraction, distraction with VR, and distraction with VR+Tactile tasks.

In summary, the entire group analysis reported that distraction with VR+Tactile is more effective than distraction with VR. Furthermore, high/low pain tolerance analysis suggested that tactile stimulation is more effective with individuals who can tolerate higher pain compared to those with low pain tolerance. Therefore, the first hypothesis (H1) holds valid across the entire group of participants.

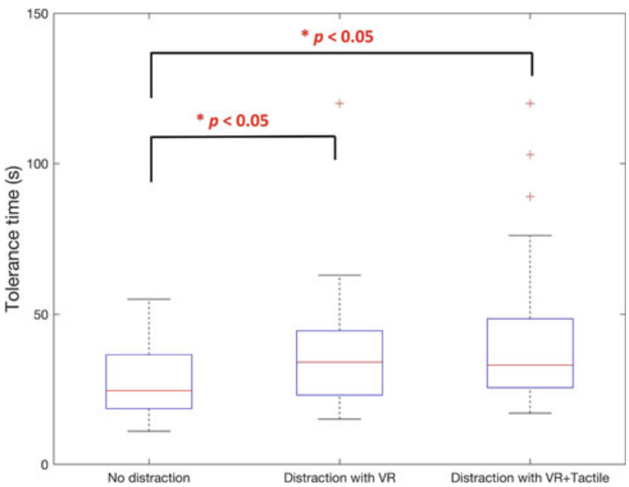

Fig. 7. Tolerance time for the LPT group (N=36). Box plots show the median and distribution of tolerance time. Kruskal-Wallis test, $^{*}p < 0.05$.

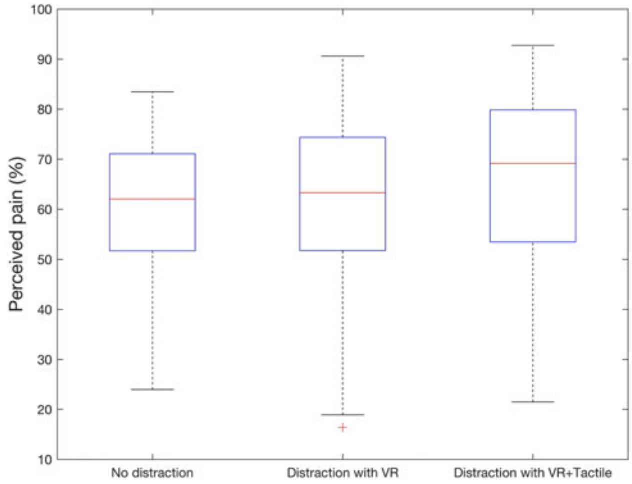

Fig. 8. Perceived pain based on distraction method (N=50). Box plots show the median and distribution of perceived pain level.

4.2 Perceived Pain

The averages and standard deviations of the perceived pain (self-reported) for the three tasks are plotted in Fig. 8. The perceived pain thresholds seem to be nearly constant through all the experiment for the entire group of participants (as noted in Fig. 8). This is expected, since by the time the participants withdraw their hands from water bath, the perceived pain reaches the most bearable pain level. This pain level is consistent among all participants. Furthermore, one-way ANOVA demonstrated no significant differences in perceived pain (F (2)=0.78, n.s.) between the three tasks (no distraction, distraction with VR, and distraction with VR+Tactile).

When considering the LPT and HPT groups, a similar observation is also demonstrated. The pain level for the LPT group slightly varied, with the highest pain level reported in the distraction with VR+Tactile task. However, one-way ANOVA demonstrated no significant differences between the three tasks. Similarly, there is no significant differences in perceived pain for the HPT group for the two distraction methods against the no distraction method. All these results confirm that the perceived pain threshold is consistently constant for participants across the entire group.

4.3 Quality of Experience

The quality of experience is calculated as the mean of the four parameters considered in the questionnaire, namely arousal, valence, realism, and performance. Based on the questionnaire results, most participants reported positive emotional experience (higher than 50 percent valence) and enhanced arousal with the tactile stimulation added to VR environment, particularly for the LPT group). This demonstrates that VR and tactile stimulation induces positive emotional reactions when used for pain distraction/control.

It is worth noting that realism did not score well (less than 50 percent) due mainly to calibration challenges. The tactile stimulation has worked very well for participants who could clearly feel it in synchronization with the visual display. However, with slight offset in the hand position rendering, the realism has dropped drastically since this made the tactile stimulation confusing. Additional calibration difficulties resulted from the inability of the Leap Motion tracker to detect the hand movements once placed inside the tactile stimulation box (probably due to multiple reflections of the infrared signal).

Furthermore, when considering the LPT and HPT groups, the quality of experience ratings are quite similar. Therefore, the entire group of participants seems to have a positive and arousing experience with the VR with or without tactile stimulation. These results confirm the H3 hypothesis that VR and tactile stimulation enhances the quality of user experience (especially for emotional reactions).

5 Discussion

Results presented in this study confirmed that augmenting VR with tactile stimulation enhances pain distraction when physical (touch) interactions are involved (this is particularly true for the high pain tolerance group and less so for the low pain tolerance group). Furthermore, VR+Tactile stimulation induced positive feelings (both valence and arousal) when virtual reality with tactile stimulation is utilized.

Previous literature reported that women experienced heightened pain sensitivity to experimentally induced pain compared with men [33]. This study also investigated gender effect, with results demonstrating no significant differences.

5.1 Analysis of Limitations

A source of random errors was the use of rulers to measure the pain level on the VAS scale, providing an error of +/- 0.05 mm. Furthermore, research shows that different people have drastically different pain tolerance levels, based on gender [34], size and body fat [1], or genetics and anatomy [2]. The current study did not control for the participants' body fat, genetics or anatomy aspects due to time and practical constraints. It is worth noting that the participants were asked to fill the questionnaire about the experience a relatively long time after the conclusion of the experiment. As such, it might well be that participants reported what they recall having felt, rather than what they actually felt.

Sources for systematic errors include the improper calibration of the hand position with respect to the tactile stimulation, the varying size of the participants' palms which made the tactile sensation barely perceivable in some cases, as well as the hand tracking errors. For instance, female participants with smaller palm size tend to feel a distorted perception of the tactile sensation. This could partially explain the lower rating of the distraction with VR+Tactile task compared to the distraction with VR counterpart.

It is a limitation of mid-air tactile stimulation using ultrasound that people can feel it only on hand palm. Indeed, other parts of human body are very difficult to feel the sensation generated by mid-air ultrasound stimulator generally [35]. However, most of the human interaction takes place in the hands and mid-air ultrasound stimulator can display various patterns, therefore it can be applied to various applications. Furthermore, ultrasound-based tactile stimulation technology is still in its infancy. Several research groups are working on improving the fidelity of tactile stimulation to display tactile sensations anywhere on the human body[36].

6 Conclusion And Future Work

This study has confirmed that VR and mid-air ultrasound tactile stimulation have a great potential to distract patients from pain during medical care and therapy. Studies of pain distraction through VR have already been extensively attempted to reduce pain during medical treatment. Especially, It is more affective for children than their parent and nurses [14]. This study shows that the effect of pain distraction can be increased through combination of mid-air tactile sensation and VR. Other types of haptic sensation are also likely to be effective for pain distraction and further studies are needed to verify this.

While there was no observable differences in the data collected regarding the emotional and realism aspects of the experiences, this study found that participants reported higher-than-midpoint values for the valence and arousal, indicating excitement and happiness across the experiments. The realism was however debatable, as its mean lied on the midpoint of the scale, indicating that participants did not find the tactile stimulation very convincing.

In the future, it is advised that work in this area should significantly increase the sample size and look at better ways of administering the tactile stimulation. It would also be interesting to study the complicated role of tactile information in the cognition of the brain. To do that, it might be worth investigating if different tactile stimulation could alter pain distraction and emotional experience. For example, vibrations and stroking movements are two different kinds of tactile stimulation that could be interpreted differently in the brain [37] and could cause different distraction behavior. Another perspective for future work is to study the relationship between the frequency and duration of VR and tactile game to enable long-term pain control. Finally, applying the proposed approach for chronic pain management/control with patients is worth exploring.

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