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Exploring the Perception of Pain in Virtual Reality through Perceptual Manipulations

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ABSTRACT

Perceptual manipulations (PMs) in Virtual Reality (VR) can steer users' actions (e.g., redirection techniques) and amplify haptic perceptions (e.g., weight). However, their ability to amplify or induce negative perceptions such as physical pain is not well understood. In this work, we explore if PMs can be leveraged to induce the perception of pain, without modifying the physical stimulus. We implemented a VR experience combined with a haptic prototype, simulating the dislocation of a finger. A user study (n=18) compared three conditions (*visual-only*, *haptic-only* and *combined*) on the perception of physical pain and physical discomfort. We observed that using PMs with a haptic device resulted in a significantly higher perception of physical discomfort and an increase in the perception of pain compared to the unmodified sensation (*haptic-only*). Finally, we discuss how perception of pain can be leveraged in future VR applications and reflect on ethical concerns.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**.

KEYWORDS

Virtual Reality; Haptic Devices; Perceptual Manipulations

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1 INTRODUCTION

Perceptual manipulations (PMs) such as redirected walking [27] are frequently used to steer the physical actions of a user. They

can also impact the perception of the environment by the user, without altering their underlying physical sensations (e.g., altering the perception of weight). [30].

While most prior work explores actions or neutral experiences, our work aims to understand if one could also apply purely visual PM to increase a highly subjective negative experience. Our focus was on pain, which is defined by the International Association For the Study of Pain (IASP) as: “*An unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage*” [26]. It is important to note that pain is not the same as nociception (the sensory system around pain receptors) but consists of more complex constructs related to emotions and impacted by biological, psychological, and social factors [19].

To explore this phenomenon, we implemented a VR experience simulating the dislocation of the user's index finger, combined with a haptic prototype. The haptic prototype slowly lifts the user's finger to a 45° angle, and the same happens to a representation of the user's hand in VR (no PM until this point). Then, only the virtual finger abruptly bends backwards, while the haptic prototype delivers a slight hit on the user's finger.

We conducted a within-subject user study (n=18) to evaluate if the visual PM (dislocation) could induce a perception of pain higher than the one created by the physical stimulus alone. The experiment had three conditions (*visual-only*, *haptic-only* and *combined*), and measured the level of pain and physical discomfort, as well as three common VR metrics: presence, ownership and enjoyment. Our results show that there was a significant difference on the median (IQR) of the participant's physical discomfort between *combined* and *haptic-only* on the 0-10 Borg scale [6], without diminishing the enjoyment of the participants. While we did not find a significant difference in pain between *combined* and *haptic-only*, the reported values still increased from 0.0 (0 to 0.75) to 1.0 (0 to 1) on median. We assume this is due to the overall low levels of pain created from the haptic device (all below 1 on a 0-10 Borg scale). Nonetheless, coupled with the significant increase in physical discomfort, this is an indicator that combining PM with haptic devices is able to increase the perception of pain and discomfort, resulting in a construct we call “*virtual pain*.”

Combining our findings around pain and discomfort with enjoyment, we found that inducing virtual pain had no negative impact on the enjoyment that people perceived during the finger dislocating experience. Therefore, we discuss potential application scenarios

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where the construct of “virtual pain” could be used to positively enhance an experience by introducing negative aspects. However, we assume that this effect mainly happens since our pain values were relatively low and present ethical reflections around the ability of PM to increase pain and discomfort in scenarios where the overall pain levels are high.

Our work has the following contributions: 1) Demonstrating in a user study (n=18) that using PM in combination with haptic feedback allows to significantly increase the perception of physical discomfort and increases the perception of physical pain, compared to a haptic-only baseline condition. 2) Discussing how this new construct of “virtual pain” could be used to enhance future VR experiences but also the potential ethical challenges behind it.

2 RELATED WORK

2.1 Enhancing VR Experiences with Perceptual Manipulations

PMs are a set of techniques leveraging human perception thresholds to enhance the user experience. Recent work [35] defined virtual-physical PMs as extended reality driven exploits that alter the human multi-sensory perception of the user’s physical actions and reactions to nudge their physical movements (e.g., the position of body and hands). From a sensorimotor integration perspective [2, 37], a VR user perceives all their sensory information and performs a physical action. Since human perception is often visual dominant, VR has the opportunity to manipulate the user’s physical action by controlling the visual input [9, 25]. Practitioners and researchers then start “hacking” human perception to overcome several limitations in current VR systems (e.g., limited tracked space, lack of haptic feedback). Prominent examples like redirected walking [27] or redirected haptic [4] use PMs to enhance the VR experience.

Although recent PMs aim to alter the user’s physical actions, they can also alter the perception of the environment, e.g., weight [30, 32], texture [10], and kinesthetic feedback [29]. Similar to redirection techniques, this line of work provides haptic feedback in VR to enhance the overall VR experience (e.g., the sense of presence and enjoyment). Instead of using the actual stimulant, these techniques aim to distort human perception and create a pseudo-haptic illusion to enhance the haptic sensation [17, 18].

PMs often aim for positive outcomes and for overcoming limitations in VR. However, their ability to amplify or induce negative perceptions such as pain is not well understood. Specifically, whether inducing pain (and other unpleasant feelings) could enhance the VR experience or be harmful to users is currently unknown. In this work, we explore whether PMs can be leveraged to induce unpleasant perceptions such as pain.

2.2 Pain and HCI research

Pain is a subjective experience localizing sensation in a particular body part and triggering an unpleasant experience of varying severity commonly associated with behaviors directed at relieving or terminating the experience [13]. In this paper, we will focus on physical pain¹, which is often localized and associated with noxious

physical stimuli, as opposed to physiological pain, which is a diffuse subjective experience [22].

The recent definition of pain shows that pain and emotion are closely related, and pain can also be defined as a type of unpleasant emotional experience [23, 26]. The usage of pain is often associated with games [1, 8] for entertainment purposes. These works used pain as a feedback (or reward) in their game mechanics to enhance the user’s experience and commitment. One particular use of pain in HCI is to create uncomfortable interactions. Benford et al. [5] designed uncomfortable interactions and used pain as one of the scenarios. They made use of acute pain to underpin positive design values related to entertainment, enlightenment, and sociality.

Humans experience physical pain through nociceptors (neuron receptors of pain) and perceive this sensory feedback. Previous works activate the pain receptors using different modalities (e.g., capsaicin for skin burning pain [14], stimulating the trigeminal nerve for temperature illusion [7]). Kono et al. similarly tried to induce pain in VR, and were able to demonstrate that different stimuli are able to induce different levels of pain (electrical muscle stimulation, solenoid, and visual) [16]. The difference to our work is that we want to keep the underlying haptic stimulus the same across all conditions, and explore if by modifying only the visual sensation (using PMs), we are able to increase the users perception of pain.

The Rubber Hand illusion [15, 28] has been used in the past to create the illusion of physical sensations. In some instances, this illusion extends to influencing pain, by creating an analgesia effect [24]. In this paper, we explore the possibility of inducing the opposite effect, and to increase the perception of pain. Moreover, the Rubber Hand illusion requires the user to embody the target prop beforehand by going through visuohaptic synchronized stimuli. Here, there is no such stimulus: the ownership on the virtual hand only comes from the agency over it.

3 FINGER DISLOCATING EXPERIENCE

To investigate how PMs can affect the perception of physical pain, we implemented a finger dislocating experience. The experience includes a haptic device that lifts the user’s index finger, and a VR experience that shows the dislocation. We focused on dislocation since it is a painful experience that can already induce negative emotions (partially through mirror neurons) when seen in other humans [34].

3.1 Haptic Device Design

The hardware prototype used in the study consists of a box, on top of which a 100x15mm plank can be lifted. Inside is a solenoid, able to generate a small impact. Figure 1 shows the user lays their hand on the surface of our prototype where their index finger stays on the plank. A servomotor lifts the plank and index finger, where the angle never goes above 45°, which is the extension range of the metacarpophalangeal joint (Figure 1c). [12]. By targeting this value, we ensure that no harm is inflicted to the participants, though they may feel discomfort from the stretching. When the maximum angle is reached, the solenoid generates an impact at the base of the user’s finger, to simulate a breaking effect. Both the servomotor and the solenoid are controlled by an Arduino UNO.

¹In the following paper, “pain” refers to physical pain.

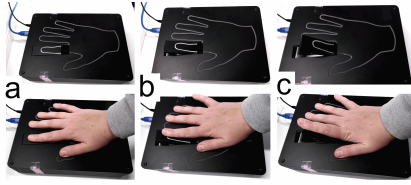


Figure 1: The haptic device used to bend the participant’s real finger: (a) no bending, (b) slight bending, (c) maximum bending

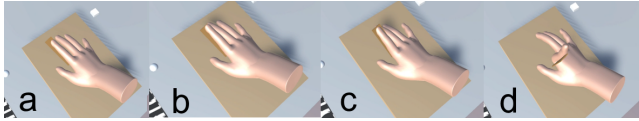


Figure 2: Progressive bending in VR: (a) no effect, (b) mild effect, (c) maximum angle before dislocation and (d) dislocation.

3.2 VR Experience Design

Using Unity3D, we built a VR scene where the participant puts their hand on a virtual box and sees their index finger being lifted by a virtual copy of the real box, then dislocated. The application is deployed on a Head-Mounted Display (HMD), the HP Reverb². As this HMD does not provide native hand and finger tracking, we used a Leap Motion controller, mounted directly on the HMD.

By overriding the finger tracking for the index finger (Figure 2), we are able to bend the virtual finger while maintaining a realistic representation of the rest of the hand in space. To simulate the dislocation, we abruptly increase the bending angle beyond 90°, so that the virtual index finger takes an unnatural position, as shown in Figure 2d.

The haptic and visual experiences are synchronized using the Uduino plugin³, which controls the Arduino UNO directly from Unity. With our parameters, both in VR and with the device, the breaking effect occurs after 10 seconds, when its angle is 45°.

4 USER STUDY: PHYSICAL SENSATIONS OF DISLOCATING FINGER IN VR

During the study participants experience the dislocation of their finger through three different conditions. For each one we evaluate the perception of physical pain and discomfort. Meanwhile, we used questionnaire to measure common VR metrics like presence, ownership, and enjoyment.

As this study tries to highlight potential negative effects for the participants, we were very careful to design it in a way that would be harmless to the participants. The recruitment process and the protocol of the user study were approved by a local ethics board.

²<https://www.hp.com/us-en/vr/reverb-g2-vr-headset-omnicept-edition.html>

³<https://assetstore.unity.com/packages/tools/input-management/uduino-arduino-communication-simple-fast-and-stable-78402>

4.1 Participants

We recruited participants (n=18) from our and neighboring institutions using convenience sampling (six females, one non-binary, and nine males, age: M=24.9, SD=3.4 years). Three participants had experience in VR development or research, one never used VR before, and the rest used VR occasionally. During the recruitment process, we excluded participants that had had hand injuries in the past, or suffered pathologies affecting their hand. Before the beginning of the study, each participant read and signed a consent form which explained the study protocol, and reminding them they could stop the experiment at any time. We ensured that the participants were flexible enough to not get hurt by the bending of their finger, by making them try the hardware device on its own.

4.2 Study Design

The experiment has one independent within-subject variable (MODALITY) with three levels, *visual-only*, *haptic-only* and *combined*. The *visual-only* condition allows us to confirm that the VR experience, on its own, induces no pain or physical discomfort in the participants. The *haptic-only* condition allows us to establish a pure sensory baseline for pain and physical discomfort, for each of the participants. The *combined* condition allows use to measure the difference in pain and physical discomfort with the *haptic-only* condition. If we notice a significant increase in the two conditions, it will mean that we successfully induced the perception of pain without changing the physical stimulus (using only visual PM).

Our hypotheses are the following:

- H1: The level of physical discomfort is higher in the *combined* condition than in the *haptic-only*.
- H2: The use of haptics increases the level of ownership felt over the user’s virtual finger.
- H3: The level of enjoyment will decrease as the level of physical discomfort increases.

4.3 Procedure

Each participant had to experience all three conditions which were counterbalanced using a 3 × 3 Latin square for minimizing the effects of surprise. For each condition, the participant is standing in front of the box, which is on a table. They have one minute to move their hand freely before they put their hand on the box and the bending begins. Each condition then lasted 10s (the time for the bending to finish).

- *haptic-only*: The participant puts their right hand on the box. They do wear the HMD, but it is used in pass-through mode: they see the real world (captured by a camera) through the headset. The haptic device then slowly bends to the maximum angle, and the solenoid creates an impact at the base of their finger.
- *visual-only*: The participant wears a VR HMD. They also put their hand on the box, but nothing happens physically. They only watch the virtual bending and dislocation.
- *combined*: The participant puts their hand on the box and wears a VR HMD. Then, synchronously, the virtual and real finger are bent. At the maximum angle, the virtual finger dislocates, and the solenoid creates an impact on the real finger.

We used the HMD in the *haptic-only* condition, even if it was not needed visually, so that the three conditions are as similar as possible for the participant (e.g., weight of the HMD). After each condition, the participant answered a paper questionnaire to assess the different metrics.

4.4 Questionnaires

The pain is measured through the Borg scale [6], where participants rate their physical pain from 0 to 10. 0 means no pain at all, and 10 is the worst pain imaginable. Besides pain, we also measured physical discomfort. While being closely related, physical discomfort is a different perception than pain [3]. Ashkenazy et al., conducted a concept analysis and presented the following definition for discomfort: “Discomfort can be physical or psychological and is characterized by an unpleasant feeling resulting in a natural response of avoidance or reduction of the source of the discomfort. Pain is one of the causes for discomfort, but not every discomfort can be attributed to pain.” Since physical discomfort and pain are closely related we also applied the Borg scale, modifying the leading question. The question used was the following: “Please rate your physical discomfort during the experiment on a scale from 0 to 10. Physical discomfort can be either pain or unpleasant sensations you felt physically (uncomfortable stretching, etc.)” The difference between physical pain and physical discomfort was explained to all participants beforehand.

We evaluated common VR metrics using existing questionnaires, all on 7-point Likert scales. Presence and ownership were only measured in the two conditions that involve the use of VR: *combined* and *virtual-only*. For the sense of presence, we used the presence questionnaire from Slater, Usoh, and Steed (SUS) [36]. In terms of ownership felt over the virtual index finger, we applied the questionnaire presented in [11]. Finally, we used the average of the enjoyment subset from the Intrinsic Motivation Inventory (IMI) [21] to measure the enjoyment level.

4.5 Results

Figure 3 depicts the responses of five dependent variables. Since the data were non-parametric, we analyzed physical pain, physical discomfort, and enjoyment with Friedman test. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied.

Physical Pain. A Friedman test revealed a statistically significant effect of MODALITY on physical pain ($\chi^2_{2,18} = 9.454, p = 0.009, r = 0.26$). The medians (IQR) of physical pain *combined*, *haptic-only*, and *visual-only* were 1.0 (0 to 1), 0.0 (0 to 0.75), and 0.0 (0 to 0). A post-hoc test using Wilcoxon signed-rank tests with Bonferroni correction showed the significant differences between *combined* and *visual-only* ($p = 0.014, r = 0.70$). Although not significant, there was a difference between pain *combined* and *haptic-only*, from 0 to 1, reflecting the effect of adding visual PMs.

Physical Discomfort. We conducted Friedman test and revealed a statistically significant effect of MODALITY on physical discomfort ($\chi^2_{2,18} = 11.789, p = 0.0027, r = 0.33$). The medians (IQR) of physical discomfort over *combined*, *haptic-only*, and *visual-only* were 2.0 (2 to 5.25), 1.0 (1 to 2.75), and 1.0 (0 to 1.75). A post-hoc test using Wilcoxon signed-rank tests with Bonferroni correction

showed the significant differences between *combined* and *visual-only* ($p = 0.008, r = 0.72$) and between *combined* and *haptic-only* ($p = 0.029, r = 0.62$). As expected, the lowest average level of physical discomfort was observed for the *visual-only* condition, which did not involve the use of the haptic device. We assume that the increase in physical discomfort between *haptic-only* and *combined* conditions is linked to the high levels of body ownership (Figure 3a) of the *combined*, resulting in triggering similar neural pathways as if this dislocation actually happened to the user.

Presence and Ownership Figure 3c shows the responses of presence and ownership on the *combined* and *visual-only* conditions. The medians (IQR) of *haptic-only* and *visual-only* on presence were 4.0 (3.5 to 4.88) and 3.75 (3 to 4.5). The medians (IQR) of *haptic-only* and *visual-only* on ownership were 4.5 (4 to 5.38) and 3.5 (3 to 4.5).

Because there were only two conditions, we applied the dependent Wilcoxon test directly. It revealed no significant effect ($W = 69.5, p = 0.096, r = 0.38$) for presence, but a significant effect for ownership ($W = 118, p = 0.0478, r = 0.48$). Thus, the use of haptic feedback combined with VR significantly enhanced ownership compared to the VR only condition.

Enjoyment Figure 3b shows the results of enjoyment over three conditions. A Friedman test revealed a statistically significant effect of MODALITY on physical pain ($\chi^2_{2,18} = 26.8, p < .001, r = 0.74$). The medians (IQR) of physical pain *combined*, *haptic-only*, and *visual-only* were 6.0 (4.45 to 6.7), 1.0 (0.45 to 1.62), and 5.83 (4.35 to 6.6). A post-hoc test using Wilcoxon signed-rank tests with Bonferroni correction showed the significant differences between *combined* and *haptic-only* ($p < .001, r = 0.87$) and between *haptic-only* and *visual-only* ($p < .001, r = 0.88$). Surprisingly, contrary to our hypothesis, *combined* and *visual-only* had a similar level of enjoyment, showing that the addition of an unpleasant physical sensation did not make the experience less enjoyable.

5 DISCUSSION

The goal of our study was to find if we could increase the perception of pain in VR using only visual PMs, without changing the underlying haptic stimulus. Our findings show that we were able to find a significant increase of the perception of physical discomfort, which is closely linked to physical pain [3]. While the direct pain metric did not have a significant increase between *combined* and *haptic-only*, we still saw an average increase (*combined*) from median 0 to 1 (on a 0-10 Borg scale). We assume that the pain that we were able to induce was overall too low and therefore was difficult to assess by the participants. Overall, we argue that we were able to find indications for a phenomenon that we refer to as “virtual pain”.

5.1 Virtual Pain

We define “virtual pain” as the increase in perceived physical pain and physical discomfort induced through a visual PM in VR.

In their definition of pain, the IASP was already indicating that “pain is always a personal experience” and that it is “influenced to varying degrees by biological, psychological, and social factors.” Since it is also not directly coupled to nociception—pain cannot be inferred solely from activity in sensory neurons—we can use these definitions and deeper understand pain to explain our results. Using

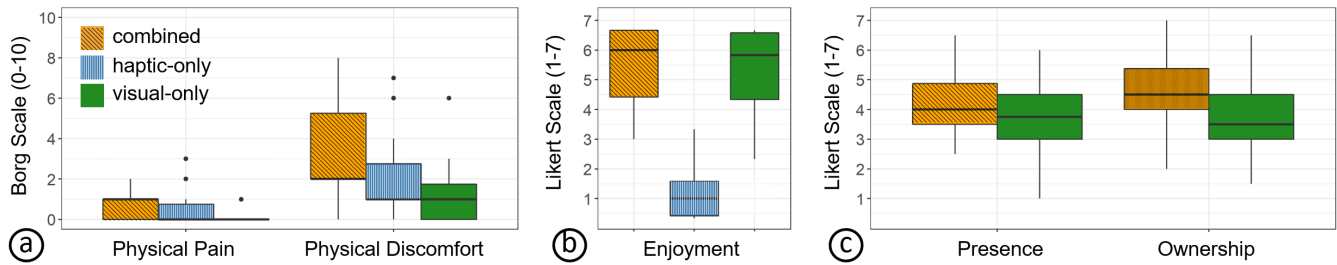


Figure 3: Boxplots showing the distribution of five dependent variables. (a) Physical pain and physical discomfort on Borg scale from 0 to 10. (b) Enjoyment on the 7-point Likert scale. (c) The sense of presence and ownership on the 7-point Likert scale.

PMs (here visual PMs) we were able to create a mechanism that is directly influencing the subjective perception of pain without changing the underlying sensation (no increase of nociception). We argue that VR combined with visual PMs is enabling an access to developers of VR applications to be able to induce this “virtual pain” on a large scale to the user. This ability comes with opportunities to improve future VR experiences but also with a responsibility around ethical concerns.

5.2 Using Virtual Pain to Create Value

Virtual Reality is currently mostly striving towards improving the overall user experience and reducing all types of annoying or negative aspects. We hypothesis that this reduction of “friction”, is leading to the experiences having less value to the user. A similar concept exists in philosophy around the emotions of happiness and sadness. Optimizing mainly for happiness can reduce the users capacity to value positive highs after negative lows [33].

A direct example would be experiencing a virtual travel application in VR. Even if we would assume a perfect virtual recreation of Rome with all the sensory stimuli, being able to jump in and out without having to go through the struggles and suffering (committing time, traveling, waiting in line, sitting in a full airplane, investing money) will reduce the value of the virtual experience compared to the actual real travel. We hypothesis that being able to induce “friction” in a controlled way could be a way to increase the value that users would have of future virtual experiences. This is in line with the argumentation of Benford et al., who argues that moments of discomfort can be beneficial to include experiences [5].

Our findings show that “virtual pain” was not reducing the enjoyment of users in our experience. This indicates that this could be used as one potential effect which could be incorporated in future VR applications to simulate “friction” without reducing the overall enjoyment. However, we are aware that “virtual pain” would only be one of the potentially many types of “friction” that could be induced, and future research has to explore what the other types could be and how they impact the value a user has of a virtual experience.

5.3 Abusing Virtual Pain

While our findings showed low overall values of physical pain, we can not exclude the possibility of future systems being able to demonstrate a significant increase in physical pain when operating

on an overall higher base level of pain. However, even the ability to induce physical discomfort using only visual PMs opens the possibility of accidents, or abuse by other individuals or entities in power.

Since “virtual pain” can be induced solely through visual PMs (which are synchronized with a haptic stimulus), having control over the visuals in a VR application might be enough to trigger unwanted “virtual pain”. In social applications (e.g., VRChat) other users could create a visual PM (animation of a hand being deformed) which they could have as an animated object positioned over the actual avatar representation of the user. Maloney et al. showed that teenagers are participating in and experiencing bullying frequently in social applications such as VRChat [20]. An prominent example of such behaviour was “VR Knuckles”, where VRChat participants used all a same avatar (a deformed knuckles from the sonic game) and played racial slurs to harass and troll others [31]. Having the ability to actually induce the perception of physical sensations would open the doors for future abuse and trolling in VR social networks.

5.4 Limitations and Future Work

To prevent actually hurting our participants, we operated always on a very low level of nociception. We assume that this was one of the reasons why we could not find a significant difference in the pure pain perception scale. Future research could explore how “virtual pain” is working having a high level of base nociception. However, this type of research becomes ethically difficult since it can potentially put the participants in danger.

In our work, we focused mainly on showing the existence of “virtual pain” through visual PMs. We are not able to explain what different specific factors were impacting the severity of the effect (e.g., visual haptic synchronicity, presence, embodiment). To be able to structurally recreate this phenomenon, future research needs to explore the individual factors and variables that are impacting the severity of “virtual pain”. One factor to explore will be the type of pain that is considered in the experiment. Here, we focused on a specific event (finger dislocation), and thus a specific form of pain. It will be interesting to see how much the “virtual pain” effect transfers to other scenarios.

6 CONCLUSION

In this paper, we showed the possibility to use visual perceptual manipulations to increase the perception of physical pain leading to a phenomenon we call “virtual pain”. In a user study (n=18), we compared three conditions (*haptic-only*, *visual-only*, and *combined*) on the perception of physical pain and physical discomfort. We found that we were able to increase the perception of physical discomfort and pain without changing the underlying sensation (no increase in nociception). Finally, we explain this phenomenon of “virtual pain” with our current understanding of pain research and present an opportunity how it could be used to increase the value of virtual experiences but also how it could be leveraged to harm and harass the VR user.

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