Circumplex Model of Affect: A Measure of Pleasure and Arousal During Virtual Reality Distraction Analgesia

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Abstract

Objective: Immersive virtual reality (VR) distraction provides clinically effective pain relief and increases subjective reports of “fun” in medical settings of procedural pain. The goal of this study was to better describe the variable of “fun” associated with VR distraction analgesia using the circumplex model (pleasure/arousal) of affect.

Materials and Methods: Seventy-four healthy volunteers (mean age, 29 years; 37 females) received a standardized, 18-minute, multimodal pain sequence (alternating thermal heat and electrical stimulation to distal extremities) while receiving immersive, interactive VR distraction. Subjects rated both their subjective pain intensity and fun using 0–10 Graphic Rating Scales, as well as the pleasantness of their emotional valence and their state of arousal on 9-point scales.

Results: Compared with pain stimulation in the control (baseline, no VR) condition, immersive VR distraction significantly reduced subjective pain intensity ($P < 0.001$). During VR distraction, compared with those reporting negative affect, subjects reporting positive affect did so more frequently (41 percent versus 9 percent), as well as reporting both greater pain reduction (22 percent versus 1 percent) and fun scores (7.0 ± 1.9 versus 2.4 ± 1.4). Several factors—lower anxiety, greater fun, greater presence in the VR environment, and positive emotional valence—were associated with subjective analgesia during VR distraction.

Conclusions: Immersive VR distraction reduces subjective pain intensity induced by multimodal experimental nociception. Subjects who report less anxiety, more fun, more VR presence, and more positive emotional valence during VR distraction are more likely to report subjective pain reduction. These findings indicate VR distraction analgesia may be mediated through anxiolytic, attentional, and/or affective mechanisms.

Introduction

THE PAIN EXPERIENCE IS A COMPLEX and highly subjective phenomenon that is not solely the function of the intensity of a noxious stimulus (i.e., nociception). Rather, pain is influenced by numerous psychological and physiological factors, including cognitive (e.g., previous pain experiences, current context) and emotional (e.g., anxiety, stress, fear) factors. Affect is one such emotional factor. As reviewed elsewhere,¹ negative affect has been described as both a consequence of pain and a key moderator that can worsen the pain experience. Recent evidence from functional neuroimaging studies has shown that negative affect increases both pain perception and pain-related brain activity, particularly in circuits involving the anterior cingulate cortex.^{2,3}

Immersive virtual reality (VR) distraction is a health game technique first described in 2000⁴ for use in acute pain settings, particularly those associated with painful medical procedures in burn care, cancer care, and routine care (e.g., intravenous catheter placement in children). In the last 15 years, over 40 published reports and reviews have described the clinical effectiveness and possible neural mechanisms of VR distraction analgesia. As described in recent reviews,^{5–7} patients typically report 20–50 percent reductions in subjective pain when VR distraction is used as an adjunct to standard clinical analgesia therapy. Of interest is that patients using immersive VR also report significant increases in the subjective variable of “fun” during these painful procedures. For example, in one report of 88 patients undergoing painful post-burn physical therapy, their mean subjective report of fun (on

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a 0–100 scale) increased from only 19 in the standard analgesia condition to 74 in the adjunctive VR distraction condition.⁸

The enhancement of fun during immersive VR distraction has potential clinical benefit in the setting of procedure pain. Specifically, when patients experience more fun, painful procedures are likely more tolerable or even enjoyable, which may increase patients' compliance and participation with future, similar procedures. However, the precise neural mechanism(s) of pain relief during VR distraction are unclear. One hypothesis is that attentional modulation of ascending nociception—by placing attentional demands on users in the interactive and immersive VR environment^{9–11}—results in a reduced pain experience through inhibitory cortical and subcortical pathways.¹² However, given the bidirectional relationship between pain and affect (i.e., emotional state),^{1–3} it is also possible that the analgesic effects of VR distraction may be mediated through central mechanisms involving affect. Because “fun” is a potential surrogate label for “positive affect,” providing a VR experience that maximally enhances the patient's positive affect could increase the analgesic potency of VR distraction.

To explore this latter mechanism of VR distraction analgesia in the pain laboratory requires a valid and reliable measure of affect and its critical domains. Initially described in 1980,¹³ the circumplex model of affect proposes that all affective states arise from cognitive interpretations of sensations that are the product of two independent neurophysiological systems—one related to valence (a pleasure–displeasure continuum) and the other to arousal (alertness).¹⁴ The goal of the current exploratory study was to more comprehensively describe the positive affect associated with immersive VR distraction analgesia in the pain laboratory using this two-dimensional circumplex model of affect, as a precursor to using the model in studies exploring the mechanisms of VR analgesia.

Materials and Methods

Healthy adult volunteers 18–60 years of age participated using a recruitment and study protocol approved by the University of Washington Human Subjects Division, as well as in accordance with the Helsinki Declaration of 1975, as revised in 2008. Subjects were recruited from the University of Washington and surrounding community by electronic and paper notices describing the research. Volunteers were screened by telephone script to ensure that they were in good health and met all inclusion (healthy subjects of all ethnic and racial origins, ability to communicate verbally in English) and exclusion (inability to communicate verbally, conditions associated with acute pain, chronic pain, current significant medical illness, history of substance abuse, current opioid medication use, severe predisposition to motion sickness, unusual sensitivity or lack of sensitivity to pain) criteria.

At the beginning of the study day each volunteer completed a screening questionnaire and interview to confirm eligibility. Thermal pain stimulation was applied using a Medoc (Ramat Yishai, Israel) TSA-2001 thermode, a computerized, thermal sensory testing device designed for quantitative assessment of small nerve fiber function. Subjects sat upright in a chair, and the thermode was placed on the dorsal surface of their right foot. A noxious thermal stimulation temperature was

individually determined for each subject using the psychometrically based “method of ascending levels.”¹⁵ In brief, a 30-second thermal stimulation was initially applied at 44°C. After this first stimulus, and with the subject's permission, additional 30-second stimulations were applied at temperatures that were increased by 0.5–1°C increments to a maximum temperature of 49°C. Subjects were instructed to select the highest temperature that was “painful, but tolerable.” The final stimulus temperature selected for the 30-second baseline thermal pain condition then served as the thermal pain stimulus temperature during the subsequent VR intervention phase of the study protocol.

Electrical pain stimulation was applied using a Grass 548 electrical stimulator (Natus Neurology Inc., Middleton, WI) with an electrode placed on the left ring fingertip. Similar to the thermal stimulator, an individualized “painful, but tolerable” noxious electrical stimulation current was determined for each subject using ascending levels of intensity (current). The final stimulus current selected for the 30-second baseline electrical pain condition then served as the electrical pain stimulus temperature during the subsequent VR intervention phase of the study protocol.

Separate baseline pain scores were collected after the final, 30-second stimulation intensity for both thermal and electrical pain. Immediately following baseline pain scoring, subjects looked into a pair of VR goggles (see below) and acclimated to immersive VR distraction for 2 minutes in the absence of pain stimulation. The VR system consisted of an XPS desktop computer (Dell, Round Rock TX) with an I7-2600 CPU, 3.4 GHz, 3.4 GHz, and 8 GB RAM.

In the virtual world (“SnowWorld” [www.vrpain.com]), subjects followed a predetermined glide path through a virtually depicted, arctic, three-dimensional canyon filled with objects that could be targeted with snowballs by pressing a peripheral mouse trigger with their right hand. Participants controlled their view within the virtual world by a peripheral mouse, seeing the sky when they looked up, canyon walls populated with animated virtual snowmen, igloos, and penguins when they turned to the left or right, and a flowing river filled with flying fish when they looked down. The customized NVIS MX90 VR goggles (NVIS Incorporated, Reston, VA) were suspended near the subject's eyes using an articulated arm goggle holder that blocked the user's view of the real world environment. The display afforded an approximately 90° diagonal field of view, with binocular resolution of 1280×1024 pixels per eye. Stereophonic sound was delivered through Bose® (Framingham, MA) QuietComfort® headphones and consisted of pleasant background music and sound effects synchronized with the virtual environment.

Following the 2-minute, pain-free VR acclimation, subjects received a standardized 18-minute pain sequence consisting of three identical, repeated cycles of alternating thermal pain (30 seconds), rest (30 seconds), electrical pain (24 pulses in 2 minutes), and rest (2 minutes). The same subject-specific stimulus intensities determined during the baseline pain conditions were used; however, the stimulation timing in the two treatment conditions differed—the baseline pain stimulation consisted of 30 seconds of thermal pain and 30 seconds of electrical pain, whereas the VR pain stimulation consisted of the 18-minute alternating sequence of thermal and electrical pain described above.

After the 18-minute pain sequence concluded, subjects immediately completed marked self-reports of subjective pain, fun, valence, arousal, anxiety, and presence in the VR environment. The sensory component of the pain experience (“worst pain intensity”) was assessed by separate 0–10 Graphic Rating Scales (GRSs) for both thermal and electrical pain. The 0–10 GRS assessing pain intensity asked subjects to rate the severity of their pain with 0 representing “no pain” and 10 representing “pain as intense as I can imagine.” The reliability and validity of the GRS have been shown in a variety of adult pain populations.¹⁶ Similar GRS ratings were also collected to assess the subjects’ subjective levels of anxiety, fun, and psychological experience of “presence” in the virtual environment (i.e., to what degree the subject felt “inside” the virtual world).^{17,18} Affective valence and arousal were assessed using two separate 9-point scales ranging in integers from –4 to +4. Anchors for the valence scale were “extremely unpleasant feelings” (–4) and “extremely pleasant feelings” (+4), and those for the arousal scale were “extreme sleepiness” (–4) and “extreme high energy” (+4). The two-dimensional circumplex model of affect that corresponds to these two scales has been correlated with psychometric studies of emotions, physiologic correlates of emotions, and functional neuroimaging signal intensity associated with emotional stimulation^{14,19–21} (Fig. 1).

Summary statistics (mean and standard deviation) were computed for all variables, and paired *t* tests were used to assess differences in subjective pain reports between the baseline (no VR) and immersive VR distraction conditions. Bivariate Pearson correlation coefficients were then computed between the post-session reports of anxiety, fun, presence, affective valence, and arousal subjects experienced during VR, as well as the differences between baseline and VR-associated ratings of both thermal and electrical pain (i.e., VR-related pain reduction). Finally, we also examined

FIG. 1. The circumplex model of affect seeks to quantify affect based on self-report (on separate 9-point scales) of the interpretation of cognitive sensations arising from two neurophysiologic dimensions: valence (pleasant feelings) and arousal (alertness). General emotions are associated with each of the four quadrants: happiness (positive affect), contentedness, sadness (negative affect), and anxiety.

differences in the measures of anxiety, fun, presence, affective valence, and arousal as a function of gender and age (using correlational analyses). Statistical significance was set at $P < 0.05$ (two-tailed).

Results

In total, 74 healthy volunteers 18–60 years of age (mean age, 29 ± 12 years), equally divided between males and females, were studied. Mean thermal stimulation temperature was $45.3 \pm 0.7^\circ\text{C}$ (range, 44.0 – 46.5°C), and mean electrical stimulation current was 3.9 ± 1.8 mA (range, 1.9 – 9.3 mA). Acknowledging the somewhat different pain stimulation sequences in the two treatment conditions, immersive VR distraction resulted in significant reductions in subjective pain intensity for both thermal pain and electrical pain compared with the baseline (no VR) pain stimulation condition (Table 1). The distribution of valence and arousal scores during pain stimulation in the immersive VR distraction condition demonstrated that the majority (41 percent) of subjects fell clearly into the upper-right quadrant (positive valence and positive arousal), corresponding to positive affect, whereas 9 percent fell clearly into the lower-left quadrant (negative valence and negative arousal), corresponding to negative affect (Fig. 2). Comparative results for ratings of subjective pain, fun, anxiety and presence in the virtual environment between subjects with positive and negative affect are shown in Table 2. The remaining 50 percent of subjects demonstrated neutral affect—their ratings for these outcomes were not significantly different from those with negative affect.

Table 3 presents the results of the analyses correlating the ratings of anxiety, fun, presence, affective valence, and arousal experienced during VR, with VR-related reductions in thermal and electrical pain. With the exception of arousal, all of these subjective ratings were significantly associated with VR-related reductions in thermal pain. Several factors—lower anxiety and greater fun, greater presence in the VR environment, and positive emotional valence—were associated with subjective analgesia during VR distraction. A similar pattern was found for reductions in electrical pain, although the associations only reached statistical significance for anxiety. Finally, there were no significant associations between either age or gender and the post-VR subjective ratings.

Discussion

The goal of this preliminary study was to better understand the circumplex factors of valence (unpleasant–pleasant) and activation (sleepy–high energy) as components of subjects’ affective state during immersive VR distraction analgesia in the pain laboratory, as a precursor to using the model in future mechanistic studies of VR analgesia. Four key findings emerged from these analyses. First, consistent with

TABLE 1. SUBJECTIVE PAIN INTENSITY SCORES FOR THE ENTIRE STUDY POPULATION ($N = 74$)

Pain	Baseline (no VR)	Immersive VR distraction	P value
Thermal	6.2 ± 1.3	5.3 ± 1.8	< 0.001
Electrical	6.0 ± 1.2	5.1 ± 1.6	< 0.001

VR, virtual reality.

FIG. 2. The distribution of valence and arousal scores is shown for all study subjects ($n=74$). The number of subjects reporting each valence/arousal dyad is given in parentheses. Subjects falling clearly into each quadrant total 30 (41 percent) in the upper-right, 5 (7 percent) in the lower-right, 7 (9 percent) in the lower-left, and 6 (8 percent) in the upper-left. The remaining 26 (35 percent) are indeterminate.

previous reports, we observed significant reductions in subjective pain reports with immersive VR distraction in subjects experiencing multimodal nociception (i.e., alternating and repeated thermal and electrical stimulation). Second, as a result of the immersive VR distraction condition, the overwhelming majority of subjects experiencing multimodal pain reported emotional valence and arousal scores consistent

with positive affect, in the two-dimensional circumplex model. Third, compared with subjects with negative affect scores, those endorsing positive affect during immersive VR reported significantly less pain and greater subjective reports of “fun” during a nociceptive stimulation paradigm that was designed to be neither comfortable nor enjoyable. Fourth, correlation analyses demonstrated that several factors—reduced anxiety, increased fun, increased presence in the VR environment, and positive affective valence—were associated with subjective analgesia during VR distraction.

VR distraction analgesia has previously been associated with significantly increased subjective reports of fun, both in clinical pain settings^{4,8,22–28} and in the pain laboratory.^{15,29–31} In these reports, subjective ratings of fun have been consistently associated with analgesic effectiveness of immersive VR distraction. In some cases, the increase in fun scores with

TABLE 2. SUBJECTIVE OUTCOMES AS A FUNCTION OF CIRCUMPLEX AFFECT MODEL CATEGORY

Variable	Positive affect ($n=30$)	Negative affect ($n=7$)	P value
Independent			
Stimulation temperature	45.3 ± 0.7	45.2 ± 0.6	0.66
Stimulation current	3.7 ± 1.4	3.9 ± 1.5	0.68
Outcome			
Analgesia score ^a			
Thermal	1.2 ± 1.5	-0.3 ± 1.5	0.03
Electrical	1.5 ± 1.5	0.4 ± 0.8	0.09
Fun	7.0 ± 1.9	2.4 ± 1.4	<0.01
Anxiety	2.1 ± 1.5	5.3 ± 1.6	<0.01
Presence	6.9 ± 1.8	4.4 ± 2.3	<0.01

The analgesia score is the arithmetic difference between the Graphic Rating Scale pain intensity scores during pain stimulation in the baseline (no virtual reality) and immersive virtual reality distraction conditions. A positive analgesic score indicates pain relief with virtual reality distraction, whereas a negative analgesic score indicates worse pain with virtual reality distraction.

TABLE 3. PEARSON CORRELATION COEFFICIENTS BETWEEN SUBJECTIVE RATINGS AND VIRTUAL REALITY-RELATED CHANGES IN THERMAL AND ELECTRICAL PAIN ($N=74$)

Variable	VR-related change in	
	Thermal pain	Electrical pain
Anxiety	-0.28^a	-0.35^b
Fun	0.33^a	0.09
Presence	0.24^a	0.14
Affective valence	0.34^b	0.19
Arousal	0.01	0.08

Significant difference: ^a $P < 0.05$, ^b $P < 0.01$.

VR distraction is dramatic—for example, in a clinical study of 12 U.S. soldiers requiring aggressive, daily burn debridement for combat-related injuries, mean fun scores during these extremely painful procedures were very low (0.2 on the 0–10 scale) in the absence of VR distraction but were significantly higher (7.5 on the 0–10 scale) in the presence of VR distraction.²⁷

Creating a more enjoyable experience in the clinical care setting can increase patient satisfaction with care.³² This is particularly true during painful procedures that patients must undergo repetitively because reluctance to participate fully in such repeated therapeutic procedures may also negatively impact clinical care outcomes. For example, daily physical or rehabilitation therapy can improve long-term functional outcomes (e.g., extremity range of motion); however, low participation in such therapy due to fear of pain, lack of enjoyment, or inability to rationalize short-term discomfort for long-term benefit may reduce the likelihood of a successful long-term outcome. Likely because of its enjoyable nature, immersive VR distraction has been reported to enhance patients' willingness and motivation to participate in such painful therapies. For example, in one study that demonstrated analgesic benefit of VR distraction for painful burn wound care, one parent commented on the son's willingness to participate in wound care saying, "Yesterday he was whining thinking about the dressing change; this morning, when I told him that you were coming [with VR] he had a grin on his face."³³ Similarly, in a case report of a teenager undergoing twice-daily painful physical therapy following multilevel spine surgery for cerebral palsy, the parent noted the child would "participate more with the treatment when the VR was on," with the therapist also noting that the child participated more effectively when using VR.³⁴

In order to better design medical therapies—including VR distraction systems and other health games—that increase patient enjoyment and clinical outcomes in the medical care setting, a more comprehensive and objective assessment of positive affect is needed, to complement the subjective reports of fun. With respect to applications of VR technologies to pain control, such a tool would allow better understanding of patient affective responses to immersive VR distraction, both as a potential mediator and as an outcome variable. The circumplex model of affect is a promising model for understanding the emotional response to VR distraction for two reasons. First, measures of the circumplex domains have been used to understand emotions, physiologic correlates of emotions, and functional neuroimaging signal intensity associated with emotional stimulation in several studies.^{14,19–21} Second, the two-domain circumplex measure used in this study is easy to administer in both clinical and nonclinical environments, requiring subject self-assessment of only two cognitive interpretations of current sensations—one related to valence (a pleasure–displeasure continuum) and the other to arousal, or alertness—each on simple 9-point integer scales.¹⁴

Although powered with sufficient sample size to provide reasonable statistical evidence for our conclusions, the current exploratory study has several limitations. First, because the pain stimulation differed in timing (but not intensity) between the baseline and VR treatment conditions, the primary study outcomes—valence and arousal scores—were only assessed during the VR intervention. This stimulation difference also prevented a detailed analysis of potential analgesia-modifying

variables, such as age or gender. In future studies, identical pain paradigms will allow assessment of all outcome variables in all treatment conditions. Second, VR distraction was always the second treatment condition in this pilot study. In future studies, treatment conditions will be randomized and counterbalanced to prevent order effect bias, such as acclimation to the pain stimuli. Third, future studies should include additional pain outcome assessments, such as those for the cognitive ("time spent thinking about pain") and emotional ("pain unpleasantness") components of the pain experience, to complement the sensory component assessed in this study. Additional variables that could also be collected include those that may moderate outcomes (e.g., baseline anxiety) or serve as alternative outcomes (e.g., heart rate), in order to develop a more comprehensive multivariate model. Lastly, control groups should be designed to better account for demand characteristics, particularly the contextual demand that novel conditions or treatments are enjoyable.

In conclusion, in a laboratory pain protocol using multimodal nociception in healthy volunteers, subjects with positive affective states during combined pain and immersive VR exposure reported the highest subjective reports of both pain relief and fun. Furthermore, several factors—lower anxiety and greater fun, greater presence in the VR environment, and positive emotional valence—were associated with subjective analgesia during VR distraction, which suggests that the analgesic mechanism of VR distraction may be multifactorial. These findings indicate that the circumplex model of affect could be very useful to better understand the impact of VR analgesia therapy on emotions and affective outcomes.

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