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ENHANCING BRAIN HEALTH AND COGNITIVE DEVELOPMENT THROUGH SENSORIMOTOR PLAY IN VIRTUAL REALITY:

UNCOVERING THE NEURAL CORRELATES

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> “If we add some science in play, many brain transformations will take place”
> Dr. Stuart Brown, founder of the National Institute for Play

Abstract

Brain health is a critical part of well-being because it is a foundation for the ability to communicate, make decisions and solve real-life problems. Virtual reality games involve motor and sensory activities that can help to improve brain connectivity by providing an immersive and interactive experience that engages multiple brain regions simultaneously. Reinforcing sensorimotor activities influences cognitive skills and improves brain health. Sensorimotor play in virtual reality is a relatively new concept that is gaining attention as a tool for promoting brain health and cognitive abilities. It is believed that this type of play can have positive impact on brain health and cognitive function, such as improving memory, enhancing focus, and reducing stress and anxiety. The aims of the current paper are (1) – to present evidence, based on neuro correlates, of the importance of the sensorimotor play to the brain health and (2) – to propose a conceptual model for a personalized VR game design using neurocognitive feedback obtained through Brain-Computer Interface that assesses brain areas during sensorimotor stimulation.

Keywords: *virtual reality, sensorimotor play, neurocognitive evidences, brain development, serious games.*

Introduction

Adding science in play can be done in various ways, some of which include using technology such as virtual reality (VR) to encourage sensorimotor integration (SMI). Sensorimotor integration is the process by which the sensory information received by the brain is integrated with the motor information necessary for movement and action (Asan et al., 2022). SMI is an important process for growth and strengthening the neurons and neural connections, contributing significantly to the development of cognitive, physical and social skills. SMI can contribute to the development of speech, working memory, cognitive flexibility and improving motor skills during play (Brugada-Ramentol, 2022). Brain areas, which are most likely to be involved in a play, include regions within the prefrontal cortex, dorsal and ventral striatum, some regions of the amygdala and habenula (Siviy, 2016). The potential of exercise during playfulness consider to induce beneficial responses in the brain, which is accompanied by an increase in Brain Derived Neurotrophic Factor (BDNF), a trophic factor associated with cognitive improvement and the alleviation of depression and anxiety (Sleiman et al., 2016). More proofs how cognitively engaging brain during physical activities enhances production of protein BDNF can be reviewed in (Liu & Nusslock , 2018) and (Mrówczyński, 2019).

VR offers a unique platform for sensorimotor stimulation, engagement and experimentation. Sensorimotor integration in VR can be facilitated through various devices, such as VR headsets, hand controllers and haptic feedback, which provide sensory inputs and motor actions. Thus, VR provides an immersive environment where users can interact physically, mentally and emotionally with a Virtual Environment (VE) that closely mimics the real world (Adamovich et al. 2009), Kober et al., 2015). SMI involves cognitive flexibility, as individuals need to adapt and adjust their motor actions based on changing sensory inputs and environmental demands (Dajani & Uddin, 2015). Cognitive flexibility is closely related to working memory, as it involves the ability to update and manipulate information in real-time. Engaging in sensorimotor activities that require planning and organization can enhance executive function skills because the player needs to make decisions and to coordinate motor actions with intention, processing and process and integrate multisensory signals from various sensory inputs (Eckardt et al., 2020). Furthermore, the use of sensorimotor play in VR is recognized as a potential approach to promote brain reorganization (Adamovich et al. 2009) through massive and intensive sensorimotor stimulation, which encourages the brain to adapt and reorganize when presented with conflicting information. Authors in (Adamovich et al. 2009) provide examples for VR games, where users are required to navigate in a virtual environment (VE) while ignoring distracting stimuli irrelevant to the task. This aims to enhance attention and cognitive control, potentially improving the transfer of skills to real-world tasks. Users engaging in VR make a conscious effort to create mental representations that match their existing knowledge and the new information provided in the virtual environment, which helps them to acquire and practice skills and solve problems autonomously (Hamad & Jia, 2022). Another benefit of sensorimotor play in VR is its accessibility. Unlike traditional forms of physical activity, virtual reality experiences can be enjoyed by people of all ages regardless of their physical condition. This makes it an attractive option for individuals who may be limited in their ability to participate in traditional forms of physical activity.

By integrating neuroscience research findings into plays and using VR activities to stimulate sensorimotor integration, it is possible to develop specific functions of the brain, such as attention, perception, memory and problem-solving, emotional regulation and social cognition, language learning in children and creation of strong memory traces through exploration and curiosity (Reio, 2012), (Sobel & Letourneau, 2018). As children engage in sensory plays, they develop an understanding of their environment and how they can interact with it (Jirout, 2020), (Christodoulou & Anastassiou-Hadjicharalambous, 2018), (Morris, 2022). Sensorimotor stimulation in VR lines up with the theory of embodiment cognition. A fundamental concept in embodiment involves the sharing of neural resources between sensorimotor and cognitive processes (Craighero, 2022), (Jaswal, 2016). In this Editorial on Perception, Action, and Cognition, it is emphasized that the discovery of mirror neurons encoding observed actions highlights the coupling of perception and action. While the perception-action link is considered relatively automatic, the Editorial highlights that this link can be affected by representations and their manipulation through cognitive processes.

Uncovering the neural correlates behind developing specific brain functions requires understanding the roles of particular brain regions that are effective for motor-cognitive development, the stimuli that activate them and the potential of non-invasive methods for assessing and using neurocognitive feedback. In general, from a neuroscientific perspective, VR offers multisensory stimulation that can evoke the mirror neuron system and mechanisms of action observation, which have been suggested to be effective for motor-cognitive development (Perez-Marcos et al., 2018), (Wright, 2014).

The authors conducted an extensive literature review on the topic of sensorimotor stimulation and its impact on neurogenesis. They aimed to integrate these findings into VR as goal-oriented interactive scenarios. The review includes hemodynamic, electrical and electromagnetic neurocognitive brain imaging techniques which examine active brain regions during sensorimotor integration, such as Functional Magnetic Resonance Imaging (fMRI), functional Near-Infrared Spectroscopy (fNIRS), Positron Emission Tomography (PET), Electroencephalography (EEG) and Magnetoencephalography (MEG). Therefore the focus of the review was on neuroscientific perspectives, rather than psychological ones, and the aim was to highlight the valuable effects of sensorimotor play on brain functioning and learning. Three research questions have been formulated:

What neuroscientific findings from the literature support the impact of sensorimotor stimulation in VR for brain development?

How have researchers demonstrated neurogenesis, specifically in measuring the growth and development of new neurons subsequent to sensorimotor stimulation?

What post-hoc analyses involving EEG, fNIRS, fMRI or MEG have been reported in papers examining brain activity data recorded during experiments incorporating sensorimotor stimulation?

The current study contributes to the field by addressing those research questions in order to uncover the neural correlates associated with specific brain functions and the activation of diverse brain regions through sensorimotor stimulation. We present how this activation is effective for motor-cognitive development, involving multiple pathways that collaboratively facilitate the generation of new neurons and the reinforcement of neural connections. The study also proposes a *conceptual model for designing VR games with neurocognitive feedback using Brain-Computer Interface* (BCI) technology to assess those neuroscience findings, underlying sensorimotor stimulation. The design focus is on specific areas of targeted brain development and personalized game design through BCI feedback. This feedback can be used to maintain the user's score and level, or for post-hoc analysis to determine progression based on previous performance outcomes. We propose examples for commercial VR games categorized according to their targeted brain development goals. These games can stimulate various aspects of brain function, such as development, production and perception of speech, improving motor skills, working memory, cognitive flexibility, attentional control, executive function, and evoking specific emotional states or promoting social cognition.

The rest of the paper is organized as follows: in the following section the authors address the research questions and conclude each subsection with a summary of the neuroscientific evidence for the benefits of intensive sensorimotor stimulation on brain development and health. Next, the authors propose a conceptual model for neuro driven design of VR games with BCI for assessing and using neurocognitive feedback for personalized brain development. Then conclusion follows.

What neuroscientific findings from the literature support the impact of sensorimotor stimulation in VR for brain development?

The next two surveys contribute to a comprehensive understanding of the interplay between sensorimotor processes and cognitive functions. A review by Seidler and Carson (Seidler, & Carson, 2017) summarized the evidence of the involvement of the sensorimotor system in various cognitive functions, such as action perception, spatial attention, memory, numerical abilities, speech and empathy. The review also discussed the potential of VR to enhance sensorimotor learning and recovery by providing meaningful, repetitive and adaptive practice, as well as salient feedback. The review suggested that VR can optimize motor learning by manipulating the practice conditions that engage different learning mechanisms, such as motivational, cognitive, motor control and sensory feedback-based mechanisms. Authors in (Ocklenburg & Peterburs, 2023) described the use of EEG and neuroimaging methods to monitor brain activity in VR, and reviewed some applications of VR in neuroscience, such as studying the neural correlates of presence, embodiment, social cognition and memory. The chapter also suggested that VR can provide a powerful tool for exploring the neural mechanisms underlying human behaviour and cognition within ecologically environments. Once again, this provides evidence that the incorporation of neuroscience principles into sensorimotor play in VR could generate effects similar to physical and emotional experiences.

The complex interplay between emotional experiences and sensorimotor responses in VR can be also understood by neuro correlates. Emotional and sensorimotor stimulations are mutually connected - emotional experiences impact sensorimotor responses and sensorimotor experiences influence emotional responses and memory formation. (Davis, Winkielman, & Coulson, 2017). The regulation of emotional states is inherently tied to the sensorimotor system (Williams et al., 2020). Emotions like fear or excitement, can lead to physiological and sensorimotor responses in the body, such as increased heart rate, release of neurotransmitters and hormones in the brain, amplified sensory perception or changes in motor behaviour. On the other hand Casasanto and Dijkstra (Casasanto & Dijkstra, 2010) inquired about the potential impact of basic motor actions on the nature of emotional memories and, as a result, on individuals' selective recall. Based on their findings, the two authors concluded that a direct and causal connection exists between action and emotion. Positive and negative life experiences were found to be connected with schematic movement representations. Additionally, the authors noted that body movements have the capacity to influence our memory recall (Casasanto, & Dijkstra, 2010). Indeed, situations involving survival are known to create strong memory traces that are more likely to be retained in the long-term memory. This is facilitated neurologically by the interaction between the Emotion and Attention systems in the brain, resulting in emotional association of information from short-term memory to long-term memory. How emotional events rapidly and automatically capture attention by activating subcortical neural structures, including the amygdala is presented in (Yamaguchi & Onoda, 2012), (Brosch et al., 2013). In line with previous neuroscientific explanations why emotional events are better remembered than neutral events, Siviy (Siviy, 2016) presented evidences that the amygdala and prefrontal cortex cooperate with the medial temporal lobe in an integrated manner that affords the amygdala modulating memory association; Kempermann et al. (Kempermann et al., 2010) argue that movement functions as an intrinsic feedback system, sending messages to the brain and its neural cells and enhancing the chances of cognitive difficulties. Asan et al. in (Asan et al., 2022) presents in details the primary areas for sensorimotor integration in the brain: the sensorimotor cortex, primary motor cortex, somatosensory cortex, cerebellum and the basal ganglia. These areas work together to process and integrate sensory information, plan and execute movements, and monitor and adjust motor performance. The primary motor cortex is responsible for planning and executing voluntary movements, while the somatosensory cortex receives and processes sensory information from the skin, muscles and joints. The cerebellum is involved in motor coordination and balance, while the basal ganglia play a role in initiating and regulating movements. In addition to these, other important areas involved are posterior parietal cortex, which is involved in planning movements and spatial reasoning, and the thalamus, which acts as a relay station, transmitting sensory and motor signals to the cerebral cortex.

Neuro correlates, which support the impact of sensorimotor stimulation in VR for brain development, are related to the similarity of VR sensorimotor training to embodiment learning. In both approaches, users interact with virtual objects and environments using their body movements, which requires the integration of sensory information from different modalities such as vision and proprioception. In both, sensorimotor stimulation provides more blood in the prefrontal cortex, which is involved in higher cognitive functions such as decision-making, attention and working memory (Gianni et al., 2022). In both approaches sensory and motor information are essential for learning and skill acquisition. The Craighero's Editorial (Craighero, 2022) explores the mechanisms of the brain during embodied learning from a neuroscientific perspective via embodied cognition theory, which proposes that *human cognition is deeply rooted in the body's interactions with the physical environment*, challenging the traditional view of the motor system as a simple executor of commands. The Editorial contains eight articles and one review that provide evidence of the involvement of the sensorimotor system in various cognitive functions, suggesting that this relationship is causal, and specific sensorimotor training can improve related cognitive functions. The findings in the article (Castellotti et al., 2022) show that cognitive and motor systems interact non-linearly and interfere with time perception processes, suggesting that they all compete for the same resources. The review in (Mazzuka et al, 2021) has shown that not only concrete words, but also abstract words are grounded in the sensorimotor system.

How have researchers demonstrated neurogenesis, specifically in measuring the growth and development of new neurons subsequent to sensorimotor stimulation?

The incorporation of neuroscience principles into sensorimotor play in VR potentially leads to changes in neurogenesis. We studied how sensorimotor integration stimulates the birth of new neurons and improves brain connectivity. Anatomical basis for cognitive-emotional connection can be seen in (Yamaguchi & Onoda, 2012). A new explanation for a novel pathway formed during emotional events that capture our attention is given in (Zikopoulos & Barbas, 2012). The authors found out that a pathway from the amygdala, the brain's emotional center, and the thalamic reticular nucleus, a key node in the brain's attentional network in the upper surface of temporal lobe, formed unusual synapses with more large and efficient terminals than the pathways from the orbitofrontal cortex, usually activated during attention. Another interesting finding in the research experimental study in (Serra et al., 2019) proves that exercise can stimulate the birth of new neurons, and it provides increased cognitive reserve, enabling animals to recover better after brain injury or disease that damages healthy neurons. The study shows that building the brain through exercise provides animals with an increased cognitive reserve, which helps them recover better from brain injury or disease that kills or damages healthy neurons. Play in rats is quantified and regulated, and brain areas involved in the modulation of play include regions within the prefrontal cortex, some regions of the amygdala and dorsal and ventral striatum, which are critical components of the reward system and decision-making.

VR can alter the functional organization and representation of brain regions by activating or inhibiting specific neural pathways and networks. VR can modulate the synaptic strength and connectivity of neurons by inducing long-term potentiation (LTP) or long-term depression (LTD) through repetitive and intensive stimulation (Cheung et al., 2014), (Mindy et al., 2015). VR can induce changes in the morphology and number of neurons, dendrites, synapses, and glial cells by stimulating neurogenesis, synaptogenesis, dendritic arborization, and gliogenesis (Cheung et al., 2014), (Mindy et al., 2015) and

(Schiza et al., 2019). Virtual reality has demonstrated neurobiological effects on neuronal plasticity, leading to increased cortical gray matter volumes, elevated concentration of electroencephalographic beta-waves and improved cognitive performance (Georgiev et al., 2021).

Authors in (Keller et al., 2020) investigated the effects of virtual reality-based treatment on the cortex grey matter changes in persons with acquired brain injury. The authors used magnetic resonance imaging and voxel-based morphometry to measure the grey matter volume and found that VR-based treatment for regaining upper extremity function induces cortex grey matter changes in persons. Another two studies found a positive correlation between gray matter volumes in the motor, premotor, and supplementary motor cortices and both power and active range of motion measured during motor tests. VR training stimulates neural recovery mechanisms, such as hippocampal neuroplasticity and neurogenesis (Toda et al., 2019), (Berdugo-Vega et al., 2020). Authors associate these processes to be linked to the stress response and emotional regulation (Cameron & Glover, 2015).

For the development of the nervous system, a factor for growth from the neurotrophin family is Brain-derived neurotrophic factor (BDNF). BDNF plays a crucial role in promoting the survival of existing neurons and initiating neurogenesis. Proofs how cognitively engaging brain during physical activities enhances production of protein BDNF can be reviewed in (Liu & Nusslock, 2018), (Mrówczyński, 2019), (Corrone et al., 2021) and (Difede et al., 2022). All authors investigated that BDNF leads to comparable significant clinical improvement.

What post-hoc analyses involving EEG, fNIRS, fMRI or MEG have been reported in papers examining brain activity data recorded during experiments incorporating sensorimotor stimulation?

What is the evidence from the EEG post hoc Analyses in papers?

EEG post hoc analysis in the article (Tosoni et al., 2021) investigates how sensory-motor modulations of EEG event-related potentials (ERPs) reflect walking-related macro-affordances. The authors performed an EEG experiment in which participants viewed images of walkable and non-walkable objects while standing or walking on a treadmill. The study found that the sensory-motor modulation of the N1 ERP component (which reflects early sensory processing) was stronger when participants were walking compared to standing, and that this effect was specific to walkable objects. The study suggests that walking-related sensory-motor modulations of early visual processing reflect the perception of walking-related macro-affordances.

In (Škola et al., 2020) EEG post-hoc analysis was conducted to assess the impact of blending interactive VR experiences with 360° storytelling on cognitive processing. The study involved 15 participants, and the electrodes were positioned in the right earlobe, pre/frontal (FPz, F3, F4, Fz), parietal (P3, P4, Pz) and occipital (Oz) areas. The analysis revealed heightened cognitive processing without associated overload, suggesting a significant level of immersion and engagement among participants. Specifically, post-hoc EEG results in the beta band provided evidence of the participants’ substantial presence, engagement and immersion in the VR experience. These neuro correlates strongly suggest that in some instances VR experiences with 360° storytelling may offer more engaging cognitive stimulation than physical experiences.

Oldrati et al. (Oldrati et al., 2016) conducted a study on the imagination of movement without actual physical movement. They found that motor imagery (MI) activates all the sensorimotor areas involved in actual action execution, specifically the dorsal premotor cortex (dPMC) and the primary somatosensory cortex (S1). MI can be performed through different modalities, with kinesthetic and visual sensory experiences being the most common. The study showed that kinesthetic MI, which involves somatic sensations that occur during movement execution, stimulates dPMC and S1 more strongly than visual MI, which is the visualization of movement viewed from the subject's own eyes or from a third-person perspective.

EEG post hoc analysis in the article (Vourvopoulos et al., 2019) refers to chronic stroke patients who underwent a BCI training program that utilized virtual reality (VR) neurofeedback. The goal of the training was to enhance sensorimotor cortical activity and improve upper limb motor function. After the completion of the study, EEG post hoc analysis was performed to investigate the changes in EEG power spectral density (PSD) in the sensorimotor cortex. The results showed that the BCI training program led to significant changes in EEG PSD in the sensorimotor cortex primarily in the beta and gamma frequency bands, which are associated with sensorimotor processing and movement planning.

Neurofeedback experiments in (Berger & Davelaar, 2018) investigated the role of frontal alpha oscillations in attentional control, as measured by a Stroop task. The authors used EEG to measure the alpha band power in the prefrontal cortex of 22 healthy participants, and provided them with real-time feedback on their alpha level in a virtual reality (VR) or a 2D environment. The authors expected that increasing the alpha level would improve the attentional control, as reflected by the Gratton effect, which is the reduction of the Stroop interference effect after a previous incongruent trial. The authors found that the participants who learned to increase their alpha level showed a larger decrease in the Gratton effect, suggesting that frontal alpha oscillations are associated with efficient neurocognitive processing. The authors also found that the VR group had a larger learning rate than the 2D group, indicating that VR can enhance the neurofeedback training.

The EEG post hoc analysis in the paper (Vourvopoulos & Bermúdez I Badia, 2016) refers to a secondary analysis of EEG data collected during a motor-imagery training task in a virtual reality environment. The authors investigated the effect of motor priming in a virtual reality environment on the efficacy of motor-imagery training in individuals with motor deficits due to stroke. Participants completed a motor-imagery task before and after a virtual reality session that included motor priming exercises. The EEG post hoc analysis involved examining the EEG signals during the motor-imagery task to identify changes in neural activity following the virtual reality session. Specifically, the analysis focused on the event-related desynchronization (ERD) and event-related synchronization (ERS) of the mu rhythm, which is associated with motor planning and execution. The results of the EEG post hoc analysis showed that the virtual reality session with motor priming exercises led to a significant increase in the ERD and ERS of the mu rhythm during the motor-imagery task. This suggests that motor priming in a virtual reality environment can enhance the efficacy of motor-imagery training for individuals with motor deficits.

A neurofeedback training study in (Kober et al., 2015) examines how the electrical activity in the sensorimotor cortex contributes to better cognitive processing, and how training with SMR (sensorimotor rhythm, 12-15 Hz) neurofeedback can influence it. The results of the experiment revealed that the experimental group showed a linear rise in SMR power throughout the training sessions, while the control group did not. This increase in SMR power was linked to enhancements in memory and attention performance. Furthermore, an increase in SMR activity has been linked to better cognitive processing as a result of reduced interference from motor functions, thus leading to improvements in various cognitive abilities. Manipulating SMR activity voluntarily had positive impact on both behavioural and electrophysiological measures in the experimental group. However, it was not the case in the control group.

What is the evidence from the fMRI or fNIRS post hoc Analyses in papers?

The authors in the paper (Anwar et al., 2016) used fMRI to measure the brain activity of healthy participants who watched a virtual avatar's actions in VR. The post hoc analysis revealed that matching actions increased the functional connectivity between the premotor cortex and the inferior parietal lobule. These regions are involved in the mirror neuron system, a network of neurons that activate both during the performance and observation of actions. The study also found that the embodiment of the avatar increased the functional connectivity between the premotor cortex and the insula, which is a region involved in interoception and empathy.

The authors in (Rodríguez et al., 2015) used fMRI to assess brain activations associated with emotional regulation during virtual reality mood induction procedures. Participants were exposed to virtual environments designed to elicit either positive or negative emotions, and were instructed to either maintain or regulate their emotional response to the stimuli. The results showed increased activation in the prefrontal cortex during emotion regulation, suggesting that this region is involved in cognitive control processes during emotional regulation. Additionally, the study found that emotional regulation was associated with decreased activation in the amygdala, which is a key region involved in emotional processing.

In the study by (Molenberghs, Cunnington & Mattingley, 2012) fMRI is used to investigate how the context of action observation modulates the activity of the mirror system areas. Twenty participants observed identical actions under different instruction context. A multi-voxel pattern analysis revealed unique patterns of activation in ventral premotor cortex and inferior parietal lobule across the difference contexts. The task was either to understand the actions, to identify the physical feature of the actions, or passively observe the action. The results showed that ventral premotor and inferior parietal areas respond differently to observed actions depending on the mindset of the observer.

In the paper by Seraglia et al. (Seraglia et al., 2011) the researchers found increased activation in the prefrontal cortex during the immersive virtual reality task (participants performing a task that simulated a shopping experience), as measured by fNIRS. Specifically, they found increased activity in the bilateral dorsolateral prefrontal cortex and left ventrolateral prefrontal cortex, which are areas associated with executive function and decision making. These findings suggest that immersive virtual reality can elicit changes in prefrontal cortex activity. The use of fNIRS to measure brain activity during immersive virtual reality tasks provides valuable insights into the neural mechanisms underlying VR experiences and how sensorimotor stimulation influences both motor and cognitive processes in the brain.

A similar study, considering the effects of action observation on the reorganizations in the bilateral ventral premotor cortex, bilateral superior temporal gyrus, the supplementary motor area and the contralateral supramarginal gyrus, was done by (Ertelt et al., 2007). Using fMRI with an independent sensorimotor task involving object manipulation, there was a notable increase in activity, encompassing regions beyond those in the mirror hypothesis. The direct comparison of neural activations between the experimental and control groups post-training provides evidence supporting the positive additional impact of action observation on the recovery of motor functions after a stroke. This effect is interpreted as the reactivation of motor areas containing the action observation/action execution matching system.

In the research by Banks et al. (Banks et al., 2007) fMRI was used to investigate the neural mechanisms underlying emotion regulation. The researchers found increased amygdala activity during the presentation of emotional stimuli, which was reduced when participants engaged in cognitive reappraisal to regulate their emotional response. Additionally, they found increased functional connectivity between the amygdala and prefrontal cortex during the cognitive reappraisal condition, suggesting that these regions work together to regulate emotions.

According to an fMRI Post hoc Analysis in the paper (González et al., 2006) reading words associated with smells such as jasmine or cinnamon activates the olfactory areas of the brain. If the words are merely “symbols”, abstract and unrelated to the body, performing a mental cognitive task will not activate brain regions associated with sensorimotor processing.

Pulvermuller (Pulvermüller, 2005) used neuroimaging techniques, such as fMRI to uncover the neural correlates of action-related language processing in the brain, with a focus on whether the comprehension of action words specifically activates the motor system in a somatotopic manner. He particularly explored the critical case of action words that are semantically related to different parts of the body, such as “lick”, “pick”, and “kick”, and whether their comprehension relies on activity in the action system. The results obtained through fMRI, could provide insights into the neural mechanisms underlying language processing related to actions and the involvement of the motor system.

What is the evidence from the Magnetoencephalography (MEG) analyses of sensorimotor stimulation in papers?

The study (Roy, Youssofzadeh, McCreadie, & Prasad, 2020) related MEG responses to both motor- and cognitive-imagery activities during a brain-computer interface (BCI) experiment. Authors reveal group source localization showed prominent desynchrony effects in bilateral premotor and motor areas during hand and feet conditions, with stronger effects at the left-hemispheric regions, left prefrontal cortex, known to coordinate between cognitive and motor regions.

A study by (Leisman, Moustafa & Shafır, 2016) discovered that both cognitive and motor function are controlled by brain areas such as frontal lobes, cerebellum, and basal ganglia that collectively interact to exert governance and control over executive function and intentionality of movements that require anticipation and the prediction of movement of others.

The study by Kennedy et al. (Kennedy et al., 2009) presents a MEG experiment, where the neural correlates of visuomotor integration were explored using a tracking task with 15 participants. The study employed a 2x2 within-subjects design, manipulating hand and eye movements during the tracking task. Results revealed bilateral beta desynchronization and contralateral gamma synchronization in the motor cortex, particularly prominent in combined manual/visual tracking conditions. Gamma synchronization was also observed in the visual cortex, correlating with behavioural performance measures.

MEG has been used to study brain regions involved in sensorimotor tasks, focusing on the temporal dynamics of the cortical representation from action to language (Nishitani et al., 2005). Nishitani and Hari revealing that the left inferior frontal cortex, specifically Brodmann's area 44 (BA44), is activated first. Subsequently, within 100–200 ms, the left primary motor area (BA4) is activated, followed by activation of the right BA4 150–250 ms later. These findings suggest that the left BA44 plays a crucial role in coordinating the human "mirror neuron system" and is particularly involved in action imitation.

Following the analysis, the authors concluded that VR activities stimulate sensorimotor integration (SMI) and enhances brain development by activating multiple brain areas and pathways. Summarized below are the most cited neural correlates associated with SMI:

1. SMI: VR-induced neural activation of motor system in action observation (visuomotor integration)

- Neural Correlate: Involvement of our motor system in action observation and mirror neurons in understanding the actions of others. The observation of similar actions performed by a virtual avatar activates and reinforces a network of neurons that fire both when performing and observing actions (Anwar, A.R. et al., 2016), (Molenberghs, Cunnington, & Mattingley, 2012). (Ertelt et al., 2007), (Nishitani et al., 2005), (Lakshminarayanan et al., 2023)

2. SMI: VR-activation of motor and sensory brain areas during language processing (audiomotor integration)

- Neural Correlate: Both motor and sensory brain areas activated during the processing of language related to actions or physical perceptions (Pulvermüller, 2005), (Mazzuka et al, 2021), (Zappa et al., 2019).

3. SMI: Mutual connection between emotional and sensorimotor stimulations

- Neural Correlate: Emotional and sensorimotor stimulations are interconnected. Emotional experiences impact sensorimotor responses, leading to improved perception and attention. On the other hand, sensorimotor experiences influence emotional responses and contribute to memory formation. (Škola et al., 2020) , (Davis, Winkielman & Coulson, 2017), (Williams-Williams et al., 2020).

4. SMI: Frontal lobe neuronal involvement in motor tasks

- Neural Correlate: The involvement of neurons in the frontal lobe during the execution of movement commands and transmitting signals to the temporal lobe, means that the sensorimotor system is involved during cognitive tasks necessary for perception and interaction with the world. (Roy, Youssofzadeh, McCreadie & Prasad 2020), (Leisman, Moustafa & Shafir, 2016), (Kennedy et al.,2009), (Seraglia et al.,2011).

- Neural Correlate: Deficit in sensorimotor stimulation also result in cognitive deficits (Vourvopoulos & Bermúdez I Badia, 2016), (Tosoni et al., 2021), (Courtney et al., 2021)

5. SMI: VR sensorimotor games enhance brain connectivity and neuroplasticity

- Neural Correlate: Improved brain connectivity, simultaneous engagement of multiple brain regions and strengthened connections among neuron groups that represent sequential events occurring in time (Berger & Davelaar, 2018), (Škola et al., 2020), (Adamovich et al., 2009)

- Neural Correlate: Adaptation and formation of new connections in response to various stimuli and experiences (Toda et al., 2019), (Mindy et al., 2015), (Cheung et al., 2014), (Bohil, Alicea& Biocca, 2011).

Conceptual model for designing VR games with neurocognitive feedback using Brain-Computer Interface for assessing SMI

In this section, a new conceptual model for personalizing a VR game design based on neurocognitive feedback using BCI technology that assesses brain areas during sensorimotor integration, is presented. The design focuses on specific areas of targeted brain development and personalized BCI feedback that is used to maintain the sensorimotor stimulation for better performance outcomes. *We summarized the neurofindings during sensorimotor stimulation in VR in the previous sections and categorized them in Table 1 according to the targeted brain development functions (TBDF), targeted brain areas (TBA), motor and cognitive engagement and responses to the sensorimotor stimulus*. The TBDF are: development, production and perception of speech, improving motor skills, working memory, cognitive flexibility, attentional control, executive function and evoking specific emotional states or promoting social cognition. The TBA are presented in the second column, however it is crucial to remember that these brain areas function collaboratively within a network.

Table 1.
Design focus on specific areas for targeted brain development

TARGETED BRAIN FUNCTIONS	TARGETED BRAIN AREAS	MOTOR AND COGNITIVE ENGAGEMENT	RESPONSE TO SENSORIMOTOR STIMULUS
Development, production and perception of speech	Broca's area (in the left hemisphere of the frontal cortex) and auditory processing areas in the temporal cortex -Wernicke's area (superior temporal gyros, left)	Listening to words and motor (speaking) activities, speech perception, auditory learning, language learning, communication skills.	Recognizing verbal communication in social interactions. Recognizing dialog tone, language cues.
Improving motor skills	primary motor cortex (planning and executing voluntary movements), the somatosensory cortex (receives and processes sensory information from the skin, muscles and joints), the cerebellum (motor coordination and balance) and the basal ganglia (initiates and regulates movements). The prefrontal cortex and posterior parietal lobe (attention-focusing and body awareness) Hippocampus	Motion Tracking in reaction to moving visual stimulus. Haptic reaction to simulate the sense of touch. Motor reactions such as moving the eyes or head to follow the object. Performing motor actions prompted by visual or audio stimuli.	Coordination, balance and motor skill refinement, sensing touch and recognizing textures in social interactions. Spatial awareness for tactile experiences. Body movement understanding. Sensorimotor coordination for processing visual information and generating appropriate motor commands.
Working memory	dorsolateral prefrontal, cingulate and parietal cortices, as well as midbrain and cerebellum	Storing visual information in memory for later recall. Engaging in physical movements or gestures in reaction to visual prompts.	Ability to hold and manipulate information in mind over short periods of time. Memory Encoding and recall.
Cognitive flexibility	prefrontal cortex, ventromedial prefrontal cortex, posterior parietal cortex, Substantia Nigra (SN) and Ventral Tegmental Area (VTA), Nucleus Accumbens (NAcc), thalamus	Adapt to changing VR situations and switch between different tasks or strategies.	Promote creative problem-solving and decision-making. Ability to understand and navigate social situations effectively.
Attention and Focus	dorsolateral prefrontal cortex, posterior parietal cortex, inferior frontal gyrus and the superior temporal gyrus, hippocampus	Directing attention toward specific visual or audio stimuli. Focusing on details or particular elements within a visual scene. Shifting attention in reaction to changes in the visual or audio stimulus.	Selectively attend to relevant sensory information, ignore irrelevant information and shift attention when needed. Spatial awareness.

TARGETED BRAIN FUNCTIONS	TARGETED BRAIN AREAS	MOTOR AND COGNITIVE ENGAGEMENT	RESPONSE TO SENSORIMOTOR STIMULUS
Executive function	dorsolateral prefrontal cortex (decision-making); ventromedial prefrontal cortex (decision-making related to social and emotional contexts, reward processing and motivation); anterior cingulate cortex (monitoring and adjusting cognitive control, error detection, conflict resolution); orbitofrontal cortex (decision-making, reward processing), thalamus.	Coordination of sensory input and motor output, Using visual information to solve problems or make decisions. Body awareness, motor planning, coordination.	Planning, coordination and execution of motor actions. Awareness of body in space, coordination.
Social cognition	temporoparietal junction, superior temporal sulcus and medial prefrontal cortex inferior frontal gyrus and the superior temporal gyrus.	Interactions in simulated social scenarios. Observing and recognizing body language. Motor planning, hand-eye coordination.	Understanding faces, dialog tone, proprioceptive cues, mimicking and interpreting gestures in social context. Ability to understand and navigate social situations.
Emotional regulation	Amygdala, prefrontal cortex (ventromedial prefrontal cortex and orbitofrontal cortex), inferior temporal cortex and anterior cingulate cortex, Hippocampus, Mirror Neurons (premotor cortex, supplementary motor area, primary somatosensory cortex and the inferior parietal cortex)	Interactions in designed scenarios for emotional regulation, evoking positive emotions such as empathy and compassion, and promoting mindfulness and relaxation.	Ability to manage and regulate emotions. Facial expressions, body language, or verbal communication to convey or suppress emotions. Seeking social support.

The conceptual model for sensorimotor stimulation of targeted brain areas in VR with EEG-based neurofeedback is presented as a flowchart in Figure 1. The integration of feedback enables users to recognize errors and motivates them to engage in exercises for skill improvement in order to progress to higher levels, thus contributing to brain development. Brain activity in TBA and valence/arousal level can be additional factors for setting challenges along with parameters like speed, task completion time and accuracy in motor skills, contributing to potential improvements in TBDF.

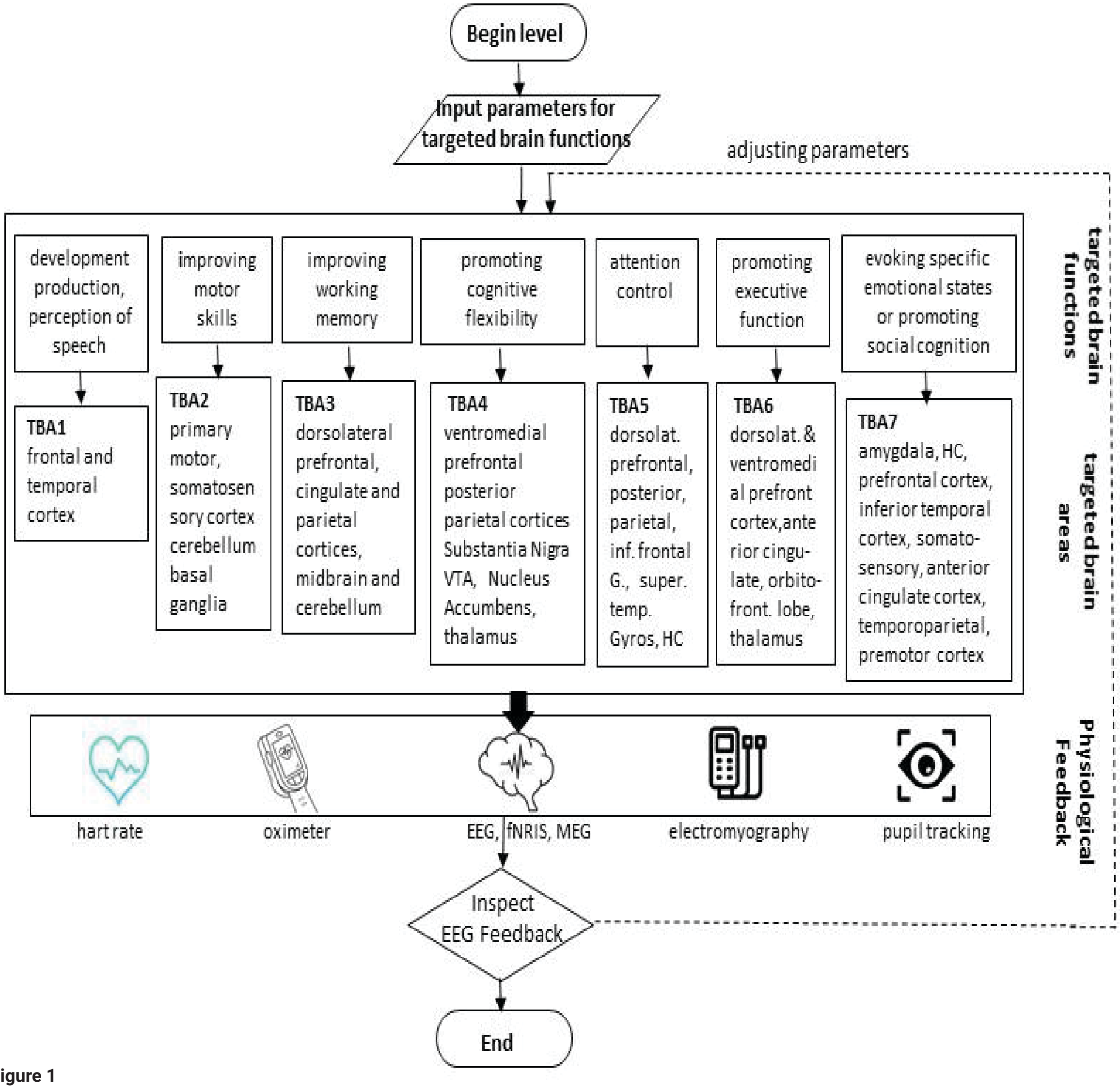

Figure 1
A conceptual model for personalizing VR games via neurofeedback

The proposed BCI neurofeedback technology for modulating sensorimotor stimuli to customize gaming experiences is based on assessments of visuomotor integration, visuoaudio integration, and interconnected emotions. These are the initial three neural correlates associated with SMI, reviewed in detail in the previous section, where the neural mechanisms associated with the integration of visual, auditory and emotional information with motor processes is presented. Technical details regarding the integration of non-invasive EEG-based BCI devices in VR settings can be seen in the systematic review by (Gramouseni et al. 2023). This review provides an overview of various BCI methodologies for acquiring, processing and classifying brain signals (Tables 4, 7, 8, 10, 14) in order to modulate the VR environment or stimuli based on the user's cognitive or emotional states, along with objectives and outcomes (sections 4.2.1, 4.3.1.4.5.1). The model, which we propose, is flexible and enables the use of different physiological feedback mechanisms, including measurements from VR headsets or external sensors for heart rate, skin conductance and other neuroimaging techniques like fNIRS and MEG. Additionally, pupil tracking, eye movement and gaze patterns can be employed to assess visual attention and perception.

Conclusion

The paper proposes some promising neural correlates under sensorimotor play in VR, which have the potential to enhance brain health and cognitive functions through neuroplasticity and improved functional networks. This leads to improvements in motor skills, cognitive abilities, and emotional and social aspects of brain development. The adaptability of VR technology allows users of different skill levels to engage in play, making it inclusive. The proposed conceptual model involves personalizing VR game design through neurocognitive feedback using BCI technology to assess brain areas during sensorimotor integration. The design emphasizes specific areas of targeted brain development and personalized BCI feedback to optimize sensorimotor stimulation for improved performance outcomes. Limitations of the current research are related to generalizability of the VR game design to enhance brain health and cognitive functions since they are not well established and there is a lack of standardized protocols to evaluate the outcomes and transferability of the skills learned in VR to real-world. In addition, there are many aspects that can influence the user's perception, motivation, and satisfaction, such as the quality of the graphics, the level of immersion, the degree of interactivity, the presence of social cues and the individual preferences and characteristics. Therefore, future research directions include more rigorous experiments with larger and diverse samples, using valid and reliable outcome measures, and comparing the results with other conventional or alternative interventions. Furthermore, user experience and engagement of the VR game design can be optimized, by applying user-centered and participatory design methods and tailoring the game features and content to the user's needs, goals, and preferences.

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