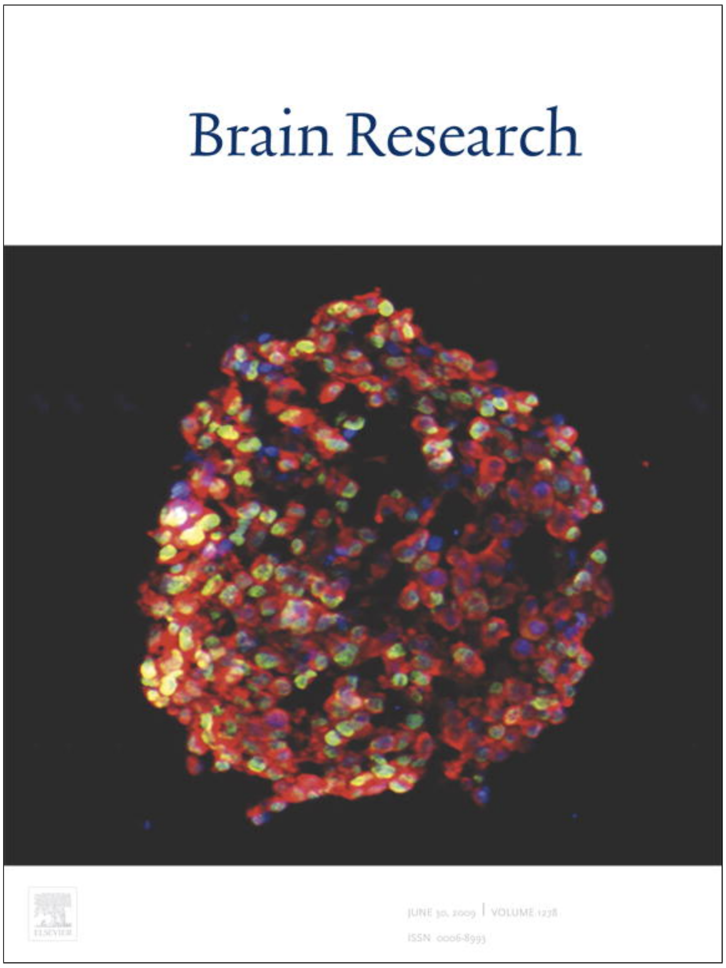

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Research Report

Facilitation of motor imagery through movement-related cueing

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ABSTRACT

In the past few years, the use of motor imagery as an adjunct to other forms of training has been studied extensively. However, very little attention has been paid to how imagery could be used to greatest effect. It is well known that the provision of external cues has a beneficial effect on motor skill acquisition and performance during physical practice. Since physical execution and mental imagery share several common mechanisms, we hypothesized that motor imagery might be affected by external cues in a similar way. To examine this, we compared the motor imagery performance of three groups of 15 healthy participants who either physically performed or imagined performing a goal-directed cyclical wrist movement in the presence or the absence of visual and/or auditory external cues. As outcome measures, the participants' imagery vividness scores and eye movements were measured during all conditions. We found that visual movement-related cues improved the spatial accuracy of the participants' eye movements during imagery, while auditory cues specifically enhanced their temporal accuracy. Furthermore, both types of cues significantly improved the participants' imagery vividness. These findings indicate that subjects may imagine a movement in a better way when provided with external movement-related stimuli, which may possibly be useful with regard to the efficiency of mental practice in (clinical) training protocols.

1. Introduction

Mental imagery is defined literally as "the ability to form pictures in the mind". A specific type of mental imagery is motor imagery, which can be defined as mental rehearsal of a motor act in the absence of overt motor output (Crammond, 1997). Motor imagery can be performed in either a visual (i.e. 'seeing' a movement) or kinesthetic way (i.e. 'feeling' a movement), and from a first-person (i.e. imagery of one's own movement) or third-person perspective (i.e. seeing someone else move). Previous studies have shown that these different modalities are mediated through (partly)

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separate neural systems (Guillot et al., in press; Jackson et al., 2006). In the present study, we specifically studied visual motor imagery from a first-person perspective. This can be defined as envisioning oneself in action by picturing movement of one's own body (parts) in interaction with the external world.

Mental practice, based on visual motor imagery, has been shown to lead to improvements in the performance of athletes, musicians and highly skilled technicians (Lotze and Halsband, 2006; Rogers, 2006). Furthermore, it can be of use in the rehabilitation of patients with neurological disorders (Braun et al., 2006; de Vries and Mulder, 2007; Johnson-Frey, 2004; Sharma et al., 2006). Although the beneficial effect of motor imagery has been shown in both normal and pathological functioning, to date very little attention has been paid to how imagery can be applied most effectively. In the present study, we address the effectiveness of motor imagery with respect to the provision of external movement-related cues. In line with Nieuwboer et al. (2007), we defined cueing as external temporal or spatial stimuli to facilitate initiation and continuation of movement (in our case, imagery of movement).

Up to now, in the motor imagery literature, no specific differentiation has been made between cued and non-cued practice. In fact, the instructions for executing the motor imagery tasks differed considerably across studies. In some studies, participants were provided with visual information to facilitate their imagery performance (Gaggioli et al., 2004; Liu et al., 2004), while in other studies subjects were explicitly instructed to look at a blank screen, perform the task in darkness or close their eyes during imagery (Rodionov et al., 2004; Stevens and Stoykov, 2003; Yoo et al., 2001). Similarly, in some studies the to-be-imagined movements were accompanied by rhythmic auditory cues (Gaggioli et al., 2004), while in others they were not.

During actual physical practice, however, the effect of external information on motor control and motor learning is well known (Newell et al., 1985). For instance, Verschueren et al. (1997), and Hurley and Lee (2006) showed that presenting augmented visual information about the movement enhances quality of performance and motor skill acquisition. Similarly, performance of rhythmic movements benefits from auditory cues (Semjen et al., 2000). Also in rehabilitation of patients with neurological conditions, the use of external cueing is known as an efficient method to facilitate motor performance (Curra et al., 2000; Nieuwboer et al., 2007; Rubinstein et al., 2002).

Although no actual movement is made during imagery, it has been shown that motor imagery and physical execution have various characteristics in common. Decety (1993), Gentili et al. (2004), and Papaxanthis et al. (2002) have shown that the time taken to mentally represent a given movement closely mimics the duration of the same movement when it is physically executed. Motor imagery also causes similar autonomic changes (e.g. changes in heart rate and respiratory frequency) as physically executed movements (Roure et al., 1998) and seems to be constrained by the same motor laws that apply to physical execution of the movement, such as Fitts's law (Decety and Jeannerod, 1996; Maruff et al., 1999). Other striking parallels are the common neural substrate of executed and imagined movements (Decety, 1996) and the fact that learning a motor task through motor imagery practice produces cerebral functional changes similar to those after physical practice of the same task (Jackson et al., 2003; Lafleur et al., 2002). Since physical and mental practice obviously share several aspects, we hypothesize that, similar to physical execution, external cueing can also play an important role to optimize motor imagery. This hypothesis may be of special importance when implementing imagery in the rehabilitation of neurological patients in general, and in patients with Parkinson's disease in specific, as it is known that their physical motor performance is highly influenced by the provision of external cues (Nieuwboer et al., 2007; Siegert et al., 2002).

To address this question, we carried out an experiment in which subjects imagined performing as well as physically performed a cyclical goal-directed aiming task at three different amplitudes, and this either in the presence or absence of visual and/or auditory cues. To evaluate the motor imagery performance, eye movements were measured during all conditions, since it was demonstrated in previous studies that eye movements can be regarded as an indicator of motor imagery (Heremans et al., 2008; Papadelis et al., 2007). Furthermore, we asked the participants to rate their imagery vividness. If external cues facilitate motor imagery, this would be reflected in more accurate eye movements and in higher vividness during imagery in the presence of cueing.

2. Results

2.1. *Number of eye movements*

During physical execution, all subjects showed a consistent number of eye movements during all three series of inter-target distances in all groups. During the imagery conditions, however, for six out of 45 subjects, the number of eye movements was lower than the criterion (see section 4.6). These subjects had an average number of eye movements of 47.9 ± 19.8% during imagery with the eyes open and of 65.9 ± 43.6% during imagery with the eyes closed. The six subjects were equally divided between the three experimental groups.

For the remaining 39 subjects, a clearly task-related eye-movement pattern was observed when subjects imagined the movements, either with their eyes open or with their eyes closed, during all cueing conditions. In Fig. 1 a typical example of the hand and eye-movement pattern during execution (Figs. 1A and B) and of the eye-movement pattern during imagery with the eyes open (Fig. 1C), imagery with the eyes closed (Fig. 1D) and rest (Fig. 1E) is given.

The ANOVA revealed no effects for inter-target distance, indicating that the number of eye movements did not depend on the distance that had to be covered. A significant main effect was obtained for Condition ($F(3,108) = 104.7$; $p < 0.01$). For all groups, the number of eye movements during rest was significantly smaller than during physical execution, imagery with the eyes open and imagery with the eyes closed, while no significant differences in the number of eye movements were found between the last three conditions (Fig. 2). Furthermore, a significant Group × Condition interaction was obtained ($F(6,108) = 2.5$; $p < 0.05$). Subsequent analysis per group did not

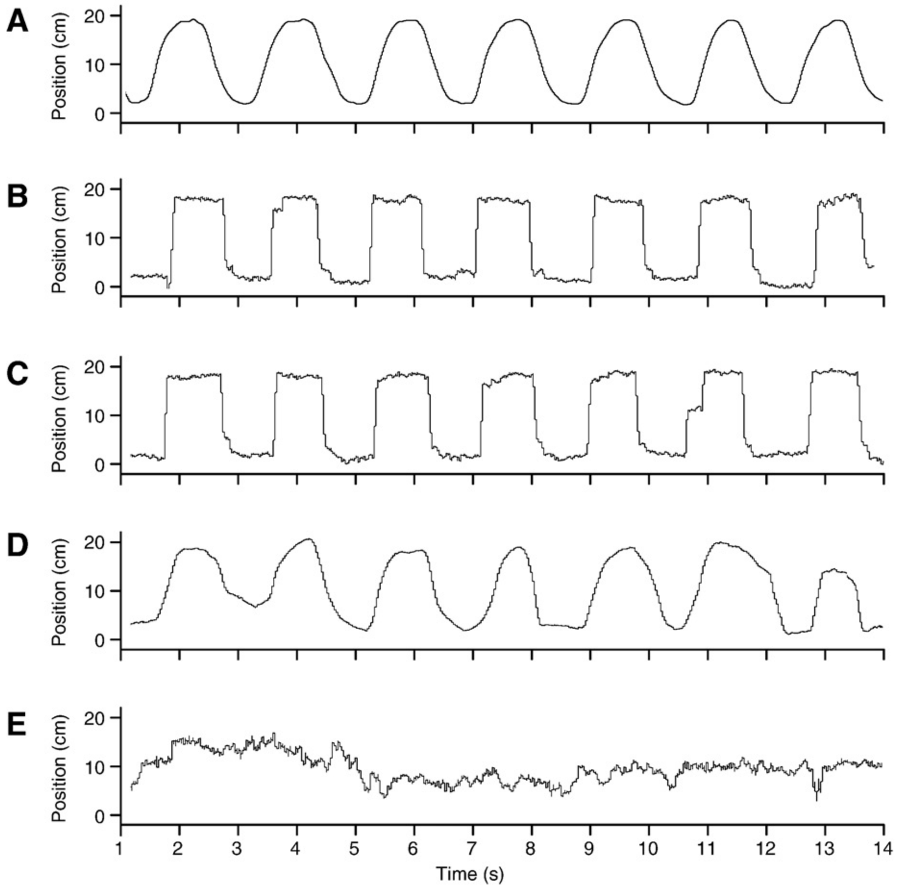

Fig. 1 – An example of the hand-movement pattern during physical execution (A) and eye-movement patterns during physical execution (B), imagery with the eyes open (C), imagery with the eyes closed (D) and rest (E) as a function of time for a typical trial in the VIS+AUD group. Position is expressed in cm 'on screen'.

reveal any simple effects regarding this interaction, suggesting that there was no difference in the number of eye movements between the execution and imagery conditions and that this accounted for all three groups. On the other hand, post-hoc analyses of the simple effects per condition revealed differences between groups: for imagery with the eyes open, the number of eye movements was higher in the VIS+AUD group than in the AUD group, while during the rest condition the reverse was found (Fig. 2).

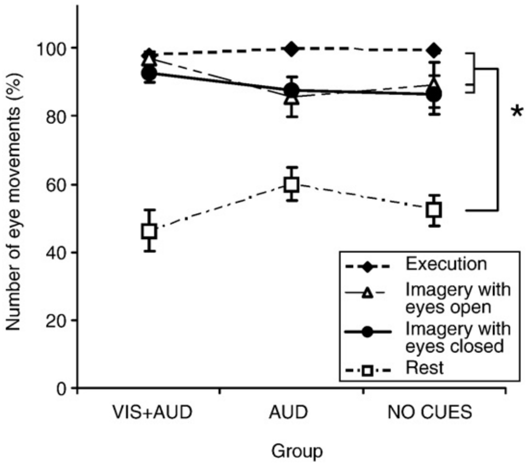

Fig. 2 – Number of eye movements per group per condition ($n = 13$ per group, mean ± 1 S.E.M.). Statistical significance ($p < 0.05$) is indicated by *. Note that, since the standard errors of the mean during the execution conditions were so small, they are not visible in the figure.

2.2. *Eye-movement amplitudes*

A significant interaction effect was found for Inter-target Distance × Condition ($F(4,144) = 25.8$; $p < 0.01$). Post-hoc analyses per condition showed that, for execution and imagery with the eyes open, the amplitudes of the eye movements differed significantly between all inter-target distances. As shown in Fig. 3, the amplitude of the eye movements adapted to the required inter-target distance during those two conditions. As expected, during the rest condition the amplitudes did not differ between inter-target distances, indicating that, during this condition, eye movements were made at random amplitudes.

In addition, a significant interaction between condition and group was found ($F(4,72) = 6.08$; $p < 0.01$). Post-hoc analyses per group showed that, for the AUD+VIS group, no significant differences between conditions were found, indicating similar eye-movement amplitudes during the execution and imagery

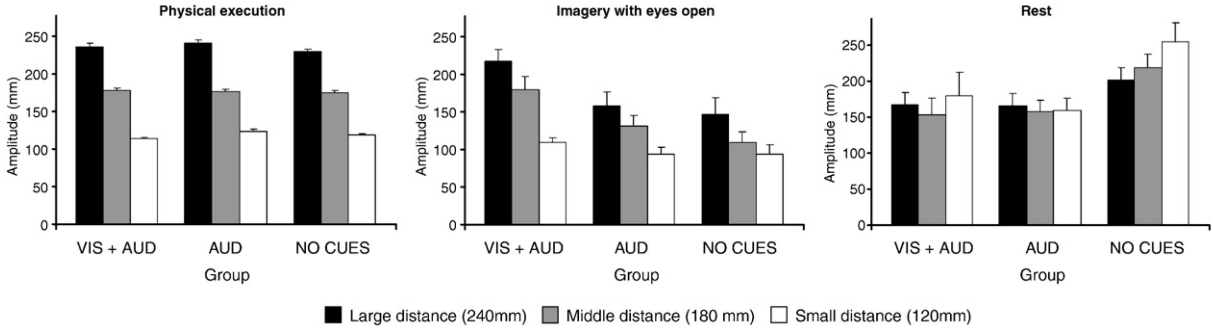

Fig. 3 – Eye-movement amplitudes per condition for the large (240 mm), middle (180 mm) and small (120 mm) inter-target distances for each group ($n = 13$ per group, mean ± 1 S.E.M.).

condition for this group. For the AUD and NO CUES groups, however, the amplitudes of the eye movements differed significantly between conditions. Fig. 3 shows that in the absence of visual cues (AUD and NO CUES groups), the eye-movement amplitudes were smaller in the imagery condition than in the physical execution condition. However, as mentioned previously, the significant interaction between condition and inter-target distance shows that, despite this underestimation, during imagery with the eyes open the eye-movement amplitudes nevertheless adapted gradually to changes in the size of the required movement distances.

2.3. *Eye-movement times*

A significant interaction effect was found for Inter-target distance × Condition ($F(6,72) = 3.42$; $p < 0.01$). Post-hoc tests showed a main effect for inter-target distance during physical execution, but not during the other conditions. A significant interaction effect was also found for Condition × Group ($F(6,108) = 5.89$; $p < 0.01$). Further analyses showed that for both the AUD + VIS group and the AUD group the movement times during imagery with the eyes open did not differ significantly from those during execution. During imagery with the eyes closed, however, movement times were significantly larger than those during physical execution and imagery with the eyes open. During the rest condition, the movement times always differed significantly from all other conditions. In the NO CUES group (i.e., the only group that did not receive temporal cues during imagery), the resemblance in movement time between imagery with the eyes open and physical execution was not present. In fact, significant differences in movement times were found between all conditions for this group.

2.4. *Movement imagery questionnaires*

At the start of the experiment, all subjects completed the revised version of the Movement Imagery Questionnaire (MIQ-R) (Hall and Martin, 1997). The subjects of the three groups all rated their imagery ability as good. The VIS + AUD group had a global mean score per item of 5.3 (SD = 0.7), the AUD group of 5.1 (SD = 0.8), and the NO CUES group of 5.4 (SD = 0.8). Mean scores for the visual imagery items only were 6.1 (SD = 0.7), 5.9 (SD = 0.9) and 6.0 (SD = 0.8), respectively. The results of the one-way ANOVAs showed no significant differences neither between the groups for all items nor for the visual items only. This indicates that the subjects of the three experimental groups had similar imagery abilities.

In the task-specific questionnaire, completed after finishing the experimental task, to examine the subjects' imagery performance during each of the imagery conditions, all subjects reported that they had experienced clear visual images from a first-person perspective of the to-be-imagined movements. Interestingly, their imagery vividness scores for imagery with the eyes open differed significantly among groups ($F(2,38) = 3.56$; $p = 0.04$). Post-hoc Scheffé tests showed that, in terms of imagery vividness, subjects scored higher for eyes-open in the AUD + VIS group ($M = 5.4 \pm 1.4$) than in the AUD group ($M = 5.00 \pm 0.8$), and in the AUD group compared to the NO CUES group ($M = 4.2 \pm 1.4$). This indicates that, when hand movements were imagined with the eyes open, imagery was more vivid when external cues were provided than when such cues were absent. In contrast, no significant differences between groups were found for imagery with the eyes closed (AUD + VIS group: $M = 5.4 \pm 1.5$; AUD group: $M = 5.5 \pm 0.8$, NO CUES group: $M = 5.5 \pm 0.8$).

3. Discussion

It has been shown in the past that mental practice, based on motor imagery, can be a useful training method (Lotze and Halsband, 2006). However, up to the present, it remains unclear how motor imagery can be applied most effectively. Since we know from previous research that external cues can facilitate physical execution (Semjen et al., 2000; Verschueren et al., 1997), we hypothesized that the provision of external cues can also be of value during motor imagery. Therefore, the main objective of the present study was to examine potential differences in imagery quality during externally cued and non-externally cued motor imagery. For this purpose, the eye-movement patterns and vividness scores were compared between subjects who received both auditory pacing and visual information concerning the hand movement that had to be imagined, subjects who received only auditory information, and subjects who received no external guidance at all.

3.1. *Eye movements during motor imagery*

Overall, it was found that 87% of the subjects tested made task-related eye movements during imagery, irrespective of the auditory and visual cues offered. The limited number of participants (six out of 45) that did not show consistent eye movements during imagery conditions was equally distributed across groups. For the remaining 87% of subjects, the number of eye movements during imagery, either with the eyes open or the eyes closed, did not in general differ significantly from the number of eye movements made during physical execution, whereas it did differ significantly from the number of eye movements made during rest (Fig. 2). Furthermore, the eye-movement amplitudes changed according to changes in the distance to-be-imagined during imagery with the eyes open, which was not the case during rest (Fig. 3). Both findings indicate that the eye movements observed during both cued and non-cued imagery were task-related, whilst those during rest were made at random. This makes us assume that eye movements are related to the motor imagery process itself, instead of being merely elicited by external cues. (Note, though, that a significant difference was observed between the VIS+AUD group and the AUD group in the imagery-with-the-eyes-open condition, which will be discussed in the next section.)

As such, our findings extend previous findings on action execution and observation, that show a robust coupling between gaze and hand movements, to the field of visual motor imagery (Flanagan and Johansson, 2003; Helsen et al., 1998). In a recent study of Gueugneau et al. (2008), the presence of such a coupling was also shown for kinesthetic motor imagery. The fact that similar eye movements occur during perception, imagery and physical execution further supports the idea that these three processes rely on similar motor programs. In this respect, Flanagan and Johansson (2003) suggested that the task-specific eye movements witnessed during action observation are probably linked to parts of the neural processes that account for planning and control of manual action. The same mechanism may account for eye movements observed during motor imagery. Support for these hypotheses can be found in neuroimaging studies, where an overlap in brain activation during observation, imagery and physical action has been shown (Grèzes and Decety, 2001).

A limitation of the use of eye-movement registration to evaluate motor imagery, however, is the fact that 13% of the participants showed a lack of consistent eye movements during the imagery tasks. This finding is in agreement with findings of previous studies on eye movements during imagery. Rodionov et al. (2004) reported horizontal eye movements in 75% of the recordings when subjects imagined body rotation. In the remaining 25% of the recordings no definite eye movements were detected during the mental maneuvers. Similarly, Heremans et al. (2008) reported that a minority of 11% of the subjects did not make task-related eye movements during motor imagery of goal-directed wrist movement, while the remaining 89% did. The reason of this altered eye-movement behaviour in a minority of subjects remains unclear. Since these subjects reported high vividness scores during imagery, it seems unlikely that their lack of eye movements reflects a complete inability to produce imagery. However, it is possible that they could not sustain attention for the complete duration of the imagery task. Other explanations can be that these subjects used a different strategy during imagery – possibly based more on kinesthetic than visual sensations or increased use of peripheral vision – making overt eye movements redundant. The latter is not unlikely, since the visual angle was small so that peripheral vision was sufficient to imagine the movement. These hypotheses, however, need further investigation.

3.2. *External cueing and the quality of motor imagery*

Although in general the number of eye movements during imagery did not differ from its number during physical execution, results indicated that the number of observed eye movements was in fact affected by cueing: when subjects imagined the movement with the eyes open, the presence of visual cues enhanced the occurrence of eye movements. Furthermore, the present findings revealed that the accuracy of the eye movements during motor imagery improved by providing the subjects with external cues. In the current context, these cues concerned temporal and spatial parameters of the (imagined) movement. In the presence of visual cues, concerning the spatial aspects of the task, the accuracy of the eye-movement amplitudes (i.e. spatial parameter) did not differ between imagery with the eyes open and physical execution of the task. In the absence of these cues, however, subjects tended to underestimate the distance that had to be covered during imagery. Nevertheless, the eye-movement amplitude still increased when the amplitude of the to-be-imagined hand movement increased. Auditory cues, offered by a metronome, also caused significant effects on motor imagery: as long as these temporal cues were provided, the movement times of the eye movements did not significantly differ between imagery with the eyes open and physical execution, while in the absence of this auditory pacing, eye movements during imagery were significantly slower than those observed during execution of the task.

Besides these effects on the spatial and temporal characteristics of the subjects' eye movements, effects of external cueing were also observed in the results of the imagery questionnaire filled out after the experiment. For imagery with the eyes open, imagery vividness scores were higher in the presence of external cues than in their absence. With the eyes closed, however, no differences were found. These findings indicate that subjects may imagine a movement in a better way when provided with external movement-related stimuli. In sum, given that eye-movement patterns may reflect (the quality of) motor imagery ability and compliance (Heremans et al., 2008), both the eye movement results and the imagery vividness scores indicate that the provision of movement-related visual and/or auditory cues facilitates the imagery of movement. We therefore hypothesize that the efficacy of motor imagery practice might benefit from the use of such external cues.

A possible explanation for the differences in performance on the cued and non-cued imagery tasks can be found in neurophysiological, clinical and human imaging studies demonstrating that separate neural systems contribute to these types of tasks. The cerebello–thalamo–cortical system appears to be preferentially involved in movements based upon external sensory cues such as those arising from the appearance of a visual target. By contrast, the basal ganglio–thalamo–cortical system appears to be preferentially involved in movements based upon internal cues such as those required to direct the eye and hand to a remembered target location (Cunnington et al., 2002; van Donkelaar et al., 1999, 2000). As such, the provision of external cues during motor imagery might be even more important when imagery is used in the rehabilitation of certain groups of neurological patients with dysfunction of this basal ganglio–thalamo–cortical system, such as patients with Parkinson's disease. Indeed, in these patients, impairments were shown in motor imagery of internally guided movements such as grasping (Frak et al., 2004). It is known that external sensory cues can help patients with Parkinson's disease to compensate for their impairment in physical execution of motor tasks (Siegert et al., 2002). We hypothesize that imagined actions might be facilitated by the provision of external cues in a similar way. Similar to physical execution, also during imagery the provision of a relevant cue may trigger the use of an alternative pathway which is functionally better preserved. Besides, it is well-known that patients with Parkinson's disease exhibit problems with the correct timing and scaling of their movements, which is expressed through a decrease in movement speed and a reduction in movement amplitude. Given the results of the present study, the provision of external temporal and spatial movement-related cues during motor imagery training might also positively affect rehabilitation in relation to such motor disorders.

However, it would be premature to draw final conclusions about the generalizability of the effects of cueing during motor imagery. First of all, the present study was limited to cyclical goal-directed wrist movements only. It remains to be investigated whether discrete goal-directed movement such as in daily life as well as non-goal-directed movements would benefit from external cueing in a similar way. Secondly, this study was limited to healthy persons who all had good imagery ability. Previous studies have shown substantial differences between individuals with good and poor imagery ability, both at the behavioural level and in the pattern of cerebral activation during imagery (Guillot et al., 2008). Therefore, studies in persons with impaired motor imagery are needed to examine whether the effect of cueing on imagery can be generalized to this group or not. Furthermore, future research is needed to determine the optimal modalities (e.g., visual, auditory) and parameters (e.g., rhythm, amplitude) of the external cues. Louis et al. (2008), for example, reported that increasing or decreasing the required motor imagery speed had a strong effect on subsequent movement speed, and this both for new as for highly automatic tasks. As such, we assume that an optimal adaptation of the cueing parameters to each performer's level of expertise and goals is crucial to obtain the desired effect. If these parameters are not carefully selected, providing cues might even disturb the formation of a vivid mental image instead of facilitating it.

In conclusion, both cued and non-cued imagery of a goal-directed aiming task are characterized by eye movements that are largely similar to the ones during actual physical execution of the task. However, the provision of external task-related cues positively affects the accuracy of the eye movements as well as the experienced vividness of the imagined movement. Although caution should be exercised before generalizing these findings to other tasks, our findings indicate that motor imagery may be easier, and possibly also more effective, when the spatial and temporal structure of the movement are provided environmentally rather than through imagery. As such, external cueing may provide potential benefits with respect to motor imagery practice in (clinical) training protocols.

4. Experimental procedures

4.1. *Participants*

Forty five subjects (19 men and 26 women; mean age of 22 years with a range of 18–28 years) voluntarily participated in the study. All subjects were right-handed as measured by the Edinburgh Handedness Inventory (Oldfield, 1971) ($M = 83.1$; $SD = 18.7$), where a laterality quotient of +100 represents extreme right-handedness and a laterality quotient of −100 represents extreme left-handedness. The participants all had normal or corrected-to-normal vision and did not have any known neurological disorders. All subjects were naive about the purpose of the study. The experiment was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and approved by the Committee for Medical Ethics of the Catholic University of Leuven. All subjects gave written informed consent before they participated in the study.

4.2. *Apparatus*

4.2.1. *Eye movements*

The subjects horizontal and vertical eye movements were recorded at a sampling frequency of 1024 Hz using a Porti 7 electro-oculography device (Twente Medical Systems International, Enschede, The Netherlands). After careful skin preparation, Ag–AgCl surface electrodes with a diameter of 5 mm were placed at the inner and outer canthus of the right eye and in the inferior and superior areas of the right orbit. A reference electrode was adhered to the contralateral pelvis. An illustration of the experimental setup is provided in Fig. 4.

4.2.2. *Muscle activity*

The aforementioned Porti 7 device was also used for recording surface EMG activity of wrist flexor and extensor muscles. Following standard skin preparation techniques, 24 mm diameter Ag–AgCl disposable disc surface electrodes (Kendall/Arbo, Tyco Healthcare, Neustadt/Donau, Germany) were placed 2 cm apart over the middle portion of the muscle bellies of the right extensor and flexor carpi radialis muscles, aligned with the longitudinal axis of the muscles. The reference electrode was the same as described for EOG recording. The EMG signal was continuously monitored during the experiment. If any muscular activity was detected during the imagery conditions, participants were immediately instructed to relax their arm, and the trial was repeated.

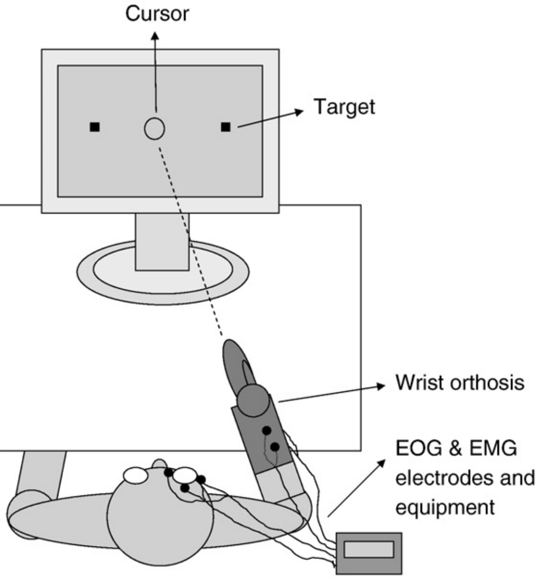

Fig. 4 – Schematic illustration of the experimental setup (top view).

4.2.3. *Wrist kinematics*

The movements of the right wrist were measured using a high precision shaft encoder attached to the axis of a wrist orthosis in which the right hand and forearm of the participant were positioned. This orthosis restricted the wrist movements to flexion and extension. Angular displacements of the limb were registered with an accuracy of 0.09° and a sampling frequency of 200 Hz.

4.3. *Task, conditions and experimental groups*

Subjects were seated in a moderately darkened room, approximately 50 cm in front of a computer screen on which the instructions and visual stimuli were presented (Fig. 4). Head movements were restricted by means of a chinrest and head-support device so that point of gaze was purely reflected by the eye movements. Their right forearm was positioned in a wrist-hand orthosis, which was fixed to a forearm support placed on the table in front of them. The participants had to perform, or imagine performing, a goal-directed cyclical aiming task. During physical execution of the task, two targets, represented by black squares with a diameter of 5 mm, were projected onto the screen. The angular position of the wrist was represented by means of a hollow circle with a diameter of 1 cm. Wrist extension corresponded to the circle moving right and wrist flexion to the circle moving left. Subjects were asked to cyclically move between the two targets at a rhythm of 1 Hz, paced by a metronome. The task was performed using three different inter-target distances (i.e., 120 mm, 180 mm and 240 mm, referred to as small, middle and large inter-target distances). These distances corresponded to wrist movement angles of 12°, 18° and 24°, respectively.

Four different conditions were applied to each inter-target distance: (i) physical execution, (ii) imagery with the eyes open, (iii) imagery with the eyes closed, and (iv) rest. During physical execution the subjects had to physically perform the task as described above under both visual and auditory guidance. During the imagery conditions, visual imagery from a first-person perspective was used. The participants were instructed to visualize seeing their own arm making the goal-directed movements as clearly and vividly as possible, either with the eyes open or the eyes closed, but without actually moving their arm. No instructions were given concerning potential eye movements in order not to influence their spontaneous eye-movement patterns. During rest, the same cues were given as during the corresponding execution and imagery trials, but subjects were asked to relax, while no further task instructions were given.

Subjects were divided in three experimental groups, each consisting of 15 participants. All subjects performed all of the aforementioned experimental conditions but with different auditory and visual cues during the imagery conditions for each group, to prevent for interference effects. The first group (=VIS+AUD group) continuously received both visual and auditory task-related information during all conditions. Visual information was provided by showing the targets, represented by black squares with a diameter of 5 mm projected at a light grey background at a Dell P992 monitor (resolution, 1024×768 pixels; refresh frequency 60 Hz). As auditory cues, metronome beeps with a duration of 5 ms, provided at a rhythm of 1 Hz, were given at a volume which was comfortable to the subject. Data of this first group were published before in detail to describe the presence of eye movements during motor imagery of cyclical hand movements (Heremans et al., 2008). For the present study, additional groups were tested to investigate the differential effects of visual and auditory cues versus no cues on the quality of motor imagery. In the second group (=AUD group), the visual cues were withdrawn during imagery while the auditory pacing remained. Finally, the third group (=NO CUES group) received no visual or auditory cues at all, so that imagery had to be performed with complete internal guidance. During the rest conditions, the same cues were provided as during the imagery conditions in all groups but no task had to be performed.

4.4. *Procedure*

At the start of the experiment, subjects were asked to fill out the revised version of the Movement Imagery Questionnaire (MIQ-R) (Hall and Martin, 1997). In this questionnaire, subjects rate the vividness with which they can imagine certain movements on a 7-point scale, where 1=very hard to see/feel and 7=very easy to see/feel. The MIQ-R consists of eight items, four concerning visual imagery and four concerning kinesthetic imagery. The final score of the subjects can range from 8 (=extremely poor imager) to 56 (=extremely good imager).

Subsequently, the participants were seated in front of the screen and the wrist orthosis and EOG apparatus were calibrated. Thereafter, task instructions were given and subjects performed two practice series to familiarize themselves with the different conditions. These practice trials were not taken into account in the data analysis. After the practice series, the subjects carried out three experimental series, each characterized by a different inter-target distance (i.e. 120 mm, 180 mm and 240 mm). These series were presented in random order. All series started with a physical execution trial, during which the visual targets were shown and the rhythm was paced to indicate the spatial and temporal task requirements of the specific series. During the series, images appeared on the screen for 4 s to indicate which condition would follow. Each series consisted of three physical execution blocks, three rest blocks and six imagery blocks (three with the eyes open and three with the eyes closed), presented in random order. Since each block consisted of 15 wrist movements, 45 movements were recorded per condition. The first and the last wrist movements of each block were excluded from the data analysis. Rest periods of 2 min were provided between series.

After finishing the experimental task, the participants completed a second questionnaire. In this task-related questionnaire, subjects were asked to score their imagery vividness for each of the imagery conditions (i.e. during eyes-open and eyes-closed). The same 7-point scale as employed in the MIQ-R was used, with a score of 1 indicating that the movement was very hard to imagine and a score of 7 that it was very easy to imagine.

4.5. *Dependent variables*

The eye-movement data were analyzed off-line using custom-made procedures based on Matlab® software. Only the horizontal gaze coordinates were taken into consideration, as the hand movements were restricted to the horizontal dimension. The signal of the horizontal eye movements was low-pass filtered (cut-off frequency: 20 Hz). Possible drift of the signal was corrected by a piecewise second order polynomial fit. A fixation of the eyes was defined as a stable gaze position (i.e., with a standard deviation of point of gaze < 1° in the last 100 ms) that was maintained for at least 100 ms (Helsen et al., 1998). The data points at the end and the start of each fixation period were taken as the eye movement start and end points, respectively. The amplitude of the eye movements was determined as the distance traveled by the eyes between the start and end points of the total eye movement. The movement time of the eye movements was defined as the time taken to move between the end point of the previous and the start point of the next fixation. The total eye movement could consist of one single primary saccade or a combination of a primary saccade and one or more corrective saccades. Note that the amplitude of the eye movements could only be measured during physical execution and during imagery with the eyes open. During the imagery-with-the-eyes-closed condition, no precise information about the eye-movement amplitudes could be derived from the data because it was impossible to calibrate the eye-movement position when the eyes were closed. The number of eye movements was counted and expressed in percentages, where 100% represents an eye movement between every two consecutive beeps.

4.6. *Statistical analyses*

For each subject, the mean values and standard deviations of the number, amplitudes and movement times of the eye movements were calculated per experimental condition. The Shapiro–Wilk test was used to check that all variables were normally distributed. Subjects where the mean number of eye movements during imagery with the eyes open or the eyes closed deviated more than two standard deviations from the mean number of eye movements made during imagery were considered as outliers. These subjects were analyzed separately. For all others, the mean number and movement times of the eye movements were submitted to a mixed analysis of variance (ANOVA) with between-subjects factor groups (AUD+VIS, AUD and NO CUES groups) and within-subjects factor inter-target distances (small, middle and large inter-target distances) and condition (physical execution, imagery with the eyes open, imagery with the eyes closed, and rest), with repeated measures on the last two factors. Note that since the eye-movement amplitudes could not be accurately calibrated when the eyes were closed, all data from the imagery with the eyes-closed condition could not be included in the movement amplitudes analysis. Consequently, the differences in eye-movement amplitudes were calculated using a three groups (AUD+VIS, AUD and NO CUES groups) by three inter-target distances (small, middle and large inter-target distances) by three conditions (physical execution, imagery with the eyes open, and rest) mixed ANOVA, with repeated measures on the last two factors. In case of a significant interaction effect, we proceeded with an analysis of the simple effects contributing to the interaction effect (Keppel, 1991). The scores of the MIQ-R and the questionnaire that was filled out at the end of the experiment were analyzed by means of one score by 3 groups (VIS+AUD, AUD and NO CUES groups) one-way ANOVAs. For all comparisons, the statistical significance (α) was set at $p < 0.05$ and post-hoc Scheffé tests were executed when necessary to correct for multiple comparisons.

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