DOI 10.1007/s11055-021-01160-9
Neuroscience and Behavioral Physiology, Vol. 51, No. 7, September, 2021

Observation of Motor Actions as a Tool for Motor Rehabilitation

Y. K. Stolbkov and Yu. P. Gerasimenko

UDC 612.821

Translated from Uspekhi Fiziologicheskikh Nauk, Vol. 51, No. 4, pp. 29–39, October–December, 2020. Original article submitted December 24, 2019. Revised version received January 18, 2020. Accepted May 19, 2020.

Experimental studies have demonstrated that observation of motor actions induces activation in the observer of the same areas of the brain activated on physical execution of these actions and that this can induce the same plastic changes in the motor system of the observer as real physical training. This raises the question of whether observation of motor actions could be used to restore lost motor skills and acquire new skills. This review presents behavioral and neurophysiological data on the use of observation of motor actions in healthy people and in clinical conditions for rehabilitation (improvement) of movements.

Keywords: movement, motor actions, learning, rehabilitation, observation of actions.

Among novel approaches to the treatment of motor impairments, the most popular are the so-called "bottom-up treatment schemes," which presume intense use of the impaired limbs with the aim of facilitating plastic changes in the brain [82]. The main proposition underlying these methods is that repeated active movements of the paretic limb induced by the patient him- or herself can promote improvements in its functionality due to reorganization of the central nervous system [40]. The training action or movement should be repeated without regard to the quality of execution – patients should relearn the movement whose execution quality has declined as a result of pathology [82].

Apart from the "bottom-up treatment schemes," novel approaches include "top-down schemes," where the physician seeks to act on the brain by other means with the aim of initiating plastic changes: these involve neuron activation linked with imaginary motor actions or observed actions [40]. This means is based on data indicating that imagination or even simple observation of motor actions performed by a person (or monkey) activate the same structures in the observer's brain as are activated by physical performance of the observed actions [78, 80]. Although observation of motor actions has long been known to have positive effects on motor learning, use of this approach in neurorehabilitation only started rather recently and the theoretical basis of this therapeutic approach is linked with the discovery of so-called mirror neurons [40].

Observed motor actions have some advantages over imaginary movements. For example, observation of actions is subject to well controlled and quantitatively measurable stimulation volumes. On the other hand, imaginary movements are poorly controlled subjectively, their use relies mainly on the patient's report, and the ability to imagine movements varies significantly from person to parson and can only be assessed indirectly [6].

Mirror Neurons. Interest in processes associated with observation of motor actions was elicited by the discovery of mirror neurons in the cerebral cortex of monkeys about three decades ago: researchers found by chance that when a monkey passively observed the experimenter taking a piece of food, its premotor cortex displayed activation of the same neurons as would be activated if the animal itself had performed the movement [64]. Neurons discharging both on execution of a motor act and on observing others perform the act were termed mirror neurons [35]. These were initially found in the ventral premotor area F5 of macaques [37, 44] and then among neurons in the inferior parietal lobes [43]. The network containing these neurons came to be termed the mirror neuron system [75]. However, subsequent studies showed that neurons in the dorsal premotor cortex [72],

---

Pavlov Institute of Physiology, Russian Academy of Sciences,
St. Petersburg, Russia;
e-mail: stolbkovyk@infran.ru, gerasimenko@infran.ru.

the supplementary motor area [61], the primary motor cortex [38, 71, 87], and the superior parietal, middle parietal, intraparietal, and parietal-occipital areas of the cortex [84] can respond to both observation and performance of actions. The more extensive network of areas involved in observation of actions is sometimes termed the action observation network, in which the classical mirror neuron system, located ventrally, is regarded as a subcomponent, though the functional differences in the interaction between them are unclear [42]. It should be noted that as long ago as 1979, Hyvärinen and Shelepin [51] reported neurons in the parietal cortex being activated both on exposure to visual stimuli and on performance of movements with the hands or lips. However, it cannot be accepted unconditionally that these were neurons of the class later termed mirror neurons, as the authors of the study cited did not assess the link between observed and performed movements, while the distinguishing feature of mirror neurons is activation on observation and performance of *the same* movement (or the same sequence of movements).

Since the discovery of these neurons in monkeys, researchers have sought to establish the existence and characteristics of analogous mirror neurons in humans. However, most studies have used indirect methods to address this, such as functional magnetic resonance imaging, electroencephalography, and transcranial magnetic stimulation [1]. Neuron activation detected by tomography in areas homologous to the mirror neuron system of monkeys on observation of actions is very likely to represent activation of a human mirror neuron system. There are very few direct data on the existence of mirror neurons in the human brain. However, there is extensive evidence that simple observation of movements evokes changes in the human motor system and that this phenomenon can be taken as evidence of some kind of link between the observation of an action and its execution in the human brain [64].

As ethical considerations do not allow single-neuron activity to be recorded in humans for purely scientific purposes, direct evidence for the existence of mirror neurons in humans has until recently been unavailable. Relatively recently, diagnostic recordings using intracranial electrodes have recorded neuron responses in the human brain to both observation of an action and its execution. These data most likely constitute the long-awaited direct evidence that a mirror neuron system exists in humans. They also confirm the extensive results obtained using neuroimaging methods and transcranial magnetic stimulation. Report [61] described recording of extracellular activity of single neurons in the medial frontal and temporal areas of the cortex while patients picked up various objects with their hands or watched the same actions performed by other patients. A significant proportion of neurons in the supplementary motor area and hippocampus responded to both observation and performance of such actions. A subgroup of these neurons showed activation during performance of an action and inhibition on observation of the action [61].

Overall, it has been proposed that the posterior part of the inferior frontal gyrus, including Broca's area and the ventral part of the inferior precentral gyrus, along with the supramarginal cortex and rostral part of the inferior parietal lobe constitute the main elements of the human mirror neuron system [80].

Observation of actions has been studied using a variety of methods, which have shown that it induces not only higher-level visual representations, but also, and more importantly, representations arising as a result of automatic visuomotor transformations, known under the almost interchangeable terms "motor imitation," "motor resonance," or "mirror mechanism" [14]. Rizzolatti [78] wrote that the mirror mechanism is a mechanism which transforms sensory representations of the actions of others into motor representations of the same actions in the observer's brain. According to [76], every time a person sees an action performed by someone else, the set of neurons in the observer's motor system supporting the action is activated. It has been suggested that after processing in the visual system, visual information is projected to the mirror neuron system, whose nucleus is located in the frontoparietal areas of the brain [47].

Interesting data on the properties of mirror neurons were reported by Cattaneo et al. [34]. This group recorded motor evoked potentials in the muscle opposing the right thumb during transcranial magnetic stimulation, when volunteers observed the experimenter working with two types of forceps – a set opened by extension of the thumb and closing with flexion ("normal" forceps) and forceps opening on flexion of the thumb and closing on extension("reverse forceps"). In one trial, the experimenter also simply opened and closed the forceps, while in another, the experimenter used them to grasp an object. In addition, participants imagined working with standard and reverse forceps. During observation of actions lacking a motor purpose (i.e., not grasping an object), the amplitude of motor evoked potentials, regardless of the type of forceps used, reflected the activation pattern of the muscle involved in carrying out the observed action. During observation of purposeful actions, potentials were modulated by the purpose of the motor action: they increased during grasping of an object despite the movement of the fingers used for this purpose in different directions. On imagination of the actions, motor evoked potentials reflected the muscle pattern required for carrying out the imaginary actions. The authors took the view that imagination of the action performed or observation of the actions of the instrument lacking an aim led to activation of the representation of the finger movements corresponding to the observed actions. Conversely, observation of the actions of the instrument with a specific purpose included the distal part of the instrument in the observer's body plan, leading to representation of a higher order – representation of the purpose of the motor act [34].

The main hypothesis for the mechanisms of the functioning of the mirror neuron systems is that of mental simulation of observed actions whereby we can reactivate the representations of actions stored in motor memory, which may help us understand the sense of observed actions and which supports motor learning [40]. It is entirely likely that observation of an action may, via the mirror neuron system, play a role in learning motor skills [25]. According to [33], the property[s of human mirror neurons are not fixed, but develop via sensorimotor training, for example in the context of social interactions. These results confirmed the idea that the mirror neuron system has an important role in forming memory, for example, in motor learning, in humans [33].

Behavioral and Neurophysiological Data Associated with Observation of Actions. Among the extensive literature on the mirror neuron network, most attention in this review if paid to results more closely associated with utilizing the observation of actions in clinical practice.

Observation of a complex motor action leads to an increase in the number of brain areas involved in the activity as compared with observation of a simple action [46]. Observation of an action induces previously nonspecific facilitation of corticospinal excitability (around 90 msec from the start of the observation) followed by a later modulation of activity specific for the muscles involved in the observed action (after 200 msec) [64, 65].

The involvement of brain areas activated by observation of an action depends on the complexity of the action [46] and on individual motor experience [31, 32]. Cerebral activation can also be influenced by the type of observed/performed action. In particular, higher levels of activation were seen during transitive processes (i.e., during purposeful movements involving an object, such as grasping a cup) than during a nontransitive process (i.e., not associated with a specific object or purpose) [9]. Familiarity with motor actions, determined by how often they are performed or observed [32], increased the recruitment of mirror neurons not only during transitive [32], but also during nontransitive [70] processes.

In studies reported in [24], subjects were asked to observe movements associated and not associated with objects performed by another person (movements of the hand, mouth, or foot) during tomography scanning. Observation of actions performed by different effectors activated different areas of the premotor and parietal cortex. Thus, there is an effector-associated pattern of somatotopic activation not only during physical performance and imagination of a movement, but also during its observation. These authors also found a significant difference between activation patterns in object-linked actions and non-object-linked actions: in the latter case activation was significantly lower or even absent [24].

Observation of hand movements even without subsequent physical imitation prevented corticomotor depression induced by immobilization of the right hand for 10 h [15].

Data reported in [69] indicate that observation of a biological movement (for example, a person walking) activated an area of the superior temporal sulcus to a significantly greater extent than observation of a nonbiological movement (movement of isolated limb segments in space). In studies reported in [36], observation of biological movements led to greater suppression of the μ rhythm than observation of nonbiological movements, while Shimada [85] showed that activity in the mirror neuron system was sensitive to connections between the external appearance and movement kinematics of the individual being observed, especially when it was of human shape. According to [81], although initial data indicated that only biological stimuli activated the observation of actions network, more recent data have shown that it is also sensitive to nonbiological stimuli.

The first results from studies on monkeys showed that mirror neurons responded only to observation and performance of object-oriented actions (such as grasping an object or moving it to a defined location) but not on observation of meaningless gestures (such as raising the hands, waving the hands, simulating grabbing without an object) or movements performed with instruments [44]. However, data on the activity of mirror neurons in these animals obtained later showed that the presence of an object was not obligatory [54] and that actions performed using instruments influenced mirror neurons [41], observations of senseless movements of the forelimbs not addressing any object also being effective [73].

In studies on monkeys, the authors of [29] found that the responses of most of the mirror neurons tested changed when the point of view from which the action was observed was altered. Ge et al. [48] showed that observation of an action from the point of view of the first and third persons were associated with similar activation patterns in key areas of the mirror neuron system, though stronger activation was seen in the former case and, apart from the main network of the mirror neuron system, observation of actions in both cases involved part of the basal ganglia and limbic system, including the putamen, insula, and hippocampus. Observation of actions from the first person was accompanied by the greatest level of suppression of the μ rhythm [11]. Significant μ desynchronization during observation of an action was also reported by Hager et al. [49], Lapenta et al. [56], and Marshall et al. [57].

Errante and Fogassi [39] studied the question of the modulation of the observation of actions network during observation of new complex actions outside the subject's personal motor experience. Healthy volunteers in these studies, without any special motor skills, watched a video demonstrating manipulations with the hands and objects carried out by a specialist with high manual dexterity, an actor with an intermediate level of training, and an unskilled person. The results showed that observation of actions performed by the unskilled person evoked stronger activation in the dorsomedial parietal-premotor network, including the superior parietal lobe and the dorsal premotor cortex than observation of the specialist.

Observational Training. Observations of actions performed by another person on assimilation of a new movement is standard practice in daily adult life, for example in sport; this is an especially widely used procedure for development of motor skills in childhood [16]. Physical imitation is the ability of people to learn to perform actions which they have seen; imitation presupposes learning and requires a visible action to be converted into an identical motor action performed by the observer [25].

The authors of [86] showed that physical and observational training (three 10-min sessions of performing or observing simple repeated thumb movements) induces a similar functional reorganization of the representations of the muscles of this thumb in the primary motor cortex, which was apparent as qualitatively identical changes in the ratios of motor evoked potentials in muscles and similar changes in the kinematic characteristics of thumb movements induced by transcranial magnetic stimulation of the primary motor cortex. Changes induced by observational training persisted for 8 min after training ended [86]. These data provided evidence that motor functioning could be improved even by observation of simple movements and by observational training to motor skills, which did not have any clear cognitive components [86].

In work reported in [13], healthy volunteers observed motor actions to learn to carry out four different sequences of pressing five computer keys with the fingers of the left hand. Functional magnetic resonance imaging was run before and after training. Comparison of the results of this study with results reported in [84], in which volunteers were trained to perform the same sequences but with physical training, demonstrated a good relationship between the results of observational and physical training, which is evidence that there are common mechanisms underlying learning of motor skills by physical and observational practice [13]. In addition, the authors showed that observational training to carry out motor sequences led to the formation of specific patterns of activity in the frontoparietal cortex by a means similar that seen as a result of physical training, i.e., by functional reorganization of the frontoparietal cortex [13].

Known experimental data can be used to suggest that the observation of an action is its own kind of motor priming, as it can facilitate performance of the following movement (action) [62]. Observation of an action is an approach which promotes the occurrence of neuronal plasticity by activation of the mirror neuron system [21].

In [58], healthy volunteers watched a video in which people were trained to move in a novel mechanical environment. These volunteers showed significantly better results on subsequent testing in the same environment than people who did not observe movements in this environment. Thus, by observing the attempts of another person to move appropriately in the novel mechanical environment, the observer was able to formulate a representation of the mechanical properties of the surrounding environment, which could be used for performing the specified movement [58].

The view taken in [52] was that observation of the action automatically triggered its mental imitation and therefore facilitated subsequent performance of the real action. According to [47], observation of an action not only shares the pattern of cerebral activity with the physical execution, but could also promote increases in the efficiency of the movements. Most studies have shown that observation of purposeful actions stimulates mental reconstruction of the observed actions and facilitates their physical imitation [83].

The problem of motor training using the observation of actions was addressed [27], where the cerebral activity of "musically illiterate" study participants was evaluated using functional magnetic resonance imaging in four situations: 1) observation of guitar chords performed by a professional guitarist; 2) a pause after watching actions of the guitarist; 3) physical imitation of the chords by the observer, and 4) while resting. The results showed that the basal network underlying imitation learning consisted of the inferior temporal lobe, the inferior fontal gyrus, and the adjacent areas of the premotor cortex. This network starts to be activated during observation of the performance of chords and remains active until their physical performance by the observer. During the pause and subsequent physical imitation, the middle frontal gyrus (area BA46) plus structures involved in motor preparation and performance (the dorsal premotor cortex, superior parietal lobe, rostral medial areas, primary motor cortex) also become active. Powerful activation of the mirror neuron system in all phases from observation of the action to performance of the action by the observer indicates that the key process in physical imitation, i.e., transformation of the visually encoded action to an identical motor action performed by the observer, rests on this network.

According to [27], on assimilation of new motor patterns using observation and physical imitation, the observed actions are resolved in terms of elementary motor acts which, with the mirror mechanism, activate the corresponding motor representations in the inferior temporal lobe in the premotor cortex, and the posterior part (tegmental part) of the inferior frontal gyrus. As soon as these motor representations are activated, they are recombined so as to correspond to the observed model. This recombination evidently occurs within the limits of the area of the hypothetical mirror neuron network in humans, perhaps area BA46, which has an organizing role. This idea is reinforced by data from [88], in which activation in area BA46 was compared in experienced musicians and students. In fact, the results demonstrated stronger recruitment of area BA46 in students as compared with experienced musicians, as expected, on the basis of the suggestion that that this area has significance in the acquisition of new motor skills [88].

Report [74] showed that although observation of an action evoked activity in brain areas analogous to those involved in its physical execution and may also serve as an effective instrument or motor training (or retraining), the optimum conditions for such interventions remain to be established. In this regard, the authors investigated the effects of manipulating the background on corticospinal arousability. The results showed that the presence of additional visual information in the background congruent with the observed movement could facilitate corticospinal arousability. The authors took the view that presentation of congruent contextual information could increase the effectiveness of the observation of an action for motor training (retraining).

Factors such as the structure of the observed physical actions, the level of expertise of the demonstrator, and the use of feedback are important moderators for the effectiveness of observational training [50].

In studies reported in [60], one group of volunteers was trained to proprioception before observational training, while another group was not. Results from observational training in the first group were significantly greater than those in the second. Thus, improvements in somatosensory function could improve the results of subsequent observational training, which is evidence of the involvement of the somatosensory system in observational training [60].

Most studies of the observation of actions have focused on visual perception. However, other signals associated with the action also act on the motor system [8]. This was first demonstrated in monkeys, where neurons responded not only to the observation of actions, but also to sounds produced by the action [53]. In humans, motor facilitation on observation of an action became maximal when action-associated auditory and visual input signals were presented simultaneously [59]. It should be noted that this result is associated with a special motor mechanism, based on integration of multimodal signals linked with the action [16]. In fact, motor facilitation increased only when the action had a specific acoustic effect, while it was not modulated by stimuli not linked with the action [10]. These results point to the opportunity to combine visual information with auditory stimuli associated with actions in rehabilitation protocols to increase the positive effects of training based on observation of an action [16].

Observation of Motor Actions in Clinical Conditions. A novel approach to movement rehabilitation known as observation of actions therapy (or "observation therapy") takes advantage of the mirror mechanism for treating motor impairments [21, 23, 83, 92]. During a typical session, patients observe a quotidian action and then perform (or try to perform) it [23, 51]. Combining observation of an action with its physical imitation currently appears to be the most fertile approach [40]. Activation of the motor zones of the brain by observation quite quickly weakens and can even disappear if the observation and the physical imitation of the movement are separated by a long time interval, indicating that the time interval between these two events plays an important role in consolidating the effects of observation of an action [18]. Observation of an action without subsequent physical imitation produced no more than a tendency to improvement in postural control in healthy subjects [47].

In his review, Buccino [23] provided the following description of a rehabilitation session: "Patients are required to observe a specific object-directed daily action presented through a video clip on a computer screen, and afterwards to execute what they have observed. Only one action is practiced during each rehabilitation session. The presented action is divided into three to four motor acts. For example, the action of drinking coffee can be decomposed into the following motor acts: (i) pouring coffee into the cup, (ii) adding sugar, (iii) turning the spoon and finally (iv) bringing the coffee to the mouth... Each motor act is ... seen from different perspectives... After observing a motor act for 3 min (observation phase), patients are required to imitate what they observed for 2 min (execution phase)... As a whole, a typical AOT rehabilitation session takes half an hour. A few minutes are needed by the physiotherapist to explain the task to the patient... then 12 min of observation (3 min for each of the motor acts into which the action is divided) and finally 8 min of execution (2 min for each motor act)... The patient, during the execution phase, has to perform the observed motor act at the best of his/her ability. However, he/she is informed that the focus of the treatment is on the observation of the action, not its execution."

It is not hard to see that each of the elements in the rehabilitation session which we have described is linked with determination of the features of the mirror neuron system as noted above. For example, the "daily action" is linked with dependence on recruiting mirror neurons and their activation on the level of familiarity of the user with the action being observed [31, 32]; use of a specific object is linked with significant discrimination between activation patterns on actions linked with the object and actions not linked with it [24]. Dissection of the motor action into separate motor acts may be linked with the following characteristics of the parietofrontal mirror neuron network noted by Rizzolatti and Sinigaglia [79]: most of these neurons encode motor acts (i.e., movements associated with a particular motor aim such as grasping an object) and not the movement itself (i.e., displacement of a body part without a specific aim, such as flexion of the fingers) and these neurons are grouped into circuits in which each neuron encodes a separate motor act.

Burzi et al. [28] noted the efficacy of "observation therapy" in improving the motor function of the hands both in adult stroke patients and children with unilateral cerebral palsy, while Buccino [23] presented data from three particular randomized controlled trials in which action observation therapy was successfully used to rehabilitate upper limb motor functions in stroke patients, in the motor recovery of patients with Parkinson's disease, and in children with cerebral palsy. It should be noted that although the results of these randomized controlled studies confirmed the suitability of using observation therapy as a rehabilitation instrument for various neurological diseases, the author himself emphasized the small number of patients (a total of 21 used observation therapy) participating in these studies. This drawback was overcome in the study reported by Sarasso et al. [83], which analyzed results from the use of observation therapy in 20 randomized controlled trials (13 in stroke, three in

Parkinson's disease, two in cerebral palsy, and two in orthopedic problems) involving a total of 663 patients and reported that most of the studies analyzed indicated that the "observation therapy" method was effective as an adjunct to standard physiotherapy for improving recovery of motor functions in people with neurological and orthopedic diseases.

On the basis of analysis of 12 randomized controlled trials involving 478 people, Borges et al. [21] reported evidence that action observation was useful for improving upper limb motor function and independence in daily life in stroke patients.

Buccino et al. [26] ran a randomized controlled trial in which 18 children (aged 5–11 years) with cerebral palsy took part: 11 were in the experimental group and seven served as controls. The state of upper limb motor functions was assessed on two functional scales at time points T1–T3. Functional measures were assessed before treatment (time point T1), at the end of treatment (time points T2), and two months later (time point T3). As compared with control children, those receiving observation therapy showed significant improvements in measures on both scales at T2, and this improvement persisted to T3. Twelve of the 18 children also underwent functional magnetic resonance investigations at time points T1 and T2. As compared with the control group, children receiving observation therapy showed stronger activation in the parieto-premotor network on interaction between the hand and an object at T2. These results confirmed the view that this therapy promoted reorganization of cerebral networks [26].

Review [67] presented study results from patients providing evidence that action observation as a supplemental therapy improved measures of locomotion and balance function after a short rehabilitation period; action observation in Parkinson's disease appeared to promote mobility and decreases in "frozen gait" episodes, while after joint replacement or stroke it produced significant improvements in gait and balance in terms of a whole series of indicators.

In [89], people with chronic stroke during robot-based motor training of the paretic arm ether observed or did not observe a video of the movements of their paretic arm (videos were made by editing). Help from the robot was either guided or not guided by the patient's EEG signals. Robot assistance in the first group was activated only when significant μ-suppression of the EEG signal occurred in the lesioned hemisphere, while robot cooperation in the second group was activated independently of EEG signals. Paretic upper limb motor functions were assessed before, immediately after, and six months after training. Only the first group showed long-term significant improvements in upper limb motor functions. In addition, significant changes in neuroplasticity (neuroimaging results) were seen only in the first group. The authors of this study felt that stable improvements in motor function could be achieved by suitable neuronal control, while neuroplasticity can be increased by appropriate neural feedback [89].

Conclusions. The detection of cerebral cortical neurons sensitive both to observation of the motor actions of another person and physical performance of the same action by the observer impelled scientists to use this phenomenon for movement rehabilitation [67]. Treatment using observation of motor actions ("observation therapy") is a novel approach to movement rehabilitation [16, 23, 26]. This is based on data indicating that observation of motor actions performed by another individual activates the same neuronal structures in the observer which were responsible for physical execution of the observed actions [78]. "Observation therapy" uses this neurophysiological mechanism for rehabilitation of motor functions. When repeated physical exercises are impossible because of severe impairments, (especially in the acute phase of trauma), pain, muscle fatigue, or inflammation, observation of an action can be regarded as an alternative opportunity for activating the motor system [16]. To date this approach has been used with success in rehabilitation of upper limb motor functions in patients with chronic stroke [21, 23], in the motor restoration of patients with Parkinson's disease [30], and in children with cerebral palsy [26]; this same approach improved lower limb motor functions in post-operative orthopedic patients [17]. The idea that people can improve existing motor skills by means of observation has recently attracted attention in the context of gait rehabilitation, though it can be suggested to have significant potential as an adjunctive treatment in routine balance training [67]. This type of therapy is well grounded in fundamental neurology and results on its efficacy have been obtained in randomized controlled trials [26].

Motor facilitation by observation of motor actions is well known [30]. Nonetheless, a better understanding of this process may improve results from using "observation therapy" [67, 73]. This requires larger randomized controlled studies, which would allow better means of using this type of therapy in clinical practice and groups of patients who would gain the most benefit from this treatment to be found [23]. Systematic assessment of the cognitive and sensory deficits which probably interfere with motor facilitation induced by observation of actions may improve individually oriented therapy; finally, of particular interest for children is the possibility of using training including action observation at the early stages of pathology, given that its possible useful effects are linked not only with training to motor skills, but also with the development of their associated cognitive aspects [16].

Contemporary "observation therapy" for movement rehabilitation uses transitive daily actions (i.e., actions associated with use of objects, for example, drinking coffee, clearing dishes off the table, etc.) followed by physical execution after observation [23], which probably limits the applicability of this therapy, as patients with severe upper limb motor impairments are barely able to use it. However, use of a familiar nontransitive task instead of a transitive task may perhaps be a suitable variant for patients in whom a transitive task is physically unavailable [46]. One task in "observation therapy" is therefore that of supporting its effects on motor function in patients where this treatment is not additive but, rather, the only possible treatment, i.e., in patients who are completely immobilized or have very weak motor function [90]. In this regard, promising data were reported by Bizio et al. [19, 20], who used demonstration of repeated simple nontransitive motor actions: pinching and separating the tips of the thumb and index finger (for 14 min) combined with peripheral electrical stimulation of the median nerve [19], or flexion of the thumb (i.e., deviation of the thumb towards the little finger) for 250 sec combined with application of vibration to the tendon of the muscle supporting this movement [20]. Results obtained using these methods not only showed an increase in the arousability of the primary motor cortex specific for the muscles supporting the observed movements, but also long-term sequelae: the arousability of the primary motor cortex remained elevated for 60 min after observation training combined with vibration ended and for 45 min after training combined with electrical stimulation. All these treatments used alone in otherwise identical regimes (observation training, electrical stimulation, vibration) did not induce changes in motor cortex arousability. The authors of [19, 20] proposed that these results suggest that observation training combined with electrical stimulation and vibrational stimulation can elicit long-term plastic changes in the primary motor cortex, allowing these methods to be used as rehabilitation interventions for patients unable to perform voluntary movements; additionally, these results point to the importance of combining different sensory inputs to stimulate plastic changes in the primary motor cortex. However, it appears that the maintenance and development of these results and their introduction into practice require further basic studies.

In conclusion, we note the following. Observation of motor actions is used in various types of therapy: "mirror therapy" [3, 4], "observation therapy" [28, 67], and virtual reality therapy [2, 5, 7,12]. These types of treatment have different mechanisms, though they all use observation of motor actions. "Observation therapy" is therefore not an entirely suitable term for the treatments discussed here. It is more the case that this is one version of observation therapy, though in the literature it comes under the term used by ourselves. It is directly orientated to mirror neurons and the mirror mechanism for the treatment of motor impairments: each element of a rehabilitation session using this therapy is linked with a particular characteristic of the mirror neuron system, as has been noted by other authors. This is evidently the simplest version of therapy using motor action observation. It is distinguished by simplicity of application, affordability, and accessibility as a rehabilitation technology which can be used by patients on their own at home.

This study was funded by the State Academies Basic Science Research Program for 2012–2020 (GP-14, section 63) and the Basic Research Program of the Presidium of the Russian Academy of Sciences, Topic No. 1.43, "Fundamental Basis of Technologies for Physiological Adaptation."

REFERENCES

1. N. N. Lebedeva, A. I. Zufman, and V. Yu. Mal'tsev, "The mirror neuron system of the brain: the ley to learning, personality formation, and understanding the consciousness of other," *Usp. Fiziol. Nauk.*, **48**. No. 4, 16–28 (2017).
2. S. V. Murav'eva and Yu. E. Shelepin, "Recovery of impaired purposeful activity in patients with psychoneurological pathology by immersion into an interactive virtual environment," in: *Neurotechnology*, Yu. E. Shelepin and V. N. Chikhman (eds.), VVM, St. Petersburg (2018), pp. 368–384.
3. M. A. Nazarova, M. A. Piradov, and L. A. Chernikova, "Visual feedback – mirror therapy in neurorehabilitation," *Ann. Klin. Eksperim. Nevrol.*, **6**, No. 4, 36–41 (2012).
4. M. A. Nazarova and M. A. Piradov, "Mirror therapy in neurorehabilitation *Ross. Med. Zh.*, **22**, No. 22, 1563–1566 (2014).
5. V. I. Skvortsova, G. E. Ivanova, and D. V. Skvortsov, "A means of rehabilitating patients in the acute stage of stroke using biological feedback and virtual reality," Patent RU 2432971 C1.10.11.2011.
6. Yu. K. Stolbkov, T. R. Moshonkina, I. V. Orlov, et al., "Imaginary movements as a means of improving and rehabilitating motor functions," *Usp. Fiziol. Nauk.*, **49**, No. 2, 45–59 (2018).
7. E. Yu. Shelepin, S. V. Murav'eva, E. G. Yakimova, and Yu. E. Shelepin, "Neurotechnology of the control of purposeful activity in humans in a virtual environment," in: *Neurotechnology*, Yu. E. Shelepin and V. N. Chikhman (eds.), VVM, St. Petersburg (2018), pp. 349–367.
8. S. M. Aglioti and M. Pazzaglia, "Representing actions through their sound," *Exp. Brain Res.*, **206**, 141–151 (2010).
9. Z. K. Agnew, R. J. Wise, and R. Leech, "Dissociating object directed and non-object directed action in the human mirror system; implications for theories of motor simulation," *PLoS One*, No. 7, e32517 (2012).
10. K. Alaerts, S. P. Swinnen, and N. Wenderoth, "Interaction of sound and sight during action perception: evidence for shared modality dependent action representations," *Neuropsychologia*, **47**, 2593–2599 (2009).
11. M. Angelini, M. Fabbri-Destro, and N. F. Lopomo, et al., "Perspective-dependent reactivity of sensorimotor mu rhythm in alpha and beta ranges during action observation: an EEG study," *Sci. Rep.*, **8**, No. 1: 12429, 1–11 (2018).
12. Apfelbaum H, Pelah A, and E. Peli, "Heading assessment by "tunnel vision" patients and control subjects standing or walking in a virtual reality environment," *ACM Trans. Appl. Percept.*, **4**, No. 1, Article 8, 1–16 (2007).
13. D. Apšvalka, E. S. Cross, and R. Ramsey, "Observing action sequences elicits sequence-specific neural representations in frontoparietal brain regions," *J. Neurosci.*, **38**, No. 47, 10,114–10,128 (2018).
14. G. Barchiesi and L. Cattaneo, "Motor resonance meets motor performance," *Neuropsychology*, **69**, 93–104 (2015).
15. M. Bassolino, M. Campanella, M. Bove, et al., "Training the motor cortex by observing the actions of others during immobilization," *Cereb. Cortex*, **24**, No. 12, 3268–3276 (2014).
16. M. Bassolino, G. Sandini, and T. Pozzo, "Activating the motor system through action observation: is this an efficient approach in adults and children?" *Dev. Med. Child Neurol.*, **57**, Suppl. 2, 42–45 (2015).
17. G. Bellelli, G. Buccino, B. Bernardini, et al., "Action observation treatment improves recovery of postsurgical orthopedic patients: evidence for a top-down effect?" *Arch. Phys. Med. Rehabil.*, **91**, 1489–1494 (2010).
18. A. Bisio, L. Avanzino, M. Biggio, et al., "Motor training and the combination of action observation and peripheral nerve stimulation

reciprocally interfere with the plastic changes induced in primary motor cortex excitability," *Neuroscience*, **348**, 33–40 (2017).

19. A. Bisio, L. Avanzino, N. Gueugneau, et al., "Observing and perceiving: A combined approach to induce plasticity in human motor cortex," *Clin. Neurophysiol.*, **126**, No. 6, 1212–20 (2015).
20. A. Bisio, M. Biggio, L. Avanzino, et al., "Kinaesthetic illusion shapes the cortical plasticity evoked by action observation," *J. Physiol.*, **597**, No. 12, 3233–45 (2019).
21. L. R. Borges, A. B. Fernandes, L. P. Melo, et al., "Action observation for upper limb rehabilitation after stroke," *Cochrane Database Syst. Rev.*, **10**, CD011887 (2018).
22. M. Brass, H. Bekkering, A. Wohlschlaeger, and W. Prinz, "Compatibility between observed and executed finger movements: comparing symbolic, spatial and imitative cues," *Brain Cogn.*, **44**, 124–143 (2000).
23. G. Buccino, "Action observation treatment: a novel tool in neurorehabilitation," *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, **369**, No. 1644, 20130185 (2014).
24. G. Buccino, F. Binkofski, G. R. Fink, et al., "Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study," *Eur. J. Neurosci.*, **13**, 400–404 (2001).
25. G. Buccino, F. Binkofski, and L. Riggioa, "The mirror neuron system and action recognition," *Brain Lang.*, **89**, No. 2, 370–376 (2004).
26. G. Buccino, A. Molinaro, C. Ambrosi, et al., "action observation treatment improves upper limb motor functions in children with cerebral palsy: A combined clinical and brain imaging study," *Neural Plast.*, **2018**, 4843985 (2018).
27. G. Buccino, S. Vogt, A. Ritzl, et al., "Neural circuits underlying imitation learning of hand actions: an event-related fMRI study," *Neuron*, **42**, No. 2, 323–34 (2004).
28. V. Burzi, G. Tealdi, R. N. Boyd, and A. Guzzetta, "Action observation in infancy: implications for neuro-rehabilitation," *Dev. Med. Child Neurol.*, **58**, Suppl. 4, 74–7 (2016).
29. V. Caggiano, M. Giese, P. Thier, and A. Casile, "Encoding of point of view during action observation in the local field potentials of macaque area F5," *Eur. J. Neurosci.*, **41**, No. 4, 466–76 (2015).
30. D. Caligiore, M. Mustile, G. Spalletta, and G. Baldassarre, "Action observation and motor imagery for rehabilitation in Parkinson's disease: A systematic review and an integrative hypothesis," *Neurosci. Biobehav. Rev.*, **72**, 210 (2017).
31. B. Calvo-Merino, D. E. Glaser, J. Grezes, et al., "Action observation and acquired motor skills: an FMRI study with expert dancers," *Cereb. Cortex*, **15**, 1243–1249 (2005).
32. B. Calvo-Merino, J. Grezes, D. E. Glaser, et al., "Seeing or doing? Influence of visual and motor familiarity in action observation," *Curr. Biol.*, **16**, 1905–1910 (2006).
33. C. Catmur, V. Walsh, and C. Heyes, "Sensorimotor learning configures the human mirror system," *Curr. Biol.*, **17**, No. 17, 1527–1531 (2007).
34. L. Cattaneo, F. Caruana, A. Jezzini, and G. Rizzolatti, "Representation of goal and movements without overt motor behavior in the human motor cortex: a transcranial magnetic stimulation study," *J. Neurosci.*, **29**, No. 36, 11134–11138 (2009).
35. L. Cattaneo and G. Rizzolatti, "The mirror neuron system," *Arch. Neurol.*, **66**, No. 5, 557–60 (2009).
36. M. C. Desy and J. F. Lepage, "Skin color has no impact on motor resonance: evidence from mu rhythm suppression and imitation," *Neurosci. Res.*, **77**, No. 1, 58–63 (2013).
37. G. Di Pellegrino, L. Fadiga, L. Fogassi, et al., "Understanding motor events: a neurophysiological study," *Exp. Brain Res.*, **91**, 176–180 (1992).
38. J. Dushanova and J. Donoghue, "Neurons in primary motor cortex engaged during action observation," *Eur. J. Neurosci.*, **31**, No. 2, 386–398 (2010).
39. A. Errante and L. Fogassi, "Parieto-frontal mechanisms underlying observation of complex hand-object manipulation," *Sci. Rep.*, **9**, No. 1, 348 (2019).
40. D. Ertelt and F. Binkofski, "Action observation as a tool for neurorehabilitation to moderate motor deficits and aphasia following stroke," *Neural Regen. Res.*, **7**, No. 26, 2063–2074 (2012).
41. P. F. Ferrari, S. Rozzi, and L. Fogassi, "Mirror neurons responding to observation of actions made with tools in monkey ventral premotor cortex," *J. Cogn. Neurosci.*, **17**, 212–226 (2005).
42. F. Filimon, C. A. Rieth, M. I. Sereno, and G. W. Cottrell, "Observed, executed, and imagined action representations can be decoded from ventral and dorsal areas," *Cereb. Cortex*, **25**, No. 9, 3144–3158 (2015).
43. L. Fogassi and G. Luppino, "Motor functions of the parietal lobe," *Curr. Opin. Neurobiol.*, **15**, No. 6, 626–31 (2005).
44. V. Gallese, L. Fadiga, L. Fogassi, and G. Rizzolatti, "Action recognition in the premotor cortex," *Brain*, **119**, 593–609 (1996).
45. V. Gallese and G. Lakoff, "The Brain's concepts: the role of the sensorymotor system in conceptual knowledge," *Cogn. Neuropsychol.*, **22**, No. 3, 455–479 (2005).
46. R. Gatti, M. A. Rocca, S. Fumagalli, et al., "The effect of action observation/execution on mirror neuron system recruitment: an fMRI study in healthy individuals," *Brain Imag. Behav.*, **11**, No. 2, 565–576 (2017).
47. R. Gatti, E. Sarasso, M. Pelachin, et al., "Can action observation modulate balance performance in healthy subjects?" *Arch. Physiother.*, **22**, No. 9, 1 (2019).
48. S. Ge, H. Liu, P. Lin, et al., "Neural basis of action observation and understanding from first- and third-person perspectives: An fMRI study," *Front. Behav. Neurosci.*, **12,** 283 (2018).
49. B. M. Hager, A. C. Yang, and J. N. Gutsell, "Measuring brain complexity during neural motor resonance," *Front. Neurosci.*, **12**:, 758 (2018).
50. D. J. Harris, S. J. Vine, M. R. Wilson, et al., "Action observation for sensorimotor learning in surgery," *Br. J. Surg*, **105**, No. 13, 1713–1720 (2018).
51. J. Hyvärinen and Y. Shelepin, "Distribution of visual and somatic functions in the parietal associative area 7 of the monkey," *Brain Res.*, **169**, No. 3, 561–4 (1979).
52. S. A. L. Jayasinghe, "The role of sensory stimulation on motor learning via action observation: a mini review," *J. Neurophysiol*, **121**, No. 3, 729–31 (2019).
53. M. Jeannerod, "Neural simulation of action: a unifying mechanism for motor cognition," *Neuroimage*, **14**, S103–S109 (2001).
54. E. Kohler, C. Keysers, M. A. Umilta, et al., "Hearing sounds, understanding actions: action representation in mirror neurons," *Science*, **297**, No. 5582, 846–848 (2002).
55. A. Kraskov, N. Dancause, M. M. Quallo, et al., "Corticospinal neurons in macaque ventral premotor cortex with mirror properties: a potential mechanism for action suppression?" *Neuron*, **64**, 922–930 (2009).
56. O. M. Lapenta, E. Ferrari, P. S. Boggio, et al., "Motor system recruitment during action observation: No correlation between mu-rhythm desynchronization and corticospinal excitability," *PLoS One*, **13**, No. 11, e0207476 (2018).
57. P. J. Marshall and A. N. Meltzoff, "Neural mirroring mechanisms and imitation in human infants," *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, **369**, No. 1644, 20130620 (2014).
58. A. G. Mattar and P. L. Gribble, "Motor learning by observation," *Neuron*, **46**, 153–160 (2005).
59. L. M. McGarry, F. A. Russo, M. D. Schalles, and J. A. Pineda, "Audio-visual facilitation of mu rhythm," *Exp. Brain Res.*, **218**, 527–38 (2012).
60. H. R. McGregor, J. G. A. Cashaback, and P. L. Gribble, "Somatosensory perceptual training enhances motor learning by observing," *J. Neurophysiol*, **120**, No. 6, 3017–3025 (2018).
61. R. Mukamel, A. D. Ekstrom, J. Kaplan, et al., "Single-neuron responses in humans during execution and observation of actions," *Curr. Biol.*, **20**, No. 8, 750–756 (2010).

62. T. Mulder, “Motor imagery and action observation: cognitive tools for rehabilitation,” *J. Neural Transm (Vienna)*, **114**, No. 10, 1265–78 (2007).
63. K. R. Naish, B. Barnes, and S. S. Obhi, “Stimulation over primary motor cortex during action observation impairs effector recognition,” *Cognition*, **149**, 84–94 (2016).
64. K. R. Naish, C. Houston-Price, A. J. Bremner, and N. P. Holmes, “Effects of action observation on corticospinal excitability: Muscle specificity, direction, and timing of the mirror response,” *Neuropsychology*, **64**, 331–348 (2014).
65. K. R. Naish and S. S. Obhi, “Timing and specificity of early changes in motor excitability during movement observation,” *Exp. Brain Res.*, **233**, No. 6, 1867–1874 (2015).
66. R. Paracampo, M. Montemurro, M. de Vega, and A. Avenanti, “Primary motor cortex crucial for action prediction: A tDCS study,” *Cortex*, **109**, 287–302 (2018).
67. M. Patel, “Action observation in the modification of postural sway and gait: Theory and use in rehabilitation,” *Gait Posture*, **58**, 115–120 (2017).
68. R. Peeters, L. Simone, K. Nelissen, et al., “The representation of tool use in humans and monkeys: common and uniquely human features,” *J. Neurosci.*, **29**, No. 37, 11523–11539 (2009).
69. K. A. Pelphrey, T. V. Mitchell, M. J. McKeown, et al., “Brain activity evoked by the perception of human walking: controlling for meaningful coherent motion,” *J. Neurosci.*, **23**, 6819–6825 (2003).
70. J. Plata Bello, C. Modrono, F. Marcano, and J. L. Gonzalez-Mora, “Observation of simple intransitive actions: the effect of familiarity,” *PLoS One*, **8**, e74485 (2013).
71. V. Raos, M. N. Evangeliou, and H. E. Savaki, “Observation of action: grasping with the mind’s hand,” *NeuroImage*, **23**, No. 1, 193–201 (2004).
72. V. Raos, M. N. Evangeliou, and H. E. Savaki, “Mental simulation of action in the service of action perception,” *J. Neurosci.*, **27**, No. 46, 12,675–12,683 (2007).
73. V. Raos, M. Kilintari, and H. E. Savaki, “Viewing a forelimb induces widespread cortical activations,” *NeuroImage*, **89**, 122–142 (2014).
74. M. Riach, P. S. Holmes, Z. C. Franklin, and D. J. Wright, “Observation of an action with a congruent contextual background facilitates corticospinal excitability: A combined TMS and eye-tracking experiment,” *Neuropsychology*, **119**, 157–164 (2018).
75. G. Rizzolatti and L. Craighero, “The mirror-neuron system,” *Annu. Rev. Neurosci.*, **27**, 169–192 (2004).
76. G. Rizzolatti, M. Fabbri-Destro, and L. Cattaneo, “Mirror neurons and their clinical relevance,” *Nat. Clin. Pract. Neurol.*, **5**, No. 1, 24–34 (2009).
77. G. Rizzolatti, L. Fadiga, V. Gallese, and L. Fogassi, “Premotor cortex and the recognition of motor actions,” *Cogn. Brain Res.*, **3**, 131–141 (1996).
78. G. Rizzolatti and S. Rozzi, “The mirror mechanism in the arietal lobe,”*Handb. Clin. Neurol.*, **151**, 555–573 (2018).
79. G. Rizzolatti and C. Sinigaglia, “The functional role of the parieto-frontal mirror circuit: interpretations and misinterpretations,” *Nat. Rev. Neurosci.*, **11**, No. 4, 264–274 (2010).
80. G. Rizzolatti and C. Sinigaglia, “The mirror mechanism: a basic principle of brain function,” *Nat. Rev. Neurosci.*, **17**, No. 12, 757–765 (2016).
81. J. W. Roberts, S. J. Bennett, D. Elliott, and S. J. Hayes, “Top-down and bottom-up processes during observation: implications for motor learning,” *Eur. J. Sport Sci.*, **14**, Suppl. 1, S250–256 (2014).
82. Y. Rossetti, G. Rode, and G. H. J. Goldenberg, “Perspectives in higher-order motor deficits rehabilitation: which approach for which ecological result?” in: *Higher-Order Motor Disorders from Neuroanatomy and Neurobiology to Clinical Neurology*, H. J. Freund et al. (eds.), Oxford University Press, Oxford (2005); pp. 475–497.
83. E. Sarasso, M. Gemma, F. Agosta, et al., “Action observation training to improve motor function recovery: a systematic review,” *Arch. Physiother.*, **5**, 14 (2015).
84. H. E. Savaki, “How do we understand the actions of others? By mental simulation, NOT mirroring,” *Cogn. Critique*, **2**, 99–140 (2010).
85. S. Shimada, “Deactivation in the sensorimotor area during observation of a human agent performing robotic actions,” *Brain Cogn.*, **72**, No. 3, 394–399 (2010).
86. K. Stefan, L. G. Cohen, J. Duque, et al., “Formation of a motor memory by action observation,” *J. Neurosci.*, **25**, No. 41, 9339–9346 (2005).
87. G. Vigneswaran, R. Philipp, R. N. Lemon, and A. Kraskov, “M1 corticospinal mirror neurons and their role in movement suppression during action observation,” *Curr. Biol.*, **23**, No. 3, 236–243 (2013).
88. S. Vogt, G. Buccino, A. M. Wohlschläger, et al., “Prefrontal involvement in imitation learning of hand actions: effects of practice and expertise,” *Neuroimage*, **37**, No. 4, 1371–1383 (2007).
89. X. Wang, W. W. Wong, and R. Sun, et al., “Differentiated effects of robot hand training with and without neural guidance on neuroplasticity patterns in chronic stroke,” *Front. Neurol.*, **9**, 810 (2018).
90. N. Wenderoth, “Changing the brain with multimodal mirrors: Combining visual and somatosensory stimulation to enhance motor plasticity,” *Clin. Neurophysiol.*, **126**, No. 6, 1065–1066 (2015).
91. T. Wiestler and J. Diedrichsen, “Skill learning strengthens cortical representations of motor sequences,” *eLife*, **2**, e00801 (2013).
92. J. J. Q. Zhang, K. N. K. Fong, N. Welage, and K. P. Y. Liu, “The activation of the mirror neuron system during action observation and action execution with mirror visual feedback in stroke: A systematic review,” *Neural Plast.*, **2018**, 2321045.