From movement to thought and back: a review on the role of cognitive factors influencing technological neurorehabilitation

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Summary

In recent years, cognitive theories have increasingly influenced the approach to motor rehabilitation. The connection between different aspects of cognitive and motor function is increasingly documented, underlining the importance of developing rehabilitation projects that take cognitive aspects into account.
The aim of this non-systematic review is to highlight the relationship between cognition and motion and, in the light of new rehabilitation technologies, to better define how aspects of cognition can affect motor rehabilitation.

KEY WORDS: cognitive rehabilitation, motor disorders, new technologies, rehabilitation.

Introduction

Many researchers agree that movement is crucial for biological systems (Chiel and Beer, 1997; Wheatley, 1999), and that we would not survive without it (Sheets-Johnstone, 2010). Movement and cognition are intrinsically linked. As shown by several studies on motion perception, both in healthy and in clinical samples (Pizzamiglio et al., 1984; Greenlee et al., 2016), sensory-motor information, rendered increasingly complex through evolutionary processes, is stored in the neural circuits of the central nervous system (CNS). In the course of evolution, this structuring of sensory-motor information led to the emergence of vital adaptive behaviors, such as the ability to recognize biological motion from the first days after birth (Simion et al., 2008). In fact, according to some Authors (Koziol et al., 2012; Pezzulo and Cisek, 2016), our high cognitive functions evolved precisely to enable us to realize complex movements. For this reason, movement needs to be studied in relation to cognition, especially when such study is relevant to the field of rehabilitation (Mulder, 2007; Franceschini, et al., 2010; dos Santos Mendes et al., 2012; Dobkin, 2007; Miniussi and Vallar, 2011; Vourvopoulos et al., 2014).

Certain concepts that may seem obvious today are actually the result of a theoretical and disciplinary evolution of the rehabilitation process. Before the 1950s, patients with stroke sequelae did not receive any cognitive treatment, and motor rehabilitation, based on the methods of Bobath, Kabat and Vojta, for example, was mostly aimed at promoting recovery of neuromotor reflexes (Perfetti et al., 1999). More recently, thanks to the innovations introduced by the neurofunctional recovery (brain plasticity) theory (Cecatto and Chadi, 2007; Berlucchi, 2011), more attention has been paid to cognitive functions involved in motor control, and cognitive-motor rehabilitation programs have begun to be more appreciated (Correa et al., 2007; Cimmino et al., 2013; Borel and Alescio-Lautier, 2014; Flöel, 2014; Prosperini et al., 2015). Accordingly, conventional therapy, based on physical treatment, is now supported by this new kind of rehabilitation, which indirectly stimulates the CNS, eliciting the aforementioned neural plasticity mechanisms (Paolucci et al., 1998a, 2000a).

Recent years have seen the emergence, development and spread of promising robotic rehabilitation devices (Sacco et al., 2011; Badesa et al., 2012; Heins et al., 2017) and brain-computer interfaces (Dobkin, 2007; Sitaram et al., 2007; Neuper et al., 2009; Pichiorri et al., 2015). These technologies are based on a “top-down” approach and involve the use of multiple feedback systems, such as exergame (Wüest et al., 2014; Munoz et al., 2014; Trombetta et al., 2017), serious game (Ma and Bechkoum, 2008; Burke et al., 2009; Ang et al., 2010; Schönauer et al., 2011), and/or complex biofeedback systems (e.g. EMG and inertial measurement units (IMUs) for muscle contraction or analysis of movement and posture) (Hwang et al., 2009; Ang et al., 2015; Iosa et al., 2016a; Morone et al., 2019). They are used to stimulate cognitive functions with the aim of increasing the effectiveness of motor rehabilitation.

The aim of this non-systematic review is to highlight the relationship between cognition and motion and, in the light of these new technologies, to better define how aspects of cognition can affect motor rehabilitation.

Figure 1 summarizes the concepts presented in this review, which are based on the findings of two previous works on the effectiveness of the use of technological devices for motor neurorehabilitation (Morone et al., 2017, 2019).

Cognition

Traditionally, motor and cognitive functions have been studied separately (Hershey et al., 2004); however, evidence from neuroscientific studies (Beisteiner et al., 1995; Lang et al., 1996; Lotze et al., 1999) has fed a growing awareness of and interest in interfacing processes between cognition and action (Paolucci, 1998b; Calderon et al., 2015). The resulting integrated rehabilitation approach is particularly useful in the early stages of motor rehabilitation, especially in patients with poor motility (Paolucci et al., 1996a, 2001a; Jackson et al., 2001; Heruti et al., 2002).

Action observation therapy (AOT) (Buccino, 2014; Caligiore et al., 2017) and mirror therapy (MT) (Altschuler et al., 1999; Cristina et al., 2015; Morkisch et al., 2017; Thieme et al., 2018) are two promising cognitive-motor treatment approaches. Both aim to enhance motor learning and promote neural reorganization using afferent input and patterns of visual feedback, and both allow patients to safely practice movements and motor tasks. For this reason, they are highly recommended in the treatment of neurological disorders (Fadiga et al., 1995; Ertelt et al., 2007; Yavuzer et al., 2008; Lamont et al., 2011; Morkisch et al., 2017; Thieme et al., 2018). During AOT sessions, the patient observes video clips showing movement of the upper limbs and performs the motor sequence shown, either simultaneously or immediately after watching the exercises. To maximize neural involvement, the action can be presented from the first-person perspective (Shih et al., 2017). Instead, MT requires the patient to move the unaffected limb and watch the movement reflected in a mirror. Since the affected limb is hidden from view, the patient has the illusion of moving the affected limb (Sathian et al., 2000; Thieme et al., 2018). This rehabilitation method focuses on visual and proprioceptive feedback of the non-affected limb, which may provide substitute input for absent or reduced proprioceptive feedback from the affected body side. Both these approaches have been used, in particular, for upper limb rehabilitation; furthermore, there have been reports, also recently, of AOT and MT rehabilitation being used to promote walking recovery (Sütbeyaz et al., 2007; Franceschini et al., 2012; Di Iorio et al., 2018; Louie et al., 2019). Another rehabilitation technique that exploits cognitive processes to improve motor rehabilitation is motor imagery (MI); in

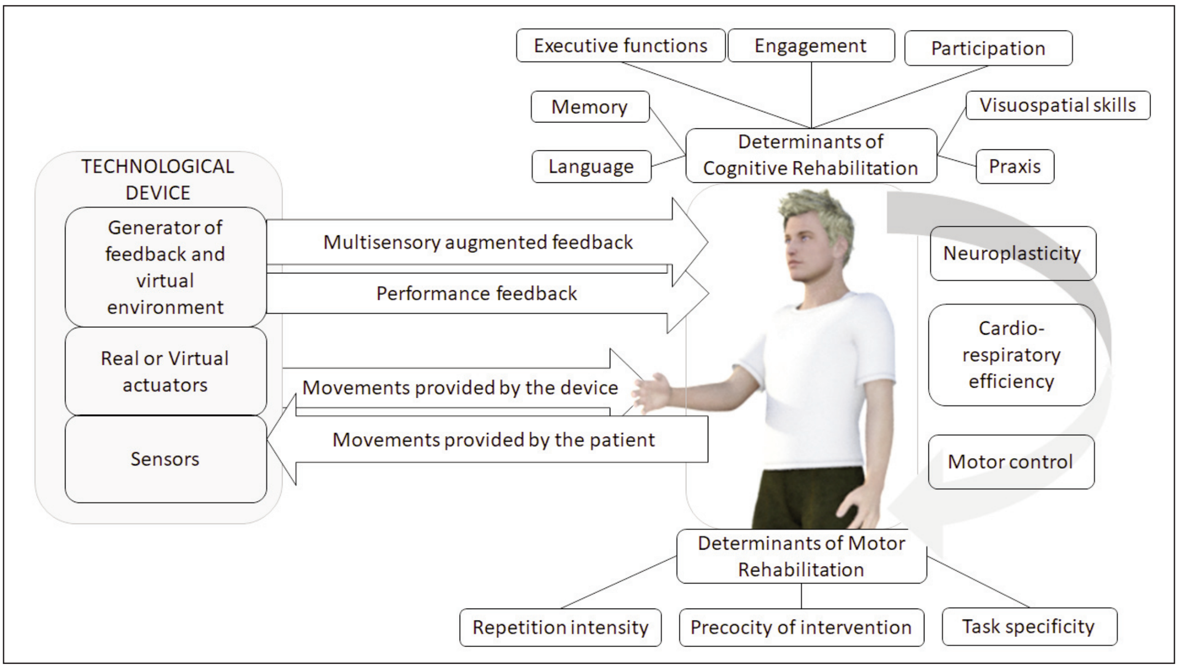

Figure 1 - The Figure shows a graphical representation of the interactions among cognitive and motor determinants through the use of technological devises.

this case, the patient has to imagine performing a motor task, without actually moving (Grush, 2004). As shown by early literature on the use of MI, this technique is based on activation of brain regions involved in movement preparation and execution, accompanied by voluntary inhibition of the motor activity (Lotze and Cohen, 2006). Recently, MI has been associated with the execution of movements that mime in part the mentally represented action (dynamic MI) (Fusco et al., 2019, 2016). Although execution and imagery are both processes that engage motor-related areas of the brain (Hanakawa et al., 2003; Wriessnegger et al., 2016), the three aforementioned approaches involve different patterns of motor observation, imagination, and execution; on the other hand, they share some similar neural bases of the mirror neuron system (Case et al., 2015; Hardwick et al., 2017). However, the different outcomes and mechanisms of these techniques are still under study (Rizzolatti and Craighero, 2004; Abbruzzese et al., 2015; Cengiz et al., 2018).

One technology found to effectively exploit cognitive functions to improve motor rehabilitation is virtual reality (VR) (Doniger et al., 2018). Since VR was first introduced in the rehabilitation field (Burdea and Langrana, 1995; Jack et al., 2001; Sveistrup, 2004), it has undergone improvements and adaptations (Lucca, 2009) that have made it suitable for different types of patients, from children to adults with motor deficits (Sisto et al., 2002; Bryanton et al., 2006; Tieri et al., 2018), and it is now very widely used. Today, rehabilitation programs implement the AOT and MI techniques in VR with good results (Holper et al., 2010), and there are numerous clinical applications of VR programs that exploit MI for motor rehabilitation (Bermúdez i Badia et al., 2012), or that induce the illusion of ownership of a virtual body part in order to reduce the pain associated with the known “phantom limb” effect (Slater et al., 2009).

Attention

Several studies have highlighted the crucial role played by attention and executive functions in motor control (Sheridan et al., 2003; Yogev-Seligmann et al., 2008; Pichierri et al., 2011), and shown that rehabilitation of these cognitive functions can improve upper limb motor recovery (Rose et al., 2005; Frisoli et al., 2009; Levin et al., 2015), balance (McCulloch et al., 2010; Saverino et al., 2016) and gait ability (Springer et al., 2006; Yogev-Seligmann et al., 2008; Beauchet et al., 2012).

In recent years the effectiveness of technological devices called serious exergames has been tested (Wong et al., 2007; Maggio et al., 2019). These devices, which are similar to videogames, can be used to train different components of attention. Essentially, subjects are required to perform attentional tasks, such as visual search (Green and Bavelier, 2003; Hubert-Wallander et al., 2011a) or visual inhibition (Wu et al., 2012) tasks. The method is based on the conventional principles of attention rehabilitation concerning the role of the timing of inputs on the outcomes of the treatment (Antonucci et al., 1995).

Attention, understood as the physiological activation necessary in order to perform motor tasks, has a pivotal role in motor performance and motor learning (Sjøgaard et al., 2000; Stefan et al., 2004; Girardi et al., 2013). Enhancement of motor arousal can be achieved through several processes, including motivation and reward (Berridge and Arnsten, 2013; Mattallaoui et al., 2017). Computer game devices, being associated with a continuous request to increase one’s score (motivation) in order to access a higher level of difficulty (reward) are strong drivers of these processes. Moreover, serious exergames provide feedback on patient performance and, if necessary, allow the patient to repeat the action correctly (Tannous et al., 2016; Estepa et al., 2016).

Alertness, by definition the reaching and maintenance of a state of high sensitivity to incoming stimuli, is another cognitive function often impaired after brain damage (Godefroy et al., 2002; Rieger et al., 2003). Alertness seems to be the most basic aspect of attention intensity, and perhaps constitutes the basis for the more complex aspects of attention selectivity.

Alertness has been extensively investigated in healthy subjects, especially the elderly (Ordnung et al., 2017; Garcia-Agundez et al., 2019), and also in pathological subjects, given that it is implicated in the correct performance of many everyday tasks that can be compromised after a head injury. Driving performance, for example, can be impaired following a head injury (Chaumet et al., 2008; Brenner et al., 2008). Many exergames are based on mechanisms that elicit responses intended to stimulate intrinsic or phasic vigilance. Intrinsic vigilance is the cognitive control of wakefulness and excitation and it is typically evaluated by means of simple reaction time tasks. Phasic vigilance, on the other hand, is trained through a dual (inhibition and reaction) task: usually, following the appearance of an acoustic stimulus, the patient must respond to a second visual stimulus with a motor reaction (Plohmann et al., 1998; Rego et al., 2010). Vigilance is a crucial aspect of motor rehabilitation as it allows the patient to prepare their body to perform the correct movement (Prosperini et al., 2015). We know that rehabilitation can be a lengthy process, and it can take months or years before a patient fully recovers. For this reason, the constant repetition of specific exercises is a key element of physical rehabilitation. Unfortunately, repetition may cause tedium followed by a decline of alertness, which leads the patient to perform the exercise incorrectly. Thanks to the constant alternation of sensory stimuli provided by games consoles, videogame therapy seems to address this problem. For example, the Walk-Even device (Krishnan et al., 2016), through real-time feedback, is able to correct the gait asymmetry commonly exhibited by post-stroke patients. The apparatus consists of customized force-sensor-embedded pads adaptable to fit any shoe size, acoustic and electro-tactile feedback, microcontroller, and wireless transceivers. The system records gait parameters (gait time, swing time, and stance time of each leg) in order to identify gait asymmetry and provides real-time biofeedback in the form of auditory and electro-tactile stimuli that allow the patient to actively correct their gait. In this specific example, alertness is maintained by the sensory stimulation, which, in the event of gait errors, prompts the patient to actively re-focus on the correct movement. Lupo et al. (2018) recently provided an example of biofeedback training based on IMUs and exergaming.

Executive functions

Much of the available knowledge on executive functions derives from studies in primates that allowed us to formulate a conceptual model of their organization and processing (Stuss, 1992). According to this empirical evidence, the neuronal networks of the frontal lobe share motor and executive information (Smith and Jonides, 1999; Marguiles et al., 2009). In particular, the prefrontal cortex plays a critical role in the perception-action cycle - a role that becomes clearer following a lesion to this region or its subcortical connections (Paolucci et al., 2001b, 2003; Gioia and Isquith, 2004; Schweizer et al., 2008; Mansouri et al., 2017a).

Recently, there have been several scientific reports on human performance in execution tasks (Kane et al., 2016; Mansouri et al., 2017b; Karr et al., 2018), and Authors agree that executive control is a multidimensional structure (Baggetta and Alexander, 2016). Executive function and attention (required for effective, goal-directed actions, and for the attentive resources needed for managing daily living activities) comprise both cognitive and behavioral components (Yogev-Seligmann et al., 2008).

The role of cognition in motor function, both in healthy and in clinical samples (Plummer-D'Amato et al., 2010; Al-Yahya et al., 2011; Plummer-D'Amato et al., 2012), is increasingly appreciated, and it is now possible to state that motion is no longer regarded as an entirely automated behavior. Updates on this topic have important implications for rehabilitation. In recent years, numerous motor rehabilitation programs have exploited executive functions to improve motor recovery, the best example of this possibly being the use of virtual reality exercise (VRe) (Levin et al., 2015). VRe simulates real-life activities; essentially, patients are asked to work on self-care skills in a VR setting. These settings serve to replicate environments that would otherwise be difficult to recreate in a hospital context. Importantly, it is only in the everyday-life environment that certain "motor requests" are formed (Josman et al., 2006), and in VRe patients encounter situations that commonly occur in daily activities. Recently, Triandafilou et al. (2018) published a research protocol in which patients were required to change the arrangement of 8 "glass" objects in a virtual dining room; if they made a mistake, they received acoustic feedback (a bell). This motor task required the activation of specific executive functions, namely: planning of motor strategies to explore the dining room effectively; working memory, to keep in mind the number of objects already moved until the 8th item; to overcome errors, the performer should inhibit the ongoing action and replace it with an appropriate one.

Similarly, over the last two decades the field of rehabilitation has undergone an important revolution linked to a growing interest in exploiting the potential of music (Lucia, 1987; Sihvonen et al., 2017). Many Authors have experimented with the effective use of music in motor rehabilitation programs aimed at patients with neurological problems (Staum, 1983; Formisano et al., 2001; Schauer and Mauritz, 2003; Calabrò et al., 2019). "Entrainment" has been identified as the neurobiological rehabilitation principle underlying the efficacy of this new rehabilitation paradigm (Thaut et al., 2009; Altenmüller and Schlaug, 2013; Thaut et al., 2015a), which is also termed "neurologic music therapy". Technically, entrainment is a physical phenomenon, namely "the frequency locking of two oscillating bodies, that is bodies that can move in stable periodic or rhythmic cycles. They have different frequencies or movement periods when moving independently, but when interacting they assume a common period" (Thaut, 2013). It was reported that the effect of rhythmic entrainment on motor control is directly linked to the firing rates of auditory neurons that entrain the firing patterns of motor neurons, affecting the motor system frequency at different levels. In this sense, auditory stimulation primes the motor system in a state of readiness to move (Thaut, 2015b). One specific aspect of entrainment is its "executive function", which influences motor planning and motor execution. In particular, "rhythmic stimuli create stable anticipatory time scales or templates" (Thaut, 2013, 2015b) which provide "time cues for the brain to plan ahead and be ready. Furthermore, successful movement anticipation is based on foreknowledge of the duration of the cue period" (Thaut, 2013, 2015b). Sejdić et al. (2012), who described the effects of rhythmic sensory cues on healthy movement behavior, suggested that "rhythmic cues could be considered as an alternative cueing modality in rehabilitation". Indeed, new strategies for motor rehabilitation in neurological disease are based on the use of rhythmic cues that enable the patient to realize cyclic movements such as gait (del Olmo and Cudeiro, 2005; Nombela et al., 2013; Suh et al., 2014).

Before concluding, it is worth mentioning, briefly, the effect of computer games on brain plasticity, as this might help to better characterize the process of motor rehabilitation based on the stimulation of executive functions. As recently reviewed by Föcker et al. (2019), the neuroplastic modifications associated with videogame-based training mostly involve the areas corresponding to the fronto-parietal networks of attention and executive functions. Several neuroimaging studies (Hubert-Wallander et al., 2011b; Bavelier et al., 2012a,b) have correlated use of action videogames with improved mechanisms of executive control. To demonstrate this correlation, the Authors compared the performance of action gamers to that of non-gamers and found differences in attentional network recruitment and distractor processing. Specifically, gamers showed less activation of the visual motion-sensitive area associated with early filtering of irrelevant information, while the non-gamers showed greater activation in the fronto-parietal network as the attentional demands increased.

Similar results were reported from an event-related potentials study on the performances of videogamers on a visual attentional task (Föcker et al., 2019). The Authors found that habitually playing action video games may modulate early sensory processing, by increasing the player's sensitivity to salient visual events that capture attention. Videogame players (VGPs) exhibited faster responses on the attentional task, with no less accuracy than non-videogame players (NVGPs). The most important difference between the groups was in the early anterior N1 component associated with parietal lobe functions, where greater amplitudes were found in the VGPs compared with the NVGPs during a task which required focused attention. Other studies on VGPs showed that continuous training with action videogames produced specific effects on the dorsal striatum (Erickson et al., 2010; Kühn et al., 2011), right posterior parietal cortex (Tanaka et al., 2013), entorhinal cortex, hippocampus, occipital cortex (Kühn and Gallinat, 2014), right hippocampal formation, and right dorsolateral prefrontal cortex, as well as both hemispheres of the cerebellum (Kühn et al., 2011).

Sensorimotor learning

The studies mentioned thus far focused on motor recovery enhancement through concomitant stimulation of the brain areas responsible for the cognitive-motor processing of the target actions. But, more often than not, when the motor damage is severe, the patient actually needs to re-learn the motor action (Bastian, 2008; Bolognini et al., 2016). Before being able to re-learn and perform the motor action correctly, many of these patients need to become aware of their deficits, in order to be able to make real-time adjustments (Deuschl et al., 1996; Gustafsson et al., 2016). This motor adaptation requires mental flexibility, and it can be trained to make motor learning more effective (Cirstea et al., 2006; Bolognini et al., 2016). In this context, rehabilitation programs based on the principles of motor adaptation, and acting at different levels of stimulation, have been developed with the aim of facilitating performance in motor learning tasks. In this regard, we may cite, for example, studies that use transcranial direct current stimulation (tDCS) (Hunter et al., 2009; Kang et al., 2016) or transcranical magnetic stimulation (TMS) (Reis et al., 2008; Celnik, 2015). These are non-invasive stimulation methods that are used specifically for research purposes because they allow us to "manipulate" brain activation in order to study which area is involved in the processing of certain information. As far as motor learning is concerned, it is known that the encoding of motor information occurs in a distributed network that includes the primary motor, premotor and supplementary motor cortices, the cerebellum, thalamic nuclei and striatum (Hanakawa et al., 2008). TMS and tDCS studies have confirmed the role of the M1 area both in the motor adaptation process and in specific motor learning tasks (Hadipour-Niktarash et al., 2007; Apolinário-Souza et al., 2016; Spampinato et al., 2019).

These stimulation methods are still under development, but some studies have already reported their effectiveness. TMS has been reported to be effective in the recovery of manual dexterity after stroke (Fregni et al., 2006), while tDCS has been associated with improved performance on a motor sequence task in chronic hemiparesis (Celnik et al., 2009). As already reported in functional MRI connectivity studies (Carter et al., 2010), motor performance depends on inter-hemispheric connectivity rather than ipsilesional connectivity, therefore stimulation performed in the contralesional hemisphere would allow good recovery of the motor deficit.

Other technological devices that may facilitate patient motor re-learning and motor adaptation are robots. Since they were first introduced into the clinical setting, robotic devices have found wide application in motor rehabilitation (Iosa et al., 2012; Poli et al., 2013; Iosa et al., 2016b); in this context, a major application is gait retraining, where the most popular device is the Lokomat (Hocoma, Rockland, MA). This consists of a treadmill, support harness, and computer-driven gait orthosis for each leg. Recently, several clinical trials reported better results in patients treated with Lokomat, compared with controls (Hornby et al., 2008; Hidler et al., 2009; Morone et al., 2014). Some of these devices facilitate motor rehabilitation by eliciting cognitive functions, such as the Mirror Image Movement Enabler (MIME) robot (Lum et al., 2006), which was the first to embed the use of the mirroring of the motion of the unaffected arm in a robotic system in order to improve the motor performance of the affected arm.

Recently, numerous studies have reported the efficacy of a combined approach of robotic therapy and brain stimulation (e.g. Hesse et al., 2011; Bolognini et al., 2011). It has also been noted that corticomotor excitability recorded after a tDCS stimulation session is similar to that recorded after robotic practice (Edwards et al., 2009), suggesting that these modalities could be synergistic.

In conclusion, robotic treatment has also been associated with improved proprioception in patients who have lost motor abilities (De Santis et al., 2015). Proprioception, linked to sensory information concerning both the external and internal environmental conditions of the body, is crucial in motor control (Riemann and Lephart, 2002).

Visual perception

Thus far, we have outlined cognitive factors that can support the rehabilitation process of patients with motor problems, and briefly examined devices and rehabilitation involving aspects of vision. In this last section, we look at how visual perception can improve motor recovery, after first trying to identify the connection between the two.

The idea that our movements derive directly from vision was strongly supported by Gibson (1979), who coined the term "affordance" to refer to internal models that contain information on the properties that define objects in operational terms. The same explanation cannot be given for motor actions elicited by everyday objects. Recent research (Castelhano and Witherspoon, 2016) has sought to clarify the role that objects can play in guiding the actions of participants in an experimental context. In this study "non-existent" objects were created, and participants were asked, under two different experimental conditions, to use the objects according to their function or according to their characteristics. The Authors found that knowledge of object function can guide attention in scenes (Castelhano and Witherspoon, 2016).

With regard to the exploitation of aspects of vision to facilitate motor neurorehabilitation, scientific research has developed rehabilitation programs based on the enhancement of visual skills. In particular, there exist VR programs designed specifically for patients with motor deficits that are based precisely on human visual skills (Dariush et al., 2011; Gamito et al., 2017). In particular, some VR treatments allow a simultaneous strengthening of both motor and visual abilities, such as those that improve spatial orientation and reduce the risk of falling (Mirelman et al., 2011; Kober et al., 2013). Technological devices, such as exergames, can be used to stimulate visual-spatial abilities during performance of a motor task; these devices help patients to remain motivated towards the rehabilitation, and also to perform a double task (Jaume-i-Capó et al., 2014), with undoubted effects on functional neuroplasticity mechanisms (Kelly and Garavan, 2004). Scientific evidence from neuroimaging during VR-based visuomotor tasks has indicated the presence of activation of brain circuits in frontal and parietal cortical areas (Prochnow et al., 2013). Since these areas are activated both when an action is actually performed and when it is simply imagined, the use of technological tools that stimulate these areas would help motor recovery in neurological patients. This has already been confirmed by previous studies on the use of VR technology in stroke patients (Jang et al., 2005).

Cognitive factors that can limit motor rehabilitation

Having outlined the connection between cognitive and motor factors, and the role they can play in facilitating motor rehabilitation, it seems appropriate to conclude with a brief reflection on how these factors may hinder effective rehabilitation, if they are not properly taken into account.

Motivation and attention are considered key elements determining motor recovery outcomes (Flores, 2008; Kim et al., 2017). Motor rehabilitation is based on the practice and repetition of exercises until the patient consolidates the ability in question. For this reason, correct communication with the patient is essential: it must be clear to the patient why a certain exercise is proposed. The exercises must be designed, explained and defined with a view to achieving realistic motor goals, i.e. within the reach of the patient (Playford et al., 2009; Mawson et al., 2016). In this way, the patient is not only actively involved, but can also be motivated to achieve more difficult goals. Instead, depression and low motivation to perform neurorehabilitation, or pursuit of an unrealistic goal, can adversely affect the rehabilitation process (Playford et al., 2009; Kwon and Lee, 2017).

The presence of hemineglect and depression has been associated with an increasing risk of low response in terms of autonomy in activities of daily living, but not in terms of mobility (Paolucci et al., 1998a). A more recent study showed that the presence of neglect was a predictor of low recovery of stair climbing, but not walking ability (Morone et al., 2018). The role of unilateral spatial neglect is fundamental not only for the autonomy of stroke patients on their return home, but also as a prognostic factor for motor outcome on discharge from rehabilitation hospital (Paolucci et al., 2001b; Iosa et al., 2016c). Patients with hemineglect had a significantly higher relative risk of poor autonomy than those with aphasia (Paolucci et al., 1996a). In view of these findings, early treatment of neglect in stroke patients is fundamental (Antonucci et al., 1995; Paolucci et al., 2000a), not only because of the deficit itself, but also to enhance rehabilitation outcomes (Paolucci et al., 1996b; Matano et al., 2015). In different settings, e.g. training performed using optokinetic stimulation (Pizzamiglio et al., 2004) or transcutaneous electrical nerve stimulation (Pizzamiglio et al., 2006), the use of technological devices has been shown to be effective in strengthening the rehabilitation of spatial hemineglect. However, it is important to be aware of the difference between extrapersonal and personal neglect, especially in rehabilitation (Iosa et al., 2016c).

A wide range of neuropsychiatric symptoms has been found in sizeable proportions of the poststroke population: mostly depression (in about two thirds of patients), followed by irritability, eating disturbances, agitation, and apathy (each present in about one third) and anxiety (in about a quarter) (Angelelli et al., 2004). Depression should be treated with antidepressant drugs, even though post-stroke depression has been confirmed to have an unfavourable influence on functional outcome despite pharmacological treatment (Paolucci et al., 2001c). Clearly, valid and reliable screening of cognitive deficits in patients with stroke, as well as other conditions that impair cognition, is fundamental (Di Iulio et al., 2019; Mancuso et al., 2016; Basagni et al. 2017; Mancuso et al. 2018). In this scenario, IT tools offer important opportunities for telemonitoring patients' status following their return home (De Bartolo et al., 2018).

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