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Motor-cognitive interaction:
The role and measurement of engagement

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Abstract

Movement and thought are intertwined in everything we do. This essay brings together four researchers who have long considered deep, thoughtful movement, to create an effective neurorehabilitation intervention. We will cover four novel tools for enhancing motor-cognitive integration: improvisational dance, partnered-dance conversations, mental imagery, and intra-cortical brain-computer interfaces.

The 21st century has critical neurological problems to solve – e.g., spinal cord injury (SCI), Alzheimer's Disease (AD), and Parkinson's disease (PD) -- all of which affect mobility and cognition. Fortunately, methods ranging from earlier approaches, e.g., dance and mental imagery, to more modern technological advances, such as brain computer interfaces (BCI), can help address these problems. Dance is a powerful form of movement that involves creative engagement and represents the literal translation of creative cognition and conversation into action. Imagery, a quasi-perceptual experience, provides the link between intentions (the desire to move in way "A") and an ideal virtual sensory environment that facilitates intention "A." Techniques promoting creative engagement and mental imagery are used by elite and non-elite 'movers' to enhance movement or, coupled with advanced neurotechnology, to regain movement after paralysis from SCI. Intra-cortical BCIs leverage neural activity during imagery, kinetic-cognitive integration, and kinesthetic cognition to reanimate paralyzed limbs through neuromuscular stimulation, translating the language of the brain into movement. These approaches involve mind-movement interaction --motor-cognitive integration. Motor skill acquisition following nervous system impairment represents a distinct form of implicit learning that inherently integrates kinetic and cognitive domains. Cognitive processes that can potentially interfere with implicit learning post-neural injury may be quieted, or inhibited, when individuals with central nervous system injury engage in creative activities.

Each section of this four-part review summarizes existing research of innovative paradigms in functional rehabilitation and proposes trajectories for future study. Creative exploration of movement through dance provides an avenue for rehabilitating *kinetic-cognitive integration* (Worthen-Chaudhari). Social aspects of dance involving touch invoke *kinesthetic cognition* (Hackney). *Mental imagery* (MI) of movement, in the absence of physical movement, is

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associated with physical training effects (Abraham). In the case of full paralysis, cutting-edge treatments may be able to bypass whole sections of the damaged nervous system to *reanimate motor-cognitive integration* (Bockbrader).

We present data addressing rehabilitation of motor-cognitive integration through experiential learning. VIa dance-based experiences, creative engagement within neurorehabilitation practice is feasible, even when cognitive function is impaired, and has the potential to increase engagement, movement dose, and outcomes within physical medicine treatments. We provide terminology and a framework for discussing sensory-motor-cognitive processes stimulated in unique ways through partnered dance. We analyze current findings and discuss future directions for MI application across the spectrum of movement capabilities. Finally, we explore neuromotor skill acquisition with BCI, which requires remapping the embodied mind to incorporate the neuroprosthetic into the sense of self. With further study, each of these paradigms of engaging motor-cognitive interaction has potential to revolutionize neurorehabilitation and human health.

Keywords: movement, cognition, neurological rehabilitation, dance, imagery, brain-computer interfaces, dementia, paralysis

The role of creative engagement in promoting neurosensory-motor rehabilitation after central nervous system injury

Neural remodeling is known to be *experience-dependent* (1). Traditionally, art is the realm within which human *experience* is explored and crafted; however, creative arts endeavors remain largely unstudied as a pathway to experience-dependent recovery of function after central nervous system (CNS) injury. The current gap between art theory and medicine represents a barrier to innovation within physical medicine. To advance the field, we explore what “movement is” within the creative arts, as well as evidence for how creatively-engaged movement may facilitate functional rehabilitation after CNS injury.

Dance is particularly promising for functional rehabilitation. Dance integrates motion with cognitive function (2) in beneficial ways for neurorehabilitation (3-8). For non-dancers and individuals with disability, exposure to dance training has been shown to positively affect muscle architecture (9), muscle function (5), balance function (3-5, 10, 11), and executive function (5). Proposed mechanisms through which these trainings’ effects are induced include movement dose (12), social engagement (3-5), and musical neurophenomena (e.g., rhythmic entrainment (13), dopaminergic transmission (14)). Notably, accompaniment by music or a partner are not necessary elements to identify a physical endeavor as dance; musical and social engagement are simply options available within dance paradigms. One distinguishing and crucial aspect of dance from other forms of physical training is *creative engagement in movement*. Dance engages the human system creat-ively and physically, representing a unique paradigm for driving experience-dependent remodeling through creatively-engaged action.

Kinetic-cognitive integration

“Kinetic-cognitive interaction” refers to the implicit connection between physical motion (also called kinetics or dynamics) and the cognitive impulse underlying movement attempts (including attention and motor planning). Through kinetic-cognitive interaction, neuromotor action is optimized within uncontrolled environments to achieve a level of functional mastery: “natural cognition in action” (15). When rehabilitating function, kinetic-cognitive integration represents one piece of the rehabilitative regimen. The field of dance offers an avenue to promote integrated kinetic-cognitive skill acquisition through the artistic practice of movement *improvisation* (improv). This paradigm has recently been studied by dance-scientist scholars and teams as an innovative approach to neurorehabilitation (6, 7, 11, 12, 16, 17).

Pedagogical techniques of movement improv involve setting a structure and tasking the performer to create, or generate, movement through exploration, or play, within that structure. Similar to jazz improv, which has performers explore pitch, tone, rhythm and other elements of musical performance within the structure of a specific song, dance improv has individuals explore dynamics of body movement within specified constraints of space and/or timing of movement. A simple dance improv exercise might involve exploring paths from sitting to standing, while a more challenging exercise might require fast, dabbing movement with one arm and coincident with slow, carving movement with the contralateral arm. While dance scholars and rehabilitation scientists practice improv as a stand-alone skill, the concept is ingrained in every dance genre. Even within choreographed dance, e.g., classical ballet, improv can be embedded in the pre-learned movements through artistic interpretation during performance. Within ballroom dance, such as American or International forms of foxtrot, waltz, or quickstep, improv is routinely incorporated as "embellishment," and is a marker of advanced ability within the form. Regardless of form, improvisational generation of movement provides a vital opportunity to practice kinetic-cognitive integration through creatively engaged movement exploration and play. In short, dance improv explicitly challenges creative-engagement within movement and represents a training model of functional rehabilitation that may affect recovery of "natural cognition in action" (15).

Many dance paradigms studied to date involve musical and social engagement. It remains unclear if creative-engagement through dance rehabilitates kinetic-cognitive integration independent of music and social effects. One clear finding is that the implicit learning network is stimulated and associated with functional change through dance improv performed to music within a dyad or group social scenario. Improv activates motor-planning and working memory areas of the CNS (2) and connects cortical and sub-cortical regions that mediate implicit neurosensory-motor learning (2, 16, 17). Research among individuals with PD showed that dance improv practice improved balance and strengthened connections between the basal ganglia and pre-motor cortex (16). Imaging data from individuals with AD, who practiced dance improv, showed increased connections throughout the implicit motor learning network (17). Creative engagement may quiet or inhibit cognitive processes (18) with potential to interfere with implicit motor learning after neural injury (19). Evidence is growing that dance-based improv forms of therapy represent a powerful avenue for rehabilitating cortical and subcortical CNS regions, and specifically targeting connections between CNS regions. Dance improv might optimize functional rehabilitation of "natural cognition in action" (15); this novel creative engagement, potentially effecting movement generation, requires additional study.

Cognitive deficits often interact with physical deficits, stressing individuals' ability to follow therapeutic instruction. To study whether individuals in neurorehabilitation can engage with movement creatively in the absence of musical or social engagement, we studied a dance technology, *Embedded Art (EA),* which allows clients to *improvise within a therapeutic movement structure.* Augmenting movement therapy with dance technology, such as EA, can transform therapeutic exercise into a personal, creative endeavor (6, 7) by allowing the participant to make their own artistically-motivated movement choices within the confines of the exercise structure set by the clinician.

Use of the EA modality involves securing a motion sensor to the moving "gesture" limb, (e.g., leg as in Figure 1A or torso). As the participant performs an exercise, the motion sensor translates the limb's movement into a trace of abstract, graphic art feedback drawn on a computer screen in the tradition of American Action Art (Figure 1D-F), thus providing aesthetic, real-time movement feedback (7). Users affect the path of the drawing through controlling their movement, translating any given exercise into a creative practice where possible movements are explored, rather than repeated per explicit instruction. While therapists establish the starting conditions and structure of an exercise, participants determine *how* they perform that exercise. Thus, EA is designed to integrate improvisational movement processes that support client creativity and autonomy (20) during their therapeutic experience.

When evaluated in inpatient movement therapy (n = 21), both patients and clinicians found the dance technology modality feasible for use, and noted increased sense of *flow*, an intensely focused mental state of intrinsic motivation and high engagement (21). An increased sense of *flow* was even noted among inpatients with low Functional Independence Measure (FIM) Cognitive scores (e.g., 25% cognitive function) (7). Preliminary data from individuals receiving outpatient therapy for balance deficits (n = 8) indicated higher movement dose (12) and improved balance more with physical therapy (PT)+EA than with physical therapy alone (Figure 1B). In a nine-month study of an older woman with a hip replacement, use of EA in balance training improved a measure of postural control predictive of fall risk (RMSml (22)) with a training effect comparable to another dance-based rehabilitation practice - Hackney's Adapted Argentine Tango (11).

Dance-based training, focused on movement generation and artistic performance quality, provides established pedagogical strategies for invoking creative engagement within physical endeavors (e.g., traditional exercise paradigms) that other types of physical training do not. We conceptualize the motor-cognitive interaction acquired through dance practice as kinetic-cognitive integration, and dance training as a powerful driver of this implicitly learned mode of intelligence within functional rehabilitation. Additional research is needed to explore how creative engagement in movement can be leveraged to rehabilitate mastery of functional movement.

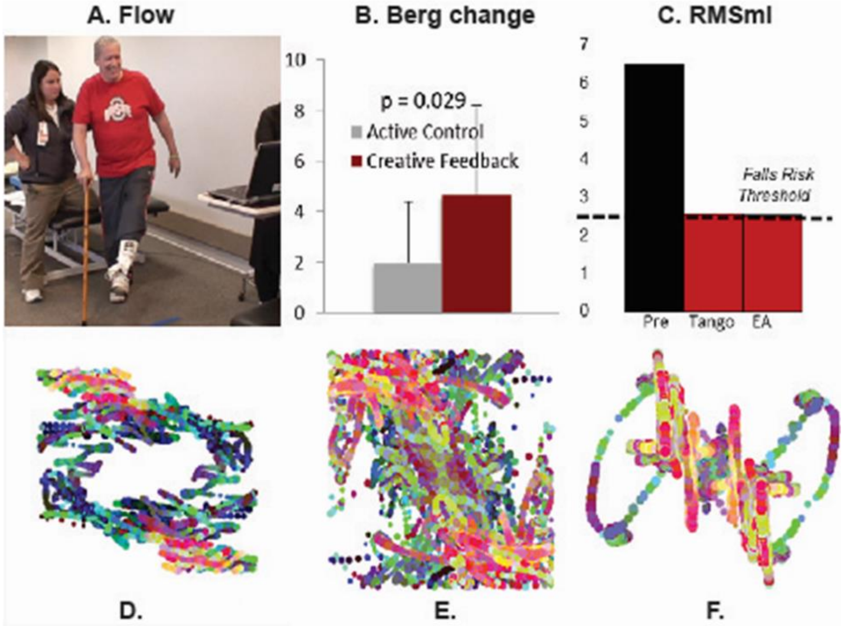

Figure 1. Preliminary data on the effect of creative engagement in balance training. A) Individual performing PT + EA. Motion sensor on gesture (left) leg. Clinician guarding/guiding. Computer screen on right. Inpatients (n = 21) reported increase flow state using this dance technology paradigm (7). B) Berg Balance Scale score improved when outpatients (n = 8) with CIPN used PT + EA vs. PT alone (p = .029). C) RMSml improved from baseline (black), reaching the threshold for decreasing fall risk (11), in 20 sessions of Argentine Tango and 6 sessions of PT + EA (n = 1; 9-month case study). D-F) Images drawn by individuals with SCI & stroke during balance training.

Partnered dance exercise is a cognitively demanding, mentally stimulating movement conversation that anyone can do

This section will provide a systematic framework of various cognitive processes related to dance, specifically within the sensory-motor goal-communicative structure of partnered dances.

To address a rising epidemic of neurological diseases like AD- and PD-related dementias, researchers and clinicians constantly seek to improve cognitive rehabilitation. As a result, many studies are beginning to examine the combination of physical and cognitive training delivered simultaneously or in close serial fashion (e.g., stationary bicycling while also completing computerized cognitive training on a screen) (23). In keeping with animal literature, rehabilitation offering a combination of physical and cognitive challenges may be most effective in inducing beneficial, lasting effects on the brain's structure and function (24).

Evidence suggests that cognitive elements of dance are a cogent vehicle for delivering cognitive rehabilitation. Dance has been shown to improve spatial cognition in people with PD, likely because dance requires participants to learn, memorize, recall, use, and be cognizant of spatial postures, relationships, patterns, and paths (2). Dance, through imagery and creative movement, engages other cognitive processes, which may act as cognitive rehabilitation. These cognitive domains include attention/working memory, executive function, memory, and language, as well as musical beat detection and interpretation. Dance requires: *attention* to partner (the next step), storage and of new steps from memory, detection and interpretation of musical beats, coordination of body and movement with external musical source and partner; use of *working memory* via learning and practicing steps, and *language* via a new vocabulary for a dance context and the abstract concept of combining steps into phrases, i.e., holding 'conversations' with partners via non-verbal communication. Spatial function may improve from dance given its central role and considering that cardiovascular fitness modulates brain activation associated with spatial learning (25).

Partnered dance, such as Argentine Tango, represents a physical training framework that integrates fundamental physical and cognitive function. Involving human-human interaction (HHI) that uniquely stimulates the tactile sensory system, partnered dance can serve as a model for investigating the interplay between haptic feedback (the tactile sensory system), cognition, and motor control. The HHI interaction, particularly with respect to the partnered dance model, is particularly powerful for study, because it requires a leader to convey explicit motor goals to a follower through a schema of motor patterns, interactions, and trajectories. These HHI are uniquely and non-verbally expressed via pressure and contact at the arms or torso between a leader (who determines timing, amplitude and direction of choreography) and a follower (who detects and responds to the messages conveyed by leader).

In partnered dance, the leader determines step length, rotation, timing and direction of the dyadic unit. In theory, the follower infers and enacts the motor intentions of the leader, which can be communicated solely through force and pressure at contact points between the two (26). However, the follower may sometimes exert considerable influence on the pair's motor goals. The term "*backleading*" is used by professional partner dance instructors to refer to instances when the follower momentarily acts as the leader. Providing tactile cues through hand and arm contact, movement of the center of mass, and gestural embellishments, *backleading* allows the follower to leverage HHI to modify movement direction, speed, and amplitude. These instances of *backleading*, also called *takeover*, are applied by the follower to correct and produce a refined version of the movement structure initiated by the leader.

Kinesthetic cognition

Because leading, following and backleading involve a mind-motor transformation, it is important to understand the cognitive context or "kinesthetic cognition," within which this communication takes place. Spatial cognition is related to interpersonal space and is necessary for mental imagery, identifying objects, and aptly moving within a space (27). Spatial cognition is vital for human mobility and coordinating physical HHIs, such as partnered dance.

Physical interactions between two people can provide a *motor manipulation* through tactile stimulation, or haptic feedback. The HHI practiced through partnered dance primarily acts as communication (28) that is also capable of altering motor behavior (e.g., gait spatiotemporal characteristics, and challenging, or stabilizing, balance). We learned that interaction forces from hands form a sensory/tactile communication channel about movement goals between partners during cooperative physical interactions (28). We demonstrated relatively *small interaction forces (10-30N)* from the hands between expert and novice partner dancers assigned to leader and follower roles while performing a pseudorandom forward-backward partnered stepping task. Whereas interaction forces were typically smaller than 5N during a predictable forward and backward stepping task, leaders were able to successfully alter *step direction* and *timing* in followers using anterior-posterior hand forces of approximately 15 N. Forces in expert-expert dyads were larger than in novice-novice dyads. The higher, more distinct interaction forces observed between expert-expert dyads could reflect more deliberate, precise, and clearer communication via forces, as well as more skilled interpretation of the motor intent of perceived forces.

Another example of a beneficial motor manipulation through HHI occurs when a physical therapist or a caregiver supportively guides a patient's hand as the client walks. One can also imagine a dance instructor teaching a new step to a student by guiding them through the step from the role of leading partner, thus facilitating the student's motor behavior through tactile input. Because the forces applied through the hands and arms are of low amplitude (<30N, approximately <5% of body weight; (28)) and do not directly actuate the lower limb joints, we believe that the motor manipulation of HHI described here expressly engages human sensing, perception, and cognition (including body schema) that we do not yet fully understand. A follower/instructor can alter clinically relevant features of gait in a partner, by applying HHI strategically during specific phases of gait/dance (e.g., at specific points during stance phase).

The importance of tactile information as a conduit for motor-cognitive processes in HHI/partnered dance is that both leading and following (excluding obstacle avoidance) can be achieved even with eyes closed (29). In basic partnering fundamentals, the goal of the dancers is to maintain light pressure between the hands, and for each partner to power his or her own movement. Haptic feedback at the hands must be perceived, and interpreted by both leader and follower, encouraging the leader to adapt their own gait dynamics and balance stability. The collaborative goal is achieved not through significant kinetic energy transfer, but through active perception of haptic feedback and cognitive engagement of both members of the dyad. With respect to the use of HHI in partner dance as rehabilitation, studies have demonstrated gait, motor-cognitive integration, functional mobility, balance, and quality of life improvements in people with sensory and mobility impairments after participation in partnered dances such as an adapted form of tango, waltz and foxtrot (3, 4, 30). People with PD who participate in Adapted Tango exhibit improved muscle coordination and consistency during gait, which is associated with improved gait and mobility per behavioral assessment (31); these same individuals also exhibit improved automatic control of balance (32). Growing evidence suggests that participation in partnered dance can induce long-term neural plasticity in human movement, enhance independence, and delay the deleterious effects of aging and neurodegenerative diseases; however, the explicit role and impact of HHI in these effects remains to be elucidated. Additionally, sensory or cognitive deficits, often seen in people with PD or dementia, impact the ability to generate and control such pressures in unknown ways.

HHI/partnered dance interactions have even been translated into dance interactions between expert partner dancer leaders and humanoid robot followers. Robotics are gaining immense attention, because of their potential to reach multiple populations in rehabilitative scenarios. HHI will be a necessary component of any 'caregiver' robot for older adults; therefore, human-robot partnered dance is an ideal scenario for testing hypotheses about motor goal communication between robots and humans. We have shown that in investigations of leading and following in human-robot interaction scenarios, touch information alone was sufficient to perform partnered dance with complex movements, similar to what social dance teaches (33). Further, we have demonstrated that a robot could be programmed to respond to (i.e., follow) touch cues given by a blinded, expert human-leader that indicated the timing, amplitude and direction of steps (26). The robot was able to follow the human-leader with a lag of 224 ± 194 ms. using only forces at the hand.

Human leaders reported that dancing with the robot was similar to dancing with a human. Gaining knowledge of the subjective experience of humans with robots in rehabilitation is vital to inform and enhance the technology for treatment delivery. We measured the objective and subjective measures of the physical human-robot interactions when robot arm stiffness and the gain of the robot's base velocity with respect to the hand forces were varied. We developed and validated a questionnaire to evaluate the subjective experience and perceptions of the human partners. The magnitude of interaction force, cadence, lag, and distance between leader and follower changed across conditions and were correlated to the subjective experience of the humans (e.g., was the robot a good dance partner? Was the experience similar to dancing with a human?). Expert dancers rated their physical interaction with the robot more favorably when biomechanical metrics of synchrony between the human and the robot were greatest and when interaction forces were lowest.

Physical and cognitive elements are integrated in dance. Dance, even with a robot as our findings suggest, may be more engaging and enjoyable than computerized cognitive training during or serially after exercise. Studies should further investigate the mentally stimulating, cognitively engaging, and potentially neuroprotective properties of HHI intrinsic to dance and leverage these "conversations" as an engaging form of rehabilitation.

Mental Imagery (MI) training in dance and neurorehabilitation

Mental imagery

The cognitive processes associated with the creation and use of images, metaphors, and other mental representations of movement, referred to as "mental imagery," are fundamental human skills (34, 35). Mental imagery (MI) of movement can be performed with or without physical execution. MI without physical execution, also referred to as Motor Imagery, has been shown to stimulate brain activity similar to that of actual physical execution of movement (36), yielding effects.

MI can be used for a variety of purposes, including initiating, enhancing, and fine-tuning various parameters (e.g., range-of-motion (37, 38), power (39), and accuracy (40)) of motor performance across different populations (e.g., athletes (41), dancers (37, 38), stroke survivors (35, 42), and people with PD (43-45)). MI may also affect non-motor elements of human behavior and performance, such as cognition (45, 46), motivation (47), concentration (43), anxiety (48), and body schema (49, 50). Advantages of MI training include little to no physical fatigue, low financial costs, no special equipment, high availability, and ability to practice in the absence of a trainer/therapist (51). MI can be practiced when physical execution is not accessible as, in the case of paralysis, injury, or post-operation (37, 52).

Research into MI in a variety of populations has expanded rapidly over the past two decades. This has focused on commonly used MI training approaches: Motor Imagery Practice (MIP) (35), Conditioning with Imagery (53), and Dynamic Neuro-Cognitive Imagery (DNI™; also known as "The Franklin Method") (45, 54, 55). These approaches differ in the MI techniques and content, methods of application, and training goals incorporated. Research into MI training in dance indicates beneficial effects on motor and non-motor aspects of dance performance in various levels of expertise. For example, training in DNI™ increased hip ROM while maintaining correct pelvic postural alignment in 33 university-level dance students, and training in MIP increased ankle ROM while maintaining equal weight bearing distribution in 25 adolescent female dance students (38). Additionally, non-motor benefits have also been associated with MI training. These include improved imagery ability and use (38, 45, 56), enhanced cognitive skills (45), concentration and attention (57), and increased confidence and reduced anxiety (48). However, interventional studies vary in parameters such as type, length, and intensity of the studied intervention, making definite conclusions difficult (38). Future studies should focus on randomized controlled trials while isolating specific parameters (e.g., comparing MI interventions of varying length or intensity), and while providing details regarding the intervention's characteristics.

MI has been suggested as neurorehabilitation for people with PD (58, 59). Interventional studies conducted on this topic are sparse but provide promising evidence for the beneficial effects of MI in PD rehabilitation (43, 45). For example, a case report describing a three-month MIP intervention reported gains in balance (based on the Tinetti Balance and Gait Evaluation Scale), motor function (measured with the Unified Parkinson's Disease Rating Scale-Motor Subscale III; UPDRS-III), and pain reduction (measured with Visual Analogue Scale) (60). Other studies reported on MIP interventions embedded within conventional rehabilitation (e.g., physical therapy (PT)) protocols (43, 44) in people with PD. One study detailed the imagery component occupying 15-20% of the total intervention's volume and compared the effects of a six-week PT intervention combined with either imagery practice or relaxation in 47 people with PD (44). This study found a general trend ($p >$ .05) of improvement in a subjective gait assessment and a 10-meter walk test for participants with mild PD in the imagery practice group. Another study found that a combined regimen of physical and imagery practice (one-hour, biweekly intervention for 12 weeks; with no details regarding the time dedicated to imagery training) showed significant improvements in functional motor task performance times (e.g., standing up and lying down), including the Timed Up and Go test (TUG; ~2.5 sec, no detailed values are given), the “number of steps required to rotate in a circle,” and UPDRS scores (especially the mentation segment) compared to a control group undergoing physical practice only (43). However, a study assessing the effects of a single session of imagery practice with physical practice versus a single session of physical practice on gait in 20 people with PD found that the added imagery practice session did not have a significant effect (61). A recent study involving 20 participants with mild-moderate PD compared an intensive, two-week of DNI™ (experimental) versus home exercise and reading (control) interventions. The results showed that the DNI™ group, unlike the control, improved significantly in MI abilities, disease severity, and motor and spatial cognitive functions (45).

MI’s mechanisms of effect appear to be both physiological and psychological (34, 62), but are not fully understood. Significant advancements in neuroscience have shed light on neural circuits and processes associated with MI (63). However, a gap still exists between this increasing body of evidence and interventional studies in clinical settings, as well as practical applications and implementation of MI into routine clinical care (45). The lack of interventional studies can be explained by the difficulties in recruiting participants due to lack of awareness in the general population of such methods and their potential benefits.

Additionally, there are challenges with quantitatively measuring and controlling MI interventions in clinical settings where research tools like functional imaging modalities are not readily available. It is impossible for the researcher to measure the levels of participants’ engagement and active participation during MI practice outside the lab (38), making interpretation of results collected in clinical settings challenging.

Significant differences exist between the controlled environments where neuroscientific measurements (brain imaging and neurophysiological assessments) are conducted and clinical environments (a dance studio or a PT clinic) where MI training is used and incorporated within routine clinical or professional care. Such differences in setting may have an influence on core elements of the training (length of intervention, number of repetitions, levels of participant concentration), potentially making some research findings somewhat less transformative to clinical applications. To overcome this issue, researchers should conduct interventional MI studies in clinical settings, while seeking to develop new methods for measuring and controlling confounding variables associated with MI training. Alternatively, researchers conducting basic MI studies in the lab should make an effort to mimic the real and natural environment of the participant. For example, researchers can provide imaging participants with similar auditory environments to the ones they are likely to encounter while using MI in everyday settings. For dancers, that may include playing similar music to the one played during dance classes. For people with PD, this may be the noise of other therapists and patients in an open space, as is the case in many PT clinics. All of this may increase the chances of gaining more relevant results and information, as well as improve the probability of transferring scientific findings into clinical care, thus promoting evidence-based clinical practice.

Two unanswered questions are: 1) To what extent is MI beneficial in the long term and to what extent can the contents and techniques of MI be used in daily life, both in conscious and unconscious levels, and with or without externally generated cueing (45)? For example, can one use the DNI™ metaphorical image of the head being lifted up like a Helium balloon (Figure 2) on a regular basis while sitting in a coffee shop or walking down the street to release tension around the cervical region and thus improve posture and function and reduce tension and pain? and 2) Could MI be internally generated (64) in both research settings and real-life scenarios? To answer these questions, further studies should be conducted to explore the factors determining participants’ engagement and transferring of content to other daily life activities in different contexts as well as the applicability and relevance of internally generated MI.

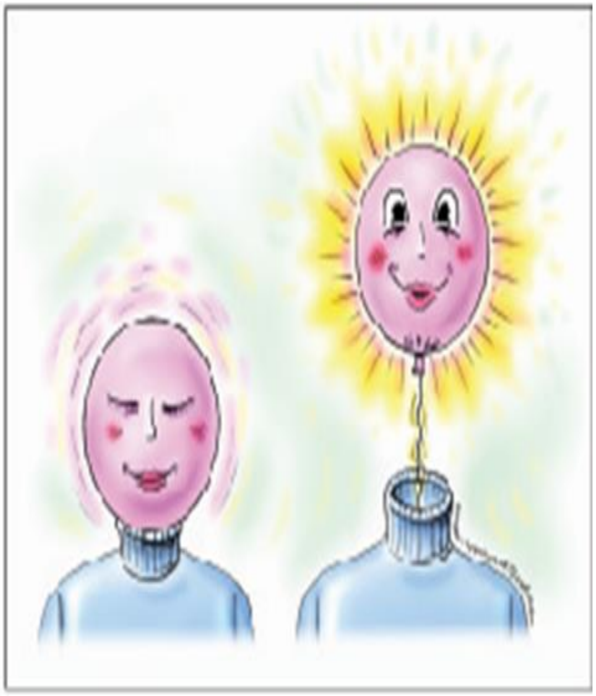

Figure 2. Dynamic Neuro-Cognitive Imagery (DNI™) Metaphorical Imagery of the “Head as a Helium Balloon” (with permission from Mr. E. Franklin). In this example, the MI practitioner visualizes his or her head being lifted up like a Helium balloon, lengthening the cervical spine and potentially improving posture.

Using mental imagery to reanimate paralyzed limbs: Translating thoughts into action

Recent advances in neurotechnology and machine learning have provided a powerful tool for translating the neural activity underlying motor imagery and intent into instructions that control neuroprosthetics, enabling amputees and paralyzed persons to regain lost motor function. In a situation where individuals have lost limbs or their ability to move limbs, the physiologic and behavioral distinctions (34, 62) between motor imagery and motor intent are blurred. Such situations resemble motor imagery, because behaviorally, no movement is generated, and physiologically, no intrinsic sensory feedback (65) occurs. However, these situations also resemble motor execution, because the individual has real motor intent and is activating (or attempting to activate) CNS motor pathways (34).

Reanimation of motor-cognitive integration

When people are paralyzed from damage to the nervous system, it is sometimes possible to capture the neural signature of their cognitive *impulse to move* and restore their ability to move through a brain-computer interface (BCI). BCIs have three parts: an input module that reads brain activity, a processor that translates brain data to (motor) commands, and an output module that executes the brain’s commands (66). Some BCIs can reanimate paralyzed limbs using an output module that selectively stimulates limb nerves and muscles to evoke patterns of movement (Figure 3). This process reintegrates intention with movement, but requires considerable cognitive effort, focus, and practice to be successful.

In addition to effecting reanimation, linking motor imagery and intent to a neuroprosthetic through a BCI provides a unique opportunity to *separate* intent from action. This artificial disconnection is impossible to reproduce in persons who have intact anatomy and neurological function. Analysis of this process using a BCI may provide a better understanding of motor control and learning mechanisms. BCI data provide evidence that kinetic, cognitive, and kinesthetic information are all represented in the motor cortex. These representations are the basic building blocks of an embodied mind and essential ingredients for implicit learning during neurorehabilitation.

The most sophisticated neuroprosthetics use implanted microelectrode arrays in the cerebral cortex to detect the electrophysiological correlates of motor imagery or intent. Microelectrode arrays provide a localized, temporally precise “microphone” for recording the activity of neural units and identifying changes in neural firing associated with movement intention. Precentral gyrus implants have been used in BCI trials that allow individuals with paralysis to control movement of robotic limbs, exoskeleton orthotics, or their own paralyzed limbs through neuromuscular stimulation (52, 67-74). Implanted BCI systems listen to the neural echoes of imagined or intended movement, capturing snippets of neural conversations every 20-100 ms. Conversations are processed through machine learning computer programs that identify patterns of neural phrases associated with specific movements.

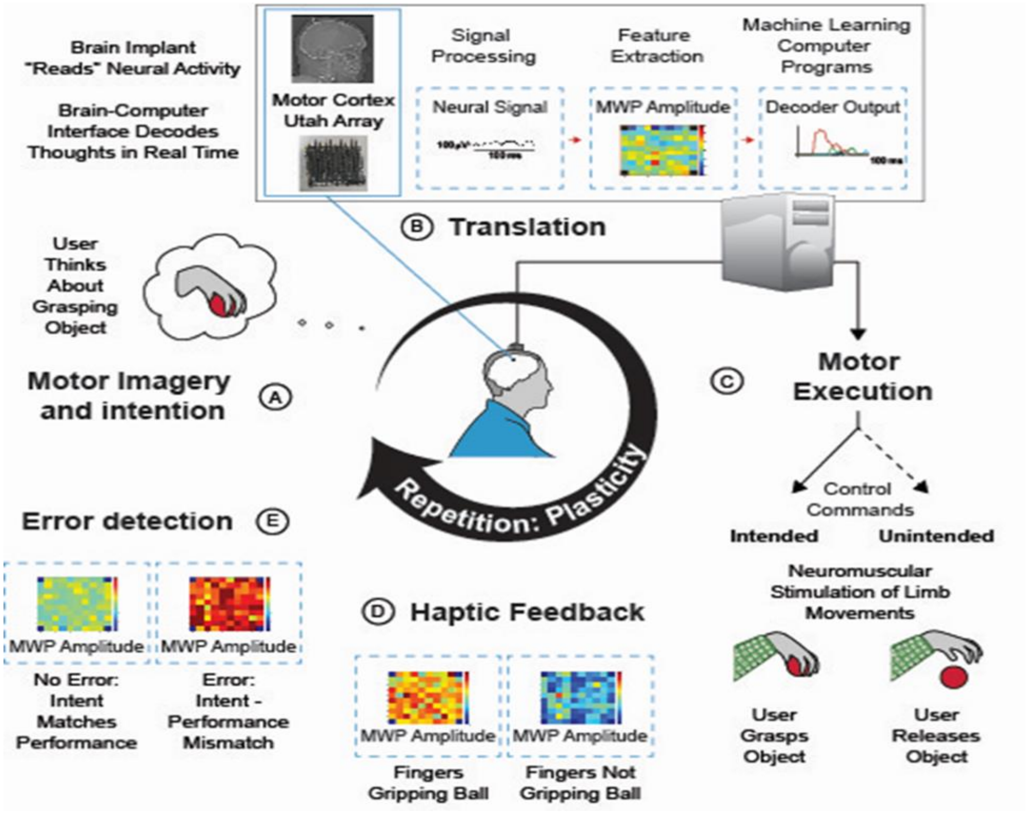

Figure 3. Translating motor imagery and intention to motor performance through a brain-computer interface (BCI) for spinal cord injury – an opportunity to separate intent from action and study the neurological correlates of the embodied mind. Stages of BCI control of neuromuscular stimulation: (A) Imagery: User imagines movement, (B) Translation: BCI decodes imagined or intended movement, e.g., by extracting mean wavelet power (MWP) from electrical activity across 96 microelectrode array channels (67), (C) Execution: BCI sends control commands for neuromuscular stimulation, causing the paralyzed limb to move – at this stage, commands can be manipulated to generate unintended movements, (D) Haptic feedback: Tactile, kinesthetic, and proprioceptive feedback influences neural activity in the motor cortex, and (E) Error detection: Cognitive processes, including error detection, influence firing rates in the motor cortex. As this cycle repeats, plasticity and learning occur.

For example, BCI systems can distinguish between firing patterns for intent to open or close one’s hand (67, 73), wiggle fingers (72), form different grips (74), or manipulate objects (75). As participants learn to use BCI systems and gain the skill to perform more complex movements with better coordination, BCI implants also provide a means to observe plasticity, or the reorganization of neural representations in the motor cortex (76).

Examining neural patterns underlying movement conversations provides insight into the functional motor-cognitive interactions encoded in the motor cortex. BCI systems are able to decode kinematics (position) and kinetics (force) of intended movement through a range of motion. Imagine performing a simple, single joint movement, but freezing at different stages of progression through the range of motion. A BCI user was asked to do this, mirroring a cued joint angle by evoking neuromuscular stimulation that flexed his wrist against resistance (52). The BCI decoded neural activity from his motor cortex into movement parameters (e.g., position/kinematics, force/kinetics) to produce graded muscle contractions for stages of wrist range of motion. This experiment revealed that coding of graded, functional muscle contractions relied on complex combinations of single channel activity within the motor cortex, with individual tuning curves of recorded signals demonstrating linear (increasing or decreasing) and non-linear (sigmoidal or parabolic) properties.

The same authors also investigated whether adding rhythm to simple flexion/extension movements changed movement representation in the motor cortex. In this study, the participant was cued to imagine extension, flexion, and 2.5 Hz "wiggle" (a regular, periodic oscillation between extension and flexion) of either his wrist or thumb (72). Distinct channels in the microelectrode array representing distinct populations of neurons were active in each of the extension, flexion, and wiggle conditions. The activation patterns appeared to be more similar for movement type than body part moved (i.e., wiggle of thumb and wiggle of wrist appeared more similar than flexion, extension and wiggle of thumb). This early evidence indicates that moving rhythmically (i.e., with a regular, repeatable pattern of gestures) as one might in dance has a representation in the primary motor cortex that is more complex than a summation of representations for the gestures themselves.

Sensory information also appears to be integrated in the motor cortex representation of movements. To demonstrate this, BCI researchers took advantage of the ability to manipulate the motor and sensory components of feedback translated from movement intent through the BCI. For example, instead of providing full visual, kinesthetic and haptic feedback of movement evoked in a paralyzed limb (77) or robotic limb movement coupled with somatosensory cortex simulation (78), the BCI can be programmed to provide no feedback, visual feedback only (via an animation or robotic limb movements), or haptic/somatosensory feedback without visual cues (i.e., when the limb is hidden). By manipulating feedback type but maintaining the same cognitive task and intended movement, one can investigate whether haptic feedback modulates neural representations of movement intent. Indeed, neural firing patterns differ for the same imagined/intended actions depending on whether feedback is given visually (through an avatar) or by electrically stimulating limb muscles to move (77). Preliminary data suggest that somatosensory feedback is associated with a traveling wave of activity that moves anteriorly from the central sulcus across the motor cortex. These findings complement older evidence (79) that haptic feedback is integrated into motor control representations in the motor cortex—that where you are and what you are touching are part of the dynamic plan for what you do next. These findings suggest that the haptic conversations in partnered dance may help shape the neural representations of movement intent for the next steps of the dance.

Finally, cognitive correlates of motor planning also appear to be embedded in the language of movement in the motor cortex. Movement intent can be deliberately mistranslated through the BCI, evoking an unintended movement in an avatar or by stimulating the wrong muscles of the user (77). We find an increased chatter among a subset of motor cortex neurons as early as 150 ms after an *expected but unintended* movement is evoked (80). This error signal is distinct, reliable and can be detected in real-time by pattern recognition programs during BCI operation. It correlates with subjective reports by the user of not being in control of the BCI-enabled movement. Error recognition also seems to be stronger for evoked movements of the user's own limbs (even when the user cannot see them) compared to movements of an avatar. Thus, even when attenuated by spinal cord injury, knowledge of performance appears to be integrated into representations in the motor cortex as an important component of the subjective experience of motor control.

In summary, new developments in BCI neurotechnology provide unique insight into the neurophysiological and neuropsychological processes of movement and neuro-motor skill acquisition. Manipulating the translation process from motor imagery and intention to motor performance reveals the interaction between kinetic, kinematic, kinesthetic, and cognitive information in the primary motor cortex. Studying BCI-enabled motor skill acquisition will provide further insight into the neurological correlates of an embodied mind and how these processes can be leveraged to facilitate implicit learning during neurorehabilitation.

Conclusion

Several innovative paradigms leveraging motor-cognitive integration hold promise for augmenting function, revolutionizing neurorehabilitation, reducing impairment, and optimizing health. In particular, creative engagement through improvisational dance, social engagement through partnered dance, physical training through mental imagery, and neuromotor skill acquisition with a BCI all provide means to target implicit learning through the kinetic, kinesthetic, and cognitive interactions of the embodied mind.

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Ethical compliance

The authors have stated all possible conflicts of interest within this work. The authors have stated all sources of funding for this work. If this work involved human participants, informed consent was received from each individual. If this work involved human participants, it was conducted in accordance with the 1964 Declaration of Helsinki. If this work involved experiments with humans or animals, it was conducted in accordance with the related institutions' research ethics guidelines.

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