Integration of VR in neuroplasticity.

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Immersive Media Technologies
Project Exegesis

Abstract

Objective: To implement neuroplasticity rehabilitation virtual reality activities on post-stroke patients suffering from paralysis.

Methodology

Conceptualization: Review the process of rehabilitation especially after stroke, while exploring the principles of neuroplasticity along with interventions that lead to its induction. In addition, discover a research gap and investigate virtual reality and its incorporation in the rehabilitation space.

Design: Formulate a VR artefact based on visuomotor imagery intervention, leading to primitive cortical rearrangement for stroke survivors. The scene should incorporate an avatar that can be operated using one controller for stroke patients who have suffered paralysis on one side of their body.

Evaluation: Test the artefact from a patient's standpoint and report limitations while suggesting components to be added in the future for enhancement

Expected Outcome: The project expects to induce cortical restructuring in aiding motor recovery. The future findings from this project could lead to the introduction of an innovative solution to neurorehabilitation.

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Introduction

In the realm of modern health care, the search for novel and effective methods for physical rehabilitation has been an ongoing endeavour. Strokes have seen an uprise in recent years, especially in young adults, a 38% rise in strokes was recorded between 2004 and 2018 in Americans aged between 18 and 44 years (Bako et al. 2022). In Australia, according to doctor certified deaths, an average 6.15% of all deaths between 2019 and 2022 were due to cerebrovascular diseases (Australian Bureau of Statistics 2023). Conditions affecting blood supply to the brain due to any damage to the blood vessel is referred to as cerebrovascular disease, with stroke being the most notable form (Australian Institute of Health and Welfare 2015). Strokes often lead to acute motor impairments, in several muscle groups and can severely impact the quality of life of the patients (Bower et al. 2015 as cited in Brepohl & Leite 2022). Physiotherapy and Occupational Therapy are two common rehabilitation practices after stroke, where occupational therapy involves helping patients with everyday tasks whilst identifying their strengths and weakness and providing feasible solutions (Occupational Therapy Australia 2023). Whereas, physiotherapy helps patients recover their muscle mobility, but in its current format has been reported to be monotonous and has seen patients abandoning their treatments (Brepohl & Leite 2022). There are various interventions in neurorehabilitation that can help with motor recovery post-stroke but need further clinical investigation. With rising cases of strokes, the demand for innovative approaches to enhance traditional rehabilitation methods is also on the rise (Brepohl & Leite 2022).

One innovative advancement that has gained a considerable amount of interest recently is the integration of Virtual Reality (VR) with rehabilitation. VR has exponentially gained popularity over the past decade with its growing accessibility and capabilities to provide tailored visual content. It permits users to experience computer-generated environments using a Head Mounted Display (HMD), by visually travelling and interacting with their perceivable surroundings using trackers and controllers, respectively. The initial attempts at harnessing the potentials of VR were focused towards enhancing entertainment experiences such as the Sensorama, which was created to shape the future of cinema, and the numerous attempts made by the gaming industry including Nintendo and Sega in the 1970s and 80s to develop a VR headset for gaming. But VR has since seen a magnification of its employability across a series of diverse occupations including rehabilitation where it has been observed to emerge as a promising tool (Glegg & Levac 2018).

This paper aims to explore the intersection of VR, rehabilitation and the concept of neuroplasticity, and provide an overview of their emergence through a literature review of existing research regarding inducing neuroplasticity and providing evidence supporting the effectiveness of VR in improving motor functionality across patients. This piece also aspires to address the benefits of VR in chronic pain management and engagement which would help understand the fundamentals of creating a tailored VR experience for stroke rehabilitation.

Rehabilitation

The World Health Organization describes rehabilitation as a practice that includes a set of interventions that help reduce disabilities by the optimization of the physical functionalities of individuals with conditions that affect the way they interact with their environment. Rehabilitation allows an individual regardless of age, to become as independent in carrying out simple or complex tasks as possible (WHO 2023). This is done by identifying symptoms and conditions, and accordingly providing the patients with environment modifications, supportive devices, and necessary education to self-manage and adapt to tasks to perform them safely (WHO 2023). The need for rehabilitation could transpire from several causes including but not limited to cardiac, respiratory or neurological conditions, fractures, cancer (Wade 2020), or simply age. Depending on the severity of the condition, health professionals across various expertise in the rehabilitation help determine rehabilitation 'goals' and prescribe the best setting they might receive their therapy dosage to achieve their goals such as inpatient, outpatient, or even at your home (SA Health 2017). Inpatient care is usually recommended for patients that require "intense, multidisciplinary rehabilitation intervention" (Department of Health 2015). Outpatient rehabilitation is intended for patients who don't require more than one kind of therapist (American Heart Association 2019) and can receive treatment individually or in a group setting (Agency for Clinical Innovation 2020).

The province of rehabilitation is vast and requires a huge workforce of therapists specialising in specific body segments and their functionalities like allied health assistant, dietitian, prosthetists, audiologists, speech therapists, occupational therapists, physiotherapists, Neuro-psychologist, social worker, etc (Agency for Clinical Innovation 2020). Even general physicians retain primordial rehabilitation information for minor occurrences. Rehabilitation is imperative post-stroke to salvage any disturbed functionality, and physiotherapy is considered to be the most popular form of rehabilitation after stroke (NIH 2023). However, the complex nature of rehabilitation specifically the assimilation of physiotherapy and neurological sciences needs prior understanding, which the successive parts of this paper provide.

Physiotherapy

Traditional physiotherapy relies on a combination of practices including variations of manual therapy and therapeutic exercises. Manual therapy or therapeutic massage approach involves manually mobilizing joints, manipulating muscles, and providing soft tissue therapy that helps decrease pain and improve mobility of the treated areas (Trigg 2022). Therapeutic exercises, on the other hand, incorporate a series of intensive movements that need to be performed by the patients with repetition, which facilitates them in strengthening their damaged body parts (Trigg 2022). Education is also seen as an important tool on the road to rehabilitation as it is imperative patients understand the gravity of their circumstances and practice safe exercise (WHO 2023). The severity of the injury or ailment determines how long the therapy lasts, with intensity advancing as treatment progresses (WHO 2023). All together the purpose of physiotherapy is the development, restoration and maintenance of functional and movement abilities that may be affected due to factors including injury, disorders, disease, ageing, conditions, ageing, etc. (Porter & Tidy 2009, p. 4).

Since the proposed Continuum Theory, movement remains to be the core objective of physiotherapy. Continuum theory conceptualized eight principles and unites pathology and holistic views towards movement which is argued to be affected by the influence of social, physical and psychological factors (Cott et al. 1995). The theory also addresses the "maximum achievable movement potential" which is the hypothetical "upper limit" and while this is physiologically and psychologically the maximum potential of movement set by an individual, it is certainly not the levels at which humans consistently function (Cott et al. 1995). The "preferred movement capability" (PMC) is what we perform daily tasks with, whereas the "current movement capability" (CMC) which in most situations is the same as the PMC, but when impacted, leads to the need for physiotherapy as the foremost goal for physiotherapy is to reduce the discrepancy between CMC and PMC (Cott et al. 1995 as cited in Porter & Tidy 2009, p. 4). The severest of cases in which the disparity between CMC and PMC is most affected is when a patient suffers paralysis, usually as an aftermath of a stroke.

Occupational Therapy

Stroke

There are two kinds of stroke, Ischemic and Haemorrhagic with ischemic reported to be the most common kind (Gomes & Wachsman 2013), as it accounts for 87% of all strokes and is caused by the obstruction of a blood vessel, transporting blood to the brain because of clot formation (American Stroke Association 2019). Haemorrhagic stroke transpires when a weak blood vessel ruptures and leads to bleeding into neighbouring brain tissue (American Stroke Association 2019). The two types of haemorrhagic strokes namely subarachnoid haemorrhage which occurs due to accumulation of blood in spaces that usually withhold cerebrospinal fluid, and intracerebral haemorrhage where blood directly spreads to neighbouring tissues, are known to have a much higher mortality rate compared to ischemic strokes (Gomes & Wachsman 2013). Transient Ischemic Attack or a "mini-stroke" occurs when a transient clot forms and causes a temporary disruption in blood flow to the brain and is usually taken as a warning sign for a future stroke while being treated like a major stroke (Centers for Disease Control and Prevention 2022).

A stroke can cause serious motor impairments if it impacts the control and balance regulator part of the brain leading to paresis i.e., weakness, or worse paralysis (NIH 2023). Paralysis and paresis can impact individual parts of the body such only an arm, leg, face, or the entire upper, lower or either side of the body in case of neglect syndrome (NIH 2023). Neglect syndrome stems from complications with cognitive functioning as another possible byproduct of a stroke, where the patient has no knowledge or recollection of one side of their body, making it problematic for them to perform even the simplest of tasks like eating, walking, or even using the bathroom (NIH 2023). Some other common poststroke effects include speech issues – problems with understanding and speaking as a result of severe nerve damage and damage to the left hemisphere of the brain, portraying emotion or expressing the wrong emotion, sensation, and pain – distressing numbness, pain or unfamiliar sensations can develop from harm to the brain's sensory region (NIH 2023).

Poststroke Statistics

Strokes are the number one cause of critical disability in adults worldwide (NIH 2023). The level of recovery post-stroke depends on the severity and disposition of initial diminution since permanent impairment can be caused within minutes to hours if the patient is not attended to (Dobkin 2005, NIH 2023). The survival rate post stroke significantly drops from 79.4% after 3 months vs 36.4% after 10 years (Peng et al. 2022). Post 6 months, integration of the affected hand is not achievable for 65% of the survivors into their daily activities (Dobkin 2005). Around 50% of stroke survivors suffer from “paretic upper extremity” post-stroke for up to 6 months, and only between 5 - 20 per cent of this population recover full upper extremity functionality (Lohse et al. 2013). Recovery post stroke occurs spontaneously especially during the first 30 days, but patients with modest to critical impairments can experience additional recovery even after 3 months (Alawieh, Zhao & Feng 2018). More recent studies have shown that it is possible for patients to continue recuperating for even up to a year after the stroke (NIH 2023). Only 25% of survivors are observed to physically function at levels that of a person unaffected by a stroke (Dobkin 2005).

Neurological Rehabilitation

In spite of knowing the advantages of physiotherapy, it can be extremely challenging for patients with limited motor skills to engage in it making it difficult to provide relevant stimuli for experience-based neural plasticity for neurorehabilitation (Garrison et al. 2010). Neurological rehabilitation, unlike investigative neurology, extends beyond the impairments and delves into functional repercussions to minimize the effects of disability on the patient’s well-being (Barnes 2003). Any formulated improvements within successive weeks following the stroke signify the restoration of neurotransmission in unaffected tissue near and away from the stroke-affected area caused by either haemorrhage or infarct (Dobkin 2005). However, progress in linguistic, cognitive, and motor skills can occur through cerebral mechanisms involved in common learning (Dobkin 2005). Increased excitability and engagement of neurons in both hemispheres of the brain are aspects of experience-driven neuroplasticity, contributing to improvement in performance, the growth of dendrites that connect neurons to other neurons, and the strengthening of these synaptic connections (Dobkin 2005). Improvement in patients’ skills has been confirmed via functional neuroimaging studies intimating cerebral activations in both hemispheres (Dobkin 2005).

Neuroplasticity

Neuroplasticity can be broadly characterized as the nervous system’s ability to respond to both internal and external stimuli by reconfiguring its interconnections, function, and overall composition (Cramer et al. 2011). In the field of cognitive neuroscience, research has made great advancements towards mapping the human brain and identifying its functions, representational components, and knowledge (Grafman 2000). According to neuroanatomy, every body part corresponds along the precentral gyrus, the primary motor cortex responsible for voluntary physical movement, which is topographically represented by the motor homunculus (Nguyen & Duong 2022) (see image 1). Similarly, the sensory homunculus represents the topography of the sensory distribution of the body (Nguyen & Duong 2022) (see image 1). At least 4 primary forms of functional neuroplasticity have been examined in humans namely: “homologous area adaption, cross-modal reassignment, map expansion, and compensatory masquerade” (Grafman 2000). This phenomenon can be comprehensively interpreted at various levels spanning from the molecular and cellular levels to systems and even observable behaviours (Cramer et al. 2011).

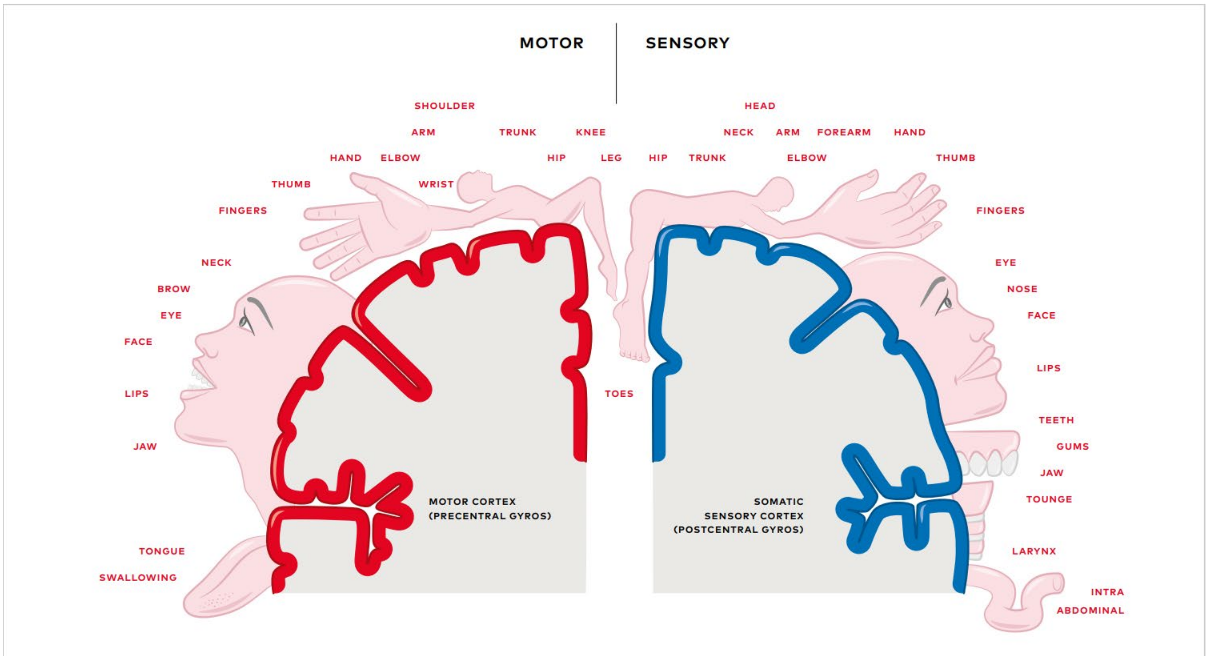

Image 1 (Nicholas, Johannessen & Trees Van Nunen 2019, p. 36)

Neuroplasticity has been observed to transpire in response to various situations such as during developmental phases, environment modifications, facilitation of learning processes, illness, and therapeutic interventions (Cramer et al. 2011). Motor recovery having been extensively studied suggests that the motor homunculus can experience spontaneous intra-hemispheric changes as a result of any damage to the region, resulting in the alteration of the topography, meaning the hand zone can shift into the shoulder or even the face zone (Cramer et al. 2011). Parallelly, the balance of the inter-hemisphere can shift to the extent where the uninjured hemisphere transcends the normal amount of movement activity (Cramer et al. 2011, Grafman 2000). This leads to overcrowding of the “new brain area” having accepted new cognitive function which squeezes the interpretation of knowledge within the modified module (Grafman 2000). In this case the potential of interference increases during the simultaneous execution of tasks that require the usage of adjacent zones in the cortex, one of which is transported from its natural location.

The following are instances that provide functional evidence of neuroplasticity: research regarding a young 7-month child incurring a severe injury including a skull fracture and a temporal haemorrhage grew up to develop relatively normal visuospatial skills (Levin et al. 1996). The functional MRI (fMRI) scans confirmed the interhemispheric transfer of visuospatial skills to the left parietal region from its natural placement which is the right parietal region (Levin et al. 1996). However, the child was also diagnosed with dyslexia and dyscalculia, suggesting left parietal dysfunction caused due to the competition between visuospatial and verbal functions in the left hemisphere (Levin et al. 1996). Another study conducted by Fuji and Nakada (2003) observed similar results when the fMRI scans depicted a shift of the right-hand grasping motion laterally to the right hemisphere, accompanied by augmented utilization of the left posterior premotor cortex and the bilateral supplementary motor region in a patient with right hemiparesis, which in a healthy cortex is generated primarily in the left motor cortex (Fujii & Nakada 2003 as cited in Cramer et al. 2011). In addition, various other studies have reported several patterns of map reorganisation following a stroke, and when it comes to reorganisation of the motor functions for the upper extremity, the most common shifts observed were towards the ventral or the posterior direction (Cramer et al. 2011).

While the notions of neuroplasticity have been confirmed, it has been also suggested that not all plasticity produces positive results and can have negative impacts. For example, new epilepsy cases are frequently found to arise following cerebral damage, often exhibiting months or even years after the initial injury. This deferred commencement implies that continuous modifications within the brain, like axonal germination and the creation of new connections, produce changes in disinhibition and neuron signalling, which can trigger seizures (Prince et al. 2009 as cited in Cramer et al. 2011). Other instances indicative of maladaptive plasticity encompass allodynia and persistent pain after limb injuries like amputation, or damage to the central nervous system (CNS) which is followed by dystonia, and cases of autonomic dysreflexia after spinal cord injury have also been reported. Hence, a combination of adaptive and maladaptive plasticity is recommended for recovery from trauma or disease which can occur alongside.

Inducing Neuroplasticity

Neuroplasticity can be time-dependent, fluctuate in response to environmental factors, exhibit specificity, and be compellingly influenced by the level of simultaneous training (Cramer et al. 2011). Promising interventions already exist that target the promotion of neuroplasticity including the Hebbian principle, mechanisms related to verbal encoding, social influences, and task-specific training. These interventions are implemented with careful incorporation of the comprehensive principles of neuroplasticity (Kleim and Jones, 2008 as cited in Cramer et al. 2011). Engaging in skill-specific training has been demonstrated to augment behavioural outcomes along with enhanced brain plasticity making it a definite instance of harnessing neuroplasticity (Cramer et al. 2011). The degree to which the outcomes can be improved through training and plasticity is directly dependent on the presence of adequate remaining neural assets irrespective of the duration or nature of the brain injury (Riley et al. 2011 as cited in Cramer et al. 2011). Whilst these interventions have come across as positive, practices such as invasive and non-invasive stimulations (Wagner et al. 2007), cognitive training, neuropharmacology (Floel & Cohen 2010), and physiotherapy have been confirmed by numerous studies to induce neuroplasticity.

Non-invasive brain stimulation includes transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) that incorporate different electromagnetic principles to noninvasively induce brain activity via scalp electrodes (Wagner et al. 2007). The principle of electromagnetic provocation is also shared by methods of deep brain stimulation, which is an invasive stimulation process, but unlike TMS and tDCS, deep brain stimulation uses implanted electrodes to transport electrical current to induce behavioural alterations (Cramer et al. 2011). When directed towards optimal stimulation spots, deep brain stimulation can have effects on emotion, behaviour and thought (Cramer et al., 2011)

Motor Imagery

This phenomenon is identified as the process of rehearsing a physical act mentally without actually performing the physical movement (Allami et al. 2007). Early discussions regarding “imagined practice” argued its effects as an interest booster and anxiety reducer whilst also as an aid to subjects in their preparation for performing actions at strategic and motivational levels but provided reasons for uncertainty about the available data and called for a persuasive demonstration to confirm the effects of imagined practice (Winters & Reisberg 1985). Further claims discussed the possible role played by one’s imagery abilities and whether imagined content played an influential role in the simultaneous physical outcomes (Winters & Reisberg 1985). Later studies mention clinical evidence implying that imagination and implementation of a physical act depend on "overlapping brain networks" and that damage to the brain region which affects action execution can also have effects on the brain's mental stimulation abilities (Allami et al. 2007). In their own conducted study, Allami et al. (2007) reported that participants benefited from mental practice for an extended period of a motor function compared to physical practice alone, a higher amount of imagined movement led to higher motor improvement, particularly for difficult tasks. Interestingly enough the effects of mental practice were observed even before the subjects enacted the task physically (Allami et al. 2007). There are extensive papers that provide evidence towards the excitability of motor learning and how the motor cortex combines external cues such as visual and contextual information and internal signals like kinesthetics and haptic feedback to produce a neural representation of simulated actions (Ruffino et al. 2017). Motor imagery's (MI) optimistic benefits on physical performance have long been studied and applied in sports psychology, where athletes use mental practice in addition to their physical preparation to enhance dexterity (Jeannerod 2006 as cited in Ruffino et al. 2017). Furthermore, mental practice with MI has been seen to improve various physical aspects such as movement, speed, muscle strength and accuracy (Ruffino et al. 2017).

MI has also been reported to facilitate post-stroke recovery in clinical rehabilitation (Jackson et al. 2004 as cited in Allami et al. 2007). There are various rehabilitation studies listed by Ruffino et al. (2017) that discuss combining physical and mental practices for superior motor recovery. Although one published study critiqued the findings and reported multiple influential factors that may alter effects derived from mental training including adherence, dosage of imagery, nature of instructions, relaxation, outcome measurement, patient selection and diversity (Malouin et al. 2013 as cited in Ruffino et al. 2017). Thus, the description and understanding of all components is necessary for MI to be beneficial, particularly in clinical settings and have the participants familiarized with mental imagery (Malouin et al. 2013 as cited in Ruffino et al. 2017). There was also evidence found in combining MI with observation as they both evoke similar neural courses i.e., the mirror neurons (Garrison et al. 2010). An increase in hand muscle response caused by the stimulation of the motor cortex was detected when subjects observed another subject's hand movements (Maeda et al. 2002 as cited in Ruffino et al. 2017).

Motor Imagery and Plasticity

Having established the principles and evidence for neuroplasticity and MI the question at hand arises of whether imagining a physical act induces neuroplasticity and whether can it assist stroke survivors with the formation of novel neural connections to regain their motor/sensory function. The link between mental practice and cortical rearrangement in healthy human brains was first demonstrated in 1995, where over 5 days, participants were required to visualize piano exercises and imagine the sound and were tested daily using TMS mapping (Pascal-Leone et al. 1995 as cited in Ruffino et al. 2017). Findings implied a progression of skill, confirmed by a reduction in errors and variability. The expansion of the cortical representation of the extensor and flexor muscle of the long finger in the opposite primary motor cortex also indicated the possibility of cortical modifications because of mental practice with MI comparable to that evoked through physical training (Pascal-Leone et al. 1995 as cited in Ruffino et al. 2017). Avanzino et al. (2015) further supported these findings by revealing that in addition to cortical rearrangement, the practice of MI also strengthened synaptic connections (Ruffino et al. 2017). Jackson et al. (2003) using their PET scans also exhibited that MI and physical practice induced homogeneous functional variations in the cerebral region which meant higher stimulation of the orbitofrontal cortex and reduced stimulation of the cerebellum, with regards to learning a successive motor task through MI (Ruffino et al. 2017). Another study integrated MI with visual and audio cues and found the facilitation of cortical reorganization (Hovington & Brouwer 2010 as cited in Ruffino et al. 2017). However, provoking plasticity in a healthy brain is quite different from inducing it in a brain that has suffered a variation of a stroke or a CNS disease, especially when the injury affects the motor region of the brain.

Mirror Therapy

Ramachandran & Rogers-Ramachandran (1996) developed an intervention called the "virtual reality box" which used a vertically placed mirror in a cardboard box that would line up perpendicularly with the patient's chest in a way that it superimposed the patient's unimpaired hand which was then used to carry out hand exercises. The size of the mirror depended on the level of disarticulation (Ramachandran & Rogers-Ramachandran 1996). The mirror, while reflecting these hand movements, evoked the illusion that the actions were being performed by the impaired hand (Stevens & Stoykov 2003). The visual component was further strengthened by instructing patients to visualize the reflected limb as their own, moving around in space (Stevens & Stoykov 2003). This method saw promising results in improving motor recovery post-stroke as results suggested increased grip strength in the affected limb along with an increase in the range of motion in the wrists (Stevens & Stoykov 2003). Another study assessed the effects of visuomotor training by comparing fMRI scans of the motor cortex before and after employing the mirror box intervention and saw a substantial growth in premotor cortex activity following the program compared to prior, along with a change in representations within the motor cortex for hand and arm in terms of activation size and level for two out of their 3 subjects (Giraux & Sirigu 2003). Such data suggests that mirror therapy can possibly induce plasticity.

VR Integration

The usage of VR has been linked with producing certain positive effects in rehabilitation patients. Post-stroke depression is commonly found in stroke survivors (Gaete & Bogousslavsky 2008), and the use of VR has been linked with improving the quality of life in patients with cognitive impairments (Afifi et al. 2022). Furthermore, there are already studies that have incorporated VR with physiotherapy that talk about the stimulating abilities of VR and how it helped make the process of rehabilitation more enjoyable and playful (Brepohl & Leite 2022). More importantly, it targets some of the most prevalent issues faced by physiotherapists including adherence and pain management (Lohse et al. 2013).

Adherence and Engagement

The most common problem physiotherapists struggle with is adherence. Therapeutic exercises require patients to be obedient and consistent with their required physical movements to induce neuroplasticity (Lohse et al. 2013), but commitment is often tough to achieve as patients are commonly seen to abandon their treatment (Brepohl & Leite 2022). It has been indicated that therapy dosage, especially the frequency of exercise repetitions is already well below the optimal level required for recovery (Lohse et al. 2013). And this is where VR has been seen emerging as a promising entity. With its competence to harness sophisticated graphics, haptics and motion tracking, VR can offer immersive experiences that can help sustain patients' motivation, while having a positive effect on their emotional state (House et al. 2016). Early research works explored the intervention of video games in physiotherapy practices to reinforce adherence, as they were observed to be highly engaging objects that motivated patients to push into achieving their goals with an added element of fun (Lohse et al. 2013, Glegg & Levac 2018, Vernadakis et al. 2014). Immersion being one of the major objectives of virtual reality when paired with a gaming component, could lead to an increase in the dosage of movements relevant to therapy (Lohse et al. 2013). Promising results were found in a study where the inclusion of Wii gaming in poststroke participants promoted motor recovery (Saposnik et al. 2010). The study included participants between the ages of 18 and 85 who suffered from their first stroke within the past 6 months, this time frame ensured maximum enhancement for recovery (Saposnik et al. 2010). Subjects were required to play sporting and cooking games using motion-sensing controllers that obliged wrist, hand and arm movements (Saposnik et al. 2010). The results concluded that motion gaming is a "safe and feasible" substitute for the promotion of rehabilitation (Saposnik et al. 2010). In another study, participants were also found wanting to continue therapy and seen recommending it to other people (Yong Joo et al. 2010 as cited in Lohse et al. 2013).

Pain Management

In the process of rehabilitation, it is unlikely for one to avoid the sensation of pain. Whether it be after an injury, operation, or stroke, the process of persuading your affected motor functionalities to reach back to their initial state or come as close to physiologically possible, can be extremely discomforting which is a significant reason for patients to reduce and even discontinue their therapy sessions (Lohse et al. 2013). Hoffman et al. (2000) were the first ones to provide evidence of VR's effectiveness as a nonpharmacological analgesic or simply a pain-relieving substance that is not medication. Their case study involved adolescent patients with deep flash burns who were provided with a VR game as a means to distract them while undergoing wound care resulted in a significant reduction in sensory pain scores for both patients and a decline in anxiety for one of the patients, which usually ascends from the visuals of dressing changes, as the patient was observed to focus more on the VR tasks than the wound (Hoffman et al. 2000). With VR's immersive capabilities, the brain is occupied with comprehending the visuals of the digital environment which draws their focus away from their impairments, which diminishes their perception of pain as distracting incentives can reduce the activity of nociceptive neural signalling (Triberti et al. 2014 as cited in Pourmand et al. 2018). In addition, most HMDs on the market currently do not offer the functionality of switching between digital and physical views, which further reduces the patient's access to their wounds and impairments. Since the publication of the case study by Hoffman et al. (2000), numerous articles have come about to support the hypothesis that VR can be used as a distraction for patients suffering from a range of chronic and acute pain conditions (Pourmand et al. 2018).

Challenges around using VR

Virtual reality users have often been witnessed to experience symptoms of motion sickness, nausea, eye fatigue, and disorientation, also frequently referred to as VR sickness or even cybersickness. We as humans recognize motion and orientation via many sensory organs and the entire procedure of movement is processed in sync among these organs making it possible for us to cognize our placement and movement with ease (Chang et al. 2020). However, when there is a disparity between the visual information and the data being input by the vestibular system, sensory conflicts can arise, which can lead to motion sickness, commonly experienced during chaotic travels that involve unexpected movements (Chang et al. 2020, Sherman 2006). It has also been claimed that the deception of motion, called vection, which is usually only experienced for a very short amount of time in the physical world, can be extended in VR due to certain visual content making the user feel like they're moving when in reality, they are not (Chang et al. 2020).

Multiple factors can trigger these symptoms in VR starting with display type, field of view, and latency, all of which can directly affect the VR experience and lead anywhere from mild to major discomfort (Chang et al. 2020). The stereoscopic nature of HMD paired with high-fidelity virtual substance can cause an inconsistency between expected and observed sensory information causing high levels of vection leading to VR sickness (Chang et al. 2020). Field of view (FOV) is considered as the range or the visual angle obtained through a display device to experience the digital environment and while a wide FOV is most favourable for an optimal viewing experience, a reduced FOV during rotation and acceleration can effectively lessen user discomfort (Chang et al. 2020). Latency can be referred to as the delay between a transmitted action and the corresponding on-screen response. A head movement in the physical world is shadowed by simultaneous movement in the surrounding area at the same speed and direction, but a movement in VR is amenable to tracking delays giving rise to blurry visuals and leading to a variation in time between user expectations and what is actually being viewed (Chang et al. 2020). Latency is a leading factor in causing VR sickness, so it is important to choose hardware that offers high refresh rates and superior motion tracking capabilities to minimize the effects of motion-to-photon latency (Chang et al. 2020).

Entities such as locomotion, the mode of movement within the virtual environment, and scene sophistication including 3D model complexity, texture quality, and controllability all sustain significant effects on the user's experience. Scene sophistication can make or break immersion and presence, which are the 2 pillars of VR. Complex scenes containing numerous 3D assets especially with dense geometry and multiple lights can take a long time to render leading to prolonged loading screens causing latency (Chang et al. 2020). Moving objects have also been observed to stimulate nausea compared to static objects (Lubeck et al. 2015 as cited in Chang et al. 2020). Along with nausea and motion sickness, prolonged use of VR can also cause eye strain and a major advocating element of this is the phenomenon known as vergence accommodation conflict (VAC), which continues to be a complicated problem in HMDs even today (Kramida 2016). It forces the user's visual sensory system to abnormally adjust to opposing signals, increasing the time required for the merging of binocular imagery while diminishing fusion veracity (Kramida 2016). The visual sensory organs adapt to the distance of the focused object and blur out the surrounding entities, but with stereoscopic views, the eyes have to look through the lenses of the HMD that are fixed, while the virtual environment consists of things located at varying distance, making it unable to perform the focusing and blurring phenomenon as the lens projects everything in focus (Kramida 2016). Therefore, it is advised not to use VR for extended periods of time.

Methodology

The prospect of applying MI for mental practice as a feasible practice for physiotherapy was initially discussed by Alan Richardson in his two reviews back in 1964 and 1967 (Ruffino et al. 2017). Since then, it has been established that MI can induce plasticity during recovery, but there's still extraordinarily little information about the origins and its connection to motor rehabilitation (Ruffino et al. 2017). The standard of existing evidence supporting commonly used interventions including MI, virtual reality and mirror therapy is moderate (Pollock et al. 2014). One study by Kaneko et al. (2003) found a correlation between MI and execution implying that a functional reorganization or reduced excitability in the cerebral cortex region involved in movement execution is likely to decrease its ability to produce voluntary muscle output after a period of immobilization. Several review articles mention and discuss the benefits of employing MI interventions to improve motor performances in numerous neurological disorders (Garrison et al. 2010, Malouin et al. 2013, Mulder 2007, Ruffino et al. 2017), but most of them found little to no evidence regarding the matter at hand. They commonly agree on initiating investigative clinical studies for more definitive conclusions regarding the capabilities of MI in stroke rehabilitation. With the urgent need for high-quality evidence to support interventions (Pollock et al. 2014), I opted to design an artefact that could help develop neuroplasticity in post-stroke survivors with regard to upper limb functionality.

VR is a tool efficient in immersing the user by providing a combination of visual and physical experience. Circling back to some of the earlier mentioned interventions, including the incorporation of MI with physical movement and action observation, VR's ability to combine these interventions via a tailored virtual experience makes it a strong alternative for studying MI and its effects on plasticity. Im et al. (2016) and Choy et al. (2023) have been observed using VR to promote MI in stroke patients and found certain assuring results. Im et al. (2016) suggest that the effects produced by combining MI with VR were superior to those produced by MI alone, however, their study did not use HMDs and instead used a PC and only focused on wrist functionality. Alternatively, Huang et al. (2022) and Choy et al. (2023) do make use of HMDs in their studies. Huang et al. (2022) being a rare randomized controlled trial, mentioned the customizable attribute of VR but used twenty commercially available environments that included various daily life activities implying the scenes weren't tailored to examine the effects of any specific interventions but just the effects of VR on neuroplasticity and upper limb motor function. Choy et al. (2023) in their review concluded that the approach of using VR to support MI has potential but needs further investigation specifically to confirm whether VR can boost neural response during the first month of recovery after stroke. All things considered, the need to explore the effects of VR using an HMD, created for a specific intervention still exists. Hence, I chose to create a VR artefact tailored to assist in enhancing MI.

Yoxon & Welsh (2020) mention that on a group level, plasticity induced through MI has relatively been inconsistent and the reason behind it could be due to differences in individuals' ability to imagine content. This complication will also be avoided with the artefact as the scene would provide common grounds for the users and researchers and be especially helpful for the ones with cognitive damage who would otherwise find it tough to fabricate imaginative content. With the earlier mentioned potentials of VR, this artefact provides an innovative solution to explore the effects of visuomotor imagery on inducing neuroplasticity towards regaining upper-body motor functionality. Reports suggest that about 55-75% of stroke survivors continue to have limited upper extremity functionality (Yavuzer et al. 2008). This is why I focused on developing the artefact to aid with upper body impairments and built it specifically for stroke survivors who have suffered from paralysis in the one side of their body as an aftermath.

Studies have used Mirror Therapy intervention over the years, the following table depicts the body parts they most utilized in carrying out the study and the effects of mirror therapy on the limbs.

Study	Body parts used	Effects of the therapy
Ramachandran & Rogers-Ramachandran (1996)	5 left limbs and 5 right limbs	Various effects across different patients but notably found evidence suggesting plasticity in the sensory homunculus and motor restoration in paralysed arm.
Stevens & Stoykov (2003)	Wrist	Increased functionality in the paretic limb
Yavuzer et al. (2008)	Wrist and finger flexion	Improvement in hand functions
Kang et al. (2012)	Left hand and left wrist	Higher cortical excitability (in VR conditions)
Im et al. (2016)	Wrist Functionality	Elevated motor evoked potentials
Thieme et al. (2018)	Full body	Moderate quality evidence depicting improved motor functionality

This table depicts the effectiveness of Mirror Therapy as it has been observed to produce some assuring results in terms of plasticity and improved functionality. These specific studies were chosen due to their direct alignment with the topic at hand which focuses on Mirror Imagery and its effects on plasticity in the homunculus. Ramachandran & Rogers-Ramachandran (1996) were the first to propose the use of Mirror Therapy and its effectiveness, so it was important to study the origination of the intervention for the purpose of design and the probable result. These studies also indicate the effectiveness of Mirror Therapy over time indicating that this intervention has been relevant since its introduction and produced promising results, especially with the addition of newer technologies. Lastly, they were selected due to their involvement of stroke patients in their trials. Thieme et al. (2018) were insightful as it was one of few studies that incorporated full body recovery as opposed to just upper body. Results although moderate quality suggested that mirror therapy improved motor impairments even beyond the first six months after stroke (Thieme et al. 2018). The table also depicts that most of the studies used upper-body movements specifically hands and wrists to derive their conclusions regarding the effects of the therapy. By analysing this information, I decided to direct the VR artefact to induce neuroplasticity to support upper-body functionality specifically the upper arm, which hasn't been studied sufficiently. Kang et al. (2012) in their comparison study mention higher cortical excitability in the upper extremity in their VR setting versus physical setting, further justifying the employment of VR.

Artefact

There are multiple game engines that are software that help produce interactive scenes or environments. The two most popular game engines are Unity and Unreal, both of which support VR. I chose to build my setup in Unity as I have been working with it for a while and in their current state Unity is preferable over Unreal for VR. The setup incorporates a mirror system using a camera that projects the renders onto a plane using a render texture, along with a desert terrain, a skybox and an Extended reality (XR) robot rig which would be embodied by the users upon usage. The Virtual scene has been set up using, the HP reverb G2 VR system, an industry favourite, which offers high-resolution lenses with 2160 pixels per eye along with a 90Hz refresh rate and weighs about half a kilo making it fairly light as well (HP 2020). These specifications help counter some important issues mentioned earlier including latency and in turn motion sickness, while providing realistic graphics that are further supposed to amplify presence and immersion (Chang et al. 2020).

The desert environment is supposed to mimic a vast open natural space as opposed to a closed and restricted hospital atmosphere. Patients have often been observed getting anxious and overwhelmed with their diagnosis bringing about anxiety during their hospital stays leading to slow recovery, an increase in pain sensitivity, and reduced adherence (Orbell et al. 2013). This instigates the need to mentally relocate patients out of a room setting making VR heavily advantageous for its integration into neurorehabilitation especially as it has been discussed earlier to tackle the adherence and elevated pain. VR's distractive attributes and their limited access to the physical world can help divert the users' attention, leading to less anxiety that arises from the visuals of their impairments and a reduction in pain levels (Pourmand et al. 2018). The simulation of natural space can also have positive effects on the user as natural spaces have been linked with considerable impact on mental health and have also been studied to encourage rapid recovery of cognitive performances (Mantler & Logan 2015). The artefact framework is inspired by the aforementioned Ramachandran & Rogers-Ramachandran's mirror therapy principle. However, instead of the reflection imagery portraying the movements of the unimpaired arm giving the illusion of perfectly normal motor functionality in the impaired arm, the VR avatar has been set up to control both arms using a single controller. This means that patients suffering from hemiparesis or neglect syndrome would essentially be able to hold the controller and move their unimpaired hand (in this case left) and the avatar would mirror those movements onto the other arm.

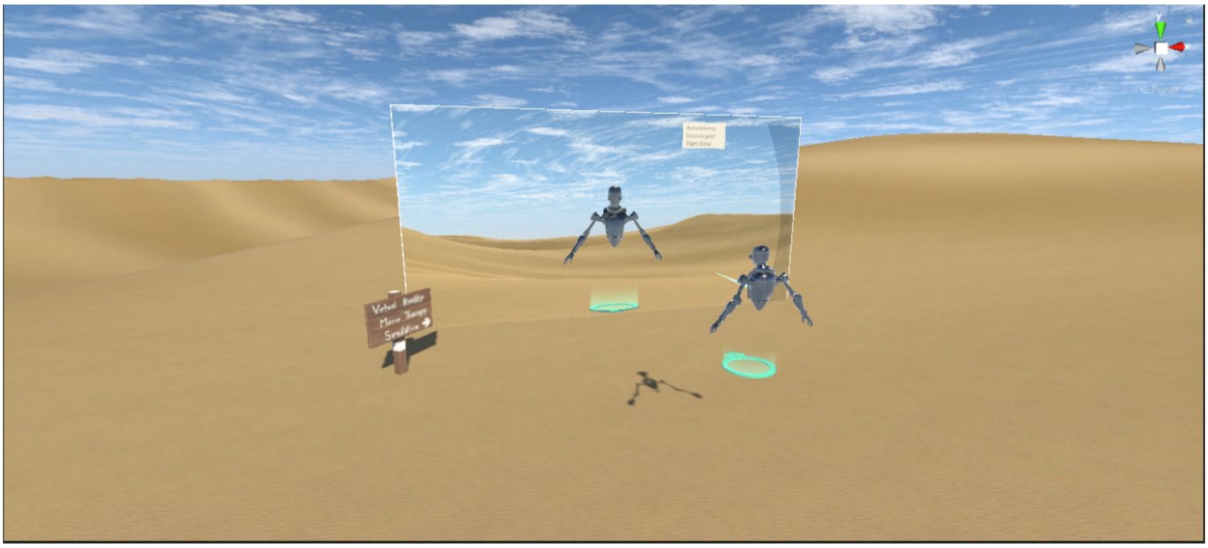

Image 2 VR artefact screenshot

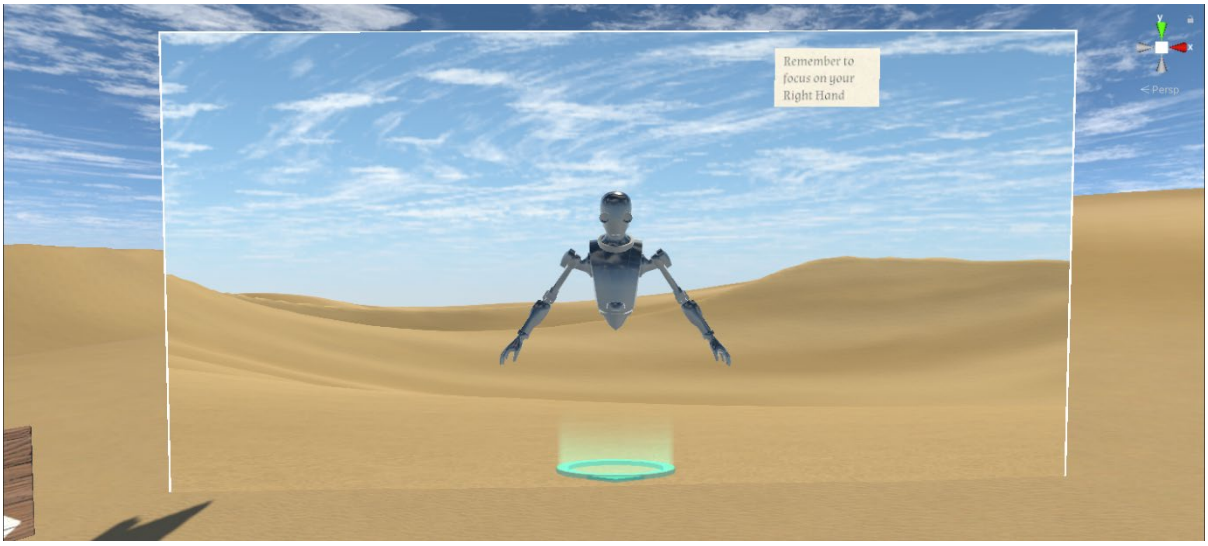

Image 3 VR artefact screenshot

VR with its immersive nature is one of very few if not the only entity that would allow disabled users the ability to have believable motor functional capabilities. This believability arises from the consciousness of the user's immediate environment which heavily depends on information gathered through the sensory system (Slater & Sanchez-

Vives 2016). And upon effective substitution of the sensory perception, the brain begins to believe what's being perceived, i.e., the data being presented through VR, which is why the consciousness gets shifted to that of the virtual environment despite the user's intelligence knowing it's not real (Slater & Sanchez-Vives 2016). Some experiments have demonstrated that it is considerably easy to transfer the sense of body ownership to either non-body part objects or even to a completely unique body, depicting how flexible body ownership is (Slater & Sanchez-Vives 2016). The shift of the consciousness will be reinforced by the mirror located directly in front of the avatar which should lead to cortical stimulation and lead to the possible induction of neuroplasticity. Having established earlier the need for a study within the first month after stroke, and that physiotherapy isn't always achievable with patients immediately after infarct, this artefact requires very limited physical movement and features promising interventions that could assist in regaining some motor recovery as there have been claims of improved motor functions following mirror therapy (Yavuzer et al. 2008). Experience-driven neuroplasticity could also strengthen synaptic connections as suggested by Dobkin (2005), which this artefact should offer, with the addition of being fun and motivating (Brepohl & Leite 2022). The artefact also contains meditative ambient music which should help in the reduction of anxiety, stress and depression in post-stroke patients as it has been found to do so when accompanied by physical activity (Wan Zhen Lee et al. 2023). It is imperative that the patients be made aware of the artefact and that they understand all components of the study as it can majorly impact the outcome of the study (Malouin et al. 2013 as cited in Ruffino et al. 2017). Hence as a reminder, the mirror also holds a note suggestive of focusing on their right (impaired) hand to produce cortical activations.

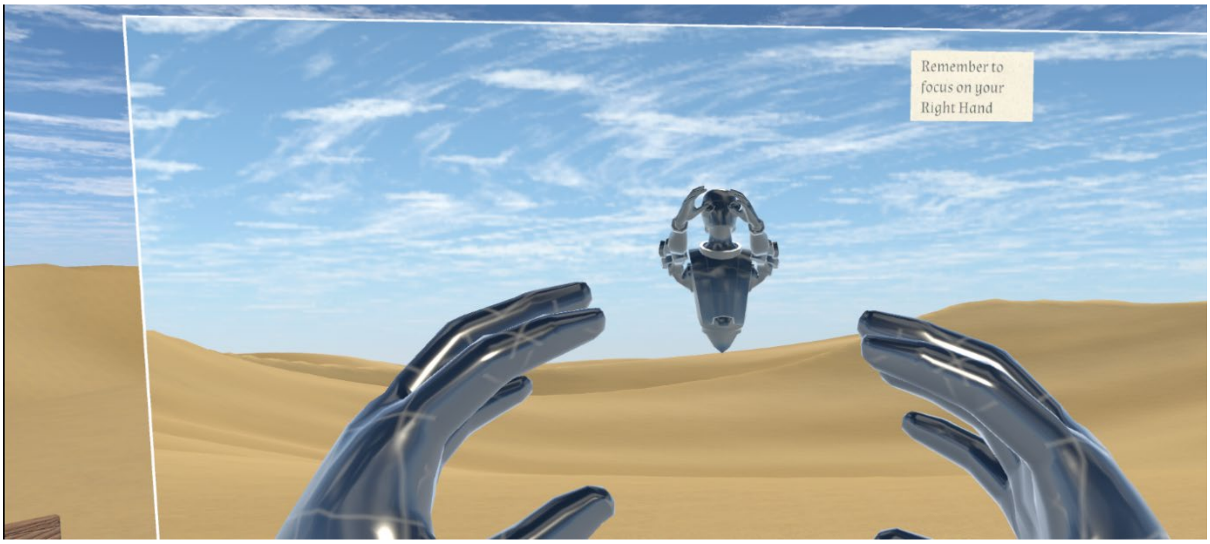

Image 4 VR artefact screenshot

Artefact Limitations

The scene does come with its set of limitations primarily due to the accessible infrastructure. While the G2 VR system has its positives, it only has 4 trackers located on the HMD and does not offer hand or full body tracking, hence the legs and finger movements are absent on the avatar. Legs all together at the moment are very tough to track in VR which has even been confirmed by the VP of Meta's Reality Lab who also said that they are "basically not workable just from a physics standpoint with existing headsets" (Metz 2022). A study found no significant difference between hands only and full-body avatars concerning cognitive function (Pan & Steed 2019) which means it shouldn't affect their sense of presence. The scene also doesn't require the users to transport around in the scene, as everything needed for the proposed mirror therapy intervention is available at the wake similar to Ramachandran & Rogers-Ramachandran's model that only used a mirror and cardboard box, with the patients seated.

This design model was also influenced by the challenges that surfaced while setting up the robot rig. For starters, the emulating arm movement effect of the rig requires a mirroring point, which has been positioned directly in front of the rig pointing at the centre of the robot's chest. This mirror point can unfortunately not be moved, meaning the rig has to remain at the same virtual location for the arm emulation to work. This also necessitates calibration before employing the artefact if there are any alterations to the physical setup of the HMD. The users would be required to sit in an immobile chair facing in the direction in which the HMD has been calibrated. This can arguably be even looked at as an advantage as no locomotion also means lesser chances for the arousal of any VR or motion sickness. Regarding limited access to the physical world, although it restricts patients to focus on their ailments, it also breaks any connection with the supervising therapists making it problematic for the user to remember and follow instructions. In its current state, the artefact rig has only been setup for people who would have suffered paralysis on the right side of the body, so the arm movements can only be controlled using the left controller.

Discussion/Future Direction

With a rising number of stroke cases especially in young adults over the past decade, the realm of rehabilitation has been adamant on exploring innovative ways to tackle the effects of disability that arises post-stroke. This path to recovery is extensively long and strenuous. But by harnessing the principles of neuroplasticity, followed by physical rehabilitation functional motor recovery is achievable. However, physiotherapy when attainable, often sees patients abandon their sessions due to its monotonous nature. The spontaneous nature of recovery post-stroke has been recognized by neuro and physical rehabilitators and has been taken advantage of to assist stroke survivors with motor recovery. Neuroplasticity playing a major role in this road to recovery, has been seen being paired with various interventions reported by numerous studies to help regain cognitive motor functionality. This paper focused on one such intervention known as motor imagery and provided an artefact that utilizes virtual reality and mirror therapy to possibly promote neuroplasticity. Through the literature review and acknowledgment of the research gap, the given artefact presents fresh grounds for a possible future study to investigate the effects of visuomotor imagery on neuroplasticity. The use of functional MRI scans would be necessary to identify any amplified activation in the "new brain" region to confirm any rudimentary claims of neuroplasticity. An added gaming element could also prove to be impactful and lead to an increase in motivation and dosage (Lohse et al. 2013). However further investigation is needed to find the optimal time when the complexities of gaming tasks could be processed by a cortically impaired user.

With a team including various therapists and VR developers, the number of limitations could be confronted with a more scientific approach along with making the necessary additions. The current VR ecosystem also needs upgrades to process better tracking and more importantly the addition of legs. A future attempt at this artefact could include full-body motion functionality, especially with the likes of the Teslasuit. This suit provides full body haptics, and motion tracking and claims to even simulate real-life feelings and sensations. The suit, nevertheless, needs rigorous testing to ensure it can deliver the stated functionalities. It is also important to understand that this artefact should only be used under the supervision of professional physio and/or neuro therapists as neuroplasticity can have negative impacts (Cramer et al. 2011). The test subject in Levin et al. (1996), saw a dysfunction in the left parietal lobe due to competition between the newly acquired skillset and the existing skillset in the region, giving rise to the assumption that a similar occurrence is possible upon the usage of the proposed artefact. Furthermore, Motor imagery accompanied by physiotherapy sessions could lead to superior motor recovery (Ruffino et al. 2017) so physiotherapy subsequent to VR sessions could promote better recovery. The scene could also benefit from an additional therapist avatar in the scene or even a set of exercises prescribed by the therapists displayed in some form within the virtual environment for patients to refer to. Customizable avatars could also possibly assist the user in seeing or relating more of themselves to their virtual character for an added presence and fun element, along with a selection menu that could possibly let users or researchers select the arm they would be using.

Final Thoughts

To the best of my knowledge, this paper proposes a first-of-its-kind VR artefact incorporating mirror therapy to recover impaired motor functions through neuroplasticity. The artefact contains limitations that need to be addressed, but the artefact holds potential for clinical use after being studied.

Reference list

Afifi, T, Collins, N, Rand, K, Otmar, C, Mazur, A, Dunbar, NE, Fujiwara, K, Harrison, K & Logsdon, R 2022, 'Using Virtual Reality to Improve the Quality of Life of Older Adults with Cognitive Impairments and their Family Members who Live at a Distance', *Health Communication*, pp. 1–12.

Agency for Clinical Innovation 2020, *Rehabilitation What it is and what to expect*.

Alawieh, A, Zhao, J & Feng, W 2018, 'Factors Affecting post-stroke Motor recovery: Implications on Neurotherapy after Brain Injury', *Behavioural Brain Research*, vol. 340, pp. 94–101.

Allami, N, Paulignan, Y, Brovelli, A & Boussaoud, D 2007, 'Visuo-motor learning with combination of different rates of motor imagery and physical practice', *Experimental Brain Research*, vol. 184, no. 1, pp. 105–113.

American Heart Association 2019, *Choosing the Right Stroke Rehab Facility*, www.stroke.org.

American Stroke Association 2019, *Types of Stroke*, www.stroke.org.

Australian Bureau of Statistics 2023, *Provisional Mortality Statistics, Jan - Dec 2022 | Australian Bureau of Statistics*, www.abs.gov.au.

Australian Institute of Health and Welfare 2015, *Leading cause of premature mortality in Australia fact sheet: cerebrovascular disease*, AIHW.

Avanzino, L, Gueugneau, N, Bisio, A, Ruggeri, P, Papaxanthis, C & Bove, M 2015, 'Motor cortical plasticity induced by motor learning through mental practice', *Frontiers in Behavioral Neuroscience*, vol. 9.

Bako, AT, Pan, A, Potter, T, Tannous, J, Johnson, C, Baig, E, Meeks, J, Woo, D & Vahidy, FS 2022, 'Contemporary Trends in the Nationwide Incidence of Primary Intracerebral Hemorrhage', *Stroke*, vol. 53, no. 3.

Barnes, MP 2003, 'Principles of neurological rehabilitation', *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 74, no. 90004, pp. 3iv7.

Bower, KJ, Louie, J, Landesrocha, Y, Seedy, P, Gorelik, A & Bernhardt, J 2015, 'Clinical feasibility of interactive motion-controlled games for stroke rehabilitation', *Journal of neuroengineering and rehabilitation*, vol. 12, BioMed Central, p. 63.

Brepohl, PCA & Leite, H 2022, 'Virtual reality applied to physiotherapy: a review of current knowledge', *Virtual Reality*.

Carson, RG & Ruddy, KL 2012, 'Vision Modulates Corticospinal Suppression in a Functionally Specific Manner during Movement of the Opposite Limb', *Journal of Neuroscience*, vol. 32, no. 2, pp. 646–652.

Centers for Disease Control and Prevention 2022, *About Stroke*, Centers for Disease Control and Prevention.

Chang, E, Kim, HT & Yoo, B 2020, ‘Virtual Reality Sickness: A Review of Causes and Measurements’, *International Journal of Human–Computer Interaction*, vol. 36, no. 17, pp. 1658–1682.

Choy, CS, Cloherty, SL, Pirogova, E & Fang, Q 2023, ‘Virtual Reality Assisted Motor Imagery for Early Post-Stroke Recovery: A Review’, *IEEE Reviews in Biomedical Engineering*, vol. 16, pp. 487–498, viewed 19 February 2023, <https://ieeexplore.ieee.org/document/9749920>.

Cott, CA, Finch, E, Gasner, D, Yoshida, K, Thomas, SG & Verrier, MC 1995, ‘The movement continuum theory of physical therapy’, *Physiotherapy Canada*, vol. 47, no. 2, pp. 87–95, viewed 11 September 2023, <https://www.researchgate.net/publication/284671257_The_movement_continuum_theory_of_physical_therapy>.

Cramer, SC, Sur, M, Dobkin, BH, O’Brien, C, Sanger, TD, Trojanowski, JQ, Rumsey, JM, Hicks, R, Cameron, J, Chen, D, Chen, WG, Cohen, LG, deCharms, C, Duffy, CJ, Eden, GF, Fetz, EE, Filart, R, Freund, M, Grant, SJ & Haber, S 2011, ‘Harnessing neuroplasticity for clinical applications’, *Brain*, vol. 134, no. 6, pp. 1591–1609.

Department of Health 2015, *Admitted rehabilitation*, Vic.gov.au.

Dobkin, BH 2005, ‘Rehabilitation after Stroke’, *New England Journal of Medicine*, vol. 352, no. 16, pp. 1677–1684.

Dong, X, Yoshida, K & Stoffregen, TA 2011, ‘Control of a virtual vehicle influences postural activity and motion sickness.’, *Journal of Experimental Psychology: Applied*, vol. 17, no. 2, pp. 128–138.

Floel, A & Cohen, LG 2010, ‘Recovery of function in humans: Cortical stimulation and pharmacological treatments after stroke’, *Neurobiology of Disease*, vol. 37, no. 2, pp. 243–251.

Fujii, Y & Nakada, T 2003, ‘Cortical reorganization in patients with subcortical hemiparesis: neural mechanisms of functional recovery and prognostic implication’, *Journal of Neurosurgery*, vol. 98, no. 1, pp. 64–73.

Gaete, JM & Bogousslavsky, J 2008, ‘Post-stroke depression’, *Expert Review of Neurotherapeutics*, vol. 8, no. 1, pp. 75–92.

Garrison, KA, Winstein, CJ & Aziz-Zadeh, L 2010, ‘The mirror neuron system: a neural substrate for methods in stroke rehabilitation’, *Neurorehabilitation and neural repair*, vol. 24, United States, no. 5, pp. 404–12, viewed 16 November 2019, <https://www.ncbi.nlm.nih.gov/pubmed/20207851>.

Giraux, P & Sirigu, A 2003, ‘Illusory movements of the paralyzed limb restore motor cortex activity’, *NeuroImage*, vol. 20, pp. S107–S111.

Glegg, SMN & Levac, DE 2018, 'Barriers, Facilitators and Interventions to Support Virtual Reality Implementation in Rehabilitation: A Scoping Review', *PM&R*, vol. 10, no. 11, pp. 1237-1251.e1.

Gomes, J & Wachsman, AM 2013, 'Types of Strokes', *Handbook of Clinical Nutrition and Stroke*, pp. 15–31.

Grafman, J 2000, 'Conceptualizing functional neuroplasticity', *Journal of Communication Disorders*, vol. 33, no. 4, pp. 345–356.

Hoffman, HG, Doctor, JN, Patterson, DR, Carrougher, GJ & Furness, TA 2000, 'Virtual reality as an adjunctive pain control during burn wound care in adolescent patients', *Pain*, vol. 85, no. 1, pp. 305–309.

House, G, Burdea, G, Grampurohit, N, Polistico, K, Roll, D, Damiani, F, Hundal, J & Demesmin, D 2016, 'A feasibility study to determine the benefits of upper extremity virtual rehabilitation therapy for coping with chronic pain post-cancer surgery', *British Journal of Pain*, vol. 10, no. 4, pp. 186–197.

Hovington, CL & Brouwer, B 2010, 'Guided Motor Imagery in Healthy Adults and Stroke: Does Strategy Matter?', *Neurorehabilitation and Neural Repair*, vol. 24, no. 9, pp. 851–857.

HP 2020, *HP Reverb G2 VR Headset*, www.hp.com.

Huang, C-Y, Chiang, W-C, Yeh, Y-C, Fan, S-C, Yang, W-H, Kuo, H-C & Li, P-C 2022, 'Effects of virtual reality-based motor control training on inflammation, oxidative stress, neuroplasticity and upper limb motor function in patients with chronic stroke: a randomized controlled trial', *BMC Neurology*, vol. 22, no. 1.

Im, H, Ku, J, Kim, HJ & Kang, YJ 2016, 'Virtual Reality-Guided Motor Imagery Increases Corticomotor Excitability in Healthy Volunteers and Stroke Patients', *Annals of Rehabilitation Medicine*, vol. 40, no. 3, p. 420.

Jackson, PL, Doyon, J, Richards, CL & Malouin, F 2004, 'The Efficacy of Combined Physical and Mental Practice in the Learning of a Foot-Sequence Task after Stroke: A Case Report', *Neurorehabilitation and Neural Repair*, vol. 18, no. 2, pp. 106–111.

Jackson, PL, Lafleur, MF, Malouin, F, Richards, CL & Doyon, J 2003, 'Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery', *NeuroImage*, vol. 20, no. 2, pp. 1171–1180.

Jeannerod, M 2006, 'The origin of voluntary action. History of a physiological concept', *Comptes Rendus Biologies*, vol. 329, no. 5-6, pp. 354–362.

Kaneko, F, Murakami, T, Onari, K, Kurumadani, H & Kawaguchi, K 2003, 'Decreased cortical excitability during motor imagery after disuse of an upper limb in humans', *Clinical Neurophysiology*, vol. 114, no. 12, pp. 2397–2403.

Kang, Y, Park, H, Kim, H, Lim, T, Ku, J, Cho, S, Kim, SI & Park, E 2012, 'Upper extremity rehabilitation of stroke: Facilitation of corticospinal excitability using virtual mirror paradigm', *Journal of NeuroEngineering and Rehabilitation*, vol. 9, no. 1, p. 71.

Kleim, JA & Jones, TA 2008, 'Principles of Experience-Dependent Neural Plasticity: Implications for Rehabilitation After Brain Damage', *Journal of Speech, Language, and Hearing Research*, vol. 51, no. 1.

Kramida, G 2016, 'Resolving the Vergence-Accommodation Conflict in Head-Mounted Displays', *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 7, pp. 1912–1931.

Kuja, R 2019, *Desert Spirituality - 'The Place of Great Undoing' - SDI Companions*, www.sdicompanions.org.

Levin, HS, Scheller, J, Rickard, T, Grafman, J, Martinkowski, K, Winslow, M & Mirvis, S 1996, 'Dyscalculia and Dyslexia After Right Hemisphere Injury in Infancy', *Archives of Neurology*, vol. 53, no. 1, pp. 88–96.

Lohse, K, Shirzad, N, Verster, A, Hodges, N & Van der Loos, HFM 2013, 'Video Games and Rehabilitation', *Journal of Neurologic Physical Therapy*, vol. 37, no. 4, pp. 166–175.

Lubeck, AJA, Bos, JE & Stins, JF 2015, 'Motion in images is essential to cause motion sickness symptoms, but not to increase postural sway', *Displays*, vol. 38, pp. 55–61.

Maeda, F, Kleiner-Fisman, G & Pascual-Leone, A 2002, 'Motor Facilitation While Observing Hand Actions: Specificity of the Effect and Role of Observer's Orientation', *Journal of Neurophysiology*, vol. 87, no. 3, pp. 1329–1335.

Malouin, F, Jackson, PL & Richards, CL 2013, 'Towards the integration of mental practice in rehabilitation programs. A critical review', *Frontiers in Human Neuroscience*, vol. 7.

Mantler, A & Logan, AC 2015, 'Natural environments and mental health', *Advances in Integrative Medicine*, vol. 2, no. 1, pp. 5–12.

Metz, R 2022, *Why you can't have legs in virtual reality (yet) | CNN Business*, CNN, viewed 22 October 2023, <https://edition.cnn.com/2022/02/15/tech/vr-no-legs-explainer/index.html>.

Mulder, Th 2007, 'Motor imagery and action observation: cognitive tools for rehabilitation', *Journal of Neural Transmission*, vol. 114, no. 10, pp. 1265–1278, viewed 11 March 2020, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2797860/>.

Nguyen, JD & Duong, H 2022, *Neurosurgery, Sensory Homunculus*, PubMed, StatPearls Publishing, Treasure Island (FL).

Nicholas, JT, Johannessen, AM & Trees Van Nunen 2019, *Tactile working memory scale a professional manual*, Stockholm Nordic Welfare Centre, p. 36.

NIH 2023, *Stroke | National Institute of Neurological Disorders and Stroke*, www.ninds.nih.gov.

Occupational Therapy Australia 2023, *About Occupational Therapy*, Occupational Therapy Australia.

Orbell, S, Schneider, H, Esbitt, S, Gonzalez, JS, Gonzalez, JS, Shreck, E, Batchelder, A, Gidron, Y, Pressman, SD, Hooker, ED, Wiebe, DJ, Rinehart, D, Hayman, LL, Meneghini, L, Kikuchi, H, Kikuchi, H, Desouky, TF, McAndrew, LM, Mora, PA & Bruce, B 2013, 'Hospital Anxiety', *Encyclopedia of Behavioral Medicine*, pp. 985–988.

Pan, Y & Steed, A 2019, 'Avatar Type Affects Performance of Cognitive Tasks in Virtual Reality', *25th ACM Symposium on Virtual Reality Software and Technology*.

Pascual-Leone, A, Nguyet, D, Cohen, LG, Brasil-Neto, JP, Cammarota, A & Hallett, M 1995, 'Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills', *Journal of Neurophysiology*, vol. 74, no. 3, pp. 1037–1045.

Peng, Y, Ngo, L, Hay, K, Alghamry, A, Colebourne, K & Ranasinghe, I 2022, 'Long-Term Survival, Stroke Recurrence, and Life Expectancy After an Acute Stroke in Australia and New Zealand From 2008–2017: A Population-Wide Cohort Study', *Stroke*, vol. 53, no. 8.

Pollock, A, Farmer, SE, Brady, MC, Langhorne, P, Mead, GE, Mehrholz, J & van Wijck, F 2014, 'Interventions for improving upper limb function after stroke', *Cochrane Database of Systematic Reviews*, vol. 11, no. 11.

Porter, S & TidyNM 2009, *Tidy Fisioterapia*, Elsevier, Amsterdam ; Barcelona, p. 4.

Pourmand, A, Davis, S, Marchak, A, Whiteside, T & Sikka, N 2018, 'Virtual Reality as a Clinical Tool for Pain Management', *Current Pain and Headache Reports*, vol. 22, no. 8.

Prince, DA, Parada, I, Scalise, K, Graber, K, Jin, X & Shen, F 2009, 'Epilepsy following cortical injury: Cellular and molecular mechanisms as targets for potential prophylaxis', *Epilepsia*, vol. 50, pp. 30–40.

Ramachandran, VS & Rogers-Ramachandran, D 1996, 'Synaesthesia in phantom limbs induced with mirrors', *Proceedings of the Royal Society of London. Series B: Biological Sciences*, vol. 263, no. 1369, pp. 377–386.

Riley, JD, Le, V, Der-Yeghiaian, L, See, J, Newton, JM, Ward, NS & Cramer, SC 2011, 'Anatomy of Stroke Injury Predicts Gains From Therapy', *Stroke*, vol. 42, no. 2, pp. 421–426.

Ruffino, C, Papaxanthis, C & Lebon, F 2017, 'Neural plasticity during motor learning with motor imagery practice: Review and perspectives', *Neuroscience*, vol. 341, pp. 61–78.

SA Health 2017, *Rehabilitation Services in country South Australia Information for consumers and carers How do I access rehabilitation services?*, October, viewed 15 April

2024, <https://www.sahealth.sa.gov.au/wps/wcm/connect/3019e274-44c1-4dc2-afbf-6a7e06528d47/Rehabilitation_Country+Brochure+Web.pdf?MOD=AJPERES&>.

Saposnik, G, Teasell, R, Mamdani, M, Hall, J, McIlroy, W, Cheung, D, Thorpe, KE, Cohen, LG & Bayley, M 2010, 'Effectiveness of Virtual Reality Using Wii Gaming Technology in Stroke Rehabilitation', *Stroke*, vol. 41, no. 7, pp. 1477–1484.

Sherman, CR 2006, 'Motion Sickness: Review of Causes and Preventive Strategies', *Journal of Travel Medicine*, vol. 9, no. 5, pp. 251–256.

Slater, M & Sanchez-Vives, MV 2016, 'Enhancing Our Lives with Immersive Virtual Reality', *Frontiers in Robotics and AI*, vol. 3, no. 74.

Stevens, JA & Stoykov, MEP 2003, 'Using Motor Imagery in the Rehabilitation of Hemiparesis 11No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit on the authors or on any organization with which the authors are associated.', *Archives of Physical Medicine and Rehabilitation*, vol. 84, no. 7, pp. 1090–1092.

Thieme, H, Morkisch, N, Mehrholz, J, Pohl, M, Behrens, J, Borgetto, B & Dohle, C 2018, 'Mirror therapy for improving motor function after stroke', *Cochrane Database of Systematic Reviews*, vol. 2018, no. 7.

Triberti, S, Repetto, C & Riva, G 2014, 'Psychological Factors Influencing the Effectiveness of Virtual Reality–Based Analgesia: A Systematic Review', *Cyberpsychology, Behavior, and Social Networking*, vol. 17, no. 6, pp. 335–345.

Trigg, L 2022, *Manual therapy vs therapeutic exercise - which is better? | Integrity Physio*, Integrity Physiotherapy, viewed 26 August 2023, <https://www.integrityphysio.com.au/blog/manual-therapy-vs-therapeutic-exercise/#:~:text=Some%20physical%20therapists%20take%20a>.

Vernadakis, N, Derri, V, Tsitskari, E & Antoniou, P 2014, 'The effect of Xbox Kinect intervention on balance ability for previously injured young competitive male athletes: A preliminary study', *Physical Therapy in Sport*, vol. 15, no. 3, pp. 148–155.

Wade, DT 2020, 'What is rehabilitation? An empirical investigation leading to an evidence-based description', *Clinical Rehabilitation*, vol. 34, no. 5, pp. 571–583.

Wagner, T, Valero-Cabre, A & Pascual-Leone, A 2007, 'Noninvasive Human Brain Stimulation', *Annual Review of Biomedical Engineering*, vol. 9, no. 1, pp. 527–565.

Wan Zhen Lee, Kuan, G, Muhammad Hafiz Hanafi & Yee Cheng Kueh 2023, 'Effect of Music and Exercise Improve Quality of Life Among Post-Stroke Patients: A Review', *Lecture notes in bioengineering*, pp. 217–228.

WHO 2023, *Rehabilitation*, www.who.int.

Winters, L & Reisberg, D 1985, *Does Imagined Practice Help in Learning a Motor Skill?*, Eric, viewed 28 September 2023, <https://eric.ed.gov/?id=ED261059>.

Yavuzer, G, Selles, R, Sezer, N, Sütbeyaz, S, Bussmann, JB, Köseoğlu, F, Atay, MB & Stam, HJ 2008, 'Mirror Therapy Improves Hand Function in Subacute Stroke: A Randomized Controlled Trial', *Archives of Physical Medicine and Rehabilitation*, vol. 89, no. 3, pp. 393–398.

Yong Joo, L, Soon Yin, T, Xu, D, Thia, E, Pei Fen, C, Kuah, CWK & Kong, K-H 2010, 'A feasibility study using interactive commercial off-the-shelf computer gaming in upper limb rehabilitation in patients after stroke', *Journal of rehabilitation medicine*, vol. 42, Sweden, no. 5, pp. 437–41, viewed 29 April 2019, <https://www.ncbi.nlm.nih.gov/pubmed/20544153>.

Yoxon, E & Welsh, TN 2020, 'Motor system activation during motor imagery is positively related to the magnitude of cortical plastic changes following motor imagery training', *Behavioural Brain Research*, vol. 390, p. 112685.

Artefact Link:

Gaurav Project Exegesis

Assets:

Dunes - Stamp Pack | 3D Landscapes | Unity Asset Store

VR Interaction Framework | Systems | Unity Asset Store

Skybox Series Free | 2D Sky | Unity Asset Store

https://quixel.com/megascans/home?category=surface&search=rippled&search=sand&assetId=sjzkfega

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Sound:

Wandering | Royalty-free Music - Pixabay

A special gratitude to:

Steve Cook

William Andrade

Ethan Schoemaker

Deb Wadham