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Creating Widely Accessible Spatial Interfaces

Mobile VR for Managing Persistent Pain

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From multitouch surfaces to affordable depth cameras, the recent commercial successes of natural user interface technologies[1] have finally made it practical to extend research in spatial user interfaces beyond the lab and into the wild. Our research builds on one of the most exciting recent results in this direction, the ability to run stereoscopic VR applications on a device as portable and widely accessible as a mobile phone.[2] To do this, we employed a small case that combines simple optical lenses with a frame to hold the phone at a fixed distance perpendicular to the patient's viewing direction (see Figure 1).

Using this platform, we developed and evaluated a series of spatial interfaces and virtual environments. Because the platform is so widely accessible and portable, we're motivated to explore VR applications that haven't previously been possible. For example, we envision that this technology could eventually enable new VR-based therapies for patients on demand in their homes.

To realize this future, many research challenges must be addressed. The computational power of today's phones is startling but still lags behind the resources typically used for head-tracked stereoscopic VR environments. The accuracy of 3D input sensors is another problem. These limitations have motivated us to revisit some core VR interaction techniques (for example, navigation by walking).

Our specific application—managing persistent pain—also suggests several new research challenges. We aim to create virtual experiences that teach patients to intentionally focus their attention on stimuli in their environment rather than on pain and pain-related thoughts. So, the VR environment must present particularly rich stimuli, which is difficult to achieve on a mobile platform. We're also designing spatial visualizations and interfaces for postures used by persons whose pain limits mobility, such as lying down and sitting. Researchers don't often consider such postures when developing VR environments. Finally, we believe creative, effective use of perceptual illusion could be especially valuable for these environments.

Three Virtual Environments

VR has already played a valuable role in pain research. This research has focused primarily on managing acute pain (for example, pain experienced during a medical procedure such as changing a burn victim's bandages[3]). There's speculation that VR could also help manage persistent pain,[4] and researchers have developed a virtual meditative walk, using a treadmill, to treat chronic pain.[5] Unfortunately, current VR technologies still get in the way. Because people suffering from arthritis, cancer, or chronic back or knee pain experience this pain daily, having them come to a VR lab at

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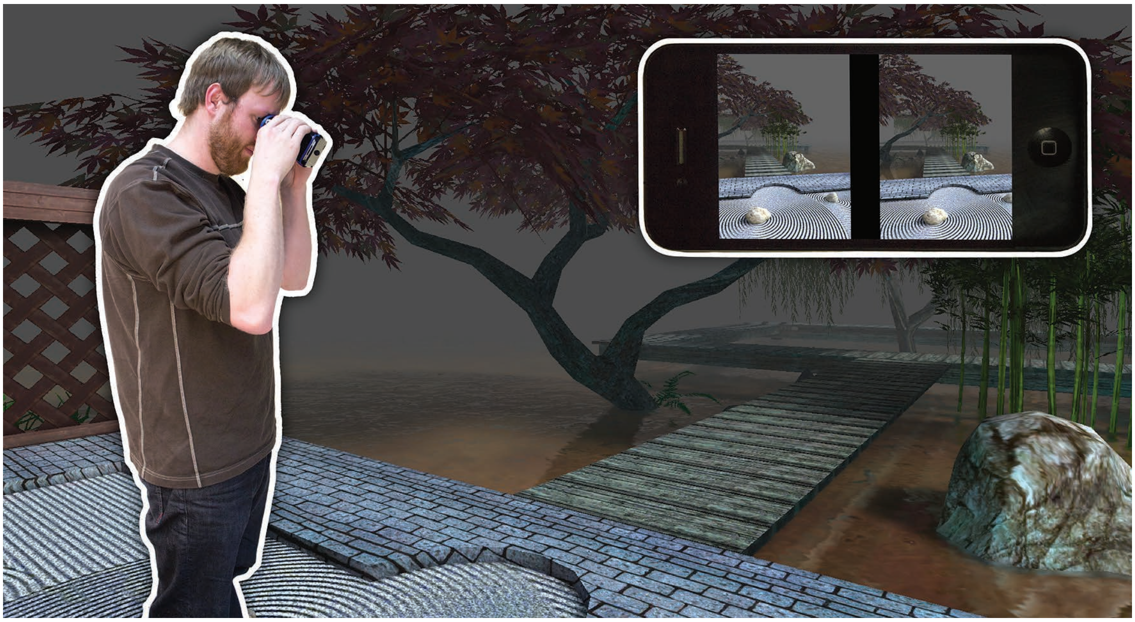

Figure 1. The mindful-movement environment. We integrated a walking-in-place interface with stereoscopic rendering and sound to create an immersive VR environment that runs on a mobile phone.

a hospital or research institution whenever pain flairs up is impractical.

We've been developing mobile virtual environments that draw on the practice of *mindfulness*. Mindfulness is a form of meditation that teaches present-moment awareness. Medical research over the past 25 years has shown how it can help treat numerous health problems; however, research is still lacking regarding chronic pain.[6] The three environments we describe here could be a catalyst for new medical research on both persistent pain and mindfulness.

The Mindful-Movement Environment

The virtual environment in Figure 1 builds confidence by providing controlled exposure to situations that typically produce pain or pain-related thoughts and feelings. The focus is on mindful walking (slow walking intended to cultivate body awareness) and body movements, such as moving from seated to standing postures. We use a tranquil garden full of the ambient sounds and rich visuals of nature to evoke calmness and the pleasantness of being outdoors. Besides rendering such an environment on the mobile platform, the main technical challenge is making the stereoscopic rendering respond appropriately to spatial movements.

Head-tracked, stereoscopic iPhone rendering. To implement the software for our examples, we used Unity3D and its iOS development toolkit. A separate virtual camera is tied to each of the two rendering viewports displayed on the phone (see the inset in Figure 1). The cameras' positions are offset horizontally to account for the patient's interocular distance. We use off-axis projections because the iPhone 4's display isn't large enough to center each viewport directly in front of each eye. To support head-tracked rendering, we apply orientation sampled from the phone's gyroscope to the parent node of the two camera objects in Unity3D's scene graph. For each session, the system assumes a fixed height and initial starting head position. It then employs navigation techniques, such as walking, to update the head position.

Navigating via slow walking in place. For navigating VR environments, both walking and walking in place can elicit a stronger sense of presence than less physically engaging interfaces such as "push-button-fly" interfaces.[7] In addition, mindful walking has a strong tradition in meditation practices. So, we developed walking-in-place navigation that works with acceleration data from sensors commonly available on mobile phones, a change from existing walking algorithms that require more accurate tracking data.

We model walking in place as an oscillatory side-to-side motion. Because the patient holds the phone horizontally, this motion correlates with the axis parallel to the phone's longest edge. During mindful walking, this motion should follow an oscillatory pattern, so we model both the position and acceleration of the motion as sine waves. The first step in our algorithm is to fit a sine wave to the acceleration data's side-to-side component.

The initial estimates for the sine parameters come from either the values used in the previous frame or an approximate solution that involves detecting rising and falling patterns in the input

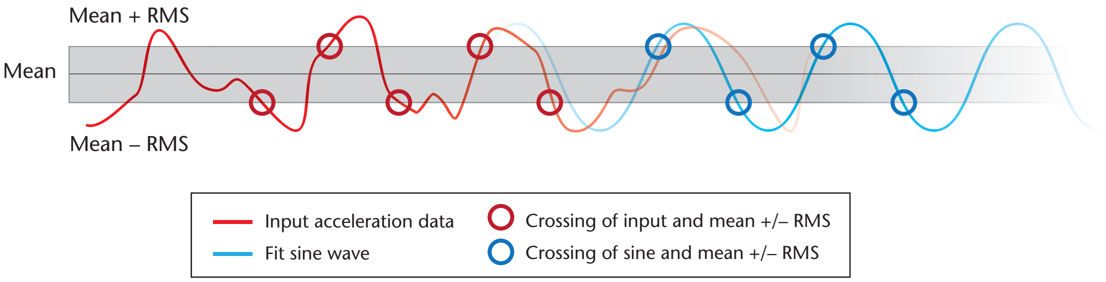

Figure 2. To detect walking-in-place motion, we fit a sine wave model to the raw acceleration data. We threshold the data to identify the wave peaks as the points outside the bounds of the mean, plus or minus the root mean square (RMS). Then, we calculate the rising and falling transitions and other parameters of the idealized sine curve that best fits the data.

data (see Figure 2). Using the data, we approximate the sine wave's phase, frequency, amplitude, and constant offset. Then, we apply a gradient-descent algorithm each frame to iteratively refine these parameters until reaching a local minimum for the sum-of-squared-distances error of the sine wave, relative to the input data.

The accompanying video (see http://doi.ieeecomputersociety.org/10.1109/MCG.2013.38) demonstrates how the sine wave fitting responds to walking motions. Each frame, the virtual head position advances in the direction of the patient's viewing vector projected onto a plane parallel to the ground. We assume a direct correspondence between the absolute value of side-to-side acceleration and forward acceleration. So, we can calculate forward movement directly from the sine wave's parameters.

One potential limitation is that the initial and final steps of a walk break the oscillatory pattern, so the sine wave fit is less robust. Consequently, the first few steps are a bit slower than the others. This hasn't been a problem for our applications and seems to match patient expectations. To improve the reliability of detecting a stop, we maintain a running weighted average of the sine wave's amplitude. If the current amplitude falls sufficiently below this average, we assign a velocity of zero.

Our implementation is encapsulated in a C library, which samples the acceleration at 60 Hz. To increase performance, the most recent five seconds of data are averaged into 100 evenly spaced bins. We then use these 100 samples for the sine fitting.

The Engaging-Multiple-Senses Environment

The virtual environment in Figure 3 teaches patients how to direct their attention toward one of the five senses by purposefully attending to stimuli in their environment. Learning to do this equips them with several pain management tools (for example, the ability to divert attention from limiting thoughts or feelings). In a series of scripted exercises, patients engage with visual, auditory, and haptic stimuli. The main technical challenge is incorporating these stimuli into a mobile VR interface.

The design draws inspiration from recent research that provides force feedback through vibrotactile motors. An array of motors in a regular

(a) **(b)**

Figure 3. The engaging-multiple-senses environment. (a) A rendering from the patient's viewpoint. (b) A custom vibrotactile device under the patient's feet that creates the feeling of rushing water. Patients learn how to direct their attention toward one of the five senses by purposefully attending to stimuli in the environment.

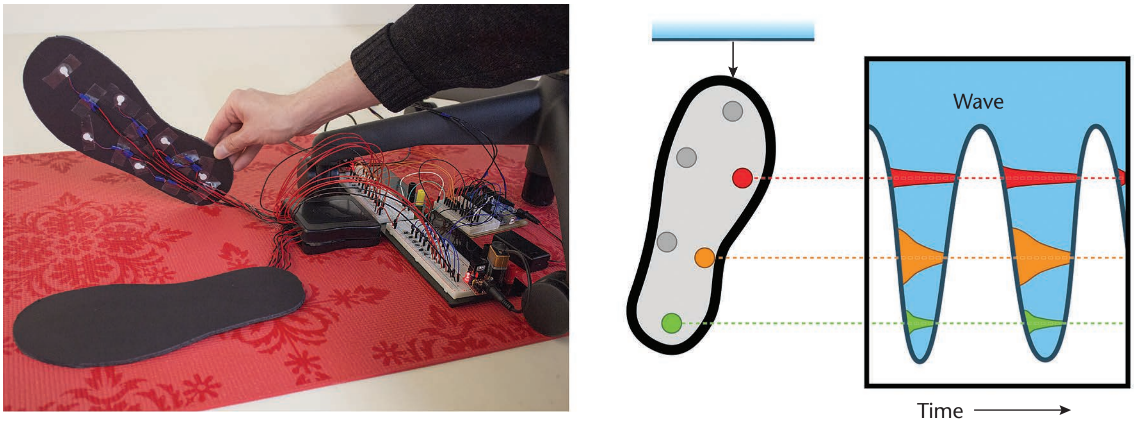

Figure 4. To simulate the feel of rushing water, six vibrotactile motors (each 1 cm diameter) under each foot activate individually.

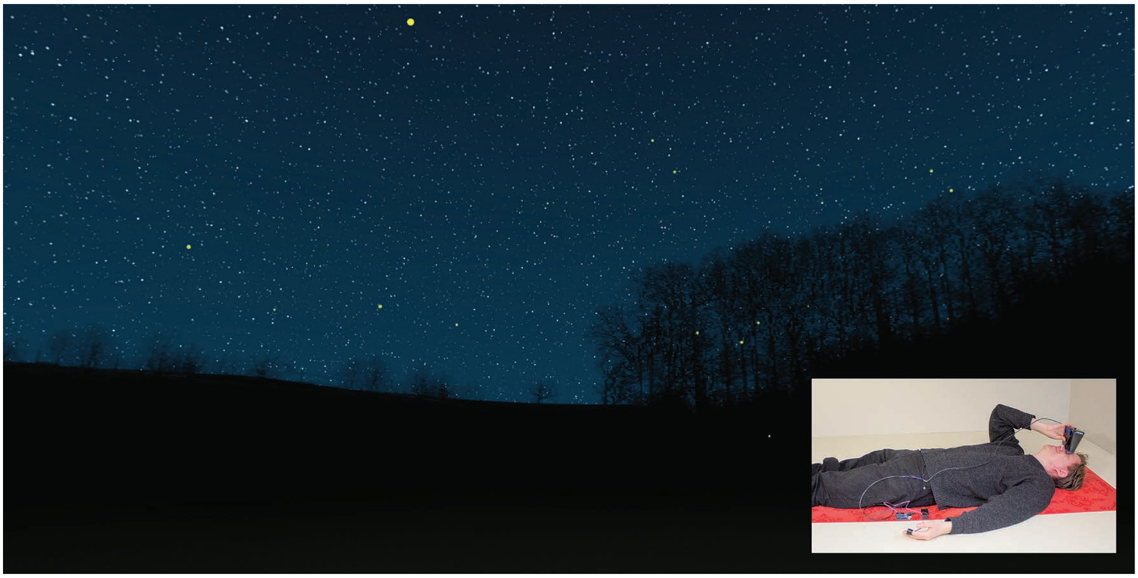

Figure 5. The lying-down, guided-rest environment. The main technical challenge is creating a mobile VR interface that works for the patient's posture and responds appropriately in real time to biometric signals.

pattern and close to the skin can produce the sensation of movement across the skin and even the illusion of movement between the motors.[8]

Figure 4 shows the haptic device we developed for this application. The motors are connected to an Arduino Mega 2560 microcontroller, which is connected to the phone via a Redpark C2-DB9 cable. The device communicates with the phone software through a custom plug-in linked to Redpark's API. The software sends a command each frame to set each motor's vibration strength.

Because each motor is at a different 3D position on the foot, each motor responds slightly differently to the wave. When the wave's position in 3D space reaches a motor's virtual position, an initial vibration spike occurs; the wave's velocity determines the spike's magnitude and duration. The vibration then settles down to a baseline "underwater" vibration, until the wave recedes and the motor is no longer "submerged." When this effect spreads across the array of motors, the patient can clearly sense the waves' direction and rhythm.

An audio script guides the patient's experience. It asks the patient to direct his or her attention toward a particular sense and notice an event or object. The event or object might be specific (for example, a particular rock) or general (for example, the entire landscape). The shift between specific and general teaches the patient that he or she can narrowly focus or broadly expand one of the senses. Visual illusions enhance the exercise. For example, portions of the scene might be drawn in full color and animated, whereas other portions are drawn as solid black silhouettes.

The Lying-Down, Guided-Rest Environment

The environment in Figure 5 teaches patients to consciously shift perspective and attitudes (for example, shifting "my pain is unbearable" to "pain is happening and can be held in awareness"). The

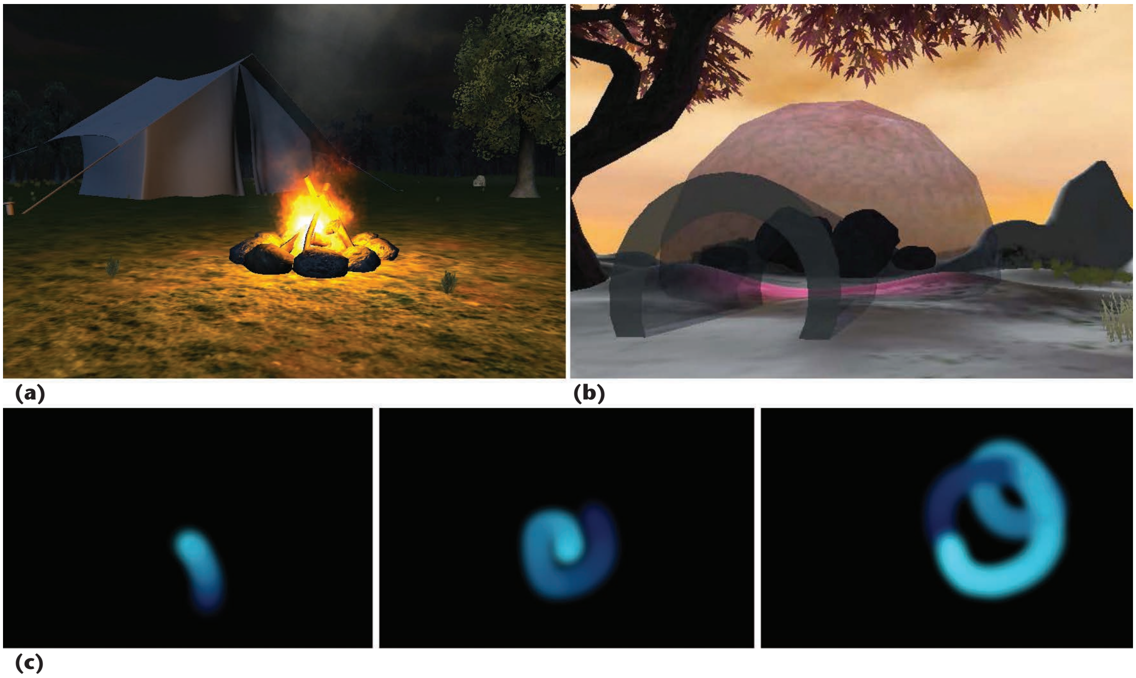

Figure 6. Three virtual environments: (a) photorealistic, (b) somewhat abstract, and (c) quite abstract. The design variables considered include visuals, motion, transformation, atmosphere, perspective, interactivity, and sound. These environments represent a range of results obtained through design, with each result informing the next and, through critique and discussion, suggesting new approaches to address specific patient tendencies. Each environment explores an alternative balancing of story, aesthetics, mechanics, and technology while mixing photorealistic and nonphotorealistic elements.

main technical challenge is creating a mobile VR interface that works for a lying-down resting posture and responds appropriately in real time to biometric signals.

A small sensor on the patient's finger and connected to the Arduino unit (https://code.google.com/p/pulse-sensor) detects the patient's heart rate. To access this input data in the rendering environment, we use serial communication similar to what we described before. We could also easily incorporate additional biometric sensors (for example, for breathing and galvanic skin response).

The patient lies down and looks at the sky while being guided through a visualization exercise. Visuals respond to the script: the sky changes color, stars twinkle. Fireflies appear in response to the prompt, "… receptive to thoughts that may arise, appearing and disappearing, like the flash of a nearby firefly."

The script frequently asks the patient to notice the difference between broad awareness, depicted as the night sky, and events (for example, thoughts), depicted as fireflies, stars, or meteors. The brightest glimmering star depicts the heart rate, which helps the patient assess a resting state. When the heart rate is high and the patient is having difficulty achieving rest, we make the task easier. The star slowly grows and gently pulses to provide a discrete focal point to stabilize attention. As the patient achieves rest, the star becomes more like the others, to help him or her rest within a broader awareness.

Design Considerations, Process, and Results

Aesthetics and design are important to these mobile VR interfaces' success. So, our research considers not just the underlying technology but also the formal design considerations and (collaborative) processes that can produce effective environments.

Toward that end, our research team includes traditionally trained designers, instructors, and students from the Advanced Virtual Environments class at the Minneapolis College of Art and Design. These team members' varied makeup lets us exploit specialized skill sets. Besides those with a key interest in game design and virtual environments, there are illustrators, graphic designers, animators, 3D modelers, sound designers, filmmakers, and photographers. Each of these specializations helps us address specific considerations relevant to managing persistent pain in a way that a generalist might not. This collaborative process has proven invaluable to our research; it also has inherent benefits for cross-disciplinary education and broadening participation in science.

We derived our workflow structure from Jesse Schell's "elemental tetrad,"[9] which describes the interrelationship between story, aesthetics, mechanics, and technology. The designers balance these factors to

- leverage the benefits of all four while contributing to the patient experience,
- understand the diverse aesthetic considerations that come into play, and
- determine the most effective use of these factors where the patient experience is concerned.

We view aesthetics as focusing on the nature and appreciation of beauty. In addition, it involves an understanding of balance, proportion, and the ability to interpret and modify the relationships between different design variables. From this viewpoint, we determine which aspects of the design elicit effective responses from patients, and in what proportion.

For example, Figure 6a depicts a photorealistic nighttime scene of a campground with a tent and campfire, surrounded by a forest. The setting is intended to evoke nostalgia and childlike wonder. When entering the tent, the patient sees a space larger on the inside than the outside, with a stage depicting a shadow puppet play. As the spatial relationships change and the setting transitions from a realistic to an illustrative one, the patient is drawn deeper into the experience. The goal is for the patient to quit focusing on his or her pain while exploring contradicting but compelling forms of imagery and visual styles.

Figure 6b is concerned less with photorealism and more with using transitions in color and atmosphere to influence the patient's response, specifically to create serenity and tranquility. Entering the igloo triggers a slow series of color changes of the igloo's translucent surface. At the same time, the environment outside also changes color. An audible breeze rises and falls on the basis of biometric input from the patient and might cause leaves to fall onto the top of the igloo. These atmospheric elements help immerse the patient in the experience because the patient's own responses to the space influence his or her behavior.

Figure 6c explores an even more abstract concept. The environment focuses on a simple visual element—a particle system—intended to have an immersive, hypnotic effect. For example, the blue is intended to induce calm. Different inputs (for example, breathing rate, heart rate, and guided motions) can cause the particles' size, color, position, and speed to change, sometimes simultaneously. These changes in turn influence the patient's behavior.

Impact and Evaluation

Our team includes a pain research group consisting of psychologists and physical therapists. The psychologists have more than 30 years' combined experience developing, refining, and testing psychosocial treatments for persistent pain. The physical therapists have more than 20 years' combined experience in implementing treatment protocols with patients having pain. Together, they have provided valuable evaluations throughout the design process, delivering feedback on new tools roughly once a month over the past eight months.

Demonstrated Impact

The group's high-level evaluation is that the interfaces and environments described in this article not only are immediately useful in clinical research but also could transform psychosocial approaches to persistent-pain management. The technical results have already changed the group's research agenda and stimulated the development of a research program. The group is designing three pilot study protocols to submit for institutional-review-board approval:

- One study would use the mindful-movement environment with osteoarthritis patients who experience pain when moving.
- Another study would use the engaging-multiple-senses environment to help patients who have had arthroscopic surgery on a hip and have difficulty tolerating increased pain while sitting.
- A third study would test how well the lying-down, guided-rest environment helps chronic-back-pain patients whose pain flares cause them to spend excessive time bedridden and coping with intolerable pain.

The group's psychologists have stated,

> These VR environments provide a powerful distraction from pain and are especially needed for patients who have difficulty disengaging from pain and fail to respond to conventional psychosocial interventions. They also offer the most promising method, to date, of enhancing the generalization of treatment effects from an office setting to home and work environments. Instead of office-based therapist-guided practice sessions with, for example, therapist-guided imagery, patients can now practice focusing and deepening their attentional focus on a much richer, immersive environment many times a day or whenever their pain is uncontrollable. Practice is

> essential for mastery of pain-coping skills, and the VR environments greatly expand the possibilities for successful and rewarding practice experiences.

Insights from Iterative Design Evaluations

The physical therapists' evaluations of the anticipated patient reactions yielded many insights, including the most appropriate style of spatial body movements to detect. For example, patients using the mindful-movement environment might have difficulty with balance. To deal with this issue and make the interface feasible for use in small spaces, we designed the walking-navigation algorithm to accommodate walking in place.

We envision eventually creating a suite of personal environment-editing tools that both patients and therapists can use.

Because walking can be too painful for some patients, the pain researchers asked whether patients could sit or lie down and use a joystick to move around the environment. The answer was certainly yes. However, the spatial interfaces we developed for sitting and lying down intentionally extend beyond traditional gaming interfaces, to demonstrate that biometric signals and even active haptic feedback can now be integrated with mobile-phone-based VR. The pain researchers are now excited about including additional user inputs (for example, muscle tension and galvanic skin response).

Early evaluations of using sound not only confirmed its importance but also prompted us to create the engaging-multiple-senses environment, which brings sound to the forefront. (Sometimes, we even black out the visuals so that patients engage with sound alone.)

We also regularly evaluated rendering. When we asked patients about pleasant, comforting images, they almost always said they preferred scenes that involve being near the water. So, we made compelling, photorealistic animated water a focus of several environments. In early implementations, the boardwalk in the mindful-movement environment intentionally included gaps between the boards for patients to view the water below. However, the physical therapists told us that a secure sense of balance and connectedness to the ground is likely more important for these patients than the benefits of this visual richness. So, we refined the environment to employ visually continuous walking paths.

Feedback on Roles for VR Environments

Evaluations showed that these interfaces could work for a range of useful environments beyond our initial meditative applications. This reinforces the value of a design-based methodology that can explore a variety of sensory experiences and narratives.

To formalize the observations from our design work and evaluations, we've identified six tendencies associated with persistent pain that mobile VR environments and spatial interfaces could address particularly well.

First, patients tend to focus on pain and pain-related thoughts and be unaware of their environment. VR could help them learn to direct their attention toward environmental stimuli rather than pain-related thoughts (for example, "I'll never be able to cope with this pain if I walk") and feelings (for example, anxiety, fear, or discouragement).

Second, patients tend to avoid situations that might cause pain or distressing pain-related thoughts and feelings. VR could help them overcome this avoidance and develop confidence through controlled exposure to pain-related situations, such as slow walking or moving from seated to standing postures.

Third, patients tend to find imagery helpful for pain relief for only short periods of time. VR could extend mental-imagery exercises' benefits by prompting more frequent practice, enhancing the experience's vividness, and providing additional multimodal stimuli to complement imagery.

Fourth, patients tend to only perform obligatory activities. VR could expose them to environments that are inherently rewarding because they are novel, are fun, or give a sense of competence (for example, learning a new language).

Fifth, patients tend to avoid focusing on the body site of pain. VR could extend research that shows mental-imagery exercises' benefits for patients who avoid looking at, imagining, or moving painful areas.

Finally, patients tend to imagine overly negative future outcomes (pain catastrophizing). VR could help them reimagine and visualize more realistic outcomes for common imagined catastrophic scenarios (for example, "I'll end up bedridden or confined to a wheelchair").

Future Directions

We plan to first assess patient outcomes in a supervised setting and aim to eventually deploy these interfaces in the home. (The only remaining technical hurdle is improving the packaging of the external electronics used for haptics.) Feedback indicates that patients don't consider the requirement to hold the display up to their eyes as a limitation. However, we still plan to explore alternative designs for hands-free phone-based displays, which could enable new interfaces. Feedback also points to the importance of providing patients with choice, because choice and a sense of control have been linked to decreased pain. We've begun by supporting custom background music; we envision eventually creating a suite of personal environment-editing tools that both patients and therapists can use.

People can now use low-cost mobile VR technologies to create a variety of rich virtual experiences involving motion sensing, physiological inputs, stereoscopic imagery, sound, and haptic feedback. These multimodal VR environments not only further the promising trend of moving spatial interfaces out of the lab and into users' hands but also open up exciting application areas. The novel interfaces and environments we've developed have already been adopted by psychologists studying pain management and could provide relief to many patients suffering from persistent pain.

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