

The Possible Role of Augmented Reality in Treating Hemiplegia

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Abstract

Hemiplegia, serious and all-too-frequent result of stroke, is becoming more and more common, leaving many debilitated and costing society increasing amounts of money. One current avenue of research in improving the effectiveness of post-stroke rehabilitation is the use of virtual reality to promote the generation of motor imagery in subjects, a task that patients with hemiplegia find extremely difficult given the nature of the brain damage from which they suffer. The aim of this line of research is to aid patients in combining mental and physical practice, which studies have shown to be more effective in stimulating brain plasticity than physical practice alone. This report presents a literature survey of the above. Further, there are indications that expanding this treatment from virtual to augmented reality might further enhance its effectiveness. Several augmented reality systems exist that seem suitable to be adapted to this purpose. This report discusses these options and presents recommendations for putting them into practice.

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1 Introduction

In the United States alone, each year more than 700,000 people suffer a stroke [48]. Although this figure has remained relatively constant over the past 30 years, the mortality rate, however, has declined. This means that since nowadays not even a quarter of these incidents result in death, this leaves almost 540,000 Americans per year in some state of stroke-related disability and requiring medical attention. As a result, stroke is now the leading cause of disability in adults in the United States [71]. In 2005, American society will have to pay approximately 58 billion dollars for medical costs and disabilities because of stroke [2].

A stroke—in many languages referred to as a ‘brain attack’—is the result of an inadequate blood flow in the brain [48]. The interruption of the blood flow in an artery deprives the surrounding brain tissue of oxygen and nutrients, causing massive death among the brain cells in the area, greatly debilitating the functions or abilities it controls [41]. A blood clot blocking an artery in the neck or brain is the cause of approximately 80 percent of all strokes. A ruptured blood vessel is the cause of the remaining 20 percent.

Even after initial medical care, about two thirds of stroke patients have lingering neural deficits that continue to impair functioning in their daily lives [71]. The most common of these disabilities is paralysis [48]. Usually, this occurs only on one side of body, a condition known as *hemiplegia*. It may affect either the whole side or just a part of it, such as an arm, a leg or half of the face. (Some texts make the distinction of using *hemiplegia* to refer to full paralysis only and *hemiparesis* to refer to partial paralysis or weakness. This distinction, however, is not a strong one as many researchers have interchanged the two terms. To avoid confusion, this document will speak solely of *hemiplegia* and will use it to include *hemiparesis*.) In particular, *upper extremity hemiplegia* (UEH) can seriously hinder patients’ independent functioning, as it makes them unable to do such everyday things like grasping objects. It is, unfortunately, a very common ailment, since only five percent of adults with UEH ever fully regain the functioning of their arm, while as much as 20 percent never regain any functional use at all.

Clearly, post-stroke rehabilitation is an important issue to address. Post-stroke rehabilitation aims to help stroke survivors to improve their quality of life and regain their independence [48]. Although there is no cure for stroke, in that we can never reverse the brain damage done, through post-stroke rehabilitation we can substantially improve the long-term outlook of stroke patients’ lives. Indeed, post-stroke rehabilitation is currently a very active field of research.

One avenue of approach that research in post-stroke rehabilitation is currently exploring is the stimulation of *brain plasticity* through movement therapy, by forcing patient to use their affected limbs [48]. In particular, using mental practice to augment physical practice has proven to be very fruitful and research in this area has come up with convincing results [64].

This document will firstly discuss findings that show that actively using the affected limb encourages brain plasticity and that motor imagery and actual movement are practically equivalent as both produce autonomic reactions, both interfere with each other in identical ways, and both obey Fitts’s law. Therefore, mentally using an affected limb should encourage brain plasticity as well. In fact, research has shown that using a combination of mental and physical practice is actually more effective in treating *hemiplegia* than using physical practice alone.

Secondly, since motor imagery is equivalent to actual movement, patients with *hemiplegia* should have great difficulty in mentally moving their affected limb.

Indeed, findings show that patients have the same difficulty to imagine moving their affected limb as they do actually moving it. In fact, Fitts's law still holds in these patients in both actual and imaginary movement and reflects the added difficulty they experience with the disabled side of their body. Thus, to be able to able even mentally move their affected limb, these patients will need all the help they can get. Research has shown that imagery shown from a first-person perspective is the most effective in invoking motor imagery and this paper will discuss a virtual reality (VR) system developed by a group of researchers that tries to capitalize on this in stimulating the generation of motor imagery in UEH patients.

Finally, it appears that images do not have to be very detailed to invoke accurate motor imagery and that the vividness of imagery generate does not bear any significance influence on its effectiveness. Instead, the evidence shows that motor imagery corresponds not to specific muscular actions but to generalized movements and that the spatial aspect has great significance.

Thus, this document poses the question: *Can augmented reality play a role in further enhancing the treatment of hemiplegia?* This document will present arguments for answering this question and will supply the reader with recommendations for future research on the topic.

The text you are reading now is chapter 1 and forms the introduction. After this, chapter 2 defines motor imagery and discusses how it functions and how it relates to actual movement. Chapter 3 discusses the effectiveness of mental practice in post-stroke rehabilitation, how it is used it in practice and the theories behind it. Chapter 4 discusses different forms of post-stroke rehabilitation from active practice, through mental practice with motor imagery, to computer-aided mental practice. Chapter 5 discusses the state of the art in mirror-based see-through augmented reality, a likely candidate technology for improving computer-aided mental practice. Finally, a conclusion with recommendations follows in chapter 6.

2 Motor Imagery

Imagery is the human ability to generate mental representations of perceptual and motor events spontaneously and at will. Human beings can call upon several types of imagery in their minds. Mental imagery is one type. This is what happens when someone actively relives an earlier sensation while the stimulus that caused it is no longer present. Another form of imagery is movement imagery, which involves someone imagining a person or object in motion. *Motor imagery* is then a specific kind of movement imagery in which the subject imagines moving their own body without performing any actual physical movements [11, 36]. The subject has full control of the motor imagery and performs it voluntarily [4].

Another type of imagery is *visual imagery*. This involves mentally manipulating visual images, such as imagining scenes in which people or objects are moving. This might seem similar to motor imagery. The difference, however, is that while in visual imagery we imagine movement in our environment, in motor imagery we imagine the kinesthetic sensation involved in moving our own bodies. The fact that visual imagery representing the space in which the motor imagery takes place often accompanies it can potentially cause confusion [37]. For this reason, sports psychologists often refer to motor imagery as *kinesthetic imagery* [29]. This report, however, assumes that from this point on it will be clear to the reader what motor imagery refers to.

Humans often use motor imagery in their daily lives, even if they are not consciously aware of its nature or definition. Elite athletes, for example, often imagine themselves performing certain actions before executing them, as a form of mental preparation [4, 46, 69]. A more involved example is the situation of a teacher trying to teach students a motor skill such as playing an instrument. The student will watch the teacher demonstrate a technique, causing them to form a mental representation of the perceived action. The student then uses their motor imagery to try to replicate the observed behavior under the teacher's watchful eye. A student will invariably make mistakes the first time around, causing conflicts with the motor imagery that the teacher executes in his mind while watching the student play, resulting in a strong feeling by the teacher of what a student does wrong and how they should have done it instead [37]. Another example of this feeling, perhaps more familiar to most, is the sensation you get when sitting in the passenger seat of a moving car next to a driver who maintains a very different driving style from your own. Anyone having experienced this situation knows that it invokes a very strong urge to compensate mentally (or even physically) for the driver's behavior.

2.1 INTERNAL VERSUS EXTERNAL IMAGERY

Another important distinction made by several researchers is that between internal and external imagery [19]. *Internal imagery* on the one hand uses a first-person perspective and relies on motor-kinesthetic information processing. *External imagery* on the other hand uses a third-person perspective and relies on visuospatial processing [9]. Both internal and external imagery involve a degree of voluntary control on the subject's part [4]. Research has shown that athletes practicing so-called 'open' skills, in which different participants directly interact with each other, rely mostly on external imagery, whereas those practicing 'closed skills', in which there is no direct interaction between participants, rely more on internal imagery [46]. Furthermore, the more advanced the athlete, the more often they used imagery during both training and competition, as well as outside the athletic setting.

More advanced athletes were also more likely to use more complex and systematic imagery than less advanced ones [34].

Only internal imagery, however, qualifies as motor imagery. Motor imagery represents the self in action and makes the subject feel as if they are executing the action, be it with their whole body or just part of it [46]. Therefore, motor imagery requires a representation of the body generating the action and not of the effects these actions have on the world outside [37]. This obviously excludes external imagery from being motor imagery.

Research by Sirigu & Duhamel has confirmed that when using internal imagery, subjects primarily rely on motor processing, while subjects using external imagery rely mostly on visual processing [63]. They found that placing the hands in a relaxed, natural position made it easier for subjects to mentally rotate one of their hands, while putting them in a more awkward position made this more difficult. This indicates that mentally moving your own hand activates motor processing, as the motor processing invoked by keeping your hands in an awkward posture interferes with it. Asking the subjects to imagine rotating another's hand, however, diametrically reversed these interactions. This clearly indicates that external imagery relies on very different cognitive processes than internal imagery. Based on their findings, Sirigu & Duhamel suggest that external imagery uses visual rather than motor processing.

2.2 EQUIVALENCE OF MOTOR IMAGERY AND ACTUAL MOVEMENTS

Even though using motor imagery does not produce any overt motion, motor imagery does actually have a lot in common with actual movement. Not only are the underlying mechanisms of both very similar, motor imagery can actually influence the subsequent execution of physical movements [12, 25, 26, 40]. In addition, it turns out that motor images and actual movements operate by the same rules and constraints, and the neural networks involved in them largely overlap [64].

One type of evidence that shows similarities between imagined and actual movements comes from observing autonomic changes during motor imagery. In several studies, the heart and respiration rate of subjects performing motor imagery of effortful actions increased beyond what could be expected from metabolic demands, considering that the subjects produced no actual movements [20, 36, 50, 67, 73]. This seems to indicate that actual and imagined movements share a common neural mechanism [9].

If imagined and actual movements are functionally equivalent, they must interfere at some level [4, 37]. In fact, when Finke made subjects wearing laterally displacing prisms imagine pointing at visual targets, they afterwards showed the same directional bias as if they would have actually pointed at the targets [25]. Evidence that is even more convincing comes from Johnson [40]. Earlier, Thorndike had shown that when subjects have memorized a simple one-dimensional movement of a given extent, introducing another movement of the same type causes a systematic bias in the recall of the original movement toward the new movement [68]. Instead of another physical movement, however, Johnson inserted an imaginary movement and, indeed, this resulted in a bias that was indistinguishable in both direction and extent from that caused by an actual movement.

Motor imagery and actual actions also appear to be temporally equivalent [12]. Parsons showed that the time taken to mentally move your hand highly correlates with the time it takes to physically execute that same movement [51]. Similarly, Decety and Michel found that it took right-handed subjects the same amount of time to mentally write their signature as it did for them to do so physically [16].

Additionally, not only were subjects slower in physically writing with their left hands, they were also proportionally slower mentally. In another experiment, Decety, Jeannerod & Prablanc asked blindfolded subjects to physically or mentally walk toward previously inspected targets at different distances and found that for the same subjects and distances the durations of the mental and physical tasks were very similar to each other [15]. These results indicate that probably a single neural substrate governs timing in both mental and actual movements [7, 9, 37, 42].

Not only is the timing of mental movements very similar to that of actual ones, it turns out that they actually obey the same principles and laws. In particular, research has shown that motor imagery obeys Fitts's law, which states that the time it takes to execute a movement is a linear function of its difficulty [27]. An early indication of this came from an experiment by Georgopolous and Massey in which they asked subjects to move an object at a varying angle from a visual stimulus direction [31]. The subjects' reaction time turned out to be a linear function of the difficulty of the task, as larger angles took longer to react to. Likewise, in an experiment by Decety, subjects instructed to walk across narrow beams of varying width showed a speed-accuracy tradeoff in the time it took them to traverse the beam relative to its width [8]. Later, Decety and Jeannerod observed that the time subjects needed to imagine that they were walking through a given gate depended on both the width of the gate and the distance between the subject and the gate [12, 36]. In fact, they found that the increase in movement time was a linear function of the task difficulty, in accordance with Fitts's law.

More evidence for the equivalence of motor imagery and physical movements that is of particular interest for this report comes from findings involving hemiplegics themselves. Several experiments have shown that patients with a brain lesion affecting the motor system are still able to produce motor imagery but that they experience the same increased effort as with their physical movements [36, 37]. As a case in point, consider the following two studies. Decety loaded blindfolded subjects with a 25-kg backpack and instructed them to walk at previously inspected targets [18]. When mentally performing the task, subjects reported a strong sensation of effort that increased with the distance to the target. Compare this to an earlier study by Gandevia [30]. In this study, hemiplegic patients initially reported a sensation of intense heaviness when attempting to physically move their weakened limbs. As their limbs strengthened and their movements became easier, however, this feeling of effort decreased.

It not only takes more effort but also more time for hemiplegic patients to move their limbs, both physically and mentally. Decety and Boisson found that it takes hemiplegics significantly more time to mentally move their paralyzed limb than it took them to move their healthy one [7, 9, 10]. In contrast, they found that patients with paralysis in all four limbs or from the waste down, typically caused by spinal injury or disease, had movement times that did not differ from normal subjects.

2.3 MOTOR IMAGERY AS A FORM OF MOTOR PLANNING

Section 2.2 has presented several types of evidence that support the idea that motor imagery and motor control share common neural mechanisms. More specifically, the evidence seems to indicate that these shared mechanisms are also responsible for programming and preparing actual actions, a process called *motor planning* [7, 9]. Motor imagery is almost identical to motor planning in that in both the brain activates a motor plan and monitors its unfolding, but there is a difference in that, while motor planning leads to action, in motor imagery the brain inhibits the execution of any motor output. To appreciate the function of motor planning, a brief

look is in order at what cognitive neuroscience defines as the three levels of computation in motor control [43]. First, at the coarsest level, the brain must plan a path. Next, at the intermediate level, the brain needs to compute the right joint angles at each point of the path to solve the inverse kinematics problem. Finally, at the finest level, the brain has to compute the muscle forces needed to move the joints in the right positions in order to solve the inverse dynamics problem. A change at any of these three levels directly interacts with the others. Motor planning and, indeed, motor imagery involves solving this puzzle [12, 37, 63].

Measurement of autonomic responses again provides us with more evidence. Adams et al. showed that changes in heart and breathing rates anticipate metabolic changes resulting from muscular activity [1]. They found that heart and breathing rates already increased within just five heartbeats and just one breathing cycle, respectively, after starting exercise. These changes are thus clearly not the result of the physical execution of the exercise itself. If the neural mechanisms of motor imagery do overlap with those used in motor planning, then autonomic activation should also occur during motor imagery and it should be proportional to the imagined effort [7]. Decety et al. found just that when monitoring subjects during mental simulation of running or cycling at different speeds [14]. They reported an absence of overt muscle activity, but nonetheless an increase in heart and breathing rates, compared to resting levels, that was proportional to the imagined intensity of the exercise. Since the mind cannot voluntarily inhibit nor control the autonomic nervous system, the observed autonomic response must be the work of a central nervous influence like that observed during motor preparation [37]. The heart and breathing rates of a subject mentally running at 12 km/h were comparable to that of the subject physically walking at 5 km/h. Wang and Morgan, too, found the same kind of proportional autonomic response in subjects mentally lifting dumbbells, immediately after they started the exercise [70]. In a follow-up experiment by Decety et al., subjects' heart rates were similarly about 25% lower than during actual exercise [13]. In contrast, breathing rates were actually even higher during mental exercise than during physical exercise.

More evidence comes from neurological studies of the brain. In the macaque, Rizzolatti et al. found premotor neurons that fired both before the monkey performed a particular goal-directed movement and during it, regardless of how exactly the monkey performed the action [58]. Later, Di Pellegrino et al. discovered that these neurons also fire when the monkey observed the experimenter perform the same meaningful hand movements [21]. This result indicates that mental representations of both other's and one's own actions share a common neural substrate with motor planning [37]. Furthermore, Decety et al. monitored the regional cerebral blood flow of subjects who were physically or mentally writing words [17]. In the mental condition, the experimenters tried to make sure the subjects used motor imagery by instructing them to imagine the movements from a first-person perspective and to try to feel themselves writing. They found that the activated areas of the brain that the two conditions had in common were the prefrontal cortex, the supplementary motor area, and the cerebellum, which are all involved in motor planning. This is strong evidence that motor imagery and motor planning share a common neural mechanism [7].

While motor imagery and motor planning differ from each other in that the former can be accessed consciously whereas the latter escapes awareness, this difference might simply be one of degree. Motor planning normally lasts only very shortly, but if we could prolong it then it might progressively turn into motor imagery. A number of clinical observations indicate that when subjects fail to execute

a motor plan, they become aware of its motor representation. Both amputees and patients with deafferented limbs, for example, feel phantom movements in their damaged limb and may describe the action they intended to perform with the limb in detail, though they cannot produce any overt movement [38, 62]. This suggests that when the brain executes a motor plan normally, it never reaches consciousness, but when the execution of the plan is blocked or delayed, such as in motor imagery, it becomes accessible to conscious processing. If both motor planning and motor imagery are indeed part of the same motor representation vehicle, then it is clear that motor imagery is not merely a byproduct of motor generation, but that it plays a causal role in it [37].

2.4 IMPORTANT ASPECTS OF MOTOR IMAGERY

A key aspect of motor imagery is that, unlike with visual imagery, humans find it quite difficult to translate it into words [37]. As Annett reports, when subjects are asked to describe in detail how to tie a bow, their explanations are often hesitant and supported by gestures, typically taking thrice as long as they would need to actually tie a bow [4]. The verbal explanation usually consists of a list of sub-goals, each corresponding to motor imagery that serves as a cue for the subject's next move. Most hesitations take place between these sub-goals.

Another important point is that motor images correspond to generalized movements and not to specific muscular actions [4]. The gestures that accompany motor imagery tasks such as the one described in the previous paragraph in no way replicate the exact movements required by the corresponding physical task. In fact, if movement of the hands is restrained, then subjects will use other body parts, such as the head, to visualize the imagined movements.

Finally, it appears that to evoke motor imagery in subjects, using correct spatial movement is more important than providing detailed visuals [4]. Johansson showed subjects footage filmed in a dark environment of an actor covered completely in black but with small lights attached to the main segments of the body [39]. When the actor stayed still, subjects were unable to find any meaningful patterns in the arrangement of the lights. As soon as the lights started to move, however, subjects were able to make subtle judgments about the actor's actions, state and gender. Reisberg and Logie further demonstrated that a spatial task such as overt movement interferes with retaining motor imagery in working memory, but leaves visual imagery intact [56].

3 Mental Practice

Also known as mental or symbolic rehearsal, *mental practice* is a training method in which a subject intensively and repeatedly rehearses the internal mental reproduction of a specific action with the aim of improving performance. Mental practice usually involves motor imagery, but is not limited to it and may involve other kinds of cognitive processes as well [36]. Researchers usually measure the effectiveness of this method by comparing the improvement in speed or accuracy gained with the results of using physical exercise to practice the same actions. Alternatively, they can rate the intensity of the mental practice by measuring the magnitude of the autonomic changes it causes [4].

3.1 EFFECTIVENESS

There is now considerable evidence that mental practice can have a significant positive effect on performance in learning motor skills [4]. Both behavioral and neurophysiological studies have reported significant *positive transfer* from mental to physical practice [9, 19, 26, 74].

Mental practice can result in actual increases in strength. Yue and Cole compared the differences between results of mentally and physically training the little finger on one hand [74]. They found that the average abduction force of the trained digit in the mental and physical conditions increased by 22% and 30%, respectively, while the maximal abduction force of the same digit on the other hand increased by respectively 10% and 14%. EMG measurements showed that during mental practice, the muscles in the digit were not active, in sharp contrast with physical practice, during which subjects in fact produced high levels of contraction. Therefore, it appears that the strength gains induced by mental practice are the result of neural changes in motor planning [7, 37].

The use of mental practice can likewise improve motor skill performance. Yáguez et al. demonstrated that 10 minutes of mental practice was sufficient to enhance subjects' performance on drawing ideograms of different sizes [75]. Studies in sport psychology have also shown that mental practice can improve the spatial accuracy and execution time of athletes' movements [22, 24, 33, 35]. These studies, however, have also shown that although mental practice is better than no practice at all, the improvements in motor skill behavior from physical practice are greater still. Research by Pascual-Leone et al., in which subjects practiced a one-handed piano task either physically or mentally, resulted in similar findings [52]. After five days of practice, the performance level of subjects who mentally practiced was equal to that of subjects who practiced physically for only 3 days. Subjects in the mental condition, however, reached the same performance level as those in the physical condition after just one subsequent day of physical training. Mental practice thus not only appears to be capable of producing changes in the brain similar to those caused by physical practice, but actually seems to augment the efficiency of any ensuing physical practice. In fact, many studies have reported a combination of both mental and physical practice to be more efficient than either of them alone is. In particular, Jackson et al. showed that adding even only a very small amount of physical practice to mental practice (a 10:1 ratio, in their case) already greatly increases the efficiency of the practice regime beyond that which can be achieved using one form of practice only [36].

Finally, it is important to note that the higher the quality is of motor imagery that subjects generate, the more effective their mental practice is. To objectively quantify

the quality of motor imagery used in mental practice, Roure et al. measured subjects' autonomic responses, such as heart and breathing rate, and change in skin resistance and potential [59]. Subjects' performance on a subsequent volleyball task correlated positively with the thus measured intensity of their motor imagery. Apparently, access to better motor imagery leads to more improvement in motor skill learning. Therefore, to maximize the effectiveness of mental practice, it clearly is important to stimulate the use of high-quality motor imagery as much as possible [36].

3.2 PRACTICAL CONSIDERATIONS

It is a well-known fact that repetition is the key to learning, and this adage applies to motor learning as well. In fact, studies with animals have shown that, rather than relying merely on the *forced use* of the affected limb, forcing its use in a repetitive motor task more effectively stimulates brain plasticity [49]. With this in mind, Whittall et al. argue that there are three major incentives for augmenting mental practice with rhythmic auditory cueing [71]. First, keeping a constant frequency ensures that the timing of the movement does not change between repetitions, so that the subject will make the exact same movement every time. Second, attempting to match a movement to a sound provides the subject with an attentional goal, which studies have shown to enhance motor learning performance [45]. Finally, research has demonstrated that receiving feedback regarding the goal, such as auditory, visual or somatosensory cues, is a vital component to effective motor learning [61]. In short, repetition through rhythmic auditory cueing greatly enhances the effectiveness of mental practice.

On another practical note, it is important to keep in mind that, though high-intensity motor imagery leads to better mental practice, the reported vividness of motor imagery does not actually correlate with the effectiveness of mental practice. Vividness is very important for visual imagery, but not for motor imagery, which relies more on controllability. Reported vividness has no impact on subjects' ability to perform mental practice [4].

3.3 THEORY OF MENTAL PRACTICE

Jackson et al.'s three levels of learning is the most recent and comprehensive model available of motor learning in general and mental practice in particular [36]. It is analogous to the three-stage model of expertise (declarative knowledge, procedural knowledge, and automaticity) of Fitts and Anderson, and consistent with Rasmussen's three levels of cognitive control (skill-based behavior, rule-based behavior, and knowledge-based behavior) [3, 28, 55, 72]. Jackson et al. propose three different levels of learning processes that interact with each other during practice. The first level is *declarative knowledge*, which denotes the explicit knowledge required before practicing a particular motor task. *Nonconscious processes*, which represent the characteristics of a skill that are not readily accessible to verbal explanation, form the second level. Finally, the third level consists of *physical execution*, which corresponds to the muscular activity necessary to accomplish the desired outcome. The level of processing employed in learning depend of the kind of practice used, as shown in Figure 1.

As the figure below shows, the model predicts physical practice to be the most advantageous since it involves all three levels interacting with each other. In addition, the model makes a clear distinction between mental practice with motor imagery and mental practice without it. In mental practice with motor imagery,

interaction between declarative knowledge and nonconscious processes improves the acquisition of motor skills. Finally, the model predicts that mental practice using a first-person perspective is more effective than using a third-person perspective, because it better activates the nonconscious processes [36].

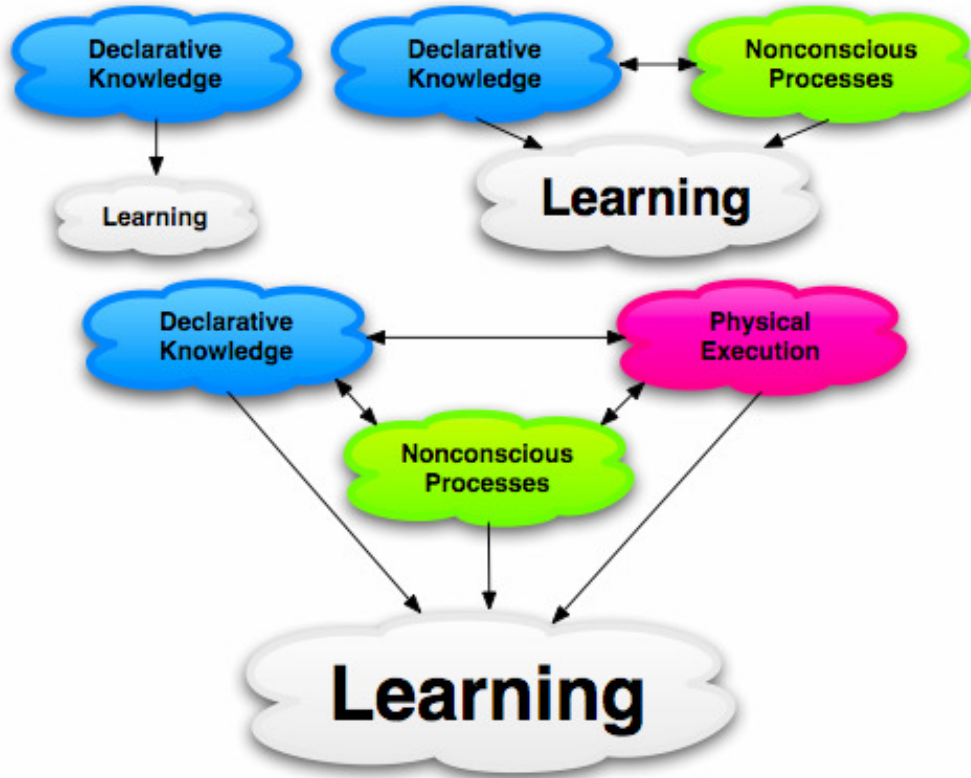


Figure 1: Jackson et al.'s Three Levels of Learning

4 Post-Stroke Rehabilitation

Post-stroke rehabilitation involves helping patients relearn skills they lost to stroke. Well-focused, repetitive practice is the most important ingredient for post-stroke rehabilitation, experts agree. Since many post-stroke patients are hemiplegic, initial treatment immediately focuses on promoting independent movement using passive or active practice. The difference between these two types of practice is that in *passive practice* the therapist actively assists the patient in moving impaired limbs in nonspecific ways, while in *active practice* the patient performs task-specific activities without receiving any physical help. Post-stroke rehabilitation generally focuses on goal-directed tasks, since they promote coordination [48].

Rehabilitation can take place in inpatient or outpatient facilities. In the first case, the patient stays in the facility day and night for several weeks as part of an intensive rehabilitation program. In the latter case, the patient spends only several days per week at the facilities and returns home at the end of the day [48].

4.1 ACTIVE PRACTICE

Traditionally, post-stroke rehabilitation has used repeated physical practice, consisting mostly compensatory training of the healthy arm and passive practice of the disabled arm to improving motor activity and stimulate brain plasticity [48]. A problem with this approach is that its effectiveness depends on the performance of the disabled limb [64]. In addition, since spontaneous recovery from stroke shows a plateau after three months, traditional stroke rehabilitation only focuses on those first three months [71].

Using active practice through forced use of the impaired arm, Liepert et al. have demonstrated that stroke patients can achieve functional gains and brain plasticity long after the three-month spontaneous recovery period [44]. In other experiments involving stroke patients and the forced use of the affected arm, subjects significantly increased the functional ability and daily use of their weakened arm [71]. These results suggest that patients have *learned nonuse* of their affected arm and that forced use can revive the dormant neuromuscular pathways [65].

Auditory cueing can significantly enhance active practice. Thaut et al. successfully used auditory to facilitate gait training in stroke patients [66]. Inspired by this, Whittall et al. devised and tested a protocol for bilateral arm training with rhythmic auditory cueing for treating patients with UEH [71]. They found that just six hours of such training led to durable improvements in sensorimotor impairments, performance time and functional use, even in patients with very severe hemiplegia who had long since completed conventional training. Thus, auditory cueing allows forced-use, task-oriented, repetitive training to successfully treat much more severe cases of stroke than would otherwise be possible.

4.2 MENTAL PRACTICE WITH MOTOR IMAGERY

Based on the findings discussed in chapters 2 and 3, many researchers have proposed using mental practice as a cost-efficient and effective means of assisting motor recovery in stroke patients [29, 64]. Indeed, there are results that indicate that mentally practicing a motor skill results in the same kind of brain plasticity that would occur because of physically acquiring the skill [12, 23, 36, 73].

Empirical evidence for the effectiveness of using mental practice with motor imagery in post-stroke rehabilitation comes from Stevens & Stoykov [64]. Their study involved the mental practice of arm movements that are important for many

daily activities and representative of movements problematic for hemiplegics, and of which the performance is quantitatively measurable. Hemiplegic patients had to perform two kinds of tasks. In the first, subjects watched a computer-generated movie showing a moving arm from varying angles and at varying speeds, after which they immediately had to mentally perform the same movement. When they had completed the imagined movement, they had to tap the space bar, enabling the experimenters to obtain the time the patients use to complete each movement. The second task involved an adaptation of an experiment in which Ramachandran & Rogers-Ramachandran used a mirror to induce subjective sensation in phantom limbs [53]. Patients sat at a table with a vertical mirror positioned in front of them in such a way that the reflection of the healthy arm visually replaced the disabled arm. The experimenters then instructed the patients to imagine that the reflection is in fact their disabled limb, moving around freely. Patients spent the first week learning to do this, after which they had to perform relatively simple exercises in the second and third week, and complex maneuvers in the fourth, final week. At the end of the four weeks, patients had made significant improvements in both accuracy and speed of movements. Patients obtained the greatest functional gains during the period of intervention, indicating that these advances are the result of active mental practice.

When applying mental practice in post-stroke rehabilitation, there are some important issues to consider. First, patients should be able to produce motor imagery at all. Without it, mental practice is simply not very effective, as indicated by Jackson et al.'s three levels of practice (see section 3.3). Second, because of the lack of direct feedback, mental practice is still less effective than physical practice [24, 29, 57]. Combined with physical practice, however, subjects can improve their motor imagery by using the feedback gained from actual movements. In this way, mental practice enables subjects to increase the number of repetitions of a movement they can make without any increase in physical demands [36]. Third, even if patients are not able to physically produce any movement in their disabled limbs, they can still benefit from mentally practicing specific skills with motor imagery, because it rehearses the neural network involved, thus priming it for the future execution of these motor skills [52].

4.3 COMPUTER-AIDED MENTAL PRACTICE

Many patients with severe hemiplegia have difficulty to produce motor imagery, even if the neural circuitry required for it is uninjured [32]. Computer-aided mental practice can assist these patients by interactively helping them to generate motor imagery. This section describes such a system developed by Gaggioli et al., which makes use of virtual reality (VR) to further the rehabilitation of UEH [29].

The system developed by Gaggioli et al. consists of two parts [29]. The first part is composed of motion tracking equipment to track the movements of the patient's healthy arm as they perform an exercise. The second part is an interactive workbench dubbed the *VR Mirror* that displays a three-dimensional animation of a movement the patient performed earlier, but mirrored so that it appears to involve the disabled arm. The display shows the animation to the patient from a first-person perspective in order to stimulate the production of motor imagery.

The use of the system, as outlined by Gaggioli et al.'s inpatient treatment protocol, is as follows [29]. Each session with the system comprises four successive phases. In the first phase, the *pre-training phase*, the therapist explains to the patient how the treatment works and encourages them to relax. Next, in the *physical training phase*, the therapist instructs the patient to perform a particular movement with their unimpaired arm, guided by rhythmic auditory cueing, so that the patients

executes the same movement every repetition and to supply the patient with the attentional goal of matching their movements to the sounds [45, 71]. While the patient performs the movement, the system identifies key frames in the motion of the arm at each auditory cue and thus creates an animated 3D model of the movement. Then, in the *imagery-training phase*, the therapist asks the patient to use motor imagery to imagine the impaired arm performing the same movement. The patient presses with their healthy hand when they initiate the mental movement and again when they have completed it, allowing the therapist to measure the mental movement time. By comparing the patient's physical and mental movement times, the therapist can evaluate the quality of the patient's motor imagery [12, 15]. Finally, in the *VR mirror-training phase*, the system shows the patient a mirror-image animation of the movement performed by the unimpaired arm, accompanied again by the same rhythmic auditory cueing as in the physical training phase. The animation gives the patient direct perceptual cues on how to perform a controlled and steady movement with their impaired arm, while the auditory cues help the patient to memorize the rhythm of the movement. Then, the patient has to attempt to perform the exercise with their impaired arm in synchrony with the animation. During this, the system tracks the motion of the impaired arm to determine the deviation from the movement of the healthy arm and provides the patient with auditory feedback about this. After the patient has gone through five to ten repetitions of the movement, the therapist ends the session and picks a more complicated exercise for the next one.

The system has several advantages for post-stroke rehabilitation. First, providing the patient with a combination of visual and auditory cues makes it easier for the patient to produce the right kind of motor imagery for effective mental practice. Second, the system does not rely on pre-programmed exercises, which is a widely known drawback of traditional computer-aided post-stroke rehabilitation. Third, the external display keeps the patient free from having to wear any awkward or obtrusive equipment, such as a head-mounted display. Fourth, by tracking the motion of the impaired arm, the system can dynamically keep the therapist updated on the patient's performance and give the patient real-time feedback on their performance, which promotes effective motor learning [60, 61]. Finally, by combining physical and mental practice and using interactive technology to reduce the patient's need for skilled support, the system provides a very efficient solution for post-stroke rehabilitation [29]. Unfortunately, yet at the time of writing this, the researchers involved had not yet published any quantitative test results.

5 Mirror-Based See-Through Augmented Reality

The goal of my Master's thesis project will be to use a mirror-based display system to develop an AR version of the system described in section 4.3. With this type of system, the user watches the reflection of a screen on a mirror, thus perceiving virtual objects displayed on the screen to be in fact located behind the mirror. For the system to be suitable for AR, the mirror must be half-silvered and not fully opaque, so that the user can both observe the reflections of the virtual objects and see through the mirror to observe the real world behind it [6, 47]. In the envisioned system, the user will be able to reach underneath this semitransparent mirror in order to be able to perform exercises. Currently, two promising mirror-based see-through AR systems are available that can serve as examples for the envisioned system: the *Virtual Showcase* and the *Personal Space Station*.

The basic design Virtual Showcase consists of a convex assemblage of semitransparent mirrors on top of a projection screen, or vice versa [6]. The mirrors reflect the objects displayed on the projection screen such that viewers perceive these objects to be colocated with real objects inside the showcase. Shutter glasses and motion tracking provide the viewers with a view-dependent, stereoscopic perspective of the virtual objects, while a controllable video projector illuminates the real objects inside the showcase on a per-pixel basis [54]. The configuration of the Virtual Showcase in which the projection screen lies above the mirrors seems a more appropriate prototype for using in the computer-aided rehabilitation of UEH, since this removes the projection screen from patients' field of view when they are observing the virtual representation of their arm.

With the Personal Space Station, the user sits in a front of a semitransparent mirror that reflects virtual objects displayed by a CRT screen above it. Shutter glasses or the combination of a polarization screen and polarized glasses provide the user with stereoscopic viewing. Two cameras monitor the area underneath the mirror, so that the user can reach there and interact with the virtual objects. The cameras are equipped with an infra-red (IR) pass filter and IR LEDs around the lens, so that they can also track real objects marked with retro-reflectors that the user handles underneath the mirror.

5.1 COMPARISON WITH HEAD-MOUNTED DISPLAYS

Most AR systems currently use head-mounted displays (HMDs). Some HMDs are video-based, which means they use completely opaque screens showing a live video stream of the physical world, while others are see-through, which means they use transparent screens to render virtual content on top of the perceived physical world [47]. All HMDs, however, share the same drawbacks: they can provide only limited screen resolution, they severely restrict the user's field of view, they are heavy and awkward to use, and they quickly cause fatigue of the eyes because of restricted focal distances [6]. Not all of these drawbacks, however, are necessarily detrimental to the application of AR in post-stroke rehabilitation. For example, as discussed in section 2.4, detailed visuals are not necessary to effectively invoke motor imagery.

Mirror-based AR has several advantages over using HMDs [5, 6, 47]. First, since the screen used can be physically larger, it is capable of providing the user with a higher screen resolution than would be possible with HMDs. Second, it is more ergonomic than using HMDs because the glasses used are lighter and less obtrusive. Third, since the focal distance to the virtual content is closer to its perceived distance than with HMDs, it provides the user with better convergence and

accommodation of the eyes. Finally, mirror-based AR systems are cheaper to construct than HMD system and can more easily colocate real objects with virtual ones. A drawback, however, is that occlusion artifacts may occur between real and virtual objects.

5.2 KNOWN ISSUES

Of course, the use of mirror-based AR also involves some trade-offs. First, unlike with HMDs, the user does not have a perpendicular view of the screen, so the system must transform all graphics so that the user does not perceive any distortion. If the rendering is to be stereoscopic or view-dependent, these transformations increase in complexity [6]. Second, occlusion artifacts may occur between real and virtual objects, because all virtual objects will seem transparent with respect to the real world, unless the system has a mechanism to explicitly compensate for this, which requires additional hardware and computational processing [47].

In order for the user to perceive the virtual objects in a correct perspective, the system needs to transform the virtual world to accommodate for the angle at which the mirror reflects the display to the user [6]. Furthermore, the virtual objects must appear to the user to be in the correct position with respect to the real objects. If the system employs a non-planar mirror, this further complicates the computation.

In the basic implementation of mirror-based AR, all virtual objects will appear translucent with respect to the real objects in the environment [47]. This is a natural result of the real objects being behind the semitransparent mirror, while the surface of the mirror reflects the virtual objects. The degree of transparency of the mirror is directly proportional to the degree of transparency of the virtual objects, but inversely proportional to the visibility of the real objects behind the mirror. In an ideal AR system, the individual transparency of each virtual object is under direct control of the system, the real objects are visible enough to the user to be able to ignore the presence of the mirror, and real objects are able to occlude the virtual ones behind them. There are two systems to date that try to achieve this ideal: LCD-based light blocking and projector-based illumination.

In *LCD-based light blocking*, a transparent LCD panel placed directly below the mirror provides per-pixel blocking of light [47]. When a pixel in the panel is directly behind a virtual object on the mirror, from the user's point of view, the system makes it black and thus opaque; otherwise, it leaves it clear and transparent. To accommodate stereoscopic viewing, the LCD panel will have to obscure different parts of the scene for the left- and right-eye views. The refresh rate of a standard LCD display, however, is not high enough to allow it alternate fast enough between the left- and right-eye views for use with shutter glasses. Therefore, LCD-based light blocking has the user employ polarized glasses and places a sheet in front of the LCD panel that polarizes light in such a way that alternate pixel lines on the LCD panel will have perpendicular polarizations. One obvious drawback of this system is that it effectively halves the resolution of the screen. Another drawback is that the LCD panel used in the only prototype of this system so far is not very transparent. Viewing the real world through the panel causes significant blurring of vision and loss of light. An LCD panel with better transparency is required for practical use.

Projected-based illumination uses a computer-controlled video projector to control the lighting of the real world component of the system on a per-pixel basis [5]. To make the virtual objects appear opaque, it dynamically projects shadows onto the real objects in the scene exactly behind the virtual objects, from the user's point of view, while using shutter glasses to provide the user with stereoscopic vision. To be able to provide view-dependent rendering, the system requires exact

knowledge of the geometry of the real objects in the scene. Another complicating factor is that the system requires a complex calibration phase to correctly register the shadows cast by the video projector. Finally, to make the virtual objects appear fully opaque, the system requires that no other light sources are present than the video projector it employs.

6 Conclusion

Motor imagery is a specific kind of movement imagery in which the subject imagines moving their own body without performing any actual physical movements. It is a form of internal imagery, as it uses a first-person perspective and relies on motor-kinesthetic information processing. It can influence the subsequent execution of physical movement, to which it is both functionally and temporally equivalent, and in fact, both obey Fitts's law. Patients suffering from hemiplegia are still able to produce motor imagery, but they experience the same increase in time and effort to do so as with physical movement. Further, motor imagery and the motor control of physical movements share a common neural mechanism responsible for programming and preparing actual actions, a process called motor planning. Motor imagery is identical to motor planning except for the latter leading to action, while motor imagery does not. Finally, motor imagery corresponds to generalized movements and not to specific muscular action. Therefore, to stimulate motor imagery in subjects, using correct spatial movement is more important than providing detailed visuals.

Mental practice is a training method involving but not limited to mental practice in which a subject intensively and repeatedly rehearses the internal mental reproduction of a specific action with the aim of improving performance. Significant positive transfer takes place from mental to physical practice. In fact, mental practice results in actual increases in strength and improves motor skill performance. The higher the intensity of the motor imagery used, the more strongly pronounced these effects are. The reported vividness of the motor imagery, however, has no impact on this. Further, the forced use of the affected limb of a hemiplegic in a repetitive motor task more effectively stimulates brain plasticity than forced use alone. Finally, Jackson et al.'s three levels of learning—the most recent and comprehensive model available of motor learning in general and mental practice in particular—predicts that using a first-person perspective in mental practice is more effective than using a third-person perspective.

Post-stroke rehabilitation involves helping patients relearn skills they lost to stroke, using passive or active practice. In the former, the therapist actively assists the patient in moving impaired limbs in nonspecific ways, while in the latter, the patients performs task-specific activities without receiving any physical help. A problem with passive practice is that its effectiveness depends on the performance of the impaired limb. Using active practice, however, through forced use of the impaired limb, stroke patients can achieve brain plasticity and functional gains long after spontaneous recovery has halted. In addition, auditory curing allows forced-use, task-oriented, repetitive training to successfully treat even much more severe cases than would be possible with passive practice. Further, mental practice of a motor skill is a cost-efficient and effective means of assisting motor recovery in stroke patients that results in the same kind of brain plasticity as physically acquiring the skill does. In order for mental practice to be effective, however, patients have to be able to produce imagery. Mental practice alone is less effective than physical practice, but combined with it, patients can use the feedback from the actual movement to improve their motor imagery, so that mental practice enables them to increase the number of movement repetitions they can make without increasing physical demands. Even if patients are not able to physical produce any movement in their disabled limbs, however, they still benefit from mental practice of motor skills, because it primes the neural network involved for future execution of these

skills. Patients with severe hemiplegia, unfortunately, experience difficulty producing motor imagery. Computer-aided mental practice, however, can interactively assist them to do so. One example of such a system—called the VR Mirror—does so by first tracking the movements of the patient's healthy arm and then showing a three-dimensional animation of this movement but mirrored so that it appears to actually involve the disabled arm as seen from a first-person perspective in order to stimulate the production of motor imagery.

One idea for further improving the effectiveness of computer-aided mental practice is to lift it from the paradigm of virtual reality to that of augmented reality. For my Master's thesis project, I am to develop an AR version of the VR Mirror, using a mirror-based, see-through approach. There are currently two mirror-based, see-through AR systems available: the Virtual Showcase and the Personal Space Station. The former is a convex assemblage of semitransparent mirrors reflecting a projection screen, so that the viewer perceives the virtual objects to be colocated with the real objects inside the showcase. The latter is a semitransparent mirror that reflects virtual objects displayed by a CRT screen above it while a polarization filter and polarized glasses provide the user with stereoscopic viewing. Parts of both these approaches seem suitable to combine to form the basis of a new colocated, reach-in AR system for computer-aided mental practice.

Most AR systems currently use head-mounted displays but these provide only limited screen resolution, severely restrict the user's field of view, are awkward to use, and quickly cause fatigue of the eyes. Mirror-based AR is capable of providing a higher screen resolution because of a physically larger screen, is more ergonomic because of lighter and less obtrusive glasses, provides the user with better convergence and accommodation of the eyes because the focal distance to the virtual content is closer to its perceived distance, and is cheaper to manufacture.

With mirror-based AR, however, the user does not have a perpendicular view of the screen, so the system must transform all graphics for the user not to perceive any distortion. If the system uses a non-planar mirror, this further complicates the computations. Further, all virtual objects will seem transparent with respect to the real world, unless the system has a mechanism to explicitly compensate for this, which requires additional hardware and computational processing. There are currently two systems for doing so: LCD-based light blocking (used in the Personal Space Station) and projector-based illumination (used in the Virtual Showcase). The former system involves a transparent LCD panel placed directly below the mirror to provide per-pixel light blocking. Its drawbacks are that it effectively halves the screen resolution and that the LCD panel causes significant blurring and light loss. The latter system uses a computer-controlled video projector to cast shadows on the real-world components of the system of a per-pixel basis. Its drawbacks are that it requires exact knowledge of the real-world geometry in the scene, a complex calibration phase to correctly register the shadows, and a complete absence of light sources other than the video projector.

In conclusion, augmented should be able to play a role in significantly enhancing the treatment of hemiplegia because it provides a more effective means of stimulating motor imagery in patients. It does so by providing spatial movement that is more correct with regard to the real world and the viewing position of the patient and by providing a view that is closer to a true first-person perspective as experienced by the patient. The biggest drawback of AR is the problem of correct occlusion between virtual and real-world objects, but because the visual detail of the animation appears to be of no influence on the effectiveness of stimulating motor

imagery, simply having transparent virtual objects instead should prove to be of no consequence in this particular application of the technology.

7 Glossary

Active practice: exercises performed by the patient with no physical assistance from the therapist.

Declarative knowledge: the explicit knowledge required before practicing a particular motor task.

External imagery: motor imagery that uses a third-person perspective and relies on visuospatial processing.

Forced use: immobilization of the unaffected arm combined with intensive training.

Hemiparesis: weakness or partial paralysis of one side of the body.

Hemiplegia: paralysis of one side of the body.

Internal imagery: motor imagery that uses a first-person perspective and relies on motor-kinesthetic information processing.

Kinesthetic imagery: a term for motor imagery often used in sports psychology.

Learned nonuse: excess motor disability maintained by a learned suppression of movement.

Mental practice: a training method in which a subject intensively and repeatedly rehearses the internal mental reproduction of a specific action with the aim of improving performance, also known as mental or symbolic rehearsal.

Motor imagery: a specific kind of movement imagery in which the subject imagines moving their own body without performing any actual physical movements.

Motor planning: the process of programming and preparing actions.

Neural substrate: the set of brain structures that underlies a specific behavior or psychological state.

Nonconscious processes: the characteristics of a skill that are not readily accessible to verbal explanation.

Passive practice: exercises in which the therapist actively helps the patient move a limb repeatedly.

Physical execution: the muscular activity necessary to accomplish the desired outcome.

Positive transfer: when a person's experience with a previous skill helps them to learn a new skill.

Transfer: the influence a previously practiced skill has on learning a new skill.

UEH: upper extremity hemiplegia or hemiparesis.

Upper extremity: the hand, wrist, elbow, arm, shoulder, and/or neck.

Visual imagery: a type of imagery that involves mentally manipulating visual images.

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