



Multisystem Integration and Neural Mechanisms in Stroke Rehabilitation: The OutbunderARS Approach

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Introduction

Stroke remains one of the leading causes of long-term disability worldwide and continues to impose an enormous clinical, social, and economic burden. According to the *World Stroke Organization Global Stroke Fact Sheet 2025*, nearly 12 million individuals experience a new stroke each year, approximately 94 million people are currently living with the consequences of stroke, and one in four adults over the age of 25 will experience a stroke during their lifetime. Despite substantial advances in acute stroke management, stroke remains the third leading cause of death and disability worldwide and is responsible for approximately 7.3 million deaths annually (Feigin et al., 2025). Consequently, there is an urgent need for rehabilitation strategies capable of enhancing neuroplasticity, promoting functional recovery, and extending meaningful recovery, even among individuals with chronic stroke who are traditionally considered to have plateaued.

Task-Oriented Therapy (TOT) remains the cornerstone of contemporary neurological rehabilitation; it focuses on basic motor skills and capitalizes on the principles of experience-dependent neuroplasticity. Effective TOT emphasizes repetitive, intensive, and meaningful practice directed toward functional activities that are relevant to everyday life (Kleim & Jones, 2008; Winstein et al., 2016). Repeated motor practice promotes neural reorganization through continuous cycles of motor execution, sensory feedback, error detection, and motor adaptation. These cycles of motor activity require high repetition, adequate intensity, and sustained engagement to achieve functional recovery. Unfortunately, conventional rehabilitation frequently becomes repetitive and monotonous, which reduces patient motivation, exercise intensity, and the total number of therapeutic repetitions performed. These limitations may diminish neuroplastic adaptation and ultimately constrain functional recovery. Robotic rehabilitation systems and virtual reality (VR) have emerged as promising approaches to address these limitations by increasing patient engagement, treatment intensity, adaptive progression, and motivation.

Robot-assisted rehabilitation enables high-intensity, repetitive, task-oriented practice while reducing physical fatigue and therapist burden. Robotic rehabilitation systems typically provide

passive limb movement, graded assistance, body-weight support, or adaptive resistance during gait or cycling activities. By contrast, *responsive robotics* involve whole-body movement (rather than focusing on body parts or regions), multisensory feedback, and real-time physical interaction to provide personalized, responsive, and safe support (Mashud, et al., 2025). The importance of this distinction will become apparent as this paper unfolds.

Virtual reality has been defined as the computer-generated creation of interactive three-dimensional environments that permit users to explore and manipulate virtual objects through real-time sensory interaction (Greenleaf & Tovar, 1994). Within neurorehabilitation, VR integrates physical activity with cognitive challenges in enriched multisensory environments that promote motor learning, attention, and task-specific practice (Rizzo & Koenig, 2017; Wade & Winstein, 2011). However, the term *virtual reality* encompasses a broad spectrum of technologies. At one end are non-immersive systems that present “virtual environments” on conventional flat computer displays while allowing interaction through keyboards, touchscreens, or handheld controllers (Laver et al., 2025). *These systems primarily enhance motivation by increasing the quantity and variety of typical therapeutic tasks* but leave the user's normal sensory experience largely intact. Nevertheless, these non-immersive approaches are still called, by some, virtual reality, i.e. *non-immersive virtual reality*. More advanced systems employ head-mounted displays together with motion tracking and varying degrees of auditory, proprioceptive, vestibular, and tactile feedback to create *immersive virtual reality*, or “iVR” (Riva et al., 2019), which some call “fully immersive virtual reality” (Demeco et al., 2023). A defining characteristic of iVR is the continuous bidirectional interaction between the user and the virtual environment, producing a closed-loop experience in which the environment continuously responds to the user's actions.

When iVR is integrated with *responsive robotics* the resulting experience extends beyond conventional iVR and results in what may be more appropriately conceptualized as *Immersive Simulation*. Unlike iVR, Immersive Simulation creates *continuous interaction* between the patient, the robotic platform, and the virtual world, generating a highly embodied therapeutic experience. This experience involves visual, vestibular, proprioceptive, cognitive, emotional, and motor systems that are engaged *simultaneously*. The bidirectional interaction allows both *bottom-up activation* arising from movement and sensory feedback and *top-down activation* involving cognitive, attentional, and executive processes to occur concurrently; potentially creating conditions that should enhance experience-dependent neuroplasticity.

To our knowledge, no published studies have specifically evaluated rehabilitation systems that combine responsive robotics, whole-body iVR, adaptive multisensory feedback, and continuous real-time interaction in the manner employed by the Outbounder Advanced Rehabilitation System; the “OutbounderARS”, or simply the “Outbounder”. Consequently, the VR literature reviewed in this paper focuses on iVR, while recognizing that Immersive Simulation represents an emerging extension of those technologies.

The OutbounderARS

The Outbounder is a robotic-assisted Immersive Simulator designed to simultaneously engage motor, sensory, cognitive, vestibular, emotional, autonomic, and reward-processing systems during neurological rehabilitation (Figure 1). The system integrates iVR, responsive robotics, motion simulation, adaptive control systems, and real-time performance analytics into a single therapeutic environment. This environment is intended to maximize experience-dependent neuroplasticity while providing individualized assistance for patients with hemiparesis and other neurological impairments.

The robotic platform consists of a recumbent cycling system mounted on a computer-controlled motion simulator. Steering “blades” enable users to actively navigate complex virtual environments, while an integrated network of sensors continuously measures cadence, force production, steering, symmetry, movement quality, and overall task performance. These data are used to dynamically regulate robotic assistance and resistance, balance the contributions of the impaired and unimpaired limbs, and maintain each individual within an optimal challenge zone. Working within this challenge zone promotes active participation while minimizing compensatory movement strategies.

Unlike conventional robotic rehabilitation devices that provide passive limb movement or fixed levels of assistance, the Outbounder continuously adapts both the physical and cognitive demands of therapy in response to patient performance. The virtual environment provides synchronized visual, auditory, proprioceptive, vestibular, and somatosensory feedback that is coordinated with the robotic motion. Patients continuously respond to changes within the virtual environment, by pedaling and using the steering blades, thus creating a closed-loop interaction between the patient, the robotic system, and the immersive environment. Controlled acceleration, deceleration, turning forces, terrain irregularities, and surface characteristics generate a strong sense of presence and embodiment, allowing patients to experience the perception of operating a recumbent quad cycle in a risk-filled environment while remaining physically secured in the simulator.

Within this environment, patients participate in continually novel, goal-directed therapeutic activities that require bilateral coordination, motor adaptation, cognitive engagement, and decision making. In this context, controlled environmental obstacles, balance perturbations, and time-dependent challenges are designed to evoke a perception of risk without exposing the patient to actual danger. We propose that the combination of embodiment, adaptive challenge, and perceived risk increases the behavioral salience of therapeutic tasks, thereby enhancing attention, motivation, autonomic arousal, and sustained engagement. Thus, as a patient navigates through the virtual environment, they experience repeated cycles of motor prediction, sensory feedback, error detection, and error correction.

By integrating iVR, responsive robotics, multisensory stimulation, bilateral movement, adaptive task progression, and continuous sensory feedback within a single therapeutic platform, the

Outbounder represents a *multisystem approach* to neurological rehabilitation. Rather than targeting isolated motor function, the platform is designed to *simultaneously recruit distributed cortical and subcortical networks* involved in movement, sensation, cognition, attention, emotion, vestibular processing, and reward. We propose that this integrated therapeutic framework creates conditions favorable for experience-dependent neuroplasticity by a number of mechanisms and experiences. These include the requirement for sustained attention, spatial processing, high-intensity repetitive practice, multi-sensorimotor integration, error detection and correction, motor learning, adaptive task progression, embodiment, and perceived risk. Collectively, these interacting mechanisms provide a biologically plausible framework for facilitating neural reorganization, improving motor recovery, and enhancing functional independence following stroke and other neurological disorders.

The purpose of this paper is to briefly review the current evidence supporting immersive Virtual Reality and neuroplasticity, and to present the theoretical, neurobiological framework underlying the design of the Outbounder Advanced Rehabilitation System. Although many of these mechanisms remain theoretical and require empirical validation, together they provide scientifically grounded support for future investigation and clinical translation.

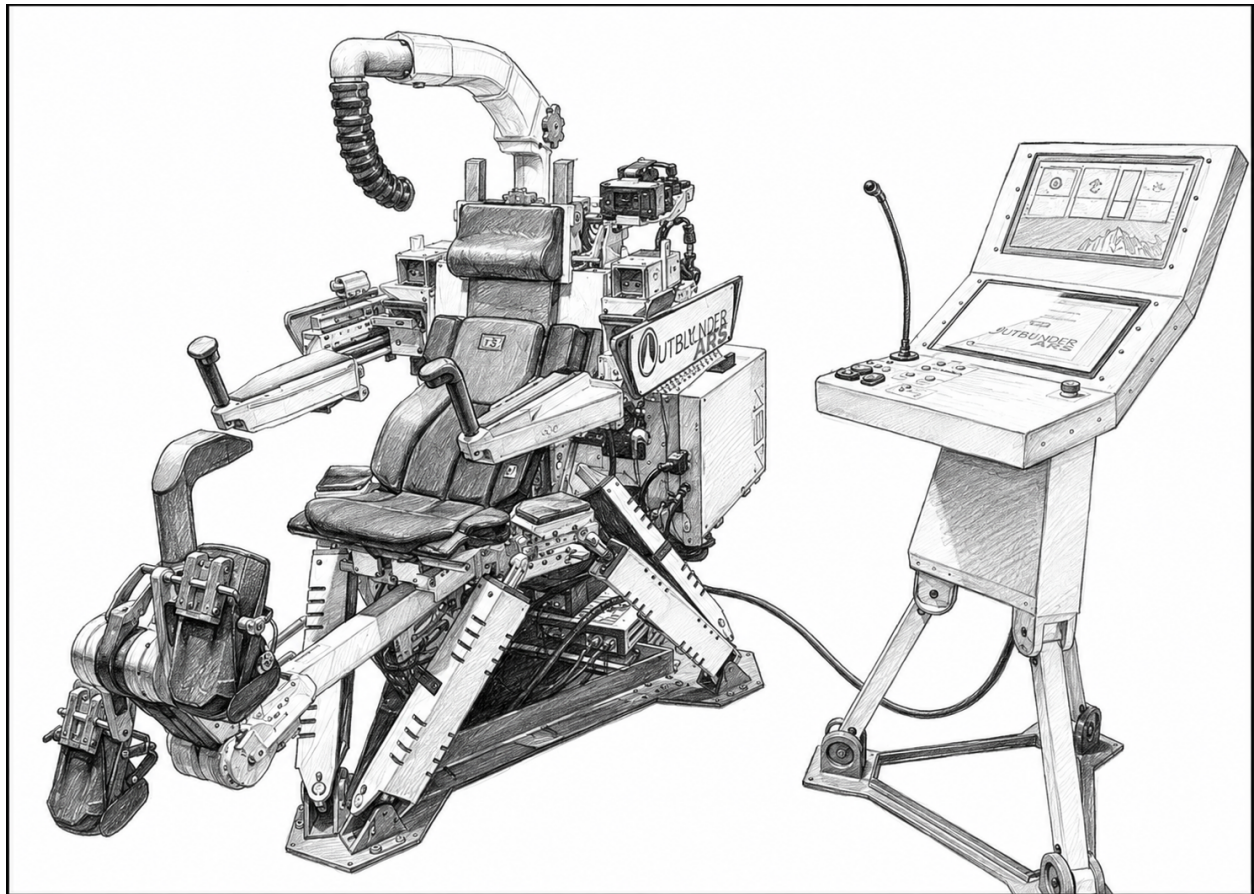


Figure 1. The Outbounder Advanced Rehabilitation System

Literature Review and Discussion

1. Distributed Neural Networks and Multimodal Brain Organization

The brain continuously monitors an immense stream of sensory information from the environment, and from within the body, and responds in ways that are meaningful. Every millisecond, millions of sensory signals are integrated to construct a coherent representation of the external world and the body's relationship to it. Most sensory information is relayed from peripheral receptors through the thalamus, the principal sensory gateway to the cerebral cortex, before reaching the primary sensory cortices where fundamental perceptual features are first processed.

Information from each primary sensory cortex is subsequently transmitted to *unimodal association* cortices, where information is analyzed and integrated with previously stored representations from within the same sensory modality. From there, information converges within *multimodal association* cortices, where visual, auditory, somatosensory, vestibular, and other sensory inputs are integrated into unified perceptual representations. Thus, information that is initially singular in its sensory experience, is distributed throughout the cortex where it is integrated with sensory information from other sensory modalities. These distributed cortical networks compare incoming sensory information with prior experience, contextual knowledge, and current behavioral goals to guide adaptive decision-making and behavior. Therefore, during rehabilitation using Immersive Simulation, current sensorimotor activity of injured regions is constantly being integrated with personal contextual sensory information stored in multimodal regions. We contend that this increases the sense of embodiment we will discuss in later sections.

Importantly, *multimodal association cortices are not isolated processing centers*. Rather, they are extensively interconnected with widespread cortical as well as subcortical networks that collectively evaluate the biological significance of ongoing experiences. These include, but are not limited to:

- *frontal cortical* systems, which are responsible for executive functions, attention, motor planning, decision-making, and anticipation
- *amygdala*, which continuously evaluates environmental stimuli for potential threat, challenge, novelty, and perceived risk
- *dorsal striatum*, which contributes to motor planning, action selection, and skill acquisition
- *ventral striatum*, including the *nucleus accumbens*, which mediates reward processing, motivation, reinforcement learning, and the sense of accomplishment associated with successful task completion
- *limbic system*, which integrates emotion, motivation, and memory into ongoing experience

- *cerebellum*, which coordinates movement, predicts sensory consequences of action, detects performance errors, and contributes to cognitive processing
- *brainstem* neuromodulator systems, which regulate arousal, attention, and autonomic responses

Collectively, these distributed neural systems continuously exchange information through reciprocal cortico-cortical, cortico-subcortical, and cerebello-cortical loops that enable perception, cognition, emotion, and movement to function as an integrated whole rather than as isolated processes (Allman & Meredith, 2007; Fuster, 2002; Hooks, 2017; Mesulam, 1990, 2000, 2002; Picton, Alain, & McIntosh, 2002; Rossi-Pool et al., 2020; Rumelhart & McClelland, 1986; Stein & Meredith, 1993). These reciprocal integrated interactions allow sensory experiences to be continuously evaluated for their behavioral relevance and assigned emotional, motivational, and reward value while simultaneously shaping motor planning and behavioral adaptation (Figure 2). This will become increasingly relevant when we explore how sensory input from motor activity is constantly responding to iVR and vice versa.

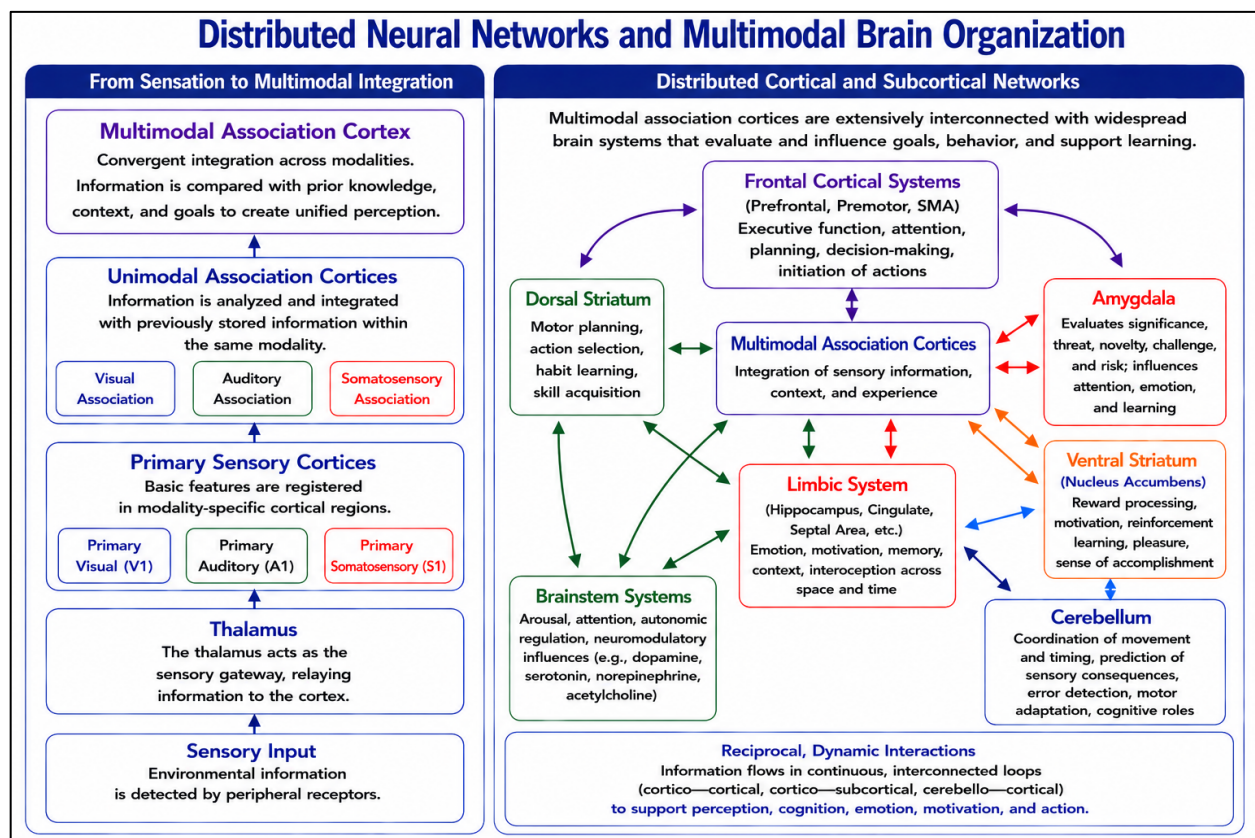


Figure 2. Distributed Neural Networks and Multimodal Brain Organization.

Although specific cortical regions exhibit functional specialization, they rarely operate independently. Focal injury to localized brain regions may produce characteristic neurological deficits because specialized functions are anatomically localized. However, these specialized

regions are embedded within highly *interconnected multimodal networks that support cross-modal integration and distributed information processing*. Consequently, disruption of a single component within these networks may impair the coordinated function of multiple systems, producing deficits that extend well beyond the site of injury. Brain function is therefore best conceptualized as simultaneously localized and distributed.

The *integrated activation* of distributed multimodal neural networks is hypothesized to enhance experience-dependent neuroplasticity by simultaneously engaging multiple cortical and subcortical systems involved in perception, cognition, emotion, motor control, learning, reward processing, and behavioral adaptation. These continuously interacting systems enable the nervous system to modify synaptic strength, reorganize functional connectivity, refine motor programs, and change behavior in response to experience. The Outbounder is designed around this systems-level view of brain organization by *simultaneously engaging these distributed neural networks* through integrated motor activity, immersive multisensory stimulation, cognitive challenge, emotional engagement, and adaptive robotic interaction. The simultaneous engagement leads to motor actions that are generated and refined in real-time. Every movement reflects the integration of sensory perception, cognitive processing, emotional significance, motivational state, and ongoing motor planning. The nervous system continually adapts these processes via *neuroplasticity* - the capacity of the brain to modify its structure and function in response to experience, learning, and environmental demands.

2. Neuroplasticity

Neuroplasticity refers to the nervous system's capacity to structurally and functionally reorganize in response to experience, learning, and injury (Kleim & Jones, 2008). It is the foundation of brain organization and the integration of modality specific sensory experience (e.g. bodily sensations, sight, hearing) with motor responses. Following stroke or traumatic brain injury, recovery depends largely on the brain's ability to recruit undamaged neural pathways and use them to build compensatory functional networks (Aderinto, 2023). Neuroplasticity can involve changes in large-scale cortical reorganization as well much smaller-scale processes. Initial homeostatic plasticity mechanisms restore neuronal functioning near the injury and begin almost immediately after the damage occurs. After this, activity-dependent Hebbian mechanisms strengthen and refine useful circuits through experience and training (Hebb, 1949; Murphy & Corbett, 2009). Neuroplastic changes involve molecular processes, synaptic plasticity, structural plasticity, and structural and functional reorganization as depicted in Figure 3 (Straudi & Basaglia, 2017). The neural changes made via these processes are, to a large-extent, responsive to sensory and motor experience. That is, they are experience dependent.

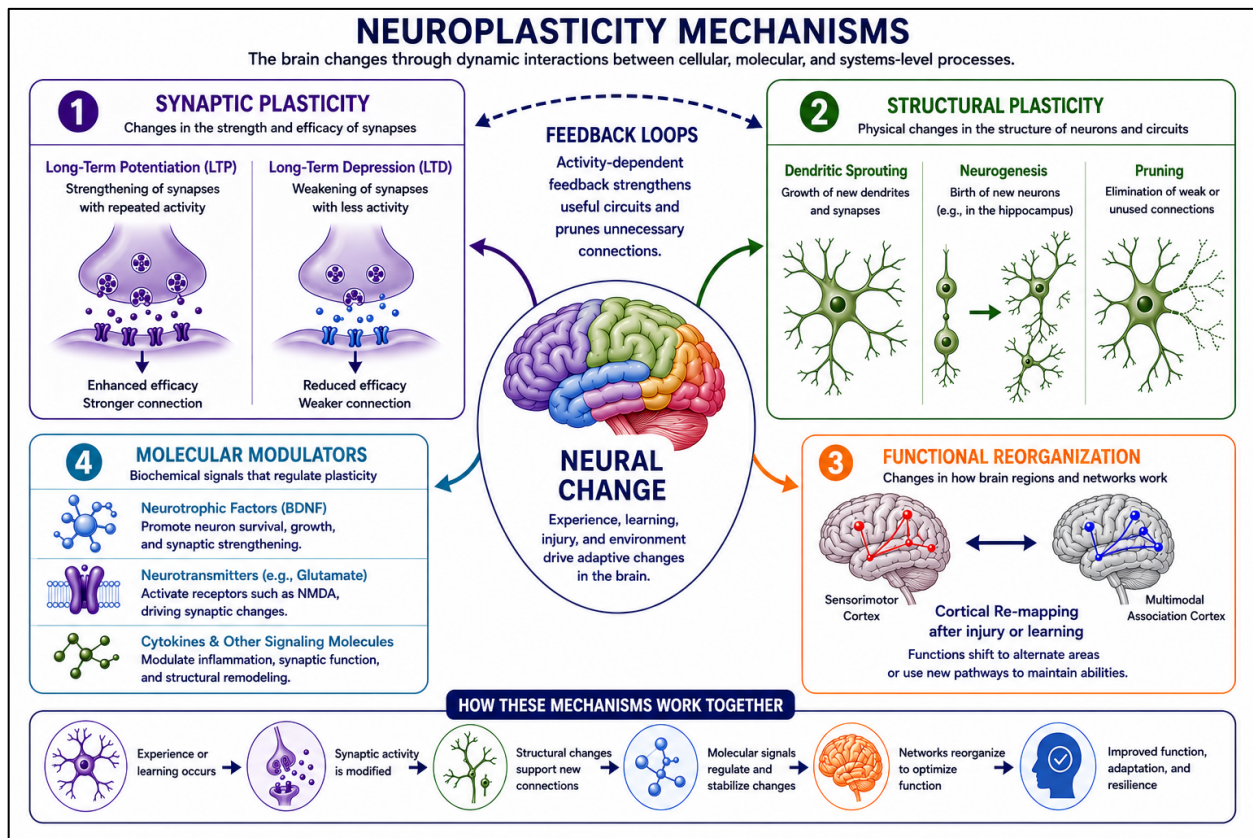


Figure 3. Selected Mechanisms of Neuroplasticity

3. Immersive Virtual Reality Engages Distributed Neural Systems

The Outbender requires participants to *navigate through complex spatial environments* propelled by lower limb activity (i.e. pedaling) and steered using upper limb activity via the previously described “blades”; thus, it effectively engages visual (what one sees in iVR) and physical spaces (the pedaling and steering) in 360 degree horizontal and vertical spaces thereby requiring extensive processing in both hemispheres. The side of the brain where the injury occurs is the ipsilesional side and the opposite side is the contralesional side. We propose that the bilateral spatial attention required within our system demands the engagement of both the ipsilesional hemisphere and contralesional hemisphere, thereby inducing greater cross-hemisphere neuron recruitment and integration. The platform is designed to engage all brain regions that play a role in visuospatial perception and attention, motor planning and initiation, threat detection, enjoyment, emotional experience, reward, and satisfaction. The requirement to navigate through the immersive simulated world also increases the sense of presence (more on that later) while simultaneously recruiting activity of distributed brain regions (Ward et al., 2012). We propose that this activity maximizes neuroplasticity and improves functionality across multiple domains.

Recent reviews indicate that iVR-based rehabilitation enhances multisensory integration and improves both motor and cognitive recovery in stroke populations (Hao et al., 2024). Such

multisystem integration activates higher-order association cortices and promotes large-scale neural network engagement. If bilateral motor engagement is added to the iVR experience, it promotes interhemispheric connectivity and compensatory reorganization (Cauraugh & Summers, 2005). Simultaneous activation of ipsilesional and contralesional motor pathways leads to numerous changes. Among them are the reduction in maladaptive cortical inhibition; the suppression of neuronal activity of the ipsilesional motor networks by the contralesional cortical motor networks following injury that can impair experience-dependent neuroplasticity. Furthermore, *symmetrical bilateral movements activate similar neural networks in both hemispheres when homologous muscle groups are simultaneously activated* (Cauraugh & Summers, 2005). Taken together, the bilateral demands of the Outbounder experience minimize inappropriate inhibition and maximize adaptive activation. Based on these data we propose that the Outbounder's bilateral sensorimotor tasks and synchronized movement patterns facilitate cross-hemispheric recruitment while reinforcing adaptive motor circuitry.

Data indicate that immersive environments synchronize visual, vestibular, auditory, proprioceptive, emotional, and tactile stimuli; thereby activating distributed neural systems involved in motor control, spatial awareness, and sensorimotor integration (Levin et al., 2015; Riva et al., 2019). This synchronization enhances Hebbian neuroplasticity (Takeuchi & Izumi, 2015). Hebbian neuroplasticity is widely considered the mechanism by which information can be coded and retained in neurons (Hebb 1949; Murphy & Corbett, 2009). As concisely stated by Krueger (2024) "The Hebbian learning principle "neurons that fire together wire together" provides the classical theoretical framework for activity-dependent plasticity: when motor intent signals (cortical discharge) and sensory afferent feedback (proprioception, tactile, and visual inputs) are precisely synchronized in time, synaptic efficacy undergoes sustained enhancement..." (Krueger et al., 2024, Chen et al. 2026).

Functional neuroimaging studies demonstrate that iVR engages the sensorimotor cortex, posterior parietal cortex, hippocampus, cerebellum, and associative cortical regions involved in motor planning and environmental navigation. Not only are these regions engaged, but *iVR environments themselves induce profound neurobiological transformation*; affecting neuronal connectivity, sensory feedback mechanisms, motor learning processes, and cognitive functions (Wankhede et al., 2025). However, unlike the conventional iVR rehabilitation paradigms mentioned above, the Outbounder's Immersive Simulation requires *patient-initiated whole-body movement*, creating more intensively embodied experiences that require continuous bilateral coordination, postural adaptation, and dynamic motor planning. Such multisensory engagement enhances neural integration and strengthens sensorimotor coupling through repeated experience-dependent activation (Kenea, 2025).

4. Avatar Embodiment, Self-Observation, and Mirror Neurons

A unique characteristic of iVR rehabilitation is the ability to generate a compelling illusion that a virtual body or avatar represents the user's own body. This phenomenon, commonly referred to as the *sense of embodiment* (SoE), occurs when visual, vestibular, proprioceptive, and motor

signals are synchronized such that the brain temporarily incorporates the avatar into its internal representation of self (Riva et al., 2019; Mottleson et al., 2023). The SoE is characterized by three sub-components. “The *sense of agency* (SoA) is the feeling of being the cause of our actions. The sense of body ownership (SoBO) is the feeling that the virtual body is the source of our sensations (like our real body). Finally, the *sense of self location* (SoSL) is the “spatial



experience of *being inside a body*” (Kiltner et al., 2012; Guy et al., 2023). Research demonstrates that a strong sense of embodiment activates neural systems involved in body awareness, motor planning, and sensorimotor integration that require the integration of several corresponding regions including the premotor cortex, supplementary motor area, posterior parietal cortex, insula, and temporoparietal junction.

Figure 4. Avatar appearance in the OutbunderARS world.

As users increasingly perceive the avatar as an extension of themselves, movements performed by the avatar become neurologically meaningful and are processed similarly to self-generated actions (Guy et al., 2023; Mottelson et al., 2023). The stronger the presence, the more powerful the impact (Rizzo et al., 2004). The Outbunder maximizes each of these qualities.

In the Outbunder, the user observes parts of their own body as represented by the avatar (Sense of Body Ownership and Self Location) as they orient themselves within and navigate through environments that consist of outdoor trail systems with obstacles, challenges, and cognitive-motor tasks (Sense of Agency). Videos of the Outbunder experience can be viewed at <https://outbunderars.com/pages/trails.html>. Figure 5 shows examples of the types of settings available for riders to choose from.



Figure 5. Examples Immersive Environment in the OutbunderARS

Avatar observation is a form of action-observation that activates mirror neuron systems. Functional neuroimaging has revealed that avatar action-observation in an iVR scene can promote the functional integration of key cortical components of the mirror neuron system and the sensorimotor cortex thereby improving the restoration of motor functioning (Fan and Luo, 2022). Consequently, when *users simultaneously perform movements while observing their avatar perform those same movements, they activate motor neuron recruitment, motor planning, motor execution, and motor observation networks*. Outbender sessions require decision-making, attention shifting, problem solving, spatial orientation, and adaptive motor planning and action; all while activating mirror neuron systems. These processes recruit the dorsolateral prefrontal cortex, anterior cingulate cortex, and frontoparietal executive networks that are all involved in cognitive flexibility and behavioral adaptation (Botvinick et al., 2004). This convergence of processes strengthens sensorimotor representations and accelerates cortical reorganization following neurological injury.

Unlike traditional Task-Oriented Therapy, in which patients observe their own isolated limb or body movements and receive verbal encouragement and feedback, users of the Outbender observe a virtual representation of themselves actively performing meaningful actions within dynamic environments receiving *continual feedback from within the system itself*. That is, verbal encouragement is *replaced* by holistic environmental feedback in which the environment responds to the avatar activity, and the avatar responds to the environment. This continuous self-observation and response enhances motor learning, improves body awareness, strengthens the sense of personal agency, and increases engagement with therapeutic tasks (Connelly et al., 2024; Shen et al., 2023, Shin et al., 2022; Hao et al., 2022; Chen & Krch, 2022).

5. Immersive Virtual Reality as a Primary Change Factor

Accumulating evidence suggests that iVR *directly influences neuroplasticity* through mechanisms extending beyond repetitive task practice. A systematic review of neurophysiological changes identified consistent evidence of cortical reorganization, increased frontal and motor cortex activation, enhanced functional connectivity, mirror system involvement, and improved interhemispheric balance following iVR interventions (Hao et al., 2022).

Immersive VR enables the creation of meaningful, goal-directed, and progressively challenging tasks that promote active engagement and sustained motivation (Riva et al., 2019). These adaptive experiences facilitate repeated cycles of motor prediction, multisensory feedback, error detection, and behavioral adjustment, which are core mechanisms underlying experience-dependent neuroplasticity (Kleim & Jones, 2008; Krakauer et al., 2019). Engaging distributed cortical and subcortical networks under conditions of heightened attention, motivation, and embodiment is thought to create neurophysiological conditions that facilitate experience-dependent synaptic plasticity, thereby promoting functional reorganization and supporting motor recovery following stroke and acquired brain injury (Kleim & Jones, 2008; Murphy & Corbett, 2009).

Studies using functional MRI, Electroencephalography, and Transcranial Magnetic Stimulation have shown that *simply being deeply immersed in a virtual environment can alter activity in visual association cortex, posterior parietal cortex, hippocampus, vestibular networks, premotor cortex and prefrontal attention networks* (Jäncke et al., 2009; Georgiev et al., 2021). These neural changes have frequently been associated with measurable improvements in motor function, gait performance, balance, and activities of daily living (Hao et al., 2024). Meta-analyses further suggest that iVR may be particularly effective compared to non-immersive VR. Immersive VR simultaneously increases treatment intensity, patient engagement, attentional focus, and multisensory integration (Hao et al., 2024). It produces a strong sense of presence, which increases attention and multisensory integration compared to viewing the same content on a flat screen (Riva et al., 2019). Riva et al. (2019) argued that *iVR functions as an embodied experience generator* activating neural systems involved in self-representation, spatial orientation, and sensorimotor prediction *even before therapeutic exercises are added*.

Immersive VR is capable of inducing measurable neuroplastic changes through multisensory integration, embodiment, presence, and attentional engagement, which collectively increase activation of sensorimotor, associative, and limbic neural networks while promoting adaptive cortical reorganization (Riva et al., 2019; Hao et al., 2022). *We propose that the Outbounder Immersive Simulations deepen the magnitude of neuroplastic adaptation*, which is amplified when immersive virtual reality is combined with the following qualities; patient-initiated movement, avatar embodiment, task-specific motor learning, cognitive challenge, emotionally salient experiences, and reward-based feedback. By simultaneously engaging the corresponding networks, immersive simulation provides an integrated multisystem neurorehabilitation environment in which *multiple mechanisms of experience-dependent plasticity operate concurrently*. The interaction among these complementary mechanisms is hypothesized to increase synaptic plasticity, learning, and functional recovery beyond what might be achieved through isolated interventions alone (Kleim & Jones, 2018; Krakauer et al., 2019; Perez-Marcos, 2018).

6. Responsive Robotics, Asymmetrical Compensation, and Motor Cortex Recruitment

Robot-assisted rehabilitation has become an established component of modern neurorehabilitation by enabling high-intensity, repetitive, task-oriented practice while reducing physical fatigue and therapist burden. Most commercially available robotic rehabilitation systems provide passive limb movement, graded assistance, body-weight support, or adaptive resistance during gait or cycling activities (e.g., Lokomat, RoboGait, Walkbot). These systems have demonstrated improvements in gait speed, walking distance, and motor performance following stroke and other neurological disorders (Lim et al., 2026). By repeatedly activating motor pathways, robot-assisted training engages the primary motor cortex, supplementary motor area, premotor cortex, corticospinal tracts, cerebellum, and spinal locomotor circuits, thereby promoting experience-dependent neuroplasticity and motor relearning (Lo et al., 2010; Kenea, 2025).

Beyond their effects on cortical motor systems, robotic rehabilitation also provides repetitive proprioceptive, mechanoreceptive, and vestibular feedback that influences spinal reflex circuits and sensorimotor integration. These repeated sensorimotor interactions enhance corticospinal excitability, interlimb coordination, movement timing, and adaptive locomotor control while reinforcing functional movement patterns through repetitive practice (Tseng et al., 2007). Collectively, these findings demonstrate that *conventional robotic rehabilitation promotes recovery primarily through repeated motor execution supported by adaptive mechanical assistance*. Additionally, there are various systems that have combined VR (to varying degrees) with robotics. A recent meta-analysis by Lim, et al. (2026) found that combining robot-assisted gait therapy with VR interventions effectively enhances gait distance and balance in stroke patients, with effects varying by intervention intensity and stage of recovery.

The Outbounder extends these established principles through a concept we describe as *responsive robotics*, in which robotic assistance, immersive virtual reality, and continuous patient interaction function as *a single adaptive therapeutic system*. The platform consists of a recumbent robotic cycling system mounted on a computer-controlled motion simulator. Steering blades enable participants to actively navigate complex virtual environments while an integrated network of sensors continuously measures cadence, force production, steering accuracy, bilateral symmetry, movement quality, and overall task performance. These measurements are processed in real time to regulate robotic assistance and resistance, balance contributions from the impaired and unimpaired limbs, and maintain the participant within an individualized optimal challenge zone that encourages active participation while minimizing maladaptive compensatory movement strategies.

Unlike conventional robotic devices that primarily assist movement using predetermined algorithms or fixed levels of support, the Outbounder continuously adapts both the physical and cognitive demands of therapy according to ongoing patient performance. Simultaneously, the patient must continuously respond to changing environmental conditions presented within the immersive virtual environment. This reciprocal interaction creates a closed-loop system involving the patient, the robotic platform, and the virtual environment, allowing motor behavior, sensory feedback, and cognitive decision-making to continuously influence one another throughout therapy.

From a neurophysiological perspective, responsive robotics extends conventional robotic rehabilitation by engaging multiple interacting neural systems simultaneously. Adaptive task difficulty, continuous performance monitoring, and immediate error correction repeatedly activate cerebellar-cortical learning circuits that refine motor planning, movement accuracy, and motor execution (Ito, 2008; Tseng et al., 2007). Because robotic assistance is continually adjusted according to performance, patients repeatedly experience cycles of motor prediction, sensory feedback, error detection, and movement correction. Rather than functioning solely as a motor training device, the Outbounder robotic system continuously interacts with cognitive,

perceptual, and sensorimotor processes that collectively support motor learning and functional recovery.

A distinguishing feature of the Outbounder is its ability to provide *dynamic asymmetrical compensation* for unilateral weakness associated with hemiparesis. Using proprietary algorithms and continuous bilateral force measurements, the *system independently monitors the force generated by each lower extremity throughout every pedal cycle*. Robotic resistance is then adjusted independently for each limb in real time; reducing resistance applied to the weaker extremity while proportionally increasing its contribution to the movement. The degree of assistance is recalculated continuously, allowing the system to adapt automatically as motor performance changes during each therapy session.

This adaptive bilateral control addresses one of the major challenges of post-stroke rehabilitation; learned non-use and compensatory reliance on the stronger limb (Taub et al., 1999). During conventional bilateral exercise, patients frequently shift effort toward the unimpaired extremity, thereby limiting activation of weakened neural pathways. By continuously balancing mechanical demands between the two limbs, the Outbounder promotes sustained recruitment of the affected extremity while minimizing maladaptive compensation. As strength and motor control improve, robotic assistance is gradually and imperceptibly reduced, progressively increasing the workload performed by the impaired limb while maintaining successful task performance (Figure 6).

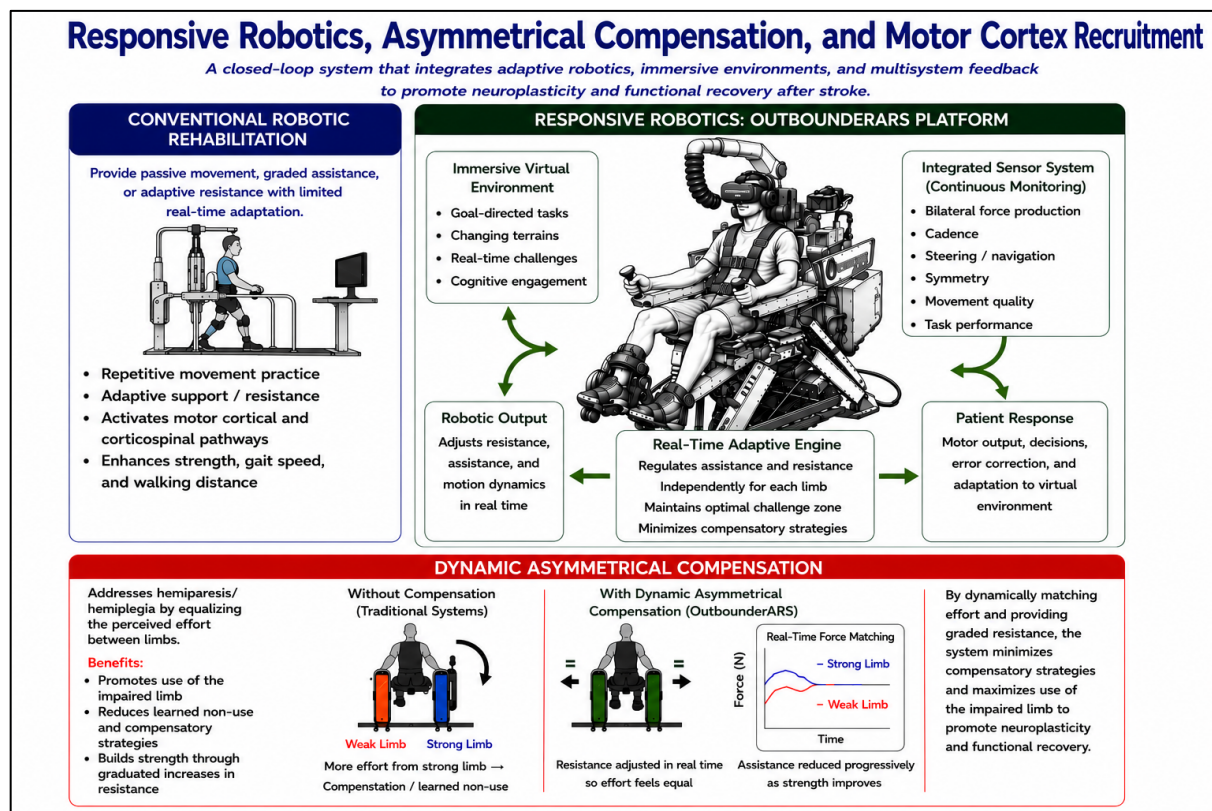


Figure 6. Mechanisms of Responsive Robotics

The Outbender is designed to create a bidirectional therapeutic process that simultaneously engages complementary top-down and bottom-up mechanisms of neurorehabilitation. Top-down processes are driven primarily by immersive virtual reality and include spatial attention, heightened anticipation of future twists/turns/obstacles, multimodal sensory integration, executive control, perceived risk, mirror neuron system activation, motor planning and execution, continuous performance monitoring, and ongoing error detection and correction. Bottom-up processes arise from repetitive task-oriented muscular activity, proprioceptive feedback, bilateral coordination, robotic interactions, and the reduction of pathological movement asymmetries through responsive robotic assistance. Rather than operating independently, *these ascending and descending processes interact continuously throughout therapy* (Figure 7). We hypothesize that this bidirectional interaction promotes distributed activation across cortical, subcortical, cerebellar, and brainstem networks, creating neurophysiological conditions that facilitate experience-dependent neuroplasticity and functional reorganization beyond those achieved through conventional robotic-assisted motor training focused primarily on repetitive movement alone.

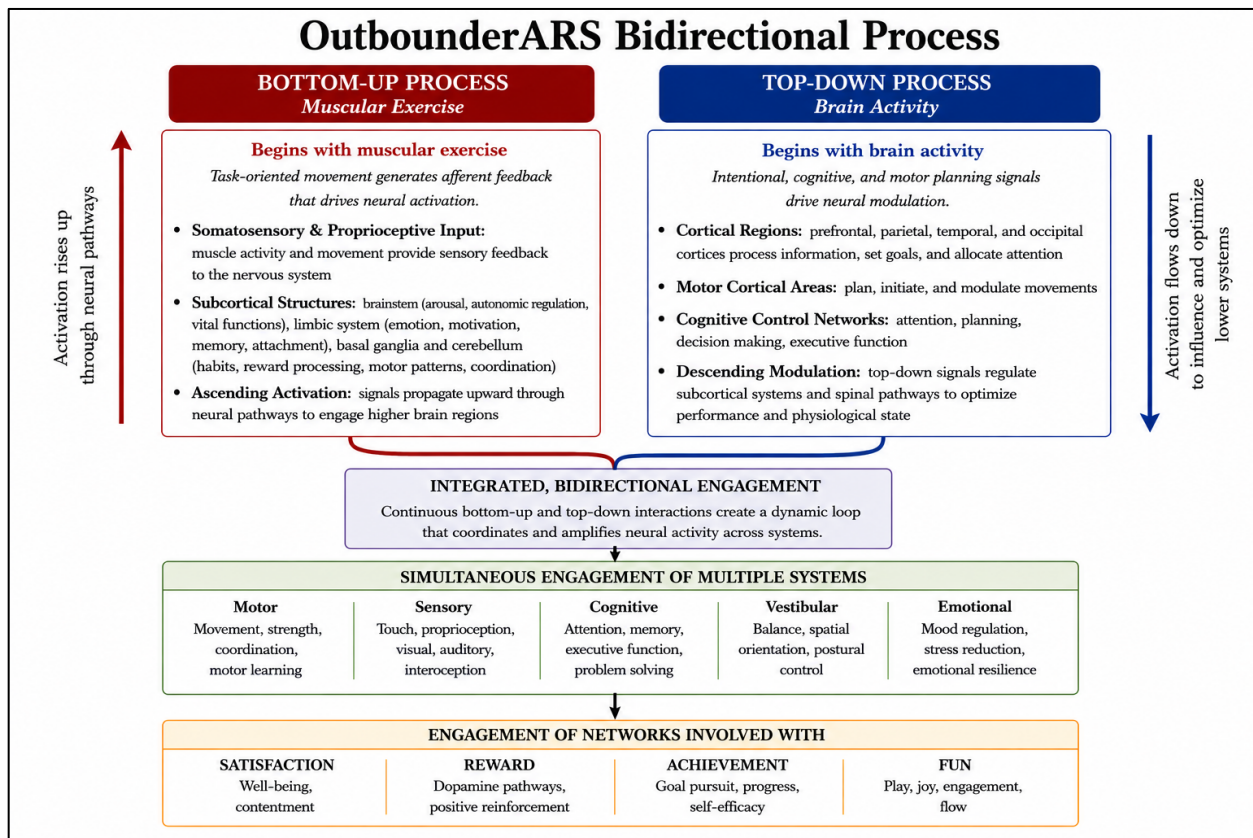


Figure 7. OutbenderARS Bidirectional Process

7. Perception of Risk

A prominent feature of the Outbender is the incorporation of perceived risk within immersive simulation. Simulated slopes, collisions, balance threats, and time-sensitive challenges activate the norepinephrine system, increasing attentional focus, arousal, and synaptic plasticity (Sara,

2009). Importantly, the risks, or what we consider “desirable difficulties”, are *perceived* cognitively and emotionally as *risk* without exposing the patient to *actual* physical danger because they are securely enveloped within and strapped to the robotic apparatus. One might also think of *perceived risk* as the *illusion of risk*.

The neurophysiological impact of perceived risk is amplified when the threat is experienced through an embodied avatar. Because patients perceive the avatar as an extension of themselves (i.e. embodiment), simulated collisions, loss of balance, vestibular sensory input, environmental hazards, or time-sensitive challenges may evoke emotional and attentional responses similar to those generated during real-world experiences. This results in a sense of *urgency* to avoid each risk and solve each navigational problem. The *combination of embodiment and perceived risk* increases activation of attentional networks, autonomic arousal systems, and neuromodulator pathways that support sensorimotor learning via implicit and explicit memory processes. Emotionally salient immersive experiences also enhance activation of such widely located structures as the anterior cingulate cortex, ventromedial prefrontal cortex, cerebellum, basal ganglia, and limbic systems, all of which, to one degree or another, are involved in error detection, reward anticipation, and adaptive learning (Botvinick et al., 2004; Wankhede, 2025). We suggest that the Outbounder creates highly salient, urgent, and meaningful sensorimotor learning experiences capable of enhancing both motor adaptation and neuroplastic change while maintaining physical safety (Figure 8).

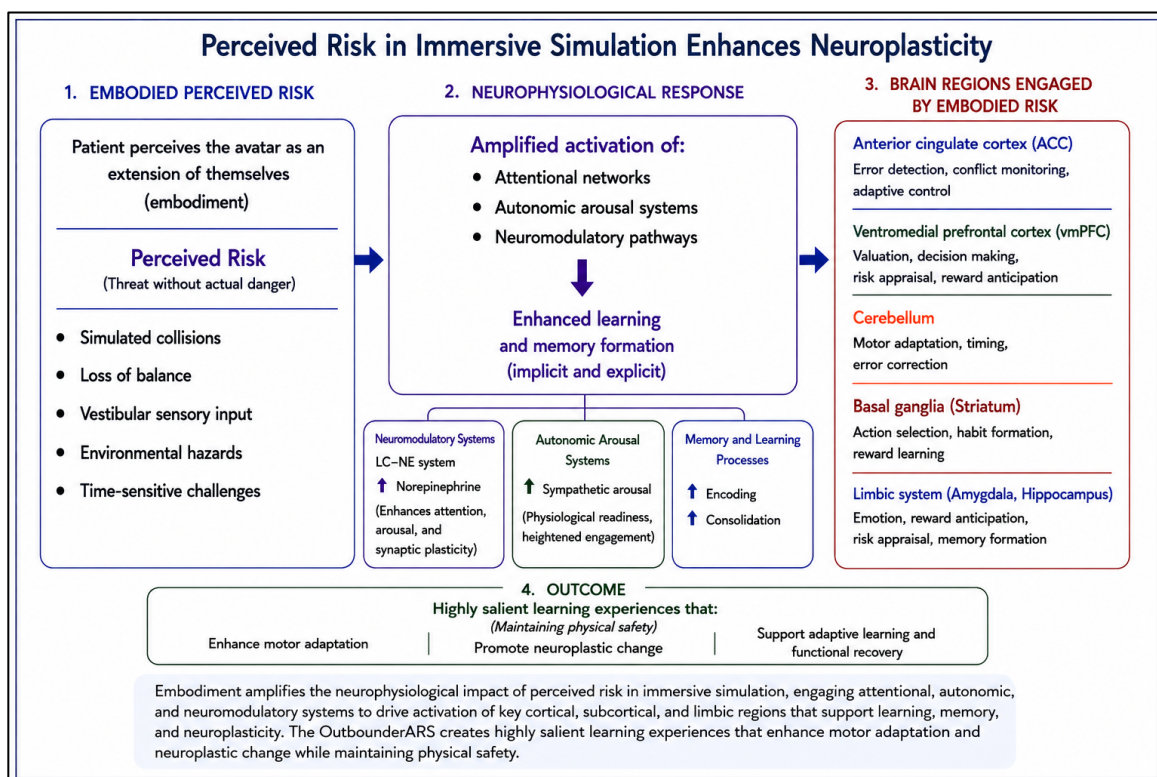


Figure 8. Immersive Simulation and Perceived Risk

One notable aspect of this virtual risk-taking experience is that it is enjoyable and fun. Experiences perceived as enjoyable engage multiple interacting neural systems involved in reward, motivation, attention, novelty detection, challenge, and learning. Within immersive virtual environments, enjoyable, goal-directed activities increase engagement, intrinsic motivation, and sustained task participation (Riva et al., 2019; Slater & Sanchez-Vives, 2016; Bohil et al., 2011). This combination of perceived risk, embodiment, and positive affect frequently induces the psychological state of “flow” (Panksepp, 1998; Wise, 2004; Csikszentmihalyi, 1990), which arises when perceived challenges are optimally matched to an individual’s current skill level, clear goals are present, and immediate feedback is available.

Flow is associated with elevated dopaminergic signaling in corticolimbic pathways, heightened noradrenergic arousal, and efficient frontoparietal attentional control. These increases are often accompanied by transient decreases in frontal lobe activity that can reduce the self-referential processing. Any sort of self-referential processing can decrease the sense of presence and thereby “pull one out” of immersion (Dietrich, 2004; Ulrich et al., 2014). Thus, flow increases immersion, which activates various neurotransmitter and distributed systems. These same neuromodulator systems are known to facilitate long-term potentiation, motor-map reorganization, and memory consolidation, the core processes of experience-dependent neuroplasticity (Kleim & Jones, 2008; Hosp & Luft, 2013). Because the Outbounder can sustain flow across repeated high-intensity sessions, it is hypothesized to convert what would otherwise be effortful, fatiguing exercise into an intrinsically motivating and fun experience.

Activation of the networks involved with the processes described above include dopaminergic reward pathways, the norepinephrine system, executive attentional networks, and limbic systems; all of which facilitate motor learning, memory consolidation, and experience-dependent neuroplasticity (Schultz, 2016; Sara, 2009; McGaugh, 2004; Kleim & Jones, 2008). Within immersive virtual environments, enjoyable, goal-directed activities increase engagement, intrinsic motivation, and sustained task participation; creating neurophysiological conditions that support skill acquisition and functional recovery (Riva et al., 2019; Slater & Sanchez-Vives, 2016; Bohil et al., 2011). These effects are thought to arise through the coordinated action of dopamine, norepinephrine, and distributed cortical and subcortical networks involved in reinforcement learning, error-based adaptation, and synaptic plasticity (Molina-Luna et al., 2009; Krakauer et al., 2019).

8. Neurotransmitter System Engagement

Neuroplasticity is mediated by a complex interplay of neurotransmitter and neurotrophic systems that regulate learning, memory, motor adaptation, and neural reorganization. Several neurochemicals have been identified as key contributors to experience-dependent plasticity, including dopamine, norepinephrine, acetylcholine, serotonin, glutamate, and brain-derived neurotrophic factor (BDNF) (Kleim & Jones, 2008; Citri & Malenka, 2008). Together, these systems influence synaptic strengthening, cortical reorganization, neuronal growth, and the consolidation of newly acquired motor and cognitive skills. Their coordinated activation is

particularly relevant to neurorehabilitation, where recovery depends on the brain's capacity to form and reinforce functional neural networks following injury (Kleim & Jones, 2008; Hosp & Luft, 2013).

We propose that the Outbounder enhances neuroplasticity, not only through simultaneous engagement of large-scale cortical and subcortical networks, but also by influencing multiple neurotransmitter systems known to support learning and experience-dependent plasticity. *This theoretical framework suggests that the platform's combination of novelty, progressive challenge, focused attention, repetitive task-oriented movement, physical exertion, positive emotional engagement, and enjoyable experiences may recruit complementary neuromodulator systems, including dopaminergic, noradrenergic, and cholinergic pathways* as described below (Figure 9). The coordinated activation of these systems is thought to create a neurophysiological environment that facilitates motor learning, memory formation, and functional recovery.

Dopamine, norepinephrine, and acetylcholine play especially important roles in modulating attention, motivation, and learning; all key components of the Outbounder. For example, *dopamine* facilitates motor learning and reward reinforcement by enhancing long-term potentiation and strengthening newly formed neural connections (Molina-Luna et al., 2009; Hosp & Luft, 2013). *Norepinephrine* promotes arousal, vigilance, and memory consolidation, increasing the efficiency of learning during challenging or novel experiences (Sara, 2009; Aston-Jones & Cohen, 2005). Whereas, *acetylcholine* contributes to focused attention and cortical map reorganization, serving as a critical mediator of rehabilitation-induced plasticity and motor cortex remodeling (Hulse et al., 2016). Together, these neurotransmitters create neurophysiological conditions that optimize the acquisition and retention of motor skills.

Additional mechanisms are related to the activity of serotonin, glutamate, and BDNF. *Serotonin* supports emotional adaptation, synaptogenesis, and neuronal growth while facilitating learning flexibility and recovery following neurological injury (Castrén, 2005). *Glutamate* serves as the primary excitatory neurotransmitter underlying long-term potentiation and experience-dependent learning through activation of NMDA receptor-dependent pathways (Bliss & Collingridge, 1993; Citri & Malenka, 2008). Brain-derived neurotrophic factor (BDNF), although technically a neurotrophic factor rather than a neurotransmitter, is widely regarded as a key regulator of neuroplasticity because of its role in neuronal survival, dendritic branching, synaptic strengthening, and activity-dependent neural remodeling (Kleim & Jones, 2008; Vaynman & Gomez-Pinilla, 2005). Levels of BDNF have been shown to be increased in response to physical exercise, enriched environments, novel learning experiences, and intensive rehabilitation interventions, all of which are associated with improved functional outcomes (Vaynman & Gomez-Pinilla, 2005) are present in the Outbounder.

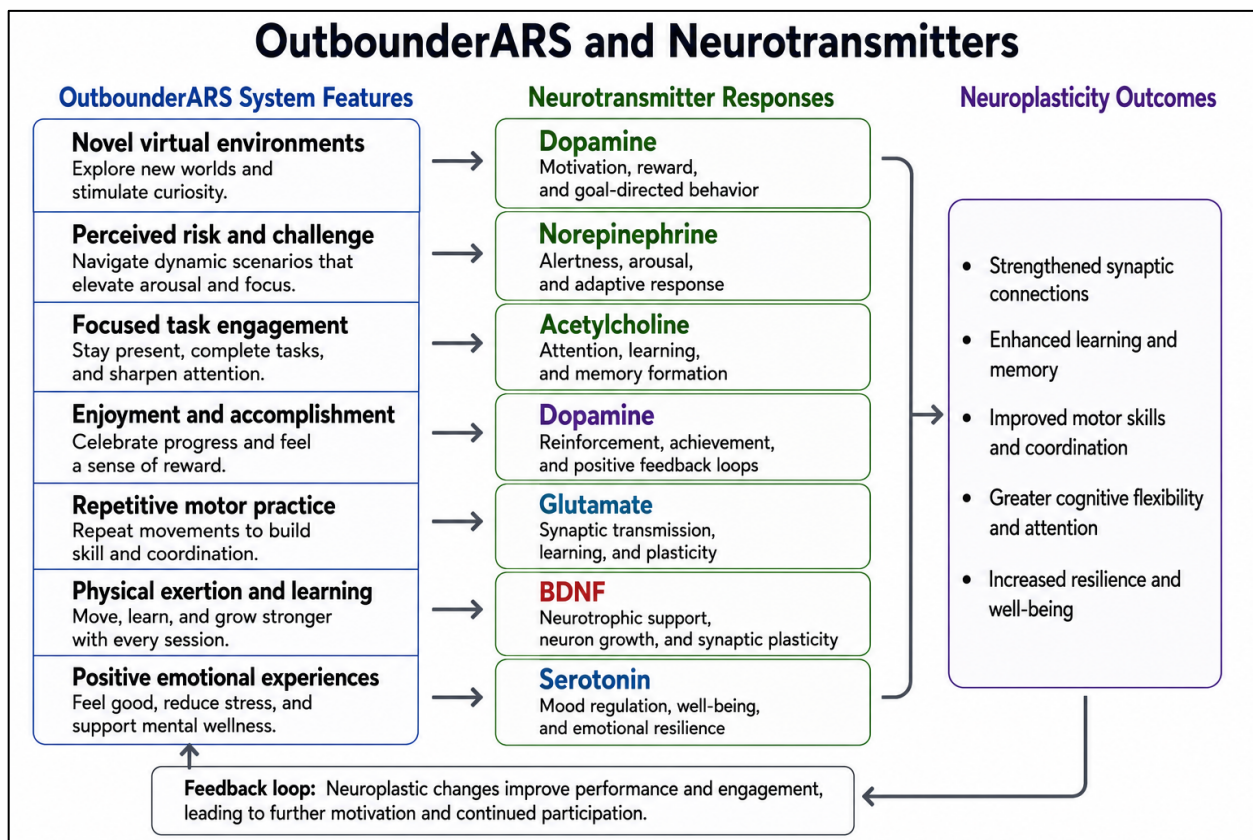


Figure 9. Neuroplasticity as Impacted by Neurotransmitters in the OutbounderARS

9. Aerobic Exercise and Growth Factors

The Outbounder requires the user to engage in *intensive aerobic exercise*. Aerobic exercise increases cerebral blood flow and promotes angiogenesis of cerebral arteries through upregulation of vascular endothelial growth factor (*VEGF*). Subsequently, enhanced vascular perfusion supports oxygen delivery and metabolic recovery within ischemic neural tissue (Swain et al., 2003). Furthermore, exercise-induced increases in brain-derived neurotrophic factor (*BDNF*), insulin-like growth factor-1 (*IGF-1*), and nerve growth factor (*NGF*) enhance neuronal survival, synaptic plasticity, and functional recovery following stroke (Cotman & Berchtold, 2002). Rhythmic lower-extremity activity of the kind found in OutbounderARS activates spinal locomotor networks and central pattern generators (centers that activate reflexive automatic movement without the need for cortical activation), *reinforcing automatic gait patterns and improving dynamic balance and coordination*. Combining aerobic movement with cognitive and sensorimotor tasks enhances frontoparietal network reorganization and improves dual-task performance, executive functioning, and motor planning (Winstein et al., 2016).

10. Conclusion

Based on the available evidence, we propose that the *Outbounder functions as a multisystem neurorehabilitation platform that simultaneously engages numerous established mechanisms of experience-dependent neuroplasticity*. Rather than relying on a single therapeutic modality, the

system integrates a number of discrete mechanisms including: immersive virtual reality, avatar embodiment, responsive robotics, multisensory stimulation, bilateral motor coordination, error-based motor learning, emotionally salient experiences, perceived risk, reward-based feedback, and aerobic exercise within a unified therapeutic environment. Collectively, these components recruit complementary sensorimotor, cognitive, emotional, autonomic, and neuromodulator processes that support neural adaptation and functional recovery.

Unlike conventional rehabilitation approaches, which often target isolated impairments or individual motor functions, the Outbender is designed to engage multiple interacting neural systems concurrently. Localized damage from stroke often results in multisystem impairment, and the Outbender is a multisystem rehabilitation system. The platform is designed to promote coordinated activation of cortical and subcortical motor networks, executive and attentional systems, vestibular and proprioceptive pathways, limbic circuits involved in motivation and emotional salience, and neuromodulator systems that regulate reinforcement learning, arousal, attention, and synaptic plasticity. By integrating these complementary mechanisms into meaningful, task-oriented experiences, the Outbender seeks to create conditions that are favorable for experience-dependent cortical reorganization.

Central to this theoretical framework is the premise that immersive embodiment, self-observation through an avatar, adaptive challenge, perceived risk, focused attention, repetitive motor practice, and intrinsically rewarding task engagement interact to amplify motor learning and motor memory formation. We propose that these mechanisms operate synergistically to enhance the neurophysiological conditions that support long-term potentiation, synaptic remodeling, and functional reorganization following neurological injury or stroke. Although each of these mechanisms has been independently supported within the neuroscience and neurorehabilitation literature, their *simultaneous integration within a single immersive robotic-enabled rehabilitation platform represents the central innovation of the Outbender*.

Accordingly, the Outbender is not simply a combination of virtual reality and robotics, but is an *integrated neuroplasticity platform* designed to coordinate multiple biologically plausible mechanisms of recovery. We hypothesize that the convergence of these mechanisms produces a therapeutic environment capable of enhancing motor learning, promoting adaptive neuroplasticity, and improving functional outcomes beyond those expected from interventions that engage these mechanisms in isolation (Figure 10). This proposition is strongly supported by the available scientific evidence. Confirmation awaits controlled clinical trials and neuroscientific studies.



Figure 10. Summary of Neuroplasticity in the Outbunder

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