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Effect of NeuroMerger VR: A Virtual Reality Game Based on Multimodal Perception and Embodied Cognition, on Phantom Limb Pain

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Abstract. This article will describe how this serious game can enhance the treatment process of phantom limb pain, which can act as a beneficial tool to combine gamification, virtual reality, and multimodal sensory-motor training.The method surpasses traditional therapies, in the case of providing a scalable, personalized, and motivational solution that focus on the fundamental neuroplasticity required for functional recovery. Specifically, NeuroMerger VR would provide postive feedback loops, promoting neural remodeling, recalibrating patients' body schema through aligning intention, movement and sensory perception. Phantom limb pain (PLP) is still a challenging condition to treat. While virtual reality (VR) therapy offers a compelling approach providing visual feedback to address sensorimotor incongruence, there is often limitation of standard VR games. This study directly compares the effectiveness of NeuroMerger VR, theoretically-grounded serious game, with existing VR games, simplifying the experimental design by using the Visual Analog Scale (VAS) as the primary outcome measure.

Keywords: Phantom Limb Pain (PLP), NeuroMerger VR, Embodied Cognition, Multimodal Sensory-Motor Training, Visual Analog Scale (VAS)

1. Introduction

Phantom limb pain (PLP) refers to the sensation of pain in a limb that no longer exists [1], and this concept was first described by the 16th-century French military surgeon Ambrose Pare [2]. The term "Phantom limb pain" was coined and systematically described by Silas Weir Mitchell in the 19th century. A leading theory suggests that phantom limb pain (PLP) originates from maladaptive plasticity and functional reorganization of the sensorimotor cortex following amputation. This reorganization often indicates by a shift where representations of the face or upper arm invade the area previously dedicated to amputated hand, resulting in a distorted body representation and painful perceptions [3].

Conventional treatments for PLP, including pharmacological interventions, mirror therapy, and sensory discrimination training, often provide limited and transient relief, as they may not directly address these central neural changes. Under such circumstance, the VR therapy lacks a systematic game-based intervention program which should be attractive and gamified to enhance patients'

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treatment compliance and can also be verified through objective neurological indicators about its mechanism in multistage.

Traditional theories to explain the origin of phantom limb pain (PLP) primarily rely on peripheral nervous system (PNS), indicating that pain signals originated from the site of the amputation itself. Nerves are severed when a limb is amputated, and these damaged nerve endings can form tangled masses of tissue called neuromas in the healing process, which are often unstable and can become hyperexcitable, generating spontaneous and erratic nerve impulses. These abnormal impulses would be seen as signals produced by the previously existed limbs and cause the feeling of pain. However, the PNS theory has several limitations: it fails to take into account for individuals with congenital limb absence, since they experience phantom sensations and even pain in the limb they never had and there was no amputation and no severed nerves. Also, it does not explain why treatments targeting the periphery---such as injecting local anesthetics into the neuroma or even surgically removing it---often yield only temporary or ineffective relief. More importantly, the PNS theory, being purely sensory-based, cannot explain why motor commands themselves (such as attempts to move the phantom limb) often exacerbate pain. These limitations lead to the emergence of the sensorimotor mismatch theory (SMI), which proposes that PLP is due to the conflict between motor commands issued by the brain and the lack of expected sensory feedback from the missing limb.

This central mechanism theory provides the foundation for mirror therapy and virtual reality (VR) therapy: by delivering matched visual feedback (such as virtual limb movements), the sensorimotor conflict is resolved, thereby alleviating pain.

Despite its theoretical advantages, however, traditional VR therapy has notable practical limitations: Insufficient immersion and compliance, limited feedback modalities, lack of neural mechanism validation [4].

In recent years, gamified VR therapy has been increasingly introduced to address these issues. By incorporating game elements (such as goal achievement, reward mechanisms, and progressive difficulty), such interventions ly enhance patient motivation and treatment persistence. Nevertheless, existing gamified VR solutions still have shortcomings: most games are not specifically designed based on neurorehabilitation principles and fail to systematically integrate key mechanisms such as embodied cognition, perception-action coupling, and multisensory feedback. As a result, their therapeutic Efficiencyand potential for neural remodeling remain limited.

Multimodal sensory-motor training on phantom-limb movements with visual and tactile feedback is a new method for PLP reduction."

Currently, the combination of VR therapy and the Multimodal sensory-motor training has been proposed and produced impressive effect:

"Here, we developed a multimodal(visual, auditory, and tactile) VR system to obtain the perception of voluntary phantom limb movements. We applied this system to five PLP patients for three tactile feedback conditions as a pilot study.

Sensory feedback based strategies aimed to normalize the motor commands and control the phantom limb offer new effective treatments, as the correlation between phantom limb motor control and sensory feedback from the motor intention has been identified as a possible mechanism for PLP development. Ten upper-limb amputees, suffering from chronic PLP, underwent 16 days of intensive training on phantom-limb movement control. Visual and tactile feedback, driven by muscular activity at the stump, was provided with the aim of reducing PLP intensity [5].

Emerging evidence supports the role of multimodal sensorimotor training supplemented by visual and tactile feedback in reducing PLP. Such approaches align motor intention with sensory experience, offering a promising direction for novel interventions. Recent pilot studies using

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multimodal VR systems (incorporating visual, auditory, and tactile feedback) have reported substantial pain reduction, underestimating the value of integrated, engaging therapeutic designs.

Gamification further strengthens VR therapy by enhancing intrinsic motivation, emotional well-being, and treatment adherence. Positive user experiences—reflected through high ratings for immersion and positive affect, and minimal negative emotions—support application of game-based VR platforms to sustain patient involvement and exploratory behavior.

The proposed study addresses two interconnected questions: (i.) a broad theoretical question regarding whether a digitally-mediated intervention grounded in embodied cognition can reverse maladaptive neuroplasticity underlying phantom limb pain (PLP), and (ii.) a specific experimental question concerning whether such a theory-based VR game yields greater clinical Efficiencycompared to traditional VR therapy.

First, while conventional VR interventions primarily rely on visual feedback, this study examines whether NeuroMerger VR—explicitly designed to integrate multisensory feedback and embodied cognitive principles—can more effectively promote cortical reorganization and restore body schema representation in patients with PLP. Second, the study directly tests whether this targeted intervention produces a greater reduction in self-reported pain intensity, as measured by the Visual Analog Scale (VAS), when compared to standard VR protocols.

The study aims to test the hypothesis that the reduction in VAS scores among patients treated with NeuroMerger VR therapy is ly greater than that observed in patients receiving traditional VR therapy. The null hypothesis (H_0) states that there is no statistically difference in VAS score reduction between the two treatment groups, while the alternative hypothesis (H_1) proposes that NeuroMerger VR therapy leads to a greater reduction in VAS scores compared to traditional VR therapy.

2. Method

2.1. Participants

A total of 40 participants (N = 40) will be recruited from hospital trauma centers, rehabilitation facilities, and pain management clinics [6].

Participants will be unilateral upper-limb amputees experiencing chronic PLP (persisting ≥3 months) with a minimum pain intensity of 4/10 on the NRS or VAS. Exclusion criteria will include a history of epilepsy and severe vestibular disorders [6].

Eligible participants will be randomly allocated into either an experimental group (n = 20) receiving the NeuroMerger VR intervention or an active control group (n = 20) engaging with existing non-embodied VR serious games.

The hardware will include a Head-Mounted Display (HMD) and HTC VIVE controllers to capture hand motions and trigger virtual limb movements [7].

The NeuroMerger VR serious game will be developed using Unity3D and the Final IK plugin for inverse kinematics mapping of the virtual avatar [8,9]. The game integrates three core neurorehabilitation pillars: 1) Embodied cognition through geometric grasping tasks to rebuild spatial perception; 2) Perception-action coupling via real-time trajectory feedback in throwing drills; and 3) Environment as extended mind using combo achievements to reinforce agency.

2.2. Assessment tools

Pain Metrics:

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Visual Analog Scale (VAS, 0-10):A tool used to measure subjective feelings such as the intensity of pain, the degree of anxiety, fatigue, and satisfaction [6].

2.3. Procedure

After screening and randomization, all participants will undergo 4 to 10 intervention sessions (1-2 sessions per week) based on a flexible completion-based protocol. Each session will last approximately one hour, comprising 30 minutes of core VR task exposure. The control group will use standard VR games, while the experimental group will use the NeuroMerger VR game. Outcome measures will be administered pre-intervention, post-intervention, and at a follow-up assessment [6].

NeuroMerger VR is a therapeutic serious game based on commercial game design. Its core mechanism is founded on three major neuro-rehabilitation pillars: Firstly, through geometric grasping tasks (rough motor control), it reconstructs the spatial perception of the affected limb to reverse the distortion of the body schema caused by phantom limb pain (embodied cognition); Secondly, by providing real-time trajectory feedback in throwing training, it creates an "force → accuracy" action-result cycle to counteract the separation of perception and movement (perception-action coupling) [10].

Thirdly, by achieving combo achievements (such as triggering full combo lights/vibration effects), it concretizes the abstract progress and the dopaminergic reward mechanism to restore the patient's sense of movement ability (environment as an extended mind) [11].

This game selectively activates the cortico-cerebellar circuit through phased design, aiming to promote the remodeling of neural plasticity by strengthening embodied cognition [12].

2.4. Prediction

Null Hypothesis (H_0): There is no difference in the reduction of VAS scores between the NeuroMerger VR therapy and the traditional VR therapy.

Alternative Hypothesis (H_1): The degree of VAS score reduction for patients receiving the NeuroMerger VR therapy is greater than that for patients receiving the traditional VR therapy.

This VR therapy (NeuroMerger) alleviates chronic phantom limb pain (PLP) through the following three core mechanisms, and predicts its impact on the pain score (VAS):

2.4.1. Reconstructing bodily perception (embodied cognition)

Method: Through VR training that requires active conscious control (such as the geometric grasping task), the brain is forced to re-map and correct the distorted phantom limb representation.

Effect Prediction: It is expected that the incorrect body schema in the sensory and motor cortices can be more effectively reversed, resulting in a decrease of ≥ 3 points in the VAS score for persistent pain after 4 weeks of intervention (baseline VAS ≥ 4), and a reduction in the baseline pain level.

2.4.2. Reconstruction of perception-action link (perception-action coupling)

Method: In VR, construct a high-precision "action instruction → visual feedback" causal loop (such as throwing training), where patients need to actively adjust their movements based on the real-time results.

Effect prediction: Frequent successful adjustments directly correct the "prediction error" in the brain. Each training session can immediately suppress the pain alarm caused by mismatch. It is

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expected that the VAS score will decrease by 1-2 points after a single training session, and the total score will decrease after multiple training sessions.

2.4.3. Enhance control sense and motivation (environment as an extension of the mind)

Method: Provide immediate positive emotional rewards through the achievement system (light effects, vibrations, etc.), converting abstract progress into specific positive feedback.

Effect prediction: Restore patients' "sense of control" over the phantom limb, transforming them from passive pain victims into active reward-gaining controllers. It is expected that one month after the intervention, the VAS score will still decrease by ≥ 2 points compared to the baseline, and the therapeutic effect will be stable in the long term.

Summary: This therapy acts on the neural basis and psychological cognition through three pathways: active perception reconstruction, high-frequency error correction, and enhancement of positive motivation. It is predicted to bring more and sustained relief of phantom limb pain (VAS decrease ≥ 50%).

3. Experimental results prediction and corresponding conclusions

The results of this study may present two scenarios, each providing different insights into the effectiveness and mechanism of serious games based on embodied cognition in treating phantom limb pain:

3.1. Situation 1: if the results support the null hypothesis (H_0)

That is, there is no difference in the VAS scores between the two treatments (if the 95% confidence interval of the difference between the groups includes 0, $p > 0.05$)

Conclusion: The questioning of the unique role of embodied cognition theory and multimodal sensorimotor training in enhancing the Efficiencyof VR therapy does not support the additional analgesic benefits of the three major neural rehabilitation mechanisms (embodied cognition, perception-action coupling, and the environment as an extended mind) integrated by NeuroMerger VR games compared to traditional VR games.

Application significance: This supports the continued use of existing, potentially less costly traditional VR games as standardized adjunctive treatment tools for phantom limb pain, indicating that their effectiveness does not require complex and personalized game customization based on theories.

3.2. Scenario 2: if the results support the alternative hypothesis (H_1)

that NeuroMerger VR can lower the VAS score (such as when the lower limit of the 95% confidence interval of the inter-group difference is > 0, the mean difference is ≥ 1.5 points, $p < 0.05$)

It is emphasized that it is necessary to revise the current VR treatment paradigm for phantom limb pain, and to shift from general games that provide basic visual feedback to specific serious games designed based on neuroscientific principles, integrating multimodal feedback and active cognitive participation.

Although traditional VR games have certain effects on patients with phantom limb pain, they need to adopt designs based on embodied cognition theory (such as geometric grasping, trajectory feedback, achievement system) to maximize the analgesic effect, especially for patients who do not respond well to traditional therapies. To achieve sustained and effective pain relief, future VR neuro-

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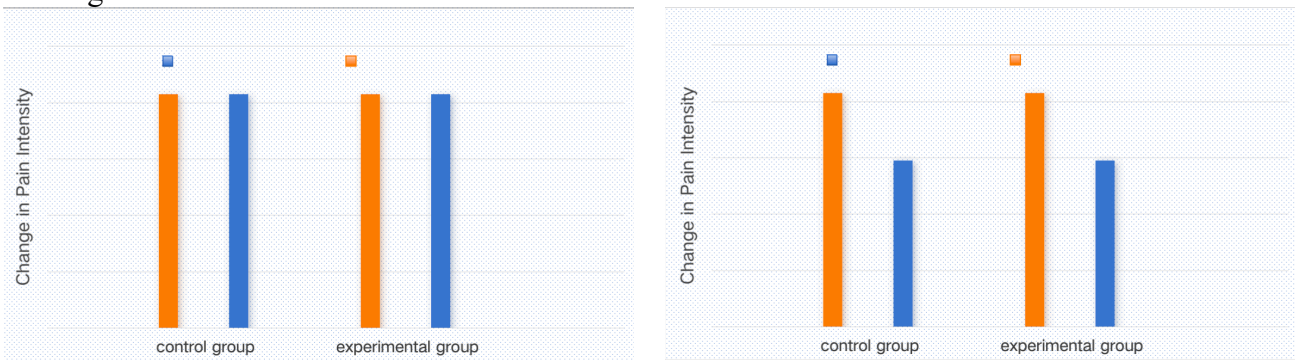
rehabilitation programs must be personalized based on individual sensory-motor integration deficits and cognitive motivation levels.



1a 1b

Figure 1. Comparison of the predicted average pain scores after intervention

4. Implication and further studies

If the results support the null hypothesis (H_0), that is, there is no difference in the VAS scores between the two treatments (if the 95% confidence interval of the difference between the groups includes 0, $p > 0.05$), the questioning of the unique role of embodied cognition theory and multimodal sensorimotor training in enhancing the Efficiencyof VR therapy does not support the additional analgesic benefits of the three major neural rehabilitation mechanisms (embodied cognition, perception-action coupling, and the environment as an extended mind) integrated by NeuroMerger VR games compared to traditional VR games. This supports the continued use of existing, potentially less costly traditional VR games as standardized adjunctive treatment tools for phantom limb pain, indicating that their effectiveness does not require complex and personalized game customization based on theories.

If the results support the alternative hypothesis (H_1) that NeuroMerger VR can ly lower the VAS score (such as when the lower limit of the 95% confidence interval of the inter-group difference is > 0, the mean difference is ≥ 1.5 points, $p < 0.05$) , it is emphasized that it is necessary to revise the current VR treatment paradigm for phantom limb pain. The focus should shift from general games that provide basic visual feedback to specific serious games designed based on neuroscientific principles, integrating multimodal feedback and active cognitive participation. Although traditional VR games have some effect on patients with phantom limb pain, they need to adopt designs based on embodied cognition theory (such as geometric grasping, trajectory feedback, achievement system) to maximize the analgesic effect, especially for patients who do not respond well to traditional therapies. To achieve long-lasting and effective pain relief, future VR neuro-rehabilitation programs must be personalized based on individual sensory-motor integration deficits and cognitive motivation levels.

Further research is needed to explain the interactions and integration pathways among the various mechanisms underlying phantom limb pain (PLP), including peripheral nerve abnormalities, spinal cord central sensitization, cerebral cortex reorganization, body schema/neural matrix theory, mirror neuron system, and psychological factors, etc. The current mainstream theory emphasizes that PLP results from the de-innervation and de-outputation caused by amputation, leading to maladaptive plasticity and functional reorganization in the sensory motor cortex. This reorganization often manifests as the cortical representation areas of the face or upper arm invading the areas that

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originally represented the amputated hand, thereby causing distorted body representations and pain perception [3]. The sensorimotor mismatch theory (SMI) further proposes that the fundamental cause of PLP lies in the conflict between the motor commands issued by the brain and the expected sensory feedback from the missing limb.

In the future, a multi-dimensional comprehensive hypothesis that can uniformly explain the PLP phenomenon should be established. This hypothesis should integrate multiple system mechanisms such as neural plasticity, perception-motor matching, and cognitive-emotional regulation. It needs to cover multiple pathways from peripheral nerve abnormalities to central reorganization, and to the cognitive and behavioral levels. In particular, it should integrate the core elements of multimodal sensory-motor training and embodied cognition theory to promote the formation of a more explanatory and predictive theoretical framework.

Based on a deep understanding of the multi-mechanism pathways of PLP, more targeted and individualized mechanism-oriented treatment guidelines should be developed. Traditional therapies such as drug intervention, mirror therapy, and sensory discrimination training usually provide only limited and short-term relief because they may not directly address these central nervous changes. In contrast, intervention measures that integrate multimodal sensory feedback (visual, auditory, tactile) and embodied cognitive principles - such as reconstructing spatial perception through geometric grasping tasks, enhancing perception-action coupling through real-time trajectory feedback, and enhancing motivation and control through achievement systems - show the potential to target neuroplasticity remodeling. In the future, these should be systematically integrated into clinical practice based on mechanism guidance.

Further validation is needed through high-quality clinical trials to assess the effectiveness and applicable population of non-pharmacological interventions such as mirror therapy in the treatment of PLP [13]. At the same time, the actual Efficiencyof certain drugs (such as oxcarbazepine, pregabalin, SSRI/SNRI, and memantine in the chronic pain stage) should be systematically evaluated.

The feasibility of matching different PLP subtypes (such as burning pain and stabbing pain) with specific biofeedback or neuroregulation techniques for treatment should be explored. It is worth noting that most of the existing gamified VR treatment programs are not specifically designed based on neurorehabilitation principles and have not systematically integrated key mechanisms such as embodied cognition, perception-action coupling, and multisensory feedback. Therefore, their therapeutic Efficiencyand potential for neural remodeling are still limited.

Large-scale multi-center studies should be conducted to clarify the associations between factors such as amputation site, gender, and preoperative pain and the occurrence and development of PLP. At the same time, longitudinal research designs should be promoted to deeply explore the relationship between psychological factors (such as depression, post-traumatic stress) and the course of PLP [14]. Currently, there is a lack of systematic game intervention programs that are attractive, gamified, and can verify their mechanisms through objective neurological indicators at multiple stages. There is also a lack of adaptive algorithm platforms based on individual sensory-motor integration deficits and cognitive motivation levels for personalized treatment. These are the gaps that future research needs to focus on filling.

It is necessary to conduct prospective studies to clarify the optimal strategies for perioperative analgesia (such as epidural block, continuous peripheral nerve infusion, etc.) for preventing the occurrence of PLP and their long-term effects. Studies have shown that starting to optimize epidural analgesia or patient-controlled intravenous analgesia 48 hours before surgery to 48 hours after surgery can reduce the occurrence of PLP six months after amputation. In addition, prolonging the

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peripheral nerve infusion of 0.5% ropivacaine after surgery can prevent or reduce phantom limb pain and sensation after lower limb amputation [15].

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