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Manipulating presence influences the magnitude of virtual reality analgesia

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Abstract

Excessive pain during medical procedures performed in unanesthetized patients is frequently reported, but can be reduced with virtual reality (VR) distraction. Increasing the person's illusion of going into the virtual world may increase how effectively VR distracts pain. Healthy volunteers aged 18–20 years participated in a double-blind between-groups design. Each subject received a brief baseline thermal pain stimulus, and the same stimulus again minutes later with either a Low Tech or a High Tech VR distraction. Each subject provided subjective 0–10 ratings of cognitive, sensory and affective components of pain, and rated their illusion of going inside the virtual world. Subjects in the High Tech VR group reported a stronger illusion of going into the virtual world (VR presence) than subjects in the Low Tech VR group, (4.2 vs. 2.5, respectively, $P = 0.009$) and more pain reduction (reduction of worst pain is 3.1 for High Tech VR vs. 0.7 for Low Tech VR, $P < 0.001$). Across groups, the amount of pain reduction was positively and significantly correlated with VR presence levels reported by subjects ($r = 0.48$ for 'worst pain', $P < 0.005$).

Keywords: Virtual reality; Presence; Analgesia; Distraction; Attention

1. Introduction

Excessive pain during medical procedures performed in unanesthetized patients is frequently reported (Gilron and Bailey, 2003; Karling et al., 2002; Melzack, 1990; Schechter, 1989; Shang and Gan, 2003) despite the widespread use of analgesic therapies. In clinical settings, side effects of opioid analgesia (e.g. nausea, post-procedure sedation, cognitive dysfunction, and constipation) limit dosage. In contrast, non-pharmacologic techniques typically produce minimal and short-lived side effects, and may serve as valuable adjuncts to traditional pharmacologies. One such non-pharmacologic technique is distraction, which has been shown to help reduce procedural pain in several settings (Fernandez and Turk, 1989; Tan, 1982).

Researchers have recently explored the use of immersive virtual reality (VR) as a pain control technique that can be used in combination with traditional pharmacologic therapies. Subjective reports of pain during a variety of painful medical procedures in the clinical setting have been shown to drop approximately 40–50% when patients are distracted by immersive VR (Hoffman et al., 2000a,b, 2001a,b, 2004a; Steele et al., 2003).

We theorize that VR analgesia works via an attentional mechanism. Humans have a limited amount of conscious attention available (Kahneman, 1973). Pain requires conscious attention (Chapman and Nakamura, 1999; Eccleston and Crombez, 1999). VR systems provide computer-generated multi-sensory input (sight, sound, and more rarely touch, taste and/or smell). Such converging sensory input, and the interactive nature of the experience help give patients the illusion of going into the virtual environment, which can make the virtual world presented difficult for the user's brain to ignore. We theorize that the more intense

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the patient's illusion of going inside the virtual environment, the more his/her attention will be drawn into the virtual world (Hoffman, 1998; Hoffman et al., 2003a), leaving less attention available to focus on pain.

In the present study, some subjects (High Tech VR) used VR hardware (VR helmet, headphones and headtracking system) designed to elicit a strong illusion of VR presence. Others (Low Tech VR) used VR hardware designed to elicit a less compelling illusion of VR presence (see-through VR glasses, no headphones, no headtracking). Regardless of the mechanism of VR analgesia, we predicted that (1) subjects' illusion of 'going into' the 3D virtual world (i.e. VR presence) would be greater for the High Tech VR group, and (2) the High Tech VR group would experience more pain reduction than the Low Tech VR group. And we predicted (3) the amount of VR presence reported would be positively and significantly correlated with the amount of pain reduction in VR. In essence, we predicted a measurable dose (increasing VR presence) response (pain reduction) relationship.

2. Method

Thirty-nine healthy undergraduate Psychology students 18–20 years of age (14 males, 25 females) from the University of Washington participated. Both written and verbal informed consent were obtained using a protocol approved by the University of Washington's Human Subjects Review Committee.

2.1. High Tech VR vs. Low Tech VR

Towards the goal of creating an immersive VR display (Slater and Wilbur, 1997), we used a High Tech VR system designed to: (1) shut out physical reality (helmet and headphones that exclude sights and sounds from the real world), (2) provide converging evidence to multiple senses, (both sight and sound), (3) provide a surrounding/panoramic view rather than limited narrow field of view, (4) be vivid/high resolution, (5) permit the participant to interact with the virtual world and (6) use head tracking, which allows subjects to view different portions of the virtual world merely by changing their head position/orientation. We also used a Low Tech VR system that (1) does not shut out physical reality (see-through VR eyeglasses and no earphones), (2) provides only one sensory input (sight only, no sound), (3) is not surrounding/panoramic but is instead limited to a narrow field of view, (4) is not vivid/high resolution, (5) does not permit the participant to interact with the virtual world, and (6) has no head tracking.

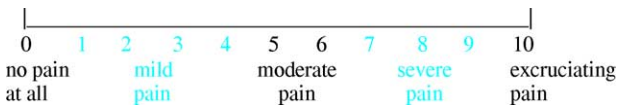
According to Slater and Wilbur (1997), immersion is an objective, quantifiable description of what a particular VR system can provide to a participant. Immersion is different from the subjective psychological illusion of going into the virtual world (defined here as VR presence), which is a psychological state of consciousness. Although immersion and presence are distinct concepts, increasing the immersiveness of a VR system often leads to a stronger illusion of presence. Several studies have identified 'high tech' improvements in VR hardware that increase the objective immersiveness of a VR system and simultaneously increase participant's subjective illusion of going into the virtual world (presence). For example, increasing the size of the eyepieces in the VR helmet (i.e. field of view, Prothero and Hoffman, 1995), adding head tracking so what the participant sees changes in the virtual environment as they change their head position (Hendrix and Barfield, 1995), and adding or improving the quality of sound in VR (Hendrix and Barfield, 1995), have all been shown to increase participants' subjective illusion of going into the virtual world. Adding tactile feedback to virtual objects has also been shown to increase presence (Hoffman et al., 2003b), but tactile cues were not used in the present study.

2.2. Experimental thermal pain model

Controlled thermal pain stimulation was applied using a commercially available Peltier thermode (www.medoc.com) designed to provide noxious heat, noxious cold, and non-noxious thermal stimulation over a range of 0–50 °C (Becerra et al., 1999; Coghill et al., 1994; Edwards et al., 2003; Kwan et al., 2000; Talbot et al., 1991). The noxious heat stimulus temperature was individually determined for each subject immediately prior to study, using the psychophysical method of ascending levels as follows. A 30-s heat stimulus (always 44 °C for the first stimulus, which all subjects found tolerable) was delivered through a thermode attached to the dorsal surface of the right foot, and the subject was asked to rate the stimulus using a 0–10 graphic rating scale (see below). With the subject's permission, the temperature for the next stimulus was then increased by 1 °C (e.g. 45 °C) and rated, and this sequence was continued until the subject reported a stimulus that was painful but tolerable. To avoid excessive pain, stimulus increments of less than 1 degree were sometimes administered at the researchers discretion, as subjects approached severe pain. The experimenter's unannounced goal was to achieve either a pain unpleasantness or worst pain rating of 7, but a number of subjects chose to stop before achieving a pain rating of 7, and this was permitted. Individualized stimulus temperatures ranged from 44 to 48 °C (mean of 46.5 °C, and were associated with ratings of 'worst pain' on a 0–10 scale ranging from 2 to 8 (mean of 5.94). The noxious baseline temperature selected (30 s thermal stimulus without distraction) also served as the pain stimulus temperature during the VR intervention phase of the study protocol (30 s of thermal pain during virtual reality).

After each pain stimulus subjects received the following instructions prior to answering six separate queries. 'Please indicate how you felt during the past 30 s pain stimulus by making a mark anywhere on the line. Your response doesn't

have to be a whole number.' In the study, the six separate queries were as follows, with a pictorial example of the labeled graphic rating scale shown for each query. 'Rate your WORST PAIN during the most recent pain stimulus (pain intensity).'



How much TIME did you spend thinking about your pain during this most recent pain stimulus? 0, none of the time; 1–4, some of the time; 5, half of the time; 6–9, most of the time; and 10, all of the time. How UNPLEASANT was the most recent pain stimulus? (a similar 10-cm line with numeric and word descriptors beneath it: 0, not unpleasant at all; 1–4, mildly unpleasant; 5–6, moderately unpleasant; 7–9, severely unpleasant; and 10, excruciatingly unpleasant). How much FUN did you have during the most recent pain stimulus? (10-cm line with numeric and verbal descriptors: 0, no fun at all; 1–4, mildly fun; 5–6, moderately fun; 7–9, pretty fun; 10, extremely fun). To what extent (if at all) did you feel NAUSEA as a result of experiencing the virtual world? (10-cm line with numeric and verbal descriptors: 0, no nausea at all; 1–4, mild nausea; 5–6, moderate nausea; 7–9, severe nausea; and 10, vomit). While experiencing the virtual world, to what extent did you feel like you WENT INSIDE the virtual world? (10-cm line with numeric and verbal descriptors: 0, I did not feel like I went inside at all; 1–4, mild sense of going inside; 5–6, moderate sense of going inside; 7–9, strong sense of going inside; 10, I went completely inside the virtual world).

Such pain rating scales have been shown to be valid through their strong associations with other measures of pain intensity, as well as through their ability to detect treatment effects (Jensen, 2003; Jensen and Karoly, 2001). The specific queries used in the current study were designed to assess the cognitive component of pain (amount of time spent thinking about pain), the affective component of pain (unpleasantness), and the sensory component of pain (worst pain). Affective and sensory pain are two separately measurable and sometimes differentially influenced components of the pain experience (Gamsa, 1994; Gracely et al., 1978). Gracely et al. (1978) have shown ratio scale measures such as the labeled Graphic Rating Scales used in this study to be highly reliable. Slater et al. (1994) introduced a 3-rating VR presence questionnaire. A single rating (to what extent did you feel like you 'went into' the virtual world) was used in the present study. Hendrix and Barfield (1995) showed the reliability of a similar VR presence rating. The measure's ability to detect treatment effects (e.g. Hoffman et al., 2003c) is preliminary evidence of our VR presence measure's validity. Nausea was assessed in an effort to identify the incidence of this component of simulator sickness sometimes associated with VR use (Kennedy et al., 1992).

2.3. Experimental group: High Tech virtual reality

The VR system consisted of a Dell (www.dell.com) 530 workstation with dual 2 GHz CPUs, 2 GB of RAM, an NVIDIA Quadro FX 3000 video card, Windows 2000 operating system, and MultiGen-Paradigm Inc Vega VR software (www.multigen.com). A Polhemus™ Fastrak position tracking system was used to monitor the position of the user's head (www.polhemus.com). When in High Tech VR, subjects followed a pre-determined path, 'gliding' through an icy 3-dimensional virtual canyon (SnowWorld). Subjects aimed with their gaze direction (head orientation) and pushed a keyboard button to shoot virtual snowballs at virtual snowmen, igloos, robots and penguins (see Fig. 1). This High Tech VR condition included head tracking (e.g. subjects saw the sky when they looked up, a canyon wall when they looked to the left, a river when they looked down), sound effects (e.g. a splash when a snowball hit the river), and animated green, blue or white colored explosions. Subjects in the High Tech VR group wore a Kaiser XL-50 (www.keo.com) high resolution helmet which completely blocked subjects' view of the real world.

2.4. Control group: Low Tech virtual reality

The Low Tech VR group flew through a similar SnowWorld environment, but experienced no head tracking, did not shoot snowballs, and heard no sound effects. Non-immersive, see-through, consumer-grade Virtual Vision™ (www.virtualvision.com) glasses provided a smaller field of view and lower image resolution for the Low Tech VR group.

3. Procedures and design

Subjects were randomly assigned via alternating assignment (the order in which they arrived) to either the High Tech VR group ($n = 20$) or the Low Tech VR group ($n = 19$). Subjects were not told that there were two different VR treatment groups and were thus blinded to the high tech vs. low tech treatment. As a result of this blinding procedure, VR presence was manipulated between-groups, without the knowledge of the subjects, so both the High Tech VR and Low Tech VR groups were under similar contextual demand characteristics. In addition, the research assistant administering the pain ratings was also kept blind to experimental condition, and was not in the room during the VR treatment.

The individualized 30-s thermal pain stimulus with no distraction (while not wearing a VR helmet), served as the baseline pain rating. When the baseline pain ratings had been completed, subjects sat quietly for 2 min, and then donned

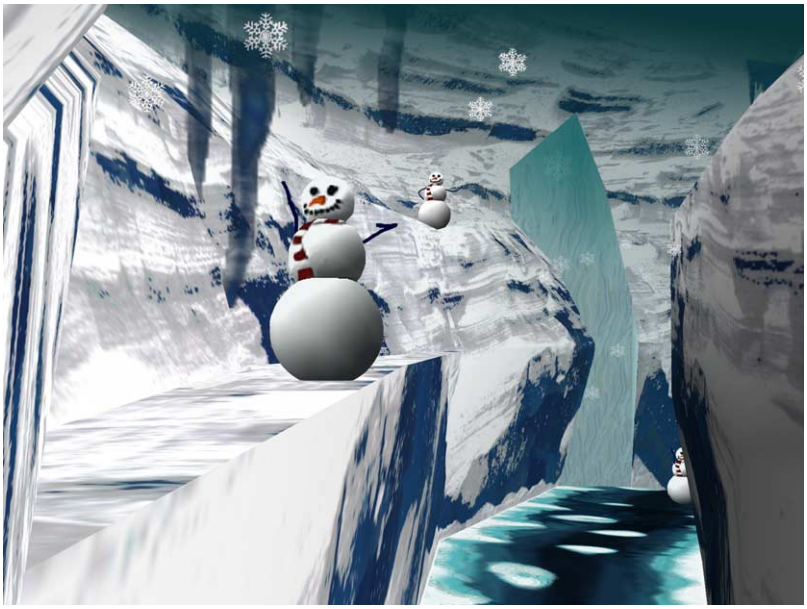


Fig. 1. A snapshot of what subjects see in the 3D virtual world named SnowWorld.

the VR helmet and 'went into' VR for a total of 2 min. This included a 1.5 min acclimatization period in VR, after which subjects received their second 30 s pain stimulus while still in VR. During their second stimulation (VR intervention) they wore the treatment group-appropriate VR helmet. After the VR thermal pain stimulus, a research assistant not involved with the pain stimulation or VR treatment entered the room and administered subjective pain ratings using the series of 10-point graphic rating scales described above.

4. Results

The temperature used during the baseline 'no distraction' stimulus was equivalent for the two groups (mean 46.2 °C for Low Tech VR and 46.7 °C for High Tech VR, $t(37) = 1.41$, $P = 0.17$, NS). The VR analgesia scores (baseline pain minus pain during VR) were calculated for each individual (max possible difference 10) for each of the three pain ratings (i.e. worst pain, pain unpleasantness, and time spent thinking about pain). These VR analgesia scores were analyzed using between-groups analysis, with $\alpha = 0.05$. The amount of pain reduction was influenced by the High Tech VR vs. Low Tech VR manipulation, with significantly greater pain reduction in the High Tech VR group (see Fig. 2 and Table 1).

The pain reported during the baseline 'no distraction' stimulus was equivalent for the two groups (mean baseline 'worst pain' is 5.84 for the Low Tech group and 6.03 for High Tech group), $t(37) < 1$, $P = 0.68$, NS. Between-group ANOVAs of raw scores 'During VR' (ignoring baseline pain ratings) are also shown in Table 1.

Subjects in the High Tech VR group reported a significantly larger increase in 'fun' in VR compared to subjects in the Low Tech VR group (mean 3.90 vs. 2.00, respectively), $F(1, 37) = 5.60$, $P < 0.05$, MSE 34.62. In addition, subjects in the High Tech VR group reported a significantly stronger illusion of 'presence' in VR compared to subjects in the Low Tech VR group (mean 4.2 vs. 2.5, respectively), $F(1, 37) = 7.68$, $P = 0.009$, MSE 28.16, and the mean nausea score was < 1 in each group.

The amount of VR presence reported correlated significantly and positively with the amount of pain reduction in VR for 'Time spent thinking about pain', $r(39) = 0.51$, two-tailed $P = 0.001$, 'Pain unpleasantness', $r(39) = 0.47$, two tailed $P < 0.005$, and 'Worst pain', $r(39) = 0.48$, $P < 0.005$. VR presence also correlated significantly and positively with subjective ratings of 'Fun' $r(39) = 0.56$,

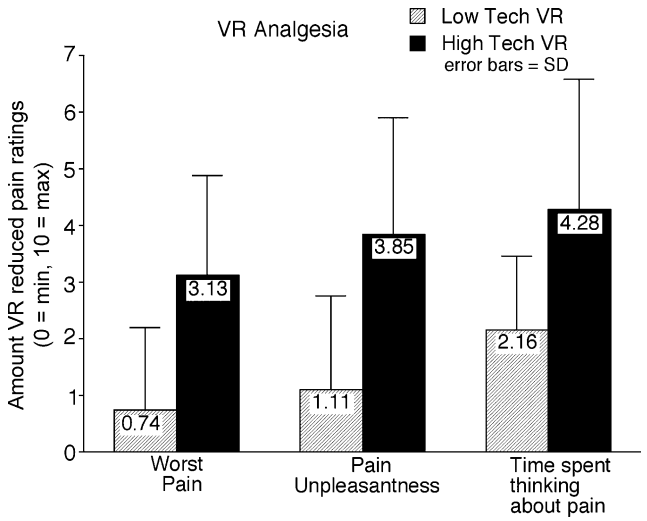


Fig. 2. The amount of VR analgesia in the Low Tech Group vs. the High Tech Group. VR analgesia is defined as the difference between baseline scores and scores during VR. Black bars and striped bars show means with SD shown as error bars.

Table 1
The amount of VR analgesia in the Low Tech Group vs. the High Tech Group

	Low tech group	High tech group
Time spent thinking about pain		
Baseline (B)	6.77 (2.1)	7.18 (1.62), $F(1,37) = 1.63$, $P = 0.50$ NS, MSE = 1.63
During (VR)	4.61 (1.66)	2.90 (1.77), $F(1,37) = 9.61$, $P < 0.005$, MSE = 28.33
B minus VR	2.16 (1.30)	4.28 (2.30), $F(1,37) = 12.30$, $P = 0.001$, MSE = 43.56
Pain unpleasantness		
Baseline (B)	5.53 (1.81)	6.25 (0.93), $F(1,37) = 2.52$, $P = 0.12$ NS, MSE = 5.10
During (VR)	4.42 (1.68)	2.40 (1.88), $F(1,37) = 12.54$, $P < 0.005$, MSE = 39.80
B minus VR	1.11 (1.66)	3.85 (2.05), $F(1,37) = 20.92$, $P < 0.001$, MSE = 73.40
Worst pain		
Baseline (B)	5.84 (1.50)	6.03 (1.27), $F(1,37) < 1$, NS, $P = 0.68$ NS, MSE = 0.33
During (VR)	5.11 (1.49)	2.90 (1.77), $F(1,37) = 17.61$, $P < 0.001$, MSE = 47.39
B minus VR	0.74 (1.45)	3.13 (1.75), $F(1,37) = 21.39$, $P < 0.001$, MSE = 55.57

Values are means for 19 and 20 subjects in the Low Tech Group and High Tech groups, respectively (with SD shown in parentheses). Values for analgesia are calculated as the difference between baseline scores and scores during VR (B minus VR).

$P < 0.001$. Pain reduction scores (pain during baseline minus pain during VR) were used in the correlations, to adjust for individual differences in baseline ratings.

5. Discussion

In the current study, we compared the relative effectiveness of Low Tech VR vs. High Tech VR distraction on pain ratings during brief thermal pain stimuli. Subjects showed the predicted dose–response relationship: higher VR presence and more pain reduction in the High Tech VR group than in the Low Tech VR group, and a significant positive correlation between subjective presence ratings and amount of VR pain reduction. The results of the present study and preliminary clinical results (Hoffman et al., 2000b, 2001a) are consistent with the notion that pain and VR compete for attention. Although the present study does not specifically identify the mechanism of VR analgesia, we speculate that the more attention is directed towards VR, the less attentional resources are available to process incoming nociceptive signals, and the less pain is consciously experienced.

To date, research exploring VR analgesia has used a within-subjects design (Hoffman et al., 2000a,b, 2001a,b, 2004a,b), such as comparing pain during 3 min of physical therapy without VR to pain during 3 min of physical therapy with VR within the same physical therapy session (Hoffman et al., 2000b). Potential nuisance variables such as plasma opioid level or how much sleep the patient had the night prior to the study were all controlled using such a within-subject design. One potential limitation of the within-subjects design is that subjects receive (and are thus aware of) both the experimental and control conditions. In the current study a double-blind, between-groups design was used to help reduce demand characteristics.

Eccelston and Crombez (1999) claim that pain is unusually attention grabbing, making it difficult to distract attention away from pain. Similarly, McCaul and Malott (1984) have proposed that distraction works for mild to moderate pain, but is much less likely to reduce extreme pain. In contrast, preliminary clinical results show that VR is able to distract severe burn patients experiencing extreme pain during wound care (Hoffman et al., 2000a) suggesting that in comparison to VR, pain does not appear to have privileged access to attentional resources. Why VR is able to compete with extreme pain for attentional resources is an important research question. The present results suggest that the illusion of going into the virtual environment may help explain why VR is so effective for reducing various components of the pain experience.

In a previous VR study not involving pain, Hoffman et al. (2003a) tested the fundamental assumption that VR requires conscious attention. Healthy volunteers monitored a string of numbers from a tape recorder for three odd numbers in a row while in VR (helmet worn and turned on) and without VR (helmet worn but turned off). Participants showed a significant reduction in performance on a divided attention task (accuracy in identifying the consecutive odd numbers) while in VR (74% correct) compared to the control condition (95% correct), and they also estimated that the amount of time they were able to attend to the task of monitoring the numbers was significantly higher with no VR than with VR (96 vs. 65%, respectively).

In the present study, compared to the Low Tech VR group, subjects in the High Tech VR group reported a significant increase in how much fun they had during VR. Pain reduction in VR was correlated with how much fun subjects reported having, and is consistent with severe burn patients who report having fun during wound care and physical therapy in High Tech VR (e.g. Hoffman et al., 2004a). In the present study, increasing the 'immersiveness' of the VR hardware also led to higher VR presence ratings and was correlated with pain reduction. Studies exploring medical applications of VR exposure therapy for treating anxiety disorders have also described manipulations of the immersiveness of the VR hardware that increased the illusion of presence and increased treatment effectiveness/clinical outcome (Hoffman et al., 2003b). We predict that further increasing the immersiveness of VR systems in future studies will further increase the participant's illusion of presence in VR, and may increase the magnitude of VR analgesia. Future laboratory and clinical studies should

systematically explore (1) the addition of converging sensory input from visual, sound, tactile, smell and vibrotactile (e.g. surround sound) stimulation, (2) increased interactivity between the participants and the virtual world, and (3) which components of the VR environment (including both hardware and software, and individual differences) contribute to the sense of presence and analgesia. Some manipulations that increase presence may also increase simulator sickness (e.g. going faster through the virtual canyon). Care should be taken to minimize simulator sickness in these more immersive VR systems, especially when used adjunctively in clinical studies in patients at risk for nausea from pharmacologic (opioid) analgesics.

A limitation of the present study is that we employed a single subjective rating of presence. We opted to use this measure to be consistent with parallel functional brain imaging and clinical studies (Hoffman et al., 2003c, 2004a,b), where it is important to minimize research intrusiveness, e.g. during fMRI brain scans or complex wound care procedures. In contrast to our short, direct questionnaire approach, Witmer and Singer (1998) proposed a multi-item questionnaire to measure presence. However, we deemed Witmer and Singer's 16-question rating tool both too long and too difficult to comprehend for clinical use in our typical clinical population. Furthermore, the validity of the Witmer and Singer Questionnaire has been questioned (Slater, 1999), and none of their 16 questions directly asks what we wanted to measure, namely how much subjects 'went into' the virtual world.

A second weakness of the current study is that VR exposure time (2 min) and pain stimulation duration (30 s) were brief. However, in preliminary clinical studies, VR therapy for procedural pain has been extended for durations of 3–15 min (Hoffman et al., 2001a). Larger clinical studies are needed to determine for how long VR reduces pain, and to help determine which patients are most likely to experience VR analgesia.

Another possible weakness of the present study is that we did not include a 'no distraction' control group who received No VR during baseline, and No VR again during treatment, to assess for potential habituation to pain stimulation. However, the Low Tech VR group showed very little drop in pain ratings on their 30-s thermal stimulus during VR. This suggests that there would also be minimal habituation to thermal pain stimulation for a No VR + No VR control group. Additionally, a pilot study of serial pain stimulation without VR (Hoffman et al., in press) found no evidence of habituation to thermal pain. Subjects received a 30-s thermal pain stimulus (followed by pain ratings) every 5 min over a 26 min period (approximately the same inter-stimulus interval used in the present study). Serial pain ratings remained unchanged, and in addition, each participant showed the same consistent pain ratings (no habituation) for five additional 26-min treatment sessions spanning several visits. In another recent study (Hoffman et al., 2004b) subjects received a thermal pain stimulus every 30 s for approximately 6 min during an fMRI brain scan. Pain-related brain activity in the regions of interest (the emotional division of the anterior cingulate cortex, the primary and secondary somatosensory cortex, the insula and thalamus) showed no evidence of habituation to thermal pain stimuli, using the objective measure of pain-related brain activity as the dependent variable.

VR is a promising non-pharmacologic analgesic, especially for patients who must undergo brief painful procedures. Results from the current study suggest design guidelines for VR analgesia systems. Specifically, highly immersive combinations of VR hardware and software that maximize the user's illusion of presence in the VR environment will likely enhance the effectiveness of virtual reality as a non-pharmacologic analgesic. Selecting participants who have a pre-disposition to feel high presence in VR may also be possible in some applications. Furthermore, we speculate that patients may respond better to some virtual worlds than others. Since excessive procedural pain is a widespread problem for the medical community, and these preliminary results provide additional support for the notion that VR might prove valuable for pain control, additional research on this topic is warranted.

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