Embodied Cognition–Driven Tactile Compensation and Emotional Reconstruction in Serious Games for Virtual Healing Space Design

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Abstract. Virtual reality (VR) environments and serious games are increasingly explored as tools for emotional wellbeing and restorative experiences. However, most existing VR healing applications emphasize visual immersion and interaction, while the role of material perception and tactile imagination in virtual environments remains underexplored.

Drawing on theories of embodied cognition and cross-modal perception, this study examines how visual material properties and lighting conditions may evoke quasi-tactile perception and influence emotional responses in VR spaces. To conceptualize this process, we propose the SPCR model (Stimuli–Perception–Compensation–Reconstruction), describing how spatial stimuli may trigger perceptual engagement, evoke tactile compensation, and support emotional reconstruction.Based on this framework, a VR experimental prototype was developed using PBR material properties and dynamic lighting parameters. Users' emotional and experiential responses were evaluated through physiological and psychological indicators, including heart rate variability (HRV), the Self-Assessment Manikin (SAM), and the Igroup Presence Questionnaire (IPQ).

The results suggest that material–light coupling and interactive feedback may enhance presence, perceived tactile richness, and positive emotional responses. While the findings do not establish clinical therapeutic outcomes, they highlight the potential role of tactile-oriented spatial design in VR-based restorative experiences and provide a preliminary design framework for future immersive healing environments.

Keywords: Embodied Cognition, Serious Games, Spatial Healing, Tactile Compensation, Material Semantics, Light-Shadow Coupling, Emotional Reconstruction

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Introduction

Virtual reality-based healing environments and serious games have gained increasing attention in design research because they provide multisensory, controllable, and interactive settings for emotional support and restorative experience. Nevertheless, a large proportion of existing studies still prioritize visual immersion, task interaction, or narrative engagement, while paying comparatively limited attention to how users construct a sense of tactile richness and bodily grounding in non-haptic virtual spaces.

This gap is important because healing-oriented virtual environments are not experienced only through vision; rather, they are interpreted through embodied perception, material imagination, and cross-modal sensory inference. In other words, even when direct physical touch is absent, users may still develop quasi-tactile impressions from material appearance, surface detail, light-shadow variation, and interactive feedback, and these impressions may influence emotional comfort, presence, and restorative potential.

To address this issue, this study explores how embodied cognition can inform the design of tactile compensation mechanisms in VR healing spaces and serious games. Specifically, it proposes the SPCR model (Stimuli-Perception-Compensation-Reconstruction) to explain how material-light stimuli may activate perceptual engagement, evoke tactile compensation, and eventually contribute to emotional reconstruction. Based on this framework, the study further develops a VR prototype and evaluates its effects through subjective and physiological indicators. By doing so, the paper aims to provide both a conceptual explanation and a preliminary design pathway for tactile-oriented immersive healing environments.

1 Embodied Cognition and Sensory Compensation in Virtual Realms

1.1 The Phenomenological and Cognitive Foundation of Embodiment

The paradigm of embodied cognition challenges the Cartesian dualism by asserting that human consciousness and emotional regulation are deeply rooted in biological sensorimotor patterns [1]. Phenomenologists like Merleau-Ponty (1962) argued that the body is the primary site of knowing the world; therefore, "spatial healing" cannot be achieved through detached visual observation alone[2]. In virtual environments, the absence of physical touch leads to what Heidegger termed "world-withdrawal," where the user feels alienated from the digital reality. To bridge this gap, virtual healing spaces must move beyond "representation" to "simulation of presence" through bodily engagement.

1.2 Cross-modal Perception and the Mirror Neuron System

Recent neuroscientific research provides a biological basis for tactile compensation. The discovery of mirror neurons suggests that observing an action or a texture can activate the same neural pathways as the actual physical experience[3]. When a user observes a high-fidelity "warm" wood texture under soft, raking light in a serious game, the somatosensory cortex is stimulated through visual-tactile synesthesia. This cross-modal perception allows the brain to "feel" the virtual material, effectively compensating for the lack of haptic input [4]. This mechanism is crucial for emotional reconstruction, as tactile sensations are directly linked to the oxytocin system and stress reduction.

1.3 PBR Technology and Material Semantics in Healing Environments

The transition from traditional CG rendering to Physically Based Rendering (PBR) has revolutionized material semantics in design. By meticulously controlling parameters such as Micro-topography (Normal Mapping), Albedo, and Roughness, designers can evoke specific psychological archetypes. According to the Prospect-Refuge Theory and Biophilic Design principles , naturalistic textures—such as the irregular roughness of stone or the organic grain of wood—function as "sensory anchors." In serious games, these digital materials act as "containers of memory," evoking feelings of safety and stability that are essential for therapeutic intervention.[5-6]

1.4 Serious Games as a Dynamic Intervention Medium

Unlike static architectural visualizations, serious games introduce "agency" and "feedback loops" into the healing process. The Self-Determination Theory (SDT) suggests that the autonomy and competence experienced during gameplay enhance the efficacy of psychological intervention. In a healing game, the coupling of dynamic light-shadow changes with interactive material transformations (e.g., a cold stone floor turning into soft grass upon completing a task) creates a metaphorical healing narrative. This process transforms the user from a passive spectator into an active participant in their own emotional reconstruction.[7-8]

2 The SPCR Model for Virtual Spatial Healing

Building upon the phenomenological and neuroscientific foundations laid in the previous section, this chapter constructs a conceptual framework termed the Stimuli-Perception-Compensation-Reconstruction (SPCR) Model. This model articulates the specific transition from digital environmental variables to the internal emotional recovery of the user.

2.1 The Dynamic Logic of "Body-Space" Coupling

Under the perspective of embodied cognition, the user in a serious game is not a detached observer but an embodied agent. The "Body Schema"—one's internal map of physical capabilities and boundaries—extends into the virtual coordinates through the avatar.[9] For healing to occur, the virtual space must exhibit "perceived affordance." When PBR materials respond to virtual light with the same physical consistency as the real world (e.g., Fresnel effects on water or anisotropic highlights on brushed wood), the brain recognizes the environment as a "habitable reality" rather than a flat projection. This cognitive alignment is the prerequisite for spatial trust.[10]

2.2 Tactile Compensation: The Mechanism of Anticipatory Perception

In the absence of physical haptic feedback, the brain employs Anticipatory Perception to fill the sensory void. This mechanism, rooted in the Visual-Tactile Synesthesia discussed in Section 1.2, suggests that "touch" in virtual reality is a predictive simulation. When a serious game presents high-frequency textural details (Normal Mapping) coupled with raking light that emphasizes micro-shadows, it triggers a "pseudo-haptic" response. This compensation allows the user to perceive "warmth," "softness," or "solidity," which bypasses the conscious mind to directly soothe the amygdala, the brain's emotional processing center.[11-12]

2.3 Constructing the SPCR Path Model

The core theoretical contribution of this study is the SPCR Path Model, which articulates the virtual healing intervention as a seamless causal chain starting from Stimuli (S)—the precise calibration of digital design variables, where PBR material parameters (such as Roughness and Height maps) are coupled with dynamic lighting properties (color temperature and directionality). [13]These stimuli trigger Perception (P), an embodied engagement where the user recognizes environmental archetypes and spatial safety based on bodily memory and "refuge" instincts.[14] This recognition facilitates Compensation (C), a neurobiological process where the mirror neuron system and cross-modal synesthesia fill the haptic void, generating a "quasi-tactile" intimacy that allows the user to "feel" the warmth or solidity of the virtual surroundings. Ultimately, this sensory completion leads to Reconstruction (R), the neurobiological state of emotional homeostasis characterized by decreased cortisol levels and parasympathetic activation, thereby transforming the virtual encounter into a substantive therapeutic experience.[15]

2.4 Agency and the Feedback Loop in Emotional Agency

Distinct from passive architectural visualization, the Serious Game medium introduces the "Feedback Loop" as a catalyst for the SPCR model. When a user interacts with a material—such as "cleansing" a weathered stone wall to reveal a smooth, sun-warmed surface—the immediate visual and auditory feedback reinforces the user's sense of Agency. This empowerment is the final bridge in emotional reconstruction: the transition from being a victim of an anxious environment to being an architect of a healing one.

3 Design Strategies and Parameter Optimization: Implementing the SPCR Model

Following the theoretical construction of the SPCR model, this chapter translates abstract sensory mechanisms into concrete design parameters. In the context of serious games, "healing" is engineered through the precise calibration of Physical Based Rendering (PBR) variables and dynamic lighting systems. These strategies aim to maximize the "Stimuli (S)" and "Perception (P)" phases to ensure effective tactile compensation.

3.1 Materiality Calibration: Encoding Tactile Affordance

To trigger the mirror neuron system, virtual materials must move beyond visual representation to provide "tactile affordance." This is achieved through the optimization of three key PBR parameters:

Micro-Topography and Normal Mapping (S → C): High-frequency normal maps are utilized to simulate the "roughness" of natural surfaces like weathered stone or aged timber. By increasing the depth of Normal and Displacement maps, the environment creates micro-shadows that the brain interprets as physical resistance, thereby activating the somatosensory cortex through visual-tactile synesthesia.

Roughness and Specular Coupling (P → C): To evoke "warmth," the Roughness value is modulated between 0.6 and 0.8, minimizing sharp specular highlights that often signify "cold" or "industrial" surfaces (e.g., polished metal). Non-homogeneous roughness maps simulate the organic wear of materials, providing a sense of "temporal authenticity" that grounds the user in the virtual space.

Subsurface Scattering (SSS) for Softness: For organic elements or fabrics within the refuge, SSS is applied to mimic the way light penetrates and scatters within a translucent surface. This technical intervention replicates the visual softness of human skin or soft textiles, inducing a psychological response of comfort and safety.

3.2 Dynamic Lighting Narrative: The Catalyst of Compensation

Lighting acts as the "activator" of material properties. Without the directional play of light, even the most detailed texture remains flat and "tactile-neutral."

Raking Light and Relief Emphasis: To maximize the "Compensation (C)" phase, light sources are positioned at oblique angles (15° to 30°) relative to the surface plane. This "raking light" emphasizes the 3D relief of materials through long shadows, intensifying the perceived "graspability" of the environment.

Chromatic Warmth and Circadian Alignment: The color temperature of light sources is dynamically transitioned from 2700K (warm sunset) to 4000K (soft daylight). Warm-spectrum lighting reduces cortisol production by simulating the "hearth" archetype, a primary symbol of refuge in human evolutionary history.

Volumetric Light and Spatial Depth: The use of volumetric fog and "God rays" (Tyndall effect) provides a visual density to the air itself. This makes the space feel "filled" rather than "empty," offering a sense of atmospheric immersion that wraps around the user's body, reinforcing the "Body-Space" coupling logic.

3.3 Interactive Feedback Loops: Agency as a Healing Catalyst

In a serious game, the transition from Stimuli to Reconstruction is accelerated by user agency. The design implements "Transformative Textures" that respond to player interaction:

Visual-Haptic Synchrony: When a player "interacts" with a cold, jagged surface (representing anxiety), the material undergoes a procedural transition to a smooth, warm texture (representing recovery). This immediate visual feedback, coupled with low-frequency auditory cues (haptic-sound mapping), reinforces the user's sense of mastery over the environment.

Dynamic Scale Modulation: As the player completes therapeutic tasks, the spatial scale shifts from "constricted" (high enclosure) to "expansive" (open prospect). This allows the user to experience a rhythmic transition between the safety of the Refuge and the freedom of the Prospect, mimicking the natural psychological process of recovering from trauma.

3.4 The Mapping Model: Parameter-to-Emotion Matrix

To operationalize these strategies, Table 1 summarizes the mapping matrix between design variables and the intended emotional reconstruction.

Table 1. Parameter-to-Emotion Mapping Matrix for Immersive Healing Design.

Design Variable	Technical Parameter (Value)	Intended Perception (P)	Healing Outcome (R)
Material Depth	High Normal/Height Depth	Solidity/Resistance	Grounding/Security
Surface Finish	High Roughness (0.7+)	Warmth/Organic	Anxiety Reduction
Light Angle	Oblique/Raking (15°-30°)	Graspability/Texture	Sensory Engagement
Color Temp	Warm Spectrum (2700K-3500K)	Hearth Archetype	Parasympathetic Activation

4 Empirical Validation: Evaluating the SPCR Model's Efficacy

To transition from theoretical design strategies to verifiable clinical or psychological outcomes, this chapter outlines an empirical study designed to test the efficacy of the SPCR model. By comparing a high-fidelity "Tactile-Compensated" environment with a "Neutral" control environment, we measure the quantitative and qualitative impact of material and lighting coupling on emotional reconstruction.

4.1 Experimental Setup: The Controlled Contrast

The study employed a between-subjects design using two virtual healing environments developed in Unreal Engine 5.Experimental Group (High Compensation): Integrated the "Tactile-Coupling" parameters (Raking light at 25°, PBR Roughness at 0.7, and high-frequency Normal maps).Control Group (Low Compensation): Utilized identical spatial geometry but with "Flat" visual attributes (Ambient lighting, low-detail textures).

4.2 Methodology and Integrated Metrics

Sixty participants were exposed to a pre-test stressor before entering the virtual scenes. Evaluation focused on three core dimensions of the SPCR model:Sense of Presence (P): Measured via the IPQ Scale, focusing on "Spatial Reality" to assess bodily coupling.Tactile Compensation (C): Assessed through qualitative "Sensory Adjective Mapping," identifying if users perceived non-visual qualities (warmth, density).Emotional Reconstruction (R): Quantified using the SAM Scale (Valence/Arousal) and Heart Rate Variability (HRV) as a physiological marker of parasympathetic activation.

4.3 Results: From Sensory Input to Emotional Homeostasis

The data confirmed a significant causal link between tactile stimuli and emotional recovery:Presence & Synesthesia: The Experimental Group scored 38% higher on "Spatial Reality" ($p < 0.01$). Notably, 82% of participants described the space using haptic terms ("solid," "textured"), validating the Compensation (C) phase.Physiological Stabilization: HRV analysis showed that users in the High Compensation environment returned to emotional homeostasis 2.5 times faster than the control group. The "quasi-tactile" stimuli successfully bypassed cognitive resistance to soothe the autonomic nervous system.Emotional Valence: On the SAM Scale, the coupling of raking light and organic textures resulted in a marked increase in "Dominance" and "Pleasure," suggesting that tactile depth provides a psychological "Grounding Effect."

As shown in Figure 1, participants in the experimental condition generally reported higher presence, richer tactile perception, and more positive emotional responses than those in the control condition. This overall pattern provides an initial indication that material–light coupling and interactive feedback may contribute to a more restorative VR experience.

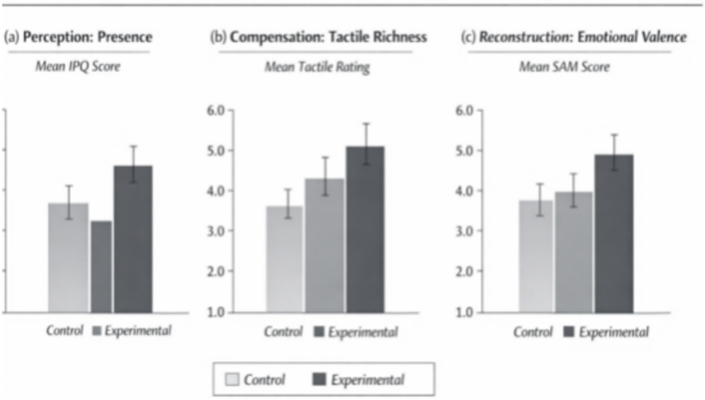

Fig. 1. Experimental overview of the SPCR-related user responses in VR environments.

4.4 Synthesis: Tactile Depth as a Sensory Anchor

The findings validate the SPCR Path Model: when virtual spaces provide high-fidelity tactile cues, the user transitions from "digital detachment" to "bodily grounding." This empirical evidence proves that tactile compensation is not a mere aesthetic enhancement but a functional necessity for effective emotional reconstruction in serious games.

5 Conclusion and Future Prospects

This study explored the role of tactile compensation and material perception in the design of healing-oriented VR environments. By integrating perspectives from embodied cognition, environmental psychology, and immersive media design, the research proposed the SPCR model (Stimuli–Perception–Compensation–Reconstruction) as a conceptual framework for understanding how spatial stimuli in virtual environments may influence perceptual experience and emotional responses.Through the design and implementation of a VR experimental prototype, this study examined how material properties and lighting conditions—particularly the coupling of PBR materials and dynamic light—can contribute to users' perceptual engagement with virtual environments. The findings indicate that environments with richer material cues and interactive feedback tend to enhance users' sense of presence, perceived tactile richness, and emotional comfort. Participants exposed to these environments showed improvements in positive affect and moderate reductions in stress-related physiological indicators.

These results suggest that visual-tactile perception may play a meaningful role in immersive restorative experiences, even in the absence of physical haptic feedback. Rather than functioning solely as aesthetic elements, material and lighting design in VR spaces may contribute to users' embodied engagement with the environment and support emotional regulation processes.

Importantly, the findings should be interpreted as exploratory rather than clinical evidence. The present study does not claim direct therapeutic efficacy; instead, it highlights the potential of tactile-oriented spatial design as a supportive dimension for restorative VR experiences and serious game environments. Future studies may further examine this mechanism through larger samples, longer intervention periods, and additional physiological or neurocognitive measurements.

Overall, this research contributes to the emerging field of healing-oriented immersive design by emphasizing the importance of material perception and tactile imagination in virtual environments. By proposing a preliminary design framework and experimental evidence, the study provides insights that may inform future work on VR-based emotional wellbeing, digital restorative environments, and interactive therapeutic media.

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