Topical Review

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Virtual reality approaches to pain: toward a state of the science

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Virtual reality (VR) applications have emerged as nonpharmacological alternatives or adjuncts for acute and chronic pain management, with the potential to reduce the need for opioid medications. Keefe et al summarized existing applications of pain-targeted VR[56] and pointed to a future where this technology could exert a positive disruptive influence on the field. Because of the fast pace of development in this area, we aim to update the 2012 review with a critical assessment of the current state of VR applications to pain. This brief review will begin by defining VR and summarizing evidence for its utility in addressing acute and chronic pain. We will then describe pressing scientific gaps and promising future directions. The current review is designed to provide a broad overview and theoretical synthesis of the field today rather than a systematic review or meta-analysis. Table S1 (available as supplemental digital content at http://links.lww.com/PAIN/B180) summarizes the literature that was identified for this review based on searches of MEDLINE (through PubMed) and Google Scholar with primary search terms of "virtual reality AND pain" and "virtual reality AND pain AND therapy" and "virtual reality AND pain management." The resultant literature included systematic reviews, narrative reviews, meta-analyses, and empirical articles. Where available, Table S1 also provides ratings of methodological rigor for individual studies based on previous systematic reviews (available as supplemental digital content at http://links.lww.com/PAIN/B180).

1. The evolving definition of virtual reality

The definition of VR has evolved alongside advancements in technical capabilities from an early stage of large projection rooms to current consumer products that use high-resolution head-mounted displays (HMDs). At its core, VR refers to simulated experiences intentionally presented to the individual's senses.[62] Virtual reality paradigms that have been used to date can be distinguished along 3 central and highly interrelated dimensions that have been dubbed the "pillars of VR": *presence*, *immersion*, and *interactivity*.[74] *Presence* refers to the "subjective experience of being in one place or environment, even when one is physically situated in another."[101] *Immersion* can refer both to the subjective user assessment (ie, a sense of being "caught up and absorbed" in the virtual world) and to the VR system configuration (eg, a 3-dimensional 360-degree virtual environment presented through HMD vs a 2-dimensional presentation on a computer screen).[52,70] Finally, *interactivity* refers to the degree to which users can influence the virtual environment,[14, 52] as facilitated by the technical configuration. The objective vs subjective nature and hierarchical organization of these mutually informative constructs continue to be discussed within VR technology research[74] and provide initial guidance in interpreting findings in the context of pain. Indeed, the definition of VR is likely to evolve as technical progress continues to offer additional perceptual experiences (eg, see "Embodiment" as User Experiential Factor below). Studies/VR interventions cited in Table S1 (available as supplemental digital content at http://links.lww.com/PAIN/B180) are categorized with respect to inclusion of the above factors, further discussed below.

2. Application of virtual reality to pain: current state of the evidence

The past 8 years have seen substantial growth in the application of virtual technologies to pain experience, with the largest expansion seen in applications for chronic pain[49,55,64] (**Fig. 1**). The current review distinguishes 3 categories of VR protocols, based on their application to acute clinical pain, acute experimental pain, and chronic clinical pain. Clinical applications of VR to acute and chronic pain are now fairly equally represented in the literature, which represents progress relative to the asymmetry observed in the 2012 review.[56] This asymmetry reflected a major growing literature on acute clinical or experimental pain; the few studies focused on chronic pain were encouraged by Keefe et al as a promising direction for future research. Since that time, there has been a large expansion of research exploring the use of VR technology to help patients with chronic/persistent pain. However, given that experimental VR studies have almost exclusively involved acute pain stimuli, there is still a considerable imbalance in terms of what we understand about chronic relative to acute VR pain intervention. Finally, it is worth reiterating that the growing clinical VR literature has not always reflected methodologically rigorous research designs, ultimately limiting our understanding of the efficacy of VR. Readers are encouraged to refer to Table S1 (available as supplemental digital content at http://links.lww.com/PAIN/B180), which identifies methodologically rigorous studies within each pain domain.

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Figure 1. Relative distribution of acute, chronic, and experimental pain studies within the current VR pain literature. "Other" refers to conditions where a single study was available. Within the chronic pain category, these include VR applications to sickle cell, pruritus, and unspecified neuropathic pain. Within the acute pain category, these include applications to chemotherapy, catheterization, biopsy, and maternal labor. CRPS, complex regional pain syndrome; VR, virtual reality.

2.1. Acute clinical pain

Since the inception of VR pain research, areas that remain well represented in this domain include burn and wound care,[63,87] needles/cannulation,[8,17,19,76] dental procedures,[4,6,31,47,93,99] and perisurgical pain and affect management.[15,20,24,26,72] The majority of these studies use immersive and interactive (but, as noted below, not embodied) platforms and successfully reduce pain and psychological distress surrounding medical procedures.[18,29,37,51] This literature also provides substantial support for the use of VR to reduce pain and suffering in pediatric populations.[27] Increasingly, VR paradigms are being adapted to novel targets, such as labor/delivery[30] and emergency department care.[5] There is also early interest in examining the cost-efficacy of larger-scale VR implementation.[23]

Although most studies find support for VR as a tool for acute pain management, systematic reviews are more cautious. A 2018 meta-analysis of 16 clinical trials found that the positive effects of VR in acute clinical pain are largely driven by burn-related physical therapy and needle procedures.[18] As a result, reviews generally suggest that the field shows early promise but calls for better, more consistent, high-quality (eg, randomized clinical trial [RCT]) methodology and more studies addressing different target domains and patient populations.

2.2. Experimental pain studies: mediators and moderators of virtual reality effects

Whereas clinical studies support the benefits of VR as a strategy to reduce acute pain, experimental studies have examined potential mediators and moderators of VR effectiveness. Unlike clinical studies, experimental studies of pain and VR draw exclusively on healthy participant samples and use pain induction procedures that allow greater experimental control. The majority of the experimental literature has been conducted with adult participants.

Given their focus on acute pain, experimental studies have primarily explicated factors underpinning *distraction*—the mechanism presumed to drive the effectiveness of acute VR intervention. Distraction is defined by the engagement of cognitive and attentional resources by VR stimuli, with hypoalgesic effects being driven by active competition for resources that are necessary for pain processing.[51] Positive affective states facilitated by VR are likewise expected to reduce pain and reinforce distraction effects.[88] To date, experimental studies have provided consistent support for VR as a form of distraction and affect modulation,[51,65] as well as a reliable method of promoting the dimensions of *presence* and *interactivity*, which correlate inversely with experimental pain.[42,43,48,80,98] There is also some support for the positive role of immersiveness as provided by a 360-degree visual environment[12,36,41,104] and auditory cues.[54,59,106] Studies looking into the salience of perspective (eg, first vs third person point of view) and virtual context (eg, "hot" or "cold" environments) have emerged with mixed results.[32,33,44,58,73,91]

Recent advancements in hand, eye, and skeletal tracking have provided new opportunities for high-integrity representation and tracking of a user's body (their avatar) in the virtual environment.[57,69] A subgroup of experimental pain/VR studies has attended to the *embodiment* effects afforded by these advancements. Embodiment refers to the "sense of having one's body"[57] and reflects the integration of multiple sensory signals (eg, visual, tactile, and kinesthetic), which in turn can be manipulated by VR. Studies of virtual embodiment have relied primarily on the colocation of the real and avatar body in space[81] and suggest that changing an appearance of an embodied body part can alter pain experience.[66–68,75,82,102] Consistent with physiologically mediated effects, threat to an embodied body part elicits autonomic and motor cortex activation.[40]

2.3. Chronic pain studies

Virtual embodiment capabilities are central to more than half of existing chronic pain studies but are largely absent in the acute clinical pain literature. In the chronic pain literature, the most consistent example of the successful application of VR embodiment is observed in studies of phantom limb pain, where intervention is designed to facilitate control over a virtual limb.[25, 45] Similar control over virtual limbs has been used to reduce neuropathic pain among individuals with spinal cord injury (eg, virtual walking).[10] In addition to phantom pain, VR has been applied to a growing number of chronic pain disorders including chronic low back pain,[2,22,28,77,78,97] neck pain,[50,84,85] fibromyalgia,[13,34,46,71] and complex regional pain syndrome.[53,86,92] Less well represented are applications to cancer pain,[9,11,38] sickle cell pain,[1] headache,[89,95] and arthritis.[3,61]

Although most VR interventions involve an attentional component, the majority of chronic pain studies do not identify distraction as a primary target. Interventions can be distinguished between those that use VR as an adjunct to deliver psychological coping skills (eg, cognitive behavioral therapy),[21,37,60,90] improve mood,[46,80,94] or promote specific behavioral activities or movement strategies, such as increased lumbar flexion among back pain sufferers with fear of movement.[16,28,97,105] Changes in these targets are expected to facilitate reduction in pain and interference. It is notable that outside the embodiment illusions generated by phantom limb and spinal cord injury interventions, a number of studies have used VR capabilities to manipulate elements of the avatar or virtual environment, thereby facilitating effects in the real world. For instance, Powell et al used altered auditory cadence and visual flow to exhort patients with musculoskeletal pain to walk faster/slower.[79]

Alongside promising findings, as in the case of clinical acute pain research, reviews caution extrapolating efficacy as most studies to date do not meet criteria for "high-quality evidence" or RCT status. For instance, since 2006, there has been only 1 published RCT of augmented reality targeting phantom limb pain,[7,83] and no high-quality RCTs for spinal cord injury–related pain have yet been identified by the review literature (note that some of the newer RCTs listed in Table S1 [available as supplemental digital content at http://links.lww.com/PAIN/B180] may not have yet been included in systematic reviews or meta-analyses).

3. Challenges and future directions

Despite substantial progress in VR and pain research in the past decade, especially in the area of chronic pain, on the whole the literature lacks sufficient well-powered or methodologically rigorous (eg, RCT) designs, and it is difficult to compare disparate technologies across studies.[35,64,103] Outside distraction effects on acute clinical and experimental pain, the growing VR (both acute and chronic pain) literature *has not been accompanied by substantial advancement in understanding of how VR exerts its impact on pain experience*. Such criticisms derive in part from the nature and relative youth of the field itself, which presents theoretical and practical challenges. For instance, despite reduced hardware costs, many studies cannot afford iterative VR development, thus naturally constraining study design. Furthermore, hardware and software capabilities evolve more rapidly than intervention testing, challenging methodological consistency and replication. Methodological rigor is further challenged by the lack of agreement regarding essential VR concepts/mechanisms of interest or associated process and outcome measures derived from those constructs; these would in turn inform best practices for VR pain research, which have not yet been established.

3.1. A heuristic model for virtual reality pain research

Today, there is a pressing need for a solid theoretical framework to scaffold VR pain research and implementation. Rather than focusing on idiosyncratic technologies, identifying and examining key factors involved in VR pain applications can facilitate communication across studies and prospectively inform purposeful (theoretically driven) design. To that end, this review offers a heuristic model as a preliminary framework to help move the field forward. As shown in **Figure 2**, VR pain applications can be examined from the perspective of distinct VR Configuration Factors, User Experiential Factors, and Pain Targets and Outcomes. *VR Configuration Factors*, described in detail elsewhere,[14] consist of VR input devices that gather real-time information about the user's explicit (eg, controller location/orientation) and implicit engagement (eg, head location/orientation). This information is fed into VR system processes to computationally model a coherent virtual world, consisting of images, sounds, physical interactions, and narrative/story. In turn, this virtual world is delivered to users through visual, audio, and haptic output devices. Ultimately, these hardware input and output devices as well as software system processes enable production of the *User Experiential Factors* of presence, interactivity, immersion, and embodiment, described above. These User Experiential Factors are interdependent constructs that serve as both moderators of the overall VR experience and mediators of subsequent changes in cognitive, emotional, social, behavioral, and physiological outcomes that serve as targets of pain-related therapy. *Pain Targets* may subsequently pave the way for larger *Outcomes* such as reduced pain intensity and disability, greater participation, and improved quality of life. Notably, experiential factors are noncategorical, meaning they exist on a continuum (ie, one can feel more or less immersed or embodied).

Critically, specific VR configurations underpin specific experiential factors. Interactivity at minimum calls for an explicit control input device and a form of visual presentation. Immersion or presence typically requires surrounding visual and audio outputs such as a HMD and spatial audio. Immersion is also highly affected by story and narrative; one can be immersed in an engrossing story without surrounding visual and auditory effects. Embodiment additionally requires careful colocation of the participant's virtual avatar with their physical body and potential haptic stimulation. Today, off-the-shelf consumer VR systems can easily provide head and controller tracking, surrounding stereo-optical display and positional audio, and sufficient processing power to provide basic interactivity, presence, and immersion. Advanced hardware can provide the haptic interactions to induce embodiment, granting other channels of

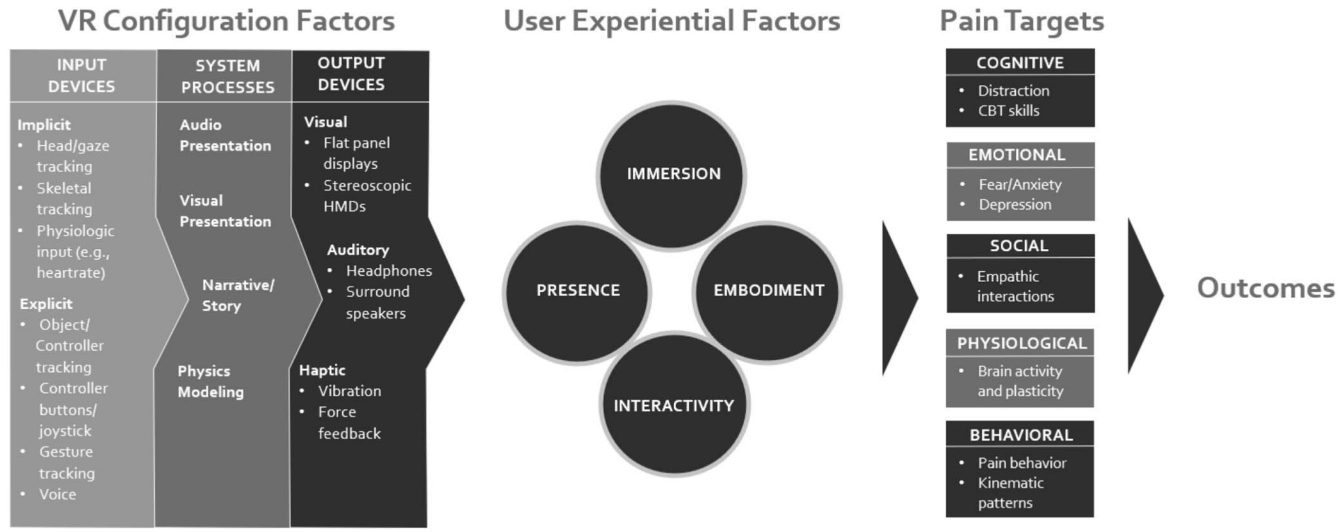

Figure 2. Proposed heuristic model, distinguishing between technical VR Configuration Factors, User Experiential Factors, and Pain Targets, which may contribute to further outcomes. Each category has a nonexhaustive list of factors, understanding of which is expected to evolve with more research. CBT, cognitive behavioral therapy; HMD, head-mounted display; VR, virtual reality.

interactivity/control over a complex physical virtual world, or for gathering advanced participant metrics such as heart rate. Custom software development is generally needed in these cases. User experiential factors can also be affected by simpler set-ups, such as with clever use of basic computer monitors, mirrors, and so on.[69,96]

Specific VR configurations and facilitated experiences are likewise more apt to address specific elements of pain experience, potentially simultaneously. The model illustrated in **Figure 2** presents a nonexhaustive list of potential cognitive, emotional, social, behavioral, and physiological targets that can be addressed by VR. For example, a haptically enabled intervention focusing on embodiment may seek to relieve phantom limb pain by promoting central nervous system plasticity. Hence, the outcome of reduced phantom pain is hypothesized to be promoted by VR configurations that maximize embodiment and in turn neurophysiological changes. Alternatively, efforts to increase lumbar flexion among back pain sufferers with fear of movement may depend on a combination of immersion, embodiment, and interactivity to engage users in virtual games that promote desired lumbar motion while distracting from fear-related cognitions.[28]

It is worth reiterating that the constructs in the model are meant to serve a heuristic function, as we recognize that they are likely to evolve with further study. For example, as technology progresses (vis-a-vis input/output devices and processing), we may distinguish additional experiential factors with significant impact on VR/pain applications. It is also useful to reinforce that the constructs listed within both Experiential Factors and Pain Targets are not mutually exclusive but rather heavily interdependent. For example, cognitive, emotional, behavioral, social, and physiological factors in pain are understood to influence each other as recognized in the very definition of pain experience.[100]

Finally, it is useful to distinguish the multiple targets of pain intervention within VR/pain research, as different VR configurations and/or experiential factors may differentially subserve specific pain targets. For example, an intervention that directly targets brain plasticity in phantom limb pain may rely heavily on embodiment and supporting technical capabilities. Distraction, a cognitive target with specific therapeutic utility in acute or procedural pain contexts, may draw from each available experiential factor relatively equally. Furthermore, an individual VR intervention may address multiple pain targets. In this way, a virtual game to promote physical exercise aims to promote distraction, positive affect, as well as behavioral and physiological change. Importantly, gaming environments are also particularly adept at engaging social elements; hence, VR/pain research holds considerable promise in furthering our understanding and application of a truly integrated biopsychosocial approach to treatment.

In sum, the proposed heuristic model offers a way of framing, planning, and interpreting VR/pain research and interventions, foremost by explicitly distinguishing between the technical and experiential elements of VR application. It also highlights that, with increasing interest in "VR mechanisms" of pain relief, it is critical to develop standardized measures and protocols to assess dimensions of user experience within VR contexts. This is because experiential factors—rather than mutable technologies—are likely to be the central contributors to pain-related outcomes. Whereas measures of user experience have been elaborated in other areas,[39,101] these instruments still need to be refined for pain-specific applications. Critically, this will facilitate communication and comparison across studies that may otherwise remain disparate with respect to technical configurations. In all, such progress will promote methodological rigor called for in the field today.

4. Conclusion

Virtual reality pain research is increasingly applied to a range of acute and chronic pain conditions. The field is spurred by rapid technological advancements and creative deployment of VR capabilities, with exciting developments in the areas of embodiment and manipulation of virtual cues to address pain-related targets. Yet, despite rapid development, this relatively young field calls for replication and standardization as part of a theoretical framework to facilitate reflective, purposeful progress that is not driven solely by technology. The heuristic model offered by the current review aims to facilitate a language and critical examination of the key elements that drive VR effects on pain experience.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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Appendix A. Supplemental digital content

Supplemental digital content associated with this article can be found online at http://links.lww.com/PAIN/B180.

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