

Overview of Technology-assisted Mindfulness Studies in Top-Tier HCI Journals

Author (year) & Country	Mindfulness Category	Technology Used	Research Methods (key instruments)	Main Findings
Rockstroh et al. (2021), Germany	Static Meditation	VR Game	Quantitative (Perceived Ease via a single item, PSS, breath awareness via a self-constructed scale)	VR-based breathing training improved diaphragmatic breathing, relaxation, and stress reduction.
Chandrasiri et al. (2020), Australia	Static Meditation	VR Video & Audio	Quantitative (TMS)	VR intervention improved decentering but did not significantly outperform audio-only mindfulness training.
Crescentini et al. (2016), Italy	Static Meditation	VR Immersive Virtual Environments	Quantitative (FFMQ, MAAS, FMI, physiological measures)	Enhanced mindfulness skills and emotional regulation, but some physiological parameters showed no significant differences.
Barton et al. (2024), Australia	Kinetic Meditation	VR Passive, Interactive, and Nature-Based Mindfulness	Mixed Methods (State Mindfulness Scale, Open-ended questions)	Interactive VR improved focus, mood, and motivation more effectively than passive versions.
Persa et al. (2022), United States	Static Meditation	Wearable app	Qualitative (Observations, interviews, surveys)	Mini-game app enhanced relaxation and attention.
Miri et al. (2020), United States	Static Meditation	Wearable Vibrotactile Breathing Pacer	Quantitative (Breathing vibrotactile pattern)	Personalization improved intervention effectiveness; abdomen was the preferred placement for pacer tactors.
Zafar et al. (2020), Qatar	Static Meditation	Paced Breath Mobile App	Quantitative (Cognitive tasks, Stroop-based Color Word Test)	Biofeedback improved breathing control and cognitive performance compared to non-biofeedback methods.
Fuller-Tyszkiewicz et al. (2019), Australia	Static Meditation	Mobile Video-Based Intervention	Quantitative (Body Image Satisfaction Subscale, Body Image Important Scale)	Mindfulness video intervention significantly improved body satisfaction.

Verduyn et al. (2021), Netherlands	Static Meditation	Smartphone Communication	Quantitative (Scale of Positive and Negative Emotions, Smartphone Use Patterns)	Mindfulness intervention reduced smartphone use and mitigated negative emotions.
Niksirat et al. (2019), Japan	Kinetic Meditation	APP design	Mixed Methods (HR rate, EEG, ANT, Feedback preference of the users, Balance via a SLS task)	ARF-based static and kinetic designs improved attention, mood, and well-being, particularly in distracting environments.

TMS= Toronto Mindfulness Scale, FFMQ= Five Facet Mindfulness Questionnaire, MAAS= Mindful Attention Awareness Scale, FMI= The Freiburg Mindfulness Inventory, PSS= Perceived Stress Scale, ANT= Attentional Network Test, SLS= Single-Leg Stance, ARF= Attention Regulation Framework

	Papers	Psychological Purpose of Engaging in Mindfulness Practices	The main Technologies	Additional Technologies	Sensory Extension Design
1	(Plencler et al., 2024)	<u>Contextual Mindfulness for Special Populations:</u> Exploring the use of VR to support mindfulness interventions for treating psychiatric disorders , particularly psychosis .	VR	N/A	Visual: 360-degree natural scenes Auditory: Guided mindfulness instructions (voice of the teachers give instruction)

2	(Scott et al., 2022)	<u>Focused Attention and Cognitive Engagement:</u> Enhancing user engagement and mindfulness awareness through neurofeedback during museum visits.	VR EEG	N/A	Visual: Abstract Graphics (3D Buddhist mandala, like squares, circles and geometries) Auditory: Guided mindfulness instructions (user is directed to relax while concentrating on the mandala); Culturally and spiritually inspired music (Tibetan and music); Modern Instrumental Music (modern minimalist-inspired piano music) Haptic: Physiological Monitoring Systems (EEG sensors for neurofeedback and brain activity, relaxation)
3	(Lan et al., 2021)	<u>Focused Attention and Cognitive Engagement:</u> <u>Bodily Awareness and Interoception:</u> Using VR with biofeedback to enhance interest and engagement in breathing exercises .	VR	EEG, pressure sensor	Visual: Human Body and Structure Representation (3D human face to show the abdominal movement visualization); Light Representation (body temperature changes in VR) Haptic: Physiological Monitoring Systems (Pressure sensor attached to the abdomen of the user); (Heating pad simulate the increase in body temperature); (EEG sensors for observing concentration)

4	(Krägeloh et al., 2019)	<u>Focused Attention and Cognitive Engagement:</u> Testing the feasibility of delivering mindfulness-based group interventions via videoconferencing to enhance adherence .	Videoconference	N/A	Visual: Video-based Content (video calls, a slideshow presentations) Auditory: Guided mindfulness instructions (the facilitator guiding participants in various mindfulness practices such as an educational mindfulness program called Pause, Breathe, Smile; a physical movement exercise similar to Taijiquan and walking meditation; and concentration meditation)
5	(Hunkin et al., 2021)	<u>Emotional Regulation and Stress Reduction:</u> <u>Focused Attention and Cognitive Engagement:</u> Evaluating the impact of auditory EEG neurofeedback on enhancing state mindfulness and improving mental health during focused attention meditation.	EEG	Muse App on Apple iPad tablets (mobile App)	Auditory: Guided mindfulness instruction (participants were guided in breath-focused meditation); Nature soundscapes (waves lapping) that change based on brain activity, indicating attention levels. Haptic: Physiological Monitoring Systems (EEG headband providing neurofeedback, mean mind wandering and recoveries from mind wandering)
6	(Yusim & Grigaitis, 2020)	<u>Emotional Regulation and Stress Reduction:</u>	Binaural Beats	N/A	Auditory: Binaural Beats (binaural beats and monaural beats with three meditation tracks of different sound frequencies); Guided meditation instructions (a human voice provided instruction on

		<u>Contextual Mindfulness for Special Populations:</u> Using binaural beat meditation technology to reduce anxiety symptoms in psychiatric and non-psychiatric populations.			how to assume a relaxed posture and enter the meditative mental space)
7	(Lee et al., 2023)	<u>Contextual Mindfulness for Special Populations:</u> Assessing the safety and effectiveness of VR-based mindfulness for psychosis patients .	VR	Dry surface electrodes, an earlobe-pulse-plethysmograph	Visual: 360-degree nature scenes (The nature scenes with calm and relaxing contents), video-based Content (educational and therapeutic videos) Auditory: Guided meditation instructions (general introduction of mindfulness, explain breathing, concept of decentering) Haptic: Physiological Monitoring Systems (Skin conductance sensors: two gold coated flat and dry surface electrodes that were covered with isotonic electrode gel and placed on the forehead; Heart Rate Monitor: earlobe-pulse-plethysmograph)
8	(Sas & Chopra, 2015)	<u>Focused Attention and Cognitive Engagement:</u> <u>Bodily Awareness and Interoception:</u>	EEG, Aural entrainment (Binaural beats)	N/A	Visual: EEG-based Visualization (3D brain activity maps)

		Developing a wearable system using EEG with an adaptive aural entrainment for real time training of mindfulness states.			Auditory: Binaural Beats (binaural beats and monaural beats, The delivered beats vary in frequency and subsequently in the perceived pitch) Haptic: Physiological Monitoring Systems (EEG headset for neurofeedback associated meditative states: stable focus of attention)
9	(Chittaro & Vianello, 2014)	<u>Compassion, Empathy, and Social Connection:</u> <u>Emotional Regulation and Stress Reduction:</u> Designing a mobile app to practice thought distancing.	Smartphone Applications	N/A	Visual: Interactive Visual Game (Visualization of thoughts as text on interactive water animation) Haptic: Interaction with a Touchscreen (create water waves and dissolve thoughts)
10	(Daudén Roquet & Sas, 2021)	<u>Emotional Regulation and Stress Reduction:</u> Developing an interactive mindfulness technology to improve mental well-being in individuals with depression.	Brain-Computer Interface (BCI)	Color palette, tablet (mobile device)	Visual: EEG-based Visualization (Generative color palette based on real-time brain activity displayed on a tablet) Haptic: Physiological Monitoring Systems (EEG headband to monitor brain activity and identify mindfulness states during mandala coloring)
11	(Haynes et al., 2022)	<u>Emotional Regulation and Stress Reduction:</u>	Pneumatic-Haptic Device (Huggable)	N/A	Auditory: Guided meditation instructions (The breathing exercise used was “Meditation Four: Breath and Body”)

		Identifying the prototype to serve as effective mindfulness-based anxiety aids .	Haptic Interface)		Haptic: Haptic and Vibroacoustic Feedback Devices (Pneumatically-driven huggable cushion simulating slow breathing)
12	(Tinga et al., 2019)	<u>Bodily Awareness and Interoception:</u> <u>Emotional Regulation and Stress Reduction:</u> Exploring respiratory biofeedback during VR meditation for lowering arousal after stress .	VR, EEG	ECG	Visual: Interactive Visual Game (Visualization of breathing using a white cloud in VR) Auditory: Guided meditation instructions (instructing to “focus on your breathing” and to “mindfully breathe in” and to “mindfully breathe out”, while “experiencing the whole body”) Haptic: Physiological Monitoring Systems (EEG, ECG and respiration sensors for monitoring physiological responses that measures objective arousal)
13	(Fani et al., 2023)	<u>Bodily Awareness and Interoception:</u> <u>Emotional Regulation and Stress Reduction:</u> <u>Focused Attention and Cognitive Engagement:</u>	Vibration Feedback Device	N/A	Visual: Video-based Content (Breathing instructions displayed on a computer screen) Haptic: Haptic and Vibroacoustic Feedback Devices (Vibroacoustic feedback delivered via a wearable subwoofer placed on the sternum, which synchronized with the breath to provide real-time tactile sensations)

		<u>Contextual Mindfulness for Special Populations:</u> Using vibrations as biofeedback during breath-focused mindfulness to enhance interoception, attention, and emotional regulation in trauma survivors.			
14	(Hu et al., 2021)	<u>Bodily Awareness and Interoception:</u> Comparing traditional mindful breathing with VR-enhanced breathing through the brain image during dissect the cortical analgesic processes.	VR	EEG, fNIRS, Plethysmography	Visual: Human Body and Structure Representation (lungs visualization) synchronized with breathing cycles in VR Auditory: Breathing sounds (Breathing cycles (inhalation and exhalation) were monitored using a plethysmography belt for synchronization and played through VR headphones) Haptic: Physiological Monitoring Systems (EEG and fNIRS sensors for neuroimaging); (Plethysmography belt for breath synchronization)
15	(Roos et al., 2024)	<u>Contextual Mindfulness for Special Populations:</u>	Smartphone Applications	N/A	Visual: Video-based Content (Animation videos illustrating mindfulness concepts) Auditory: Guided meditation instructions

		<u>Emotional Regulation and Stress Reduction:</u> Developing a digital mindfulness intervention to support emotional recovery in individuals with substance use disorders .			
16	(Payne et al., 2024)	<u>Focused Attention and Cognitive Engagement:</u> Understanding VR immersion through self-report and objective distraction measures .	VR	Vibrating tactor	Visual: 360-degree natural scenes Auditory: Guided meditation instructions Haptic: Haptic and Vibroacoustic Feedback Devices (A small vibrating tactor device attached to the participants' skin.)
17	(Greig et al., 2024)	<u>Compassion, Empathy, and Social Connection:</u> <u>Bodily Awareness and Interoception:</u> Testing visual biofeedback during self-compassion training.	VR	Wearable heart rate monitor	Visual: Human Body and Structure Representation (3D avatars to representations of both themselves and others); Light Representation (A pulsating red light visualizing heart rate) Haptic: Physiological Monitoring Systems (Wearable heart rate monitor)
18	(Seabrook et al., 2020)	<u>Focused Attention and Cognitive Engagement:</u>	VR	N/A	Visual: 360-degree natural scenes (forest)

		Exploring the role of VR in supporting mindfulness practice and user experience .			Auditory: Guided meditation instructions; Nature soundscapes (sound originating from the forest)
19	(Nieto-Vallejo et al., 2021)	<u>Focused Attention and Cognitive Engagement:</u> <u>Emotional Regulation and Stress Reduction:</u> Designing an EEG neurofeedback system with multisensory stimuli to improve relaxation and focused attention .	EEG	LED ring, Water pump, vaporizer	Visual: Light Representation (LED ring providing real-time visual feedback) Auditory: Nature soundscapes (Sound feedback from water flow controlled by brain activity levels) Haptic: Physiological Monitoring Systems (EEG headset for neurofeedback) Olfactory: Nature-inspired Scents (Bergamot scent provided through a vaporizer emitting the fragrance.)
20	(Riches et al., 2024)	<u>Contextual Mindfulness for Special Populations:</u> <u>Emotional Regulation and Stress Reduction:</u> Implementing VR-based interventions to enhance well-being among mental health staff .	VR	N/A	Visual: Interactive Visual Game (interactive 3D virtual environment) Auditory: Guided meditation instructions

21	(Heeter et al., 2020)	<u>Bodily Awareness and Interoception:</u> Testing interoceptive awareness in virtual environments.	VR	N/A	Visual: 360-degree natural scenes (Colorado River scene) Auditory: Guided meditation instructions; Nature soundscapes (flowing water)
22	(Finck et al., 2023)	<u>Focused Attention and Cognitive Engagement:</u> <u>Bodily Awareness and Interoception:</u> Enhancing mindfulness using multisensory design .	Multisensory environment	Video, Chest strap	Visual: Video-based Content (Video projections of life cycle imagery, interactive tree growth visual responding to heart rate) Auditory: Nature soundscapes (earth, water, wind, fire, bird and insect sounds); Instrumental music (piano) Haptic: Physiological Monitoring Systems (recorded the electrocardiogram (ECG) of each participant using the Polar ® H10 sensor chest strap)

					Olfactory: Nature-inspired Scents (The idea of nature: Fragrances of “Outdoors” and “Ylang” to enhance the sense of smell)
23	(Hugh-Jones et al., 2023)	<u>Contextual Mindfulness for Special Populations:</u> <u>Emotional Regulation and Stress Reduction:</u> Co-designing a VR resource to support emotional regulation and well-being among students in schools .	VR	N/A	Visual: 360-degree natural scenes (3D beach, forest, and starry night) Interactive Visual Game (3D virtual interactive environment) Auditory: Guided meditation instructions; Nature soundscapes (e.g., bird songs)
24	(Fonseca et al., 2024)	<u>Emotional Regulation and Stress Reduction:</u> <u>Contextual Mindfulness for Special Populations:</u> Using VR-assisted mindfulness to reduce anxiety in perioperative caregivers .	VR	N/A	Visual: 360-degree natural scenes (waterfall landscapes, polar lights) Auditory: Guided meditation instructions
25	(Le Roy et al., 2024)	<u>Focused Attention and Cognitive Engagement:</u>	VR	N/A	Visual: 360-degree natural scenes (forests and mountain plains)

		Investigating the impact of physical exercise in a VR environment.			Human Body and Structure Representation (3D human model on a bike) Auditory: Nature soundscapes (e.g., waterfall); Activity-Associated Sound Prompts (bike mechanism sound increases as speed increases) Haptic: Haptic and Vibroacoustic Feedback Devices (haptic feedback (i.e., vibrations) according to the terrain, Interaction with the ergocycle providing physical feedback during exercise)
26	(Navarro-Haro et al., 2019)	<u>Emotional Regulation and Stress Reduction:</u> Comparing two mindfulness-based interventions (MBI with and without VR) for anxiety reduction .	VR	N/A	Visual: 360-degree natural scenes (river with natural elements like trees, boulders and mountains) Auditory: Guided meditation instructions (observing sounds, observing visuals, or wise mind)
27	(Perales et al., 2019)	<u>Bodily Awareness and Interoception:</u> <u>Emotional Regulation and Stress Reduction:</u> Assessing VR pain management with binaural acoustic stimulation .	VR, Binaural beats	wristband	Visual: Interactive Visual Game (players can change the virtual environment, like lake, meadow and office) Auditory: Binaural beats; Instrumental Music (Pachelbel's Canon in D major)

					Haptic: Physiological Monitoring Systems (Use of the Empatica E4 wristband for measuring Electrodermal Activity (EDA) and heart rate during the sessions)
28	(Salminen et al., 2022)	<u>Compassion, Empathy, and Social Connection:</u> Using shared visualizations in social VR to evoke empathy .	VR EEG	N/A	Visual: Human Body and Structure Representation (statue-like avatars); Light Representation (e.g., the color change of aura and bridge tiles represents the users' level empathy) Auditory: Nature soundscapes (the sound of wind) Haptic: Physiological Monitoring Systems (EEG cap for measuring brain activity); Respiration belt for tracking breathing
29	(Cebolla et al., 2019)	<u>Compassion, Empathy, and Social Connection:</u> <u>Emotional Regulation and Stress Reduction:</u> Testing self-compassion meditation to enhance positive affect, self-care , and adherence to mindfulness practice.	VR	N/A	Visual: Human Body and Structure Representation (VR environment allowing participants to see themselves from a third-person perspective with body swap illusion) Auditory: Guided meditation instructions Haptic: Self-body Touch (e.g., placing the hand on the knee and moving it slowly, self-hugging).

30	(Choi et al., 2022)	<u>Emotional Regulation and Stress Reduction:</u> <u>Focused Attention and Cognitive Engagement:</u> Supporting mindful breathing to reduce perceived workload while balancing daily routines.	Haptic Feedback Device	N/A	Haptic: Haptic and Vibroacoustic Feedback Devices (Pneumatic-haptic device providing customizable tactile feedback, simulating breathing movements with soft inflatable actuators clipped on the user's body)
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