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Research report

The eyes as a mirror of our thoughts: Quantification of motor imagery of goal-directed movements through eye movement registration

Elke Heremans *, Werner F. Helsen, Peter Feys

Katholieke Universiteit Leuven, Faculty of Kinesiology and Rehabilitation Sciences, Department of Biomedical Kinesiology, Tervuursevest 101, 3001 Leuven, Belgium

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Abstract

It has been suggested that motor imagery possesses a range of useful applications in sport as well as in rehabilitation. Until now, research in this field has been hampered by the lack of an objective method to monitor the subjects' participation in the task. In this present study, a new approach to quantifying motor imagery of goal-directed hand movements by means of eye movement registration is examined. Eye movements of 15 right-handed subjects were recorded using EOG during both physical execution and visual motor imagery of a cyclical aiming task, performed at three different inter-target distances. We found that 89% of subjects made task-related eye movements during imagery with the eyes open and 84% of participants also did so during imagery with the eyes closed. Both the number and amplitude of the eye movements during imagery closely resembled those of eye movements made during physical execution of the task. This indicates that the coupling between neural patterns for eye and hand movements remains intact when hand movements are merely imagined as opposed to being physically executed. Therefore, eye movement recordings may be used as an objective technique to evaluate subjects' compliance, motor imagery ability, and spatial accuracy.

Keywords: Eye movements; Motor imagery; Electro-oculography; Visual imagery; Hand movements; Eye–hand coordination

1. Introduction

Imagery is a phenomenon that has intrigued people for a very long time. As far as we know, Aristotle (384–342 B.C.) appears to have been the first to discuss the concept of imagination. In his work "De Anima", he argued that the soul never thinks without an image ('phantasma') [1]. Therefore, he suggested that imagery plays an essential role in all forms of thinking. Since then, imagery has remained a topic of interest for philosophers, and for researchers in the cognitive and behavioural sciences.

Despite being a familiar word in everyday language, imagery is a very complex concept, which appears to have radically different meanings and connotations when used in different contexts. In this paper, we report on the visual imagery of motor actions, which is also called visual motor imagery. Motor imagery is defined as a mental representation of a movement with no concomitant production of muscular activity to implement the movement [5]. Visual motor imagery can be described as the ability to see yourself performing the task in your mind's eye.

Applications of motor imagery techniques in daily life have been studied extensively during the past decade. It has been shown that mental training based on imagery leads to improvements in the performance of athletes [8,24], musicians [21], and highly skilled manual technicians such as surgeons [29]. Recent papers suggest that imagery techniques can also be used as an adjunct to the physical rehabilitation of patients with neurological disorders [2,11,31]. With respect to healthy persons, most people are thought to be able to use imagery accurately. In patients with neurological lesions, however, this cannot be taken for granted. It has been shown in the past that lesions in the parietal cortex and the putamen can lead to disturbances in the ability to imagine movements [3,19]. This might also be the case in patients with lesions in other areas. So, before investigating the application of motor imagery in the rehabilitation of specific patient groups, it seems necessary to determine if these patients are still able to accurately perform the imagery tasks. Potential problems may be that subjects are unable to accurately imagine

* Corresponding author. Tel.: +32 16 32 90 69; fax: +32 16 32 91 97.
E-mail address: elke.heremans@faber.kuleuven.be (E. Heremans).

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the required movement in the temporal and spatial domain, that they use alternative strategies, or fail to suppress muscular activity during imagery. A simple procedure to check that muscles remain silent during motor imagery is provided by EMG recordings. However, it is much harder to gain insight into the ability of subjects to imagine normal movements and the strategies they use. Methods that are traditionally used in psychology to measure the imagery ability of subjects are questionnaires and interviews. Although these methods provide useful information, they remain rather subjective since subjects are undertaking a self-evaluation of their general motor imagery performance. A semi-objective method that is often used is mental chronometry. This measurement provides interesting information on the quality of the temporal organization of an imagined movement. Unfortunately, it does not allow for evaluation of the vividness and spatial accuracy of the imagery process. In addition, mental chronometry primarily focuses on a global movement instead of providing a detailed constant monitoring of the ongoing mental process. Taken together, only very basic and general information on the motor imagery performance can be obtained at present, given that a precise monitoring tool of the compliance and imagery ability of subjects is lacking.

Therefore, the present study aimed at investigating the value of an alternative approach to providing an objective assessment of motor imagery, based on the technique of eye movement registration. The 16th century proverb “the eyes are the mirror of the soul” seems to contain truth on more than the purely symbolic level. Previous research has indeed shown that eye movement data provide an excellent on-line indication of cognitive processes, such as those underlying visual search and reading [20]. Recently, the study of eye movements has been introduced in the field of imagery research. Spivey and Geng [33] recorded eye movements while subjects listened to played pre-recorded descriptions of visual scenes. Although the subjects faced a blank white screen, they tended to make saccades towards the same positions as the spatiotemporal dynamics of the auditory presented scene description. Laeng and Teodorescu [15] asked their subjects to visually imagine recently viewed pictures. In line with Spivey and Geng [33], they found that as participants formed a visual image of the stimulus, their eye movements reflected the content of that stimulus. The authors concluded that eye scanpaths during visual imagery of visual objects are highly correlated to those of actual perception of the same visual scene and that these eye movements are functionally involved in the mental imagery process. De’Sperati [4] showed that such spontaneous ocular behaviour also occurred during motion imagery tasks such as circular motion imagery and visuospatial mental rotation. Motion imagery has been defined as the ability to imagine an object in motion. The studies of Spivey and Geng [33], Laeng and Teodoresco [15], and De’Sperati [4] all confirm that, during visual imagery of a stationary or dynamic scene, eye movements can be a precise marker of the spatiotemporal evolution of the underlying mental process.

Despite the evidence that eye movements may be useful in the field of imagery research, hardly any research has been undertaken regarding the occurrence of eye movements during motor imagery. As far as we know, the only study that has recorded eye movements during motor imagery is a study by Rodionov et al. [28]. In this study, the objective was to investigate if intentional imagination of body rotation could induce oculomotor activity similar to the vestibulo-ocular reflex. For the majority of subjects, responsive eye movements that consisted of horizontal eye movements and a typical pattern of nystagmus were found in response to imaginary rotations. The authors concluded that eye movements may serve as an objective sign of the subject’s mental performance.

The present study aimed at investigating whether these findings may be generalized to motor imagery of limb movements, and more specifically, to goal-directed movements. Support for this hypothesis can be found in the literature concerning eye–hand coordination. In the past, a tight temporal and spatial coupling between eye and hand movements has been observed during both discrete and cyclical goal-directed aiming tasks [10,17,30]. In a study investigating steering performance, Wilson et al. [38] showed that coordinated eye movements were made during steering, even when vision was denied so that the eye movements could not yield any useful visual information. Therefore, we hypothesize that this tight coupling between neural patterns for eye and hand movements remains intact, also when hand movements are only imagined.

Another gap in the existing literature considering eye movements during imagery is that, regardless of the type of imagery, most studies only measured eye movements during imagery with the eyes opened. However, many subjects spontaneously close their eyes when they are asked to imagine an object or a movement. In this paper, therefore, a methodological approach is used that permits the recording of eye movements both when the eyes are opened and when they are closed.

The central question in this current paper is two-fold: do individuals make eye movements during motor imagery of goal-directed limb movements with either the eyes open or the eyes closed? And if so, are these eye movements similar to those made during physical execution of the same tasks?

2. Materials and methods

2.1. Participants

Seven male and eight female volunteers (aged 21–25 years) voluntarily participated in the study. All were students at the Catholic University of Leuven. All subjects were strongly right-handed as measured by the Edinburgh Handedness Inventory [27] ($X = 83.1$; S.D. = 18.7), where a laterality quotient of +100 represents extreme right-handedness and a laterality quotient of −100, extreme left-handedness. All had normal or corrected-to-normal vision and were naive to the hypothesis being tested. 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 voluntarily gave written informed consent before they took part in the study.

2.2. Apparatus

2.2.1. Eye movements

To record eye movements, both when the eyes were open and when they were closed, the electro-oculographic signal of the subject’s right eye was recorded by means of a Porti 7 device (Twente Medical Systems International, Enschede, the Netherlands) with a sample frequency of 1024 Hz. After skin preparation, one pair of Ag–AgCl surface electrodes with a diameter of 5 mm (Twente Medical Systems International, Enschede, the Netherlands) was adhered nasally and temporally to the eye and another pair above and below the eye. Based on the potential difference between the electrodes, the horizontal as well as the vertical eye movements could be detected.

2.2.2. Wrist kinematics

The apparatus for measuring the wrist angular position has been used in previous studies by Feys et al. [6] and Lavrysen et al. [16]. It consists of 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.

2.2.3. Muscle activity

Electromyographic signals (EMG) were recorded by means of 24 mm diameter Ag–AgCl surface electrodes (Kendall/Arbo, Tyco Healthcare, Neustadt/Donau, Germany) placed over the bellies of the extensor and the flexor carpi radialis muscles, following standard skin preparation techniques. Identical to the recording of EOG signals, EMG signals were measured with the Porti 7 at a sample frequency of 1024 Hz. The surface EMG was continuously monitored during the experiment. If any muscular activity was detected during the imagery conditions, participants were instructed to relax their arm.

2.3. Task and design

Participants were seated facing a 17-in. computer screen at a distance of 50 cm. A chinrest was used to restrict head movements. Their right forearm, positioned in the wrist-hand orthosis, was secured in a forearm support on the table in front of them prohibiting movements in the elbow joint. During execution of the task, the wrist position was displayed on the screen as a hollow round cursor with a diameter of 1 cm. Extension of the right hand resulted in the cursor moving right, whilst flexion of the hand resulted in the cursor moving left. Two identical squares with a diameter of 0.5 cm, which were projected on both the left and right side of the screen, represented the stationary targets. Participants were asked to perform cyclical wrist flexion-extension movements between the two targets respecting a rhythmical pattern of 1 Hz that was ordered by an auditory metronome.

Participants performed the task under four conditions. During the execution condition, subjects faced the screen and were asked to carry out the cyclical task as described above. The imagination conditions involved visual imagery of the hand movements. Subjects were instructed to imagine seeing their hand making the movement as clearly and vividly as possible without actually moving the wrist. Both an imagery condition with the eyes open and an imagery condition with the eyes closed were performed. During imagery with the eyes open, participants faced the same display as during the execution task. However, no visual feedback of the cursor representing the hand was provided as hand movements were not allowed. During rest, subjects faced the same display as during physical execution and imagery, but no task instructions were given. All conditions were applied for three different inter-target distances, 240 mm (large), 180 mm (middle), and 120 mm (small), respectively.

2.4. Test procedure

Prior to the test, the imagery ability of each subject was assessed by means of the modified version of the Movement Imagery Questionnaire Revision (MIQ-R) [7]. The MIQ-R is comprised of eight items, four concerning visual imagery and four concerning kinesthetic imagery. Ratings for each item on the MIQ-R are made from a 7-point scale, where 1 = very hard to see/feel and 7 = very easy to see/feel. Subsequently, participants performed two practice series to become familiar with the different conditions and the temporal and spatial task constraints. The practice series consisted of three trials, one for each condition. One trial consisted of 15 successive wrist movements (wrist flexion or extension) performed at a rhythm of 1 Hz. These practice trials were not taken into account in the data analysis. Thereafter, three experimental series were performed, with different inter-target distances (240, 180, or 120 mm). During each series, both imagery conditions were presented three times, always preceded by the execution condition to ensure that the required spatial inter-target distance (large, middle, small) was imagined. Rest trials were provided every fifth trial. Before the start of each condition, an image appeared for 4 s to indicate which condition would follow. The imagery conditions with the eyes open and closed and the three experimental series were presented in a random order. Between the series, an additional rest period of 2 min was provided. At the end of the experiment, the subjects' perception of their own performance was assessed by means of a short questionnaire, developed in our own laboratory for this purpose.

2.5. Dependent variables

Only the horizontal gaze coordinates were taken into consideration, as the limb movements only occurred in the horizontal dimension. The signal of the horizontal eye movements was processed with a low-pass filter with a passband range from 0 to 20 Hz to reduce the noise. Possible drift of the signal was corrected by piecewise second order polynomial fitting. Fixations of the eyes were defined as stable gaze positions (a standard deviation of point of gaze less than 1° in the last 100 ms) that were maintained for at least 100 ms. The data points just before and after eye fixations at the turning points were considered as the start and end points of the eye movements. The amplitude of the eye movements was determined as the distance travelled by the eyes between the start and end points of the total eye movement. The total eye movement could consist of one single primary saccade or a combination of a primary saccade and one or more corrective saccades. The amplitude of the eye movements was accurately measured during the physical execution and imagery with the eyes open conditions. It was not possible to calibrate the position of the eye movements while the eyes were closed as the size of differences in electrical potentials between the electrodes turned out to be not comparable between the eyes open and the eyes closed conditions. As such, we could not obtain reliable information considering the eye movement amplitudes during imagery with the eyes closed. As a consequence, this parameter was not included in the further analyses of the imagery with the eyes closed condition.

The number of eye movements was counted and expressed in percentages, where 100% represents an eye movement between every two consecutive beeps of a trial. Thus, a number of eye movements of 100% mean that subjects made exactly 13 eye movements per trial, since the rhythm was set at 1 Hz and the first and last movement of the trials, lasting 15 s each, were excluded from the analysis.

2.6. Statistical analysis

2.6.1. Analyses per condition

The average values for both the number and amplitude of the eye movements were calculated per subject per condition for all three inter-target distances. Differences in eye movement amplitudes between the three different series of inter-target distances were analysed using a one condition by three inter-target distances (large, middle, small) repeated measures ANOVA design. This analysis was undertaken separately for both physical execution and imagery with the eyes open. Post hoc Tukey HSD tests were executed when necessary to correct for multiple comparisons. The statistical significance (α) was set at $p < 0.05$.

2.6.2. Comparisons between conditions

To compare the number of eye movements between conditions, a one variable by four conditions (execution, rest, imagery with eyes open, imagery with eyes closed) repeated measures ANOVA was used. Differences in amplitudes between the conditions were analysed by means of a one variable by three conditions (execution, rest, imagery with eyes open) repeated measures ANOVA. These analyses were performed for all three series of inter-target distances. Post hoc Tukey HSD tests were executed when necessary for significant effects. The α was set at $p < 0.05$ for all comparisons.

2.6.3. Additional analyses: Equivalence tests

The absence of significant differences in repeated measures ANOVA's and post hoc tests does not yet allow to claim that the number and amplitude of the eye movements in two conditions are equal. Therefore, additional statistical tests for equivalence were performed as documented by Lesaffre et al. [18]. This equivalence test is based on an interval of equivalence, defined in advance

Table 1
Eye movement characteristics during all conditions in all inter-target distances for all subjects who make eye movements

	Large inter-target distance			Middle inter-target distance			Small inter-target distance		
	Subjects	EM (%)	Amp (mm)	Subjects	EM (%)	Amp (mm)	Subjects	EM (%)	Amp (mm)
Execution	15	100 ± 0	233 ± 15	15	95.8 ± 7.2	176 ± 14	15	97.7 ± 3.1	115 ± 9
Imagery eyes open	13	96.5 ± 7.8	218 ± 47	14	96.8 ± 6.2	178 ± 16	13	95.7 ± 5.6	110 ± 14
Imagery eyes closed	12	94.3 ± 9.0	/	13	90.0 ± 16.0	/	13	90.0 ± 11.8	/
Rest	15	39.3 ± 22.0	168 ± 65	15	51.7 ± 25.0	168 ± 93	15	43.6 ± 22.0	167 ± 125

The number of subjects, the mean number of eye movements (EM), and the mean amplitude of the eye movements ± standard deviations are given for every condition.

by the researcher, and the 95% confidence interval (CI). We defined the interval [criterion amplitude +10%; criterion amplitude −10%] as the interval of equivalence for amplitude. For the number of eye movements, the interval [criterion number of eye movements +10%; criterion number of eye movements −10%] was used as the interval of equivalence. As the criterion amplitude, the distance between the targets was taken, being 240, 180, and 120 mm for the large, middle, and small amplitude, respectively. The criterion number of eye movements was defined as 100%, which corresponds to 13 eye movements per trial. Only if the 95% CI for the true difference lies entirely in this a priori defined interval of equivalence, does this correspond to a significant p value (<0.05) and can the two conditions be regarded as equivalent. When $p \geq 0.05$ in an equivalence test, this signifies that the two treatments cannot be declared equivalent. As such, we claim that the eye movements during execution and imagery with the eyes open are considered as equivalent when the difference in their number of eye movements and amplitudes does not exceed 10% (in absolute value).

3. Results

3.1. Analyses of eye movements per condition

An overview of all results per condition per inter-target distance is provided in Table 1. Illustrations of typical eye movement patterns per condition are given in Fig. 1.

3.1.1. Execution

All subjects showed a consistent eye movement pattern during physical execution of the task during all trials of the three inter-target distances. Eye movements accompanied on average 97.8% of the hand movements. For the analysis of the movement amplitudes, a significant main effect was found for inter-target distance ($F(2,14) = 293.9$; $p < 0.01$). Post hoc Tukey HSD tests showed that the movement amplitudes of the eyes were consistently larger for the large inter-target distance than for the middle distance, and for the middle compared to the small distance (Fig. 2). All mean amplitudes were close to the criterion values of the corresponding inter-target distances of 240, 180, and 120 mm, respectively. This indicates a correct execution of the task and a tight coupling between the eye and the hand movements.

3.1.2. Rest

During the rest condition none of the subjects showed a consistent task-related eye movement pattern. In the majority of the subjects, however, some random eye movements could be detected. The mean number of eye movements during rest

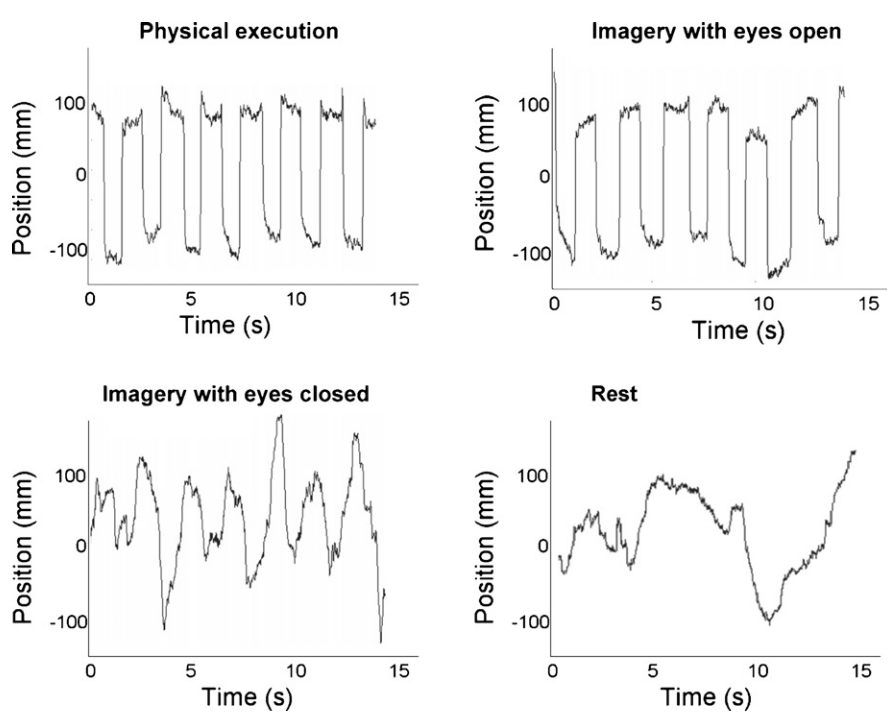

Fig. 1. Typical examples of eye movement patterns during the different conditions (all for the middle inter-target distance), carried out by a single representative subject.

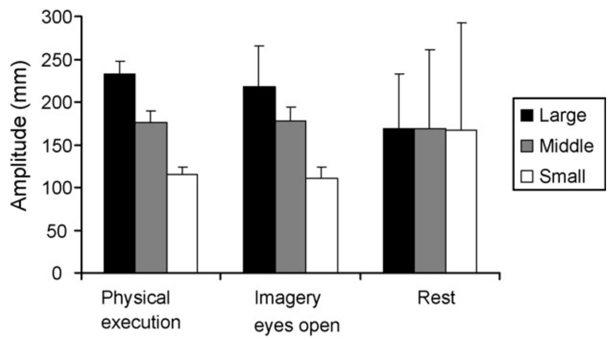

Fig. 2. Mean eye movement amplitudes and their standard deviations for all three series of inter-target distances (large, middle, small) per condition.

was 44,9%, corresponding to half of the normal number of eye movements per condition. Unlike the other conditions, no main effect for inter-target distances was found for movement amplitude ($F(2,14) = 0.00$; $p > 0.05$). The lack of differences between the amplitudes during the three series combined with the very large standard deviations in number and amplitude of the eye movements indicate that the eye movements during the rest condition were made in a random way, and were not related to either the execution or the imagery task (Table 1 and Fig. 2).

3.1.3. Imagery with the eyes open

The majority of subjects, 88.9% on average across series, made eye movements related to the task (Table 1). Two subjects (subjects 4 and 11) did not show eye movements when performing the series with the large and the small inter-target distances, while one subject (subject 4) also did not show eye movements during the series with the middle inter-target distance. Consequently, they were disregarded for further analyses of the characteristics of the eye movements. The mean number of eye movements for the remaining subjects was 96.3%. Similar to the execution condition, also for the imagery with the eyes open condition, the eye movement amplitudes closely resembled the required inter-target distances (Fig. 2). Again, significant differences in movement amplitudes among all three series with different inter-target distances were found ($F(2,14) = 70.1$; $p < 0.01$). This indicates that subjects imagined the wrist movements according to the presented inter-target amplitudes.

3.1.4. Imagery with the eyes closed

Similar to the analysis of the imagery condition with the eyes open, subjects who did not make any eye movements at all were disregarded for the analysis. Subjects 4 and 11 were removed from the analyses of all series. Subject 14 was selectively removed from the series with the large inter-target distance only. So, on average, 84.5% of the participants made task-related eye movements during imagining the task with the eyes closed. They made eye movements in 91.4% of the trials (Table 1). As mentioned previously, the amplitudes of the eye movements were not analysed in this condition due to the impossibility of accurately calibrating eye movement position when the eyes were closed.

3.2. Comparisons of eye movement characteristics between conditions

For the comparisons between conditions, the subjects who made no eye movements at all during imagery were excluded from the analyses. For imagery with the eyes open this was the case for 11.1% of the subjects. For imagery with the eyes closed, 15.5% of the subjects were excluded from the analyses.

3.2.1. Imagery with the eyes open versus execution and rest

No significant differences between execution and imagery with the eyes open were found for the number and amplitude of the eye movements. This was the case during all three series of inter-target distances. During imagery with the eyes open and rest, however, the number of eye movements differed significantly (Table 2). Subjects made less eye movements during rest compared to during imagery, and this during all three series. Concerning eye movement amplitudes, significant differences were found between rest and imagery for the series with the large inter-target distance. No significant differences were found for the middle and small inter-target distances, most likely due to much larger standard deviations in the rest condition compared to the execution and imagery conditions (Tables 1 and 2).

3.2.2. Imagery with the eyes closed versus execution and rest

The number of eye movements did not differ significantly between physical execution and imagery with the eyes closed for all three series of inter-target distances. On the contrary, between rest and imagery with the eyes closed significant differences were found for all series (Table 2).

3.3. Additional analyses: Equivalence tests

Since, based on ANOVA's and post hoc tests, no conclusions can be drawn about equivalence between conditions, additional statistical tests for equivalence were carried out for all comparisons. All intervals of equivalence and 95% confidence intervals of the equivalence tests as well as the *p*-values of the post hoc Tukey HSD tests are shown in Table 2.

3.3.1. Imagery with the eyes open versus execution and rest

For the number of eye movements, the equivalence tests between imagery with the eyes open and execution showed equivalence for all inter-target distances. For amplitude, equivalence was only found for the middle inter-target distance. For the small and large inter-target distances, the 95% confidence interval was wider than the 10% interval that was established as the region of equivalence. However, differences between intervals were small, indicating a clear tendency towards equivalence (Table 2). Further inspection revealed that the wider interval was due to only a few subjects showing a variable eye movement pattern during imagery, causing large variation within the data. A variable eye movement pattern was defined as a mean number

Table 2
p-Values of the post hoc Tukey HSD tests, equivalence intervals and the 95% confidence intervals of the equivalence tests for comparisons between conditions

	No. of eye movements			Eye movement amplitude		
	p	Equivalence interval	95% CI	*p*	Equivalence interval	95% CI
Large inter-target distance						
Execution vs. imagery eyes open						
Total group	0.86	[10; −10]	[8.2; −1.2]*	0.57	[24; −24]	[48.4; −10.9]
Non-var group	0.99	[10; −10]	[1.2; −0.2]*	0.99	[24; −24]	[15.1; −19.7]*
Execution vs. imagery eyes closed						
Total group	0.59	[10; −10]	[11.5; −0.0]	–	–	–
Non-var group	<0.01*	[10; −10]	[5.9; −6.8]*	–	–	–
Execution vs. rest						
Total group	<0.01*	[10; −10]	[72.9; 48,5]	<0.01*	[24; −24]	[102.3; 28.3]
Rest vs. imagery eyes open						
Total group	<0.01*	[10; −10]	[70,3; 44.1]	0.01*	[24; −24]	[94.3; 4.7]
Rest vs. imagery eyes closed						
Total group	<0.01*	[10; −10]	[68.5; 41.5]	–	–	–
Middle inter-target distance						
Execution vs. imagery eyes open						
Total group	0.99	[10; −10]	[4.9; −6.1]*	0.99	[18; −18]	[11.8; −12.2]*
Non-var group	0.99	[10; −10]	[4.9; −6.1]*	0.99	[18; −18]	[11.8; −12.2]*
Execution vs. imagery eyes closed						
Total group	0.87	[10; −10]	[16.6; −4.8]	–	–	–
Non-var group	<0.01*	[10; −10]	[9.8; −5.9]*	–	–	–
Execution vs. rest						
Total group	<0.01*	[10; −10]	[58.5; 29.7]	0.92	[18; −18]	[59.6; −44.0]
Rest vs. imagery eyes open						
Total group	<0.01*	[10; −10]	[59.5; 30.7]	0.88	[18; −18]	[62.0; 42.8]
Rest vs. imagery eyes closed						
Total group	<0.01*	[10; −10]	[56.4; 22.4]	–	–	–
Small inter-target distance						
Execution vs. imagery eyes open						
Total group	0.97	[10; −10]	[5.6; −2.2]*	0.99	[12; −12]	[14.6; −6.4]
Non-var group	0.94	[10; −10]	[6.1; −2.5]*	0.99	[12; −12]	[6.0; −10.1]*
Execution vs. imagery eyes closed						
Total group	0.32	[10; −10]	[14.8; −0.1]	–	–	–
Non-var group	<0.01*	[10; −10]	[6.6; −3.4]*	–	–	–
Execution vs. rest						
Total group	<0.01*	[10; −10]	[66.4; 41.8]	0.58	[12; −12]	[17.6; −121.4]
Rest vs. imagery eyes open						
Total group	<0.01*	[10; −10]	[64.9; 39.3]	0.51	[12; −12]	[13.9; −127.9]
Rest vs. imagery eyes closed						
Total group	<0.01*	[10; −10]	[60.4; 32.4]	–	–	–

The results of all subjects who show eye movements (total group) as well as the results of a subgroup of subjects who show a non-variable pattern only (non-var group) are given for both number of eye movements and eye movement amplitude.
* Significant *p*-values and intervals showing equivalence.

of eye movements, which deviated more than 25% from the criterion number of eye movements or as a mean amplitude which deviated more than 25% from the criterion amplitude. For the series with the middle inter-target distance, none of the subjects showed a variable eye movement pattern. However, for the large inter-target distance three subjects (subjects 10, 13, and 17) and for the small inter-target distance two subjects (subjects 10 and 13) did show a variable eye movement pattern. So across series, 11.1% of the subjects made eye movements during imagery but in a variable way. After excluding those participants, equivalence in eye movement amplitudes between execution of the task and imagery with the eyes open was found for all three inter-target distances (Table 2).

Equivalence tests between rest and imagery with the eyes open and between rest and physical execution showed no equivalence for both amplitude and number of eye movements when all subjects were taken into account. The very wide confidence intervals suggested no tendency towards equivalence at all. No subgroup of subjects could be distinguished that showed equivalence for any of the two variables in any of the three series (Table 2).

3.3.2. Imagery with the eyes closed versus execution and rest

When analysing all subjects who made eye movements during imagery with the eyes closed, no equivalence in number of eye movements could be shown for all three inter-target distances. However, the small differences in intervals indicated a tendency towards equivalence (Table 2). Similar to the analysis of the imagery with the eyes open condition, subjects with a variable pattern were detected. Only the criterion of number of saccades was used to define what was considered as a variable pattern, since no reliable amplitude measurements could be obtained with the eyes closed. Two subjects were removed from the series with the large inter-target distance (subjects 10 and 13), three for the middle distance (subjects 3, 13, and 15) and three for the small distance (subjects 3, 9, and 14). An equivalence test was now performed on the remaining 66.6% of the subjects who showed a consistent eye movement pattern during imagery of the task with their eyes closed. For these subjects, equivalence between number of eye movements during execution and imagery with the eyes closed was found for all three inter-target distances (Table 2).

Similar to the imagery with the eyes open condition, the comparison between eyes closed and rest also showed no tendency towards equivalence (Table 2).

3.4. Questionnaires

Before the start of the experiment, participants filled out the revised version of the Movement Imagery Questionnaire (MIQ-R) [7]. They rated the ease/difficulty with witch they imagined certain movements on a 7-point scale, where 1 = very hard to see/feel and 7 = very easy to see/feel. All participants rated their own imagery ability as good, with a global mean score per item of 5.3 (S.D. = 1.1) and a mean score, specific for visual imagery, of 6.1 (S.D. = 1.1). After performing the experiment, participants filled out another questionnaire, containing questions about the way they experienced the tests. They all asserted they did not experience any problem in performing the imagery tasks. During imagery with the eyes open they reported mean vividness scores of 5.4 (S.D. = 1.3) and during imagery with the eyes closed of 5.5 (S.D. = 1.5). All participants thought that they had made eye movements during all conditions.

4. Discussion

The aim of this study was to investigate whether people make eye movements during visual motor imagery, and if so, to what extent these eye movements resemble those made during physical execution of the task. This was studied during imagery of reciprocal goal-directed wrist movements at a rhythm of 1 Hz, both with the eyes open and the eyes closed. To examine whether spatial differences in the movements that had to be imagined were reflected in the characteristics of the eye movements during imagination, the task was performed at three different inter-target distances for every condition. It was found that more than 80% of participants made task-related eye movements during both imagery with the eyes open and with the eyes closed. These eye movements showed remarkable similarities in eye movement characteristics with those made during physical execution of the same task and differed significantly from the eye movements that were made during rest. During both execution and imagery with the eyes open, the amplitudes of the eye movements closely matched the criterion inter-target distances. No significant differences were found in both the amplitudes and the number of eye movements during physical execution and imagery with the eyes open. In addition, there was no difference in the number of eye movements between physical execution and imagery with the eyes closed for each inter-target distance. Moreover, for the majority of these subjects, equivalence could be shown for the above-mentioned comparisons. As such, the results of this current study support the hypothesis that findings from other types of imagery research are also applicable to the field of motor imagery.

As far as we know, Jacobson [12] and Totten [36] were among the first researchers to study oculomotor behaviour during visual imagery. They found evidence that saccadic eye movements followed predicted patterns when subjects were instructed to form visual images of spatially extended objects. Thirty years later, Hebb [9] argued that eye movements are not merely epiphenomenal but play a necessary role during visual imagery. He suggested that the same scanpaths are elicited during the imagining of an object as during viewing that object. This was confirmed in later studies comparing eye movements during perception and imagery [15,25,26]. Other studies have shown that eye movements also reflect the content of the imagined stimulus during the imagery of auditory presented scenes, moving stimuli and mental rotation [4,13,28]. The results of this current study showing that eye movements during imagery closely resemble those during physical execution of wrist movements indicate that these findings may be generalized to motor imagery of upper limb movements.

Laeng and Teodorescu [15] suggested that, during the perception of visual scenes, ocular motor commands are stored along with the visual representation for further use as spatial index in a motor based coordinate system for the proper arrangement of parts of an image. During visual imagery of the same scene, this oculomotor activity might be re-enacted as it may be relevant in the construction of the mental image. A similar explanation may apply to the occurrence of task-related eye movements during motor imagery, as observed in the vast majority of subjects in this study. The characteristics of the eye movements may be stored in memory in a common motor program with the hand movements. This is also supported by research in the field of eye–hand coordination showing a tight spatiotemporal coupling between both eye and hand control systems during goal-directed actions [10,35,37]. This coupling is a robust finding even when no visual feedback is available [16,38]. Spatial coupling implies that there is a common representation of the target location [30].

This is illustrated by the similarity in movement amplitudes of the eye and hand movements in coordinated aiming tasks. Concerning the temporal coupling, the eyes typically arrive at the target before the hand reaches peak velocity, leaving sufficient time for correction processes to take place [34]. In addition, behavioural evidence has been found that coordinated eye and hand movements are more accurate than independent eye or hand movements alone [22,37]. Miall and Reckess [23] showed that information from eye movements, which is consistent with the required hand movement response, helps to predict the appropriate velocity and direction of the subsequent hand movement. These findings suggest that the eyes provide useful information to guide the hand to the target during physical execution of coordinated hand movements. If the hypothesis is correct, that during imagery a mental representation is used that is treated in a similar way to its physical counterpart [4,14], then it can be expected that eye movements can help us to correctly position the imagined hand movements within the mental space. In the present study, we found that the amplitudes of the eye movements closely resembled the inter-target distances that had to be covered by the hand both during physical execution and during imagery, even when no visual feedback of the hand could be used. This suggests that the spatial coupling between eye and hand movements, which has been found in previous studies concerning goal-directed aiming, remains intact when subjects merely imagine making a movement instead of physically executing it. Therefore, the present study might offer support for the hypothesis that an internal representation exists, which is treated in a similar way to the external world.

Johansson et al. [13] has argued that during visualisation we might use visual features from our environment as visual indexes of spatial location of the mental image. The explanation that eye movements during imagery are triggered by external visual cues cannot be rejected when only imagery with the eyes open is measured. However, in this current study, we also detected spontaneous eye movements in the vast majority of participants during imagery with the eyes closed, when absolutely no visual input was available. This is in line with previous findings of Spivey et al. [32] who recorded eye movements during comprehension of spoken scene descriptions while subjects kept their eyes closed. It was found that, even when no instructions to imagine anything were given, and even when eyes were closed, participants tend to make eye movements in the same direction as the described scene when listening to a spatially extended scene. Spivey et al. [32] mentioned that imagining is akin to viewing it 'in our mind's eye', and that (perhaps epiphenomenally) our executed eye movements simply echo the motion of our internal spectating. The latter observations, as well as the results of our study, support the idea that eye movements are inherent to the imagery process, instead of being triggered by visual cues. It appears to be the case that the visual input is derived from the memory and that both the motor and visual components of the movement are re-enacted during motor imagery of the task. This may indicate that the 'scanpath theory' of perception and imagery proposed by Noton and Stark [25,26] can also apply to physical execution and motor imagery. This theory posits that an image is internally represented as a sequence of sensory and motor activities.

Based on these arguments, it cannot be claimed with certainty either that eye movements play a functional role assisting the construction of the mental image or that they reflect a merely reflexive behaviour. A first argument in favour of the functional role of eye movements provided by this study is the strong correspondence between the amplitudes of the eye movements during imagery and physical execution. A second piece of evidence stems from the occurrence of eye movements during imagery with the eyes closed. This is in accordance with findings of Laeng and Teodorescu [15] who observed a functional role of eye movements during visual imagery of static visual scenes. However, it must be noted that not all participants made task-related eye movements during the imagery tasks. Eleven percent of subjects did not make any task-related eye movements at all during imagery with the eyes open, and another 11% of subjects showed a rather variable pattern with eye movements that were lacking or strongly deviated in amplitude. During imagery with the eyes closed, these percentages increased to 16 and 17%, respectively. These numbers are close to those found in a study by Rodionov et al. [28]. In this study, the authors examined whether imagery of body rotation with the eyes closed induced ocular activity. Horizontal eye movements were found in 75% of recordings, while in the remaining 25% no definite eye movements could be detected during the mental manoeuvres. For the latter subjects, the above-mentioned framework does not seem to hold. A possible explanation could be an inability of these subjects to accurately imagine the movement. However, in the questionnaire that was filled out after participating in the present experiment, all subjects mentioned that they were quite successful in imagining the task, both with the eyes open and closed. In addition, the task that was used in this study consisted of a simple one-dimensional wrist movement, making it rather unlikely that subjects would be unable to imagine it. Alternative explanations may be that subjects used a different strategy in which eye movements are superfluous or that they made use of their peripheral vision without making overt eye movements. This could be the case, as the required visual angle was rather small so that peripheral vision was sufficient to imagine the movement. The fact that a subgroup of subjects showed eye movements in a variable way might be due to a lack of sustained attention. This is conceivable given the rather large number of repetitions with limited variation in task requirements.

Another point of discussion is that eye movements were also found during the rest conditions. However, these eye movements do not necessarily relate to motor imagery, since no instructions to fixate a target were given to the subjects during the rest condition in order not to influence their spontaneous eye movement patterns during imagery conditions. The fact that far less eye movements were made during rest than during imagery, with obvious larger standard deviations in eye movement number and amplitude, suggest that the eye movements made during rest reflect a random pattern. Further support for this hypothesis can be found in the lack of significant differences in eye movement amplitudes between the three series with different inter-target amplitudes and in the lack of a tendency towards equivalence in the comparison with the execution condition. During imagery, on the contrary, the eye movement amplitudes were clearly dependent on the required movement amplitude that had to be imagined. Besides, there was a clear tendency towards equivalence with the eye movements during physical execution of the task, indicating a task-related eye movement pattern.

A limitation of the present study, however, is that we used visual targets and that the movement speed was auditory cued. As such, it cannot be completely excluded that the eye movements were generated in response to these cues. Future research will be conducted to clarify whether eye movements also occur during the imagery of internally generated movements, during movements which are externally cued in a non-auditory way, or during more complex motor tasks.

Although it is premature to draw final conclusions about the generalizability of our findings and the functional role of eye movements during imagery, the observations in this study do show that eye movements provide a unique window into the mind during motor imagery of goal-directed wrist movements. Eye movement registration has the advantage that, in contrast with other methods, it can serve as an objective and real-time indicator of what the subject is actually doing during imagery. As such, eye movement recordings can be considered an objective complementary technique to evaluate motor imagery ability and spatial accuracy for the majority of subjects. This technique can be further explored in future studies in which new applications of motor imagery are investigated. It might be of particular interest in research concerning the implementation of motor imagery techniques in neuromotor rehabilitation. For neurological patients, it is absolutely necessary to test their imagery ability before considering the implementation of imagery techniques in their rehabilitation program, because it is entirely possible that their ability to imagine movements is diminished or lost completely as a consequence of their pathology.

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