Motor imagery training in hemiplegic cerebral palsy: a potentially useful therapeutic tool for rehabilitation

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PUBLICATION DATA
Accepted for publication 20th April 2009.

Converging evidence indicates that motor deficits in cerebral palsy (CP) are related not only to problems with execution, but also to impaired motor planning. Current rehabilitation mainly focuses on alleviating compromised motor execution. Motor imagery is a promising method of training the more 'cognitive' aspects of motor behaviour, and may, therefore, be effective in facilitating motor planning in patients with CP. In this review first we present the specific motor planning problems in CP followed by a discussion of motor imagery and its use in clinical practice. Second, we present the steps to be taken before motor imagery can be used for rehabilitation of upper limb functioning in CP. Motor imagery training has been shown to be a useful addition to existing rehabilitation protocols for poststroke rehabilitation. No such study has been conducted in CP. The age at which children can reliably use motor imagery, as well as the specific way in which motor imagery training needs to be implemented, must be researched before motor imagery training can be employed in children with CP. Based on the positive results for poststroke rehabilitation, and in light of the motor problems in CP, motor imagery training may be a valuable additional tool for rehabilitation in CP.

Recently it was proposed that the motor deficits occurring in individuals with cerebral palsy (CP) are related not only to problems with motor execution, but also to impaired motor planning.[1] Nevertheless, current rehabilitation techniques are predominantly focused on alleviating the compromised motor execution facet of action performance, and have not specifically targeted the motor preparation or planning processes. As motor imagery is a promising method of training the more 'cognitive' aspects of motor behaviour, it may be effective in facilitating motor planning in CP. In this article, we will first give a short introduction to motor planning problems in CP. We will then discuss motor imagery, its neural correlates, evidence for the efficacy of motor imagery training for motor performance, and studies that have already been carried out in individuals with motor impairments. In the final section we will present a research agenda for the use of motor imagery for rehabilitation of motor planning in children with CP.

METHOD

Motor planning in cerebral palsy

There is converging evidence suggesting that, in children with congenital hemiparesis, not only is the ability to move the affected arm compromised, but the capability to be engaged in anticipatory motor planning is also affected. This higher-level deficit may, in turn, severely hinder activities of daily living.[1] As children with congenital hemiparesis predominantly use their less affected hand to perform actions in daily living, this compromised planning ability demands attention in rehabilitation. Anticipatory motor planning is defined here as the ability to go beyond immediately available information and take into account the demands of an upcoming task. For example,

 DOI: 10.1111/j.1469-8749.2009.03371.x

suppose you want to pick up a cup that is placed upside down on the table to fill it with water. You can pick up the cup with a comfortable grip in which the thumb points upwards. If grasped in this manner, the hand will be in an uncomfortable end posture once the cup is turned over. In contrast, if the hand is pronated first when the cup is grasped, then turning over the cup will leave the hand in a comfortable end posture. In most instances, despite the fact that the hand is in an uncomfortable posture upon grasping the cup, individuals 'sacrifice' initial comfort. This implies that they plan forward. This anecdote exemplifies that the way in which individuals initially grip an object may give us a clue as to whether they are engaged in anticipatory planning. Several studies have examined motor planning in participants with congenital hemiparesis when they had to grasp an object with their less affected hand and subsequently perform another action with it.[2–4] Compromised motor planning was especially evident in participants with right hemiparesis, namely left hemisphere damage,[4] a finding that corroborates neuroimaging studies showing left hemisphere dominance for action selection.[5]

Presently, upper limb rehabilitation in CP predominantly focuses on the affected arm, either alone (constraint-induced movement therapy)[6,7] or together with the less affected upper extremity (bimanual training[8,9]). Although sequential actions that demand planning are exercised in these protocols, motor planning is not explicitly trained, with emphasis and instruction focused on movement execution. We propose here that motor imagery training may be a promising addition to existing programmes to aid in the rehabilitation of compromised motor planning ability.

Motor imagery: neural correlates, theory, and training

Motor imagery is an active cognitive process in which the action representation is internally reproduced within the working memory, without motor output,[10] for example, imagining stretching out your left hand without actually doing so. Hence, the internal representation of movement is open to conscious awareness while overt execution of the movement plan is inhibited. This specific facet makes motor imagery a method 'par excellence' for studying the nature of action representations in individuals with brain injury without potential confounds related to sensory feedback and motor output. More importantly, it was recently suggested that motor imagery may be used as 'backdoor' access to the motor system, or neural representation of movement.[11] Indeed, converging evidence in individuals with subacute and chronic stroke supports the notion that motor imagery training may promote general rehabilitation of upper limb function.

Numerous studies have shown that imagined and executed movements share common neural substrates, with the former differing in the magnitude of activation of the shared substrates, which is often weaker, and an absence (or suppression) of the final efferent command.[12] A recent meta-analysis of neural structures involved in mental rotation tasks[13] showed that brain regions that were consistently activated included the superior parietal, frontal, and inferotemporal cortex. Studies using positron emission tomography[14] and functional magnetic resonance imaging (fMRI)[15] have also shown involvement of the premotor cortex, supplementary motor cortex, parietal cortical areas, and the primary motor cortex.

Despite the fact that these commonalities among neural structures for both imagined and executed actions may suggest that similar networks are active, concerns have been raised about the validity of this claimed homology,[16] as neuroimaging (positron emission tomography and fMRI) provides only correlation data, and causal roles of distinct areas cannot be established directly. To overcome this problem, transcranial magnetic stimulation (TMS) has recently found its way into motor imagery research. In line with the neuroimaging studies, it was shown that the excitability of the corticomotor pathway is modulated with the same temporal and spatial characteristics during motor imagery as during actual movements.[17] Furthermore, studies using TMS have revealed important new insights into cortical organization with respect to motor imagery. Most notably, these findings suggest that motor imagery may be lateralized. Fadiga et al.[18] showed that magnetic stimulation of the left motor cortex increased corticospinal excitability when participants imagined ipsilateral as well as contralateral hand movements. Stimulation of the right motor cortex, on the other hand, revealed only a facilitatory effect induced by imagery of contralateral hand movements. These findings, recently replicated by Stinear et al.,[19] indicate a pattern of lateralization, with the left hemisphere playing a dominant role in motor imagery. Thus, the dominant role of the left motor cortex during motor imagery may mirror its role during actual performed tasks.

Extensive research in cognitive psychology has shown that motor imagery is effective for learning and optimization of general motor performance and sport skills.[20] Two meta-analyses have revealed that motor imagery is beneficial compared with no practice, but not as robust as physical practice.[21,22] As an example, Gentili et al.[20] compared performing versus imagining, pointing to targets in the frontal plane as quickly and accurately as possible. Although motor improvement was larger in the physical training condition, the participants in the motor imagery group also improved their performance after training.

Specifically, movement duration decreased and peak acceleration increased compared with a control group receiving no training at all. The authors concluded that these results show that mental training facilitates motor learning. The benefit of mental training has also been shown in a sports context.[23]

One theoretical account to explain the effects of motor imagery training is the cognitive–symbolic theory.[24] The principal idea is that mental practice facilitates those skills whose movements involve a symbolic component. Mental practice effects are thought to be a result of the rehearsing of the cognitive components of the motor task. But what aspect of the action is optimized by motor imagery? Johnson-Frey[16] argued that the observed effects in motor imagery could be attributed to experience-dependent changes in higher-level brain regions involved in the planning, rather than the execution, of movements. In the recent 'planning–control' model of visuomotor performance, Glover[25] made a distinction between the planning and execution aspects of upper limb actions. Representations responsible for planning are thought to integrate a broad range of visual and cognitive information, whereas on-line control is dependent on direct visuomotor processes, without much cognitive interference. Consistent with this, it has been shown that a cognitive interference task affected motor planning, but not execution, during an object manipulation action.[26]

These behavioural findings, together with the reported neural underpinnings, have two important implications. First, motor imagery may be a suitable tool to train the neural network after injury. Second, the planning aspects of an action may especially benefit from motor imagery training. These two facets suggest that motor imagery is a promising technique for the rehabilitation of motor planning in CP.

RESULTS

Motor imagery training

Detailed descriptions of existing studies on the use of motor imagery training for rehabilitation of stroke cases and their outcomes have been reported elsewhere in two recent review papers.[11,27] The outcomes of these reviews show that most studies use some form of imagined use of the affected arm in functional, daily life tasks,[28] but protocols that include computer displays or mirror boxes are also used.[29] Individuals are trained under supervision[30] or at home.[31] Often, motor imagery is trained in combination with conventional physical and/or occupational therapy[28,32,33] or with physical training.[31] Frequency of training ranges from 2 days a week[30] to 5 days a week;[32] durations vary from 10 minutes[28] to 1 hour[32] over a period ranging from 2 weeks[34] to 6 weeks.[30] Evaluations are generally performed using the Fugl–Meyer Assessment of Motor Recovery[30] and the Action Research Arm Test,[28] while the Vividness of Movement Imagery Questionnaire is sometimes administered to assess the ability of individuals to be engaged in motor imagery.[35] Studies range from case studies[36] to a randomized, placebo-controlled trial of 32 participants.[30]

Importantly, the majority of the studies that were discussed in the two review papers[11,27] have shown that mental practice improves recovery of the upper limb at both the impairment and functional levels in stroke patients. One study showed that improvement was sustained after a 3-month follow-up period[37] and that it also generalized to untrained tasks.[32] The review by Sharma et al.[11] included five studies that focused exclusively on motor imagery of upper limb function and rehabilitation after stroke. They concluded that, although outcome measures varied between the studies, all assessed motor function of the affected upper limb and found that motor imagery training was beneficial compared with a control condition, as shown by improved performance on the Fugl–Meyer Assessment of Motor Recovery, the Action Research Arm Test, and the Motricity Index. The review by Braun et al.[27] included 10 studies that included randomized controlled trials, controlled clinical trials, cohort studies, and single-case studies. This systematic review found positive evidence for mental practice as an additional treatment tool for poststroke recovery. However, like Sharma et al.,[11] these authors noted that general conclusions are limited owing to variations in individual characteristics, the nature of the intervention, and the outcome measures (with respect to both the measurement domain and the timing of measurement).

Positive effects of motor imagery training are not confined to poststroke rehabilitation. Wilson et al.[38] examined the effects of imagery training in children with developmental coordination disorder (DCD; age range 7–12y) on motor skill development. The results of this training (one 60-min session a week for 5wks) showed that it was equally beneficial compared with traditional perceptual motor training. Thus, even in children with impaired motor coordination, this intervention facilitates motor skills. This begs the question as to whether such benefits have been shown for upper limb rehabilitation in children with CP. To answer this question, we conducted a systematic search of the MedLine, PsychLit and PubMed databases for the following key words: (1) motor imagery, or mental imagery, or mental training, or mental practice; combined with (2) upper limb and (3) rehabilitation. Subsequently, these four sets of three key words were combined with (4) congenital and (5) CP. Strikingly, no study on the use of mental training for upper limb recovery in CP was found.

INTERPRETATION

Can we use motor imagery training in cerebral palsy?

It is clear from existing reviews that motor imagery training may be an effective adjunct to physical practice for upper limb rehabilitation.[11,27] However, at the same time, our own search showed that this therapeutic intervention has not yet been employed in children with CP. In these children, not only is movement execution with the affected upper extremity impaired, but motor planning ability is compromised in a way that affects action performance with both hands; the latter may be targeted by motor imagery training.

Can motor imagery training be used to enhance motor planning in CP? At present there is no empirical evidence supporting or refuting this question. However, theoretically, it is valid to consider it as a potential rehabilitation method. What steps need to be taken before motor imagery training in this group can commence? First, it needs to be established whether these children can perform motor imagery at all. Second, we need to establish the age at which motor imagery can reliably be used in children. These two issues are discussed below.

Based on the converging evidence showing that motor planning is compromised in children with right hemiparesis, namely left hemisphere damage,[1,39] it may be hypothesized that the ability to use motor imagery may be impaired in this group. We recently tested the ability to use motor imagery in a group of participants with left and right congenital hemiparesis (age range 14–20y), under the assumption that motor imagery is a prerequisite for motor planning.[40,41] In both studies, three participant groups (children with left or right hemiparesis and a comparison group) performed a mental rotation task. Pictures of rotated hands were shown on a screen and participants had to make a laterality judgement ('is it a right hand or a left hand?') by pressing a corresponding button as quickly as possible. In general, larger stimuli rotation angles led to longer reaction times, indicating that the pictures of the hands are mentally rotated back to a start position. That this mental rotation takes time is evidenced by increased reaction times in the case of increasing rotation angles. In one study[40] we used stimuli of hands that were depicted from a palm view. Thus, in order to make a laterality judgement, two types of mental rotations had to be made. In addition to the 'basic' rotation back to the start position, hands also needed to be rotated 180° along the longitudinal axis of the forearm. The results of this study showed that participants with left hemiparesis and those in the comparison group exhibited the typical linear relation between reaction times and rotation angles of the pictures. This demonstrates that these participants made use of mental rotation to solve the task. However, participants with right hemiparesis did not show this linear relation, suggesting a disorder in using mental rotation. In a follow-up study,[41] we used stimuli of hands viewed from the back of the hand. Consequently, the displayed hands needed to be mentally rotated back along only one axis, in other words only back to the start position. In this study, all three groups showed the linear relations between reaction time and angle of rotation of the stimuli. Thus, from this study it may be concluded that participants with CP are able to use some form of mental rotation to solve the task. However, did they do so from a first-person perspective or third-person perspective? Crucially, if a 'first-person' perspective was utilized, i.e. if they really used motor imagery and not an alternative strategy, laterality judgements should be constrained by the biomechanical properties of the body. In hemiparesis, one of the body sides is affected, and movements and rotations of this side are slower than on the less affected side. Thus, if participants were indeed engaged in imagery from a first-person perspective, their judgements of rotated hands of the affected side should be slower. However, this was not evident from the data, suggesting that the ability to mentally rotate stimuli is still intact in participants with hemiparesis, but that this may be done not from a 'first-person' perspective, but from a 'third-person' perspective.

From these collective findings, two conclusions can be drawn that have implications for the use of motor imagery training in CP. First, more complex mental rotations along more than one axis, as was the case in our first study,[40] may not be possible for individuals with right hemiparesis (left brain damage). This finding is in line with behavioural studies showing that complex sequential action performance is compromised in participants with right hemiparesis.[2,39] Thus, if complexity of the mental rotation task increases, participants with right hemiparesis are not able to make the transformations/rotations that are necessary for mental imagery. A similar result was recently found in children with severe DCD (scoring below the 5th centile on the Movement Assessment Battery for Children) and mild DCD (scoring between the 6th and the 15th centile).[42] Whereas the children with severe DCD displayed a general motor imagery deficit, children with mild DCD had a compromised motor imagery ability for complex tasks only, and not for simple tasks. Taken collectively, the results of our studies in CP and others in DCD suggest that motor imagery training in individuals with CP should use simple displays. Stimuli that need transformations from multiple axes may severely hinder the mental rotation capacity, and consequently an alternative strategy may be used.

Second, an important lesson from these studies is that engagement is crucial for motor imagery to be effective (for a similar argumentation in poststroke rehabilitation see Simmons et al.[43]). That is, participants need to rotate stimuli from the first person perspective. If participants use such a strategy, similar neural networks are active as in actual action performance, which is a prerequisite for motor imagery training to be effective. The alternative strategy of visual imagery predominantly activates visual areas in the brain.

Engagement can be facilitated by instructing participants to rotate stimuli from a first-person perspective. It should be pointed out that no specific instruction was given to participants in our studies[41,42] to rotate the hands from a 'first-person' perspective. Nonetheless, it has been suggested that such an instruction is crucial to engage a participant into such a strategy[44] and that engagement of an individual into mentally representing the action from a 'first-person' perspective is a key for motor imagery training to be effective.[43] Additionally, standardized questionnaires that assess imagery ability, such as the Vividness of Movement Imagery Questionnaire, can be used to identify appropriate candidates for training. The scores on these questionnaires can be used as an exclusion criterion, such that only individuals who have the ability to use motor imagery are included.

A final note of caution about the interpretation of the motor imagery studies in CP should be made here. It was also a facet of the study that participants with CP were generally slower in their laterality judgements than were the comparison group. Therefore, we cannot completely rule out the possibility that they may have used motor imagery, but were generally slower in their judgement. In line with this argument, Johnson et al.[45] showed that patients with chronic densely hemiplegic stroke retain the ability to internally simulate limb movements (motor imagery) of which they are no longer physically capable. In summary, before implementing motor imagery training in individuals with CP, a first step is to scrutinize the motor imagery ability in this group meticulously such that a better picture of the specific motor imagery deficit can be provided as well as the hemispheric differences related to this deficit.

Can we use motor imagery training in young children?

Once the particulars of the motor imagery capacity in CP are clearer, training protocols can be developed. As there have been no clinical trials on motor imagery training in children with CP, rehabilitation protocols are not available. When developing a new rehabilitation protocol, several issues need to be resolved first, which may in part be informed by what is known from studies on motor imagery training in stroke or DCD. These issues are related to the type of motor imagery training, frequency and duration of motor imagery training, and inclusion and exclusion criteria (age, attention/motivation, severity of deficit). First, as children with CP are clearly different from older individuals with acquired brain damage, protocols for motor imagery training need to be 'child friendly'. Obviously, children need to be trained in tasks that are close to their daily experience. For example, they may be instructed to imagine picking up their favourite toy (or a puppet) and placing it in a particular way in a box.[46,47] Second, the duration of a motor imagery training session should not be too great. It is better to have multiple short sessions than to have one long session as long sessions carry the risk of being too demanding in terms of attention and motivation. With respect to these factors, Gordon et al.,[48] examining the effect of age on the efficacy of constraint-induced movement therapy in two groups of children (aged 4–8y and 9–13y), noted that the younger children needed more redirections to attend to the task and were less motivated than the older children to achieve the goals. These observations are important as the goal of motor imagery may be even more abstract, or remote, for young children.

Molina et al.[47] showed that the capacity to form a mental image of their own movement emerges in children at age 7 years. In their study, children aged 5 years could not be engaged in a motor imagery process. Furthermore, Funk et al.[46] showed that imagery in children aged 5 and 6 years is strongly dependent on posture. In two separate experiments, young children (5–6y) were tested on a mental rotation task with pictures of cars ('is the car driving to the left or to the right?') or hands ('is it a left or a right hand?'). Of the 20 children tested, 12 achieved a score higher than expected by chance in the hands task (the corresponding result in the car task was achieved in 20 of 22 children). Hence, at this age approximately half of children are able to use motor imagery. Furthermore, studies in children (8–12y) with DCD have found a compromised motor imagery ability,[49] and this motor imagery deficit was related to the degree of motor impairment.[42] In a training study in children with and without DCD (7–12y), however, it was shown that motor clumsiness in these children was ameliorated to the same extent after motor imagery training and physical training.[38] Thus, motor imagery training can be effective in children as young as 7 years, but engagement is crucial and, therefore, instructions should be very explicit. Clearly, the exact age at which children are able to use motor imagery is still not established.

Thus, more studies in younger children need to be conducted first, as there is currently little developmental information as to the exact age at which children can reliably use motor imagery. In addition, motor imagery training in CP should commence with older children first, and then work backwards to assess the minimum age for motor imagery training in CP to be effective. Clearly, as in constraint-induced movement therapy, it may be expected that there is an advantage to starting such training as early as possible in order to have a long-term benefit.

Taken collectively, based on the combined findings from the neuroscience literature[16,18,19] and behavioural studies in children with CP[4,40,41] and DCD,[38] two predictions may be made considering the efficacy of motor imagery training in children with CP. First, motor imagery training will be especially efficient for improving motor planning. Second, motor imagery training will be most effective in children with right hemisphere damage; its efficacy in children with left hemisphere damage may be questionable. These two predictions warrant empirical testing. Another empirical question is the extent to which improvements in movement execution at the affected side can be expected. It is conceivable that actions learned with the less affected upper extremity can be used to improve performance of the more affected upper extremity.[50] This form of motor imagery is termed 'kinematic mirroring' and is incorporated into intensive training protocols such as constraint-induced movement therapy and bimanual training.[9]

CONCLUSION

Motor imagery training may be a valuable additional tool for rehabilitation in children with hemiparetic CP. At present, the use of this rehabilitation tool has not been explored in this group of participants, but it is a theoretically feasible method to activate motor networks involved in motor planning. Results of clinical studies in patients with acquired brain damage (stroke) and DCD are promising in this respect. An additional advantage of this training is that it will include participants that are normally excluded from physical movement programmes owing to limited physical capabilities. The exact age at which this specific training should start, as well as the way in which engagement can be promoted, needs further study before this therapeutic intervention technique can be implemented in children with CP.

REFERENCES

1. Steenbergen B, Gordon AM. Activity limitation in hemiplegic cerebral palsy: evidence for disorders in motor planning (review). *Dev Med Child Neurol* 2006; **48:** 780–83.
2. Mutsaarts M, Steenbergen B, Bekkering H. Anticipatory planning deficits and task context effects in hemiparetic cerebral palsy. *Exp Brain Res* 2006; **172:** 151–62.
3. Steenbergen B, Hulstijn W, Dortmans S. Constraints on grip selection in cerebral palsy: minimising discomfort. *Exp Brain Res* 2000; **134:** 385–97.
4. Steenbergen B, Meulenbroek RGJ, Rosenbaum DA. Constraints on grip selection in hemiparetic cerebral palsy: effects of lesional side, end-point accuracy, and context. *Cogn Brain Res* 2004; **19:** 145–59.
5. Schluter ND, Krams M, Rushworth MFS, Passingham MFS. Cerebral dominance for action in the human brain: the selection of actions. *Neuropsychologia* 2001; **39:** 105–13.
6. Eliasson AC, Krumlinde-Sundholm L, Shaw K, Wang C. Effects of constraint-induced movement therapy in young children with hemiplegic cerebral palsy: an adapted model. *Dev Med Child Neurol* 2006; **47:** 266–75.
7. Taub E, Ramey SL, DeLuca S, Echols K. Efficacy of constraint-induced movement therapy for children with cerebral palsy with asymmetric motor impairment. *Pediatrics* 2004; **113:** 305–12.
8. Charles J, Gordon AM. Development of hand–arm bimanual intensive training (HABIT) for improving bimanual coordination in children with hemiplegic cerebral palsy. *Dev Med Child Neurol* 2005; **48:** 931–36.
9. Gordon AM, Schneider JA, Chinnan A, Charles JR. Efficacy of a hand–arm bimanual intensive therapy (HABIT) in children with hemiplegic cerebral palsy: a randomized control trials. *Dev Med Child Neurol* 2007; **49:** 830–38.
10. Decety J, Grezes J. Neural mechanisms subserving the perception of human actions. *Trends Cogn Sci* 1999; **3:** 172–78.
11. Sharma N, Pomeroy VM, Baron JC. Motor imagery: a backdoor to the motor system after stroke? *Stroke* 2006; **37:** 1941–52.
12. Crammond DJ. Motor imagery: never in your wildest dream. *Trends Neurosci* 1997; **20:** 54–57.
13. Zacks JM. Neuroimaging studies of mental rotation: a meta-analysis and review. *J Cogn Neurosci* 2008; **20:** 1–19.
14. Jackson PL, Lafleur MF, Malouin F, Richards CL, Doyon J. Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. *NeuroImage* 2003; **20:** 1171–80.
15. Hanawaka T, Immisch I, Toma K, Dimyan MA, van Gelderen P, Hallet M. Functional properties of brain areas associated with motor execution and imagery. *J Neurophysiol* 2003; **89:** 989–1002.
16. Johnson-Frey SH. Stimulation through simulation? Motor imagery and functional reorganization in hemiplegic stroke patients *Brain Cogn* 2004; **55:** 328–31.
17. Hashimoto R, Rothwell JC. Dynamic changes in corticospinal excitability during motor imagery. *Exp Brain Res* 2003; **125:** 75–81.
18. Fadiga L, Buccino G, Graighero L, Fogasso L, Gallese V, Pavesi G. Corticospinal excitability is specifically modulated by motor imagery: a magnetic stimulation study. *Neuropsychologia* 1999; **37:** 147–58.
19. Stinear CM, Fleming MK, Barber PA, Byblow WD. Lateralization of motor imagery following stroke. *Clin Neurophysiol* 2007; **118:** 1794–801.
20. Gentili R, Papaxanthis C, Pozzo T. Improvement and generalization of arm motor performance through motor imagery practice. *Neuroscience* 2006; **137:** 761–72.
21. Feltz DL, Landers DM. The effects of mental practice on motor skill learning and performance: a meta-analysis. *J Sport Psychol* 1983; **5:** 25–57.

22. Driskell JE, Copper C, Moran A. Does mental practice enhance performance? *J Appl Psychol* 1994; **79:** 481–92.

23. Zijdewind I, Toering ST, Bessem B, van der Laan O, Diercks RL. Effects of imagery motor training on torque production of ankle plantar flexor muscles. *Muscle Nerve* 2003; **28:** 168–73.

24. Mulder T. Motor imagery and action observation: cognitive tools for rehabilitation. *J Neural Transm* 2007; **114:** 1265–78.

25. Glover S. Visual illusions affect planning but not control. *Trends Cogn Sci* 2002; **6:** 288–92.

26. Creem SH, Proffitt DR. Grasping objects by their handles: a necessary interaction between cognition and action. *J Exp Psychol Hum Percept Perform* 2001; **27:** 218–28.

27. Braun SM, Beurskens AJ, Brom PJ, Schack T, Wade DT. The effects of mental practice in stroke rehabilitation: a systematic review. *Arch Phys Med Rehabil* 2006; **87:** 842–52.

28. Page SJ, Levine P, Sisto SA, Johnston MV. A randomized efficacy and feasibility study of imagery in acute stroke. *Clin Rehabil* 2001; **15:** 233–40.

29. Ietswaart M, Johnston M, Dijkerman HC, et al. Recovery of hand function through mental practice: a study protocol. *BMC Neurol* 2006; **6:** 1–7.

30. Page SJ, Levine P, Leonard AC. Mental practice in chronic stroke: results of a randomized, placebo-controlled trial. *Stroke* 2007; **38:** 1293–97.

31. Dijkerman HC, Ietswaart M, Johnston M, MacWalter RS. Does motor imagery training improve hand function in chronic stroke patients? A pilot study *Clin Rehabil* 2004; **18:** 538–49.

32. Liu KP, Chan CC, Lee TM, Hui-Chan CW. Mental imagery for promoting relearning for people after stroke: a randomized controlled trial. *Arch Phys Med Rehabil* 2004; **85:** 1403–08.

33. Page SJ. Imagery improves motor function in chronic stroke patients with hemiplegia: a pilot study. *Occup Ther J Res* 2000; **20:** 200–15.

34. Crosbie JH, McDonough SM, Gilmore DH, Wiggam MI. The adjunctive role of mental practice in the rehabilitation of the upper limb after hemiplegic stroke: a pilot study. *Clin Rehabil* 2004; **18:** 60–68.

35. Butler AJ, Page SJ. Mental practice with motor imagery: evidence for motor recovery and cortical reorganization after stroke. *Arch Phys Med Rehabil* 2006; **87**(Suppl. 2): S2–11.

36. Gaggiogi A, Meneghini A, Morganti F, Alcaniz M, Riva G. A strategy for computer-assisted mental practice in stroke rehabilitation. *Neurorehabil Neural Repair* 2006; **20:** 503–07.

37. Stevens JA, Stoykov MEP. Using motor imagery in the rehabilitation of hemiparesis. *Arch Phys Med Rehabil* 2003; **84:** 1090–92.

38. Wilson PH, Thomas PR, Maruff P. Motor imagery training ameliorates motor clumsiness in children. *J Child Neurol* 2002; **17:** 491–98.

39. Crajé C, van der Kamp J, Steenbergen B. Visual information for action planning in left and right congenital hemiparesis. *Brain Res* 2009; **1261:** 54–64.

40. Mutsaarts M, Steenbergen B, Bekkering H. Impaired motor imagery in right hemiparetic cerebral palsy. *Neuropsychologia* 2007; **45:** 853–59.

41. Steenbergen B, van Nimwegen M, Crajé C. Solving a mental rotation task in congenital hemiparesis: motor imagery versus visual imagery. *Neuropsychologia* 2007; **45:** 3324–28.

42. Williams J, Thomas PR, Maruff P, Wilson PH. The link between motor impairment level and motor imagery ability in children with developmental coordination disorder. *Hum Mov Sci* 2008; **27:** 270–85.

43. Simmons L, Sharma N, Baron JC, Pomeroy VM. Motor imagery to enhance recovery after stroke: who might benefit, daily dose, and potential effects. *Neurorehabil Neural Repair* 2008; **22:** 458–67.

44. Sirigu A, Duhamel L. Motor and visual imagery as two complementary but neurally dissociable mental processes. *J Cogn Neurosci* 2001; **13:** 910–19.

45. Johnson SH, Sprehn G, Saykin AJ. Intact motor imagery in chronic upper limb hemiplegics: evidence for activity-independent action representations. *J Cogn Neurosci* 2002; **14:** 841–52.

46. Funk M, Brugger P, Wilkening F. Motor processes in children's imagery: the case of mental rotation of hands. *Dev Sci* 2005; **8:** 402–08.

47. Molina M, Tijus C, Jouen F. The emergence of motor imagery in children. *J Exp Child Psychol* 2008; **99:** 196–209.

48. Gordon AM, Charles JR, Wolf SL. Efficacy of constraint-induced movement therapy on involved upper-extremity use in children with hemiplegic cerebral palsy is not age-dependent. *Pediatrics* 2006; **117:** E363–73.

49. Wilson PH, Maruff P, Butson M, Williams J, Lum J, Thomas PR. Internal representation of movement in children with developmental coordination disorder: a mental rotation task. *Dev Med Child Neurol* 2004; **46:** 754–59.

50. Gordon AM, Charles J, Steenbergen B. Fingertip force planning during grasp is disrupted by impaired sensorimotor integration in children with hemiplegic cerebral palsy. *Pediatr Res* 2006; **60:** 587–91.