Duration of Mentally Simulated Movement: A Review

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ABSTRACT. The authors review studies of mentally simulated movements. In automatic or cyclical movements, actual and motor imagery (MI) durations are similar. When athletes simulate only dynamic phases of movement or perform MI just before competing, however, environmental and time constraints lead to an underestimation of actual duration. Conversely, complex attention-demanding movements take longer to image. Finally, participants can modify the speed of MI voluntarily when they receive specific instructions. To complete the available data, the authors compared imagined and actual durations in tennis and gymnastics. Results showed systematic and disproportionate overestimation of actual duration. The authors found a relationship between complex motor skills and MI duration. They discuss the factors leading to over- and underestimation and the hypotheses that could be tested.

Key words: mental chronometry, motor imagery, sport, temporal characteristics

Is the time needed for mentally simulated actions close to that required for actual performance? Although that is often the case, there are some contexts in which it is not. For that reason, new studies directed at clarifying the factors that cause the inconsistent findings should be performed. Individuals do not perceive time as such, but changes or events in time and their temporal relations (spatial distances and other relations between objects). The term mental chronometry refers to the time course of information processing by the nervous system (Posner, 1978). In many early research studies, investigators have addressed motor, attention, and perceptual and psycholinguistic reaction times, but in some studies of prolonged mental activities such as mental calculation, chronometric methods were used (see Groen & Parkman, 1972). For example, Landauer (1962) showed that overt and implicit recitations of the alphabet take almost the same length of time; times for speaking aloud or thinking the same series of letters or numbers were similar. Landauer concluded that the same central processes are involved in both patterns of behavior. If a mental image depicts spatial extent, then the metric properties of object surfaces may be explicit in visual images (Denis & Kosslyn, 1999). As shown by Kosslyn (1973) in a simple image-scanning paradigm, more time should thus be required to scan longer distances across images. As reviewed in the following discussion, such results have been reported. However, motor imagery experiments have provided evidence that temporal equivalence between imagined and actual movements is not systematic and may be affected by several factors.

Visual Scanning and Mental Rotation Experiments

In mental scanning experiments, participants are required to learn a visual configuration comprising several objects, each at a specific location. Participants then have to mentally scan the distance separating those objects and to indicate when scanning has been completed. Visual scanning of an actual configuration and mental scanning of the visual image of that configuration result in very similar chronometric patterns (Kosslyn, Ball, & Reiser, 1978). Similar relationships occur when mental scanning of representations is extracted from verbal descriptions; such images have structural and metric properties similar to those extracted from perception (Denis & Cocude, 1989, 1992, 1997; Denis, Goncalvez, & Memmi, 1995). Such results have also revealed that individuals require more time to explore longer distances. That relationship depends,
moreover, on participants’ visuospatial abilities (Cocude, Mellet, & Denis, 1999): Participants with high visuospatial capabilities obtained a significant time–distance correlation coefficient, whereas those with poorer abilities formed images with no real structural properties. Experimental data derived from mental rotation tasks have led to the same conclusion (Amorim et al., 2000; Amorim & Stucchi, 1997; De’Sperati & Stucchi, 1997; Shepard & Feng, 1972; Shepard & Metzler, 1971; Wexler, Kosslyn, & Berthoz, 1998; Wohlschlager & Wohlschlager, 1998). Generally, when participants are asked to judge whether objects or body segments that differ in orientation are spatially congruent, their reaction times increase with angular discrepancy. To succeed in such a task, participants must master an internal rotation, which implies reorientation of the rotated objects or body segments in relation to each other.

The Case of Motor Imagery (MI)

MI is defined as mental representation of movement with no concomitant production of muscular activity to implement the movement (Denis, Chevalier, & Eloi, 1985). MI may involve the whole body or be limited to part of the body, thus requiring body representation as the generator of acting forces and not only of the effects of those forces on the external world (Jeannerod, 1994). Athletes commonly use MI to improve motor task performance (Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983; Roure et al., 1999). According to Feltz and Landers, combining mental and physical practice is more efficient than, or is at least equal to, physical execution, when there is no decrease in total physical performance time. Mental practice leads to rehearsal of a skill and to the opportunity to codify parts of the skill into meaningful cognitive units (Driskell et al.). However, Roure et al. (1999; Roure et al., 1998) provided evidence that the characteristics of mental training and execution must be close. In a volleyball task, they observed that MI led to improved performance, but that the benefit of mental training was not transferred, even in a close (but different) motor sequence. Although MI resembles representations involving mental manipulation of visual images (e.g., mental scanning or mental rotation), it should be distinguished from such mental activity. One unique aspect of MI relates to the temporal characteristics of mental images.

When participants are required to grasp an object or to think about grasping it, MI may contribute to solving the problem of movement selection, a major component of the construction of the premotor plan (Johnson, 1998, 2000). MI duration may be influenced by variables affecting motor-performance duration. Specifically, the time required to select a grip increases as a function of the angular distance to the location of the selected posture along the shortest biomechanically plausible trajectory. According to Jeannerod (1995, 1999) and Johnson (2000), the imagined movement obeys the biomechanical constraints of the represented movement. One may use MI to evaluate the biomechanical costs associated with concurrent response options during motor preparation (Johnson, Corballis, & Gazzaniga, 2001). Petit, Pegna, Mayer, and Hauert (2003) found that MI of a moving body segment took longer than mental representation of an object of another nature, with no anatomical constraints. By comparing the length of time for individuals’ mental rotation of their hand or foot into awkward target postures, Parsons (1987) previously found that the durations of MI and movements along biomechanically plausible trajectories were consistent. In that way, Parsons (1994, 2001) showed that mental rotation times for the hand were very close to corresponding actual rotation times. Accordingly, when the picture of a hand with a given orientation was presented, the time to determine its side (right or left) was close to the time for actual movement into that orientation.

Temporal Equivalence Between MI and Motor Performance

Highly Automatic Movements

One influencing factor on MI accuracy is the duration of mental simulation. By comparing the temporal organization of graphic movements executed actually or mentally, Decety and Michel (1989) showed that mental and actual temporal organization of movements were similar and involved the same planning program. Watson and Rubin (1996), using a line-drawing task, confirmed that MI preserved the temporal order. Likewise, Papaxanthis, Pozzo, Skoura, and Schieppati (2002) found that the duration of imagined movement was similar to that of actual movement in a drawing task, although the variability of imagined movement duration increased in comparison with that of actual performance. Similarly, in visually guided pointing tasks, the speed of imagined motor performance was found to be highly correlated with the speed of actual movement. According to Sirigu (1996), the critical frequency with which participants failed to hit imaginary targets and real targets was the same. Maruff and Velakoulis (2000) found that the durations of both real and imagined performance in a visually guided pointing task were equivalent in healthy participants, but not when participants were required to simulate injury. On the basis of those converging results, one can conclude that in highly automatic movements, such as writing, reaching, and grasping, MI duration and motor performance are systematically close.

Complex Motor Skills: Cyclical Activities

In the absence of specific instructions, the speed at which a movement or series of movements is performed usually correlates with its MI (Boschker, Bakker, & Rietberg, 2000; Gould & Damarjian, 1996; Nideffer, 1985; Weinberg & Gould, 1995). By comparing the actual time taken to walk toward targets placed at various distances with the time for mental simulation of walking to the same targets, Decety, Jeannerod, and Prablanc (1989) showed
that mental walking times and the times measured in the actual walking condition were closely similar. Papaxanthis, Pozzo, et al. (2002) recently confirmed that temporal equivalence. Results from Berthoz (1996) and Ghaém et al. (1997) also accord with such previous findings. In the study by Barr and Hall (1992), MI duration and the actual movement duration were found to be similar in top elite rowers, indicating a relationship between expertise level and MI. In the same way, McIntyre and Moran (1996a, 1996b) showed that MI duration of a slalom course was similar to actual paddling times in a canoe–kayak competition. Durations of MI and actual action (500-m skating sprint) were shown by Oishi, Kasai, and Maeshima (2000) to be very close to each participant’s personal-best performance (from 35–38 s). In those studies, athletes were instructed to imagine that they were in an actual competition. The same comparison was made with a new and unfamiliar task (pedalo): Again, a high correlation between actual and MI durations was found (Munzert, 2002). The time taken for execution and mental simulation of closed and cyclical movements such as walking or rowing are thus assumed to be based on common mechanisms.

Such results confirm that MI does not depend on a completed premotor plan (Jeannerod, 1994) but instead may be involved in the programming process itself. Those convergent findings also support functional equivalence between MI and motor preparation (Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998). Papaxanthis, Schieppati, Gentili, and Pozzo (2002) showed that both inertial and gravitational constraints were accurately incorporated in the timing of MI, which appeared therefore to be functionally close to programming and performance of actual movement.

Overestimation of Movement Duration

**MI Duration Increases With Task Difficulty**

With regard to results obtained by Kosslyn et al. (1978) in a visual scanning task, several authors (Mitchell & Richman, 1980; Pylyshyn, 1973, 1981; Richman, Mitchell, & Reznick, 1979) have argued that action duration generally increases because of individuals’ tacit knowledge of what will happen when they walk mentally over longer distances. In the mental imagery condition, temporal invariance may have thus resulted from a strategy of replication of the temporal sequence recorded in the actual condition. However, Finke and Pinker (1982) and S. K. Reed, Hock, and Lockhead (1983) showed that the increase could not be explained by tacit knowledge. Their results were consistent with the hypothesis that participants really do scan spatial images in the mental scanning task and do not rely on scanning times to estimate lengths. According to Jeannerod (1994), that question is not easily answered because one must determine the cues used to identify the duration of a mental event. It has been found in numerous studies, however, that it takes longer to simulate a difficult movement. Decety and Lindgren’s (1991) participants had to imagine writing a sentence and drawing a Necker’s cube with either their right, dominant hand or their left hand while also hopping around a square on either their right or left foot. Results revealed that the sensation of effort increased across the trials, and a correlation was established between the difficulty of imagining the task and the subjective sensation of effort. In the study by Decety et al. (1989), movement time increased linearly as a function of task difficulty, in accordance with Fitts’s (1954) law. That finding was confirmed by Decety and Jeannerod (1996), who showed that the time needed to imagine oneself walking through a gate was affected by both the gate’s distance from the starting point and its width. Duration thus increased as a function of task difficulty (Jeannerod, 1995, 1999). Cerritelli, Maruff, Wilson, and Currie (2000) also used the conventional, visually guided pointing task to investigate the speed–accuracy tradeoff that occurs as target size is varied for both real and imagined performances. For both the no-load and load conditions (external load of 2 kg), the speed–accuracy tradeoff conformed to Fitts’s law (actual and imagined performances). The duration of imagined movements increased significantly (by 30%) with the added load. Those results are in accordance with the findings of both Decety and Jeannerod (1996) and Maruff et al. (1999). Force and timing components of imagined movements may be assembled independently and immediately in response to current task demand characteristics.

To evaluate the impact of an external load on the duration of actual and mental movements, Decety and Boisson (1990) and Decety et al. (1989) required participants carrying a 25-kg weight in a rucksack to walk as accurately as possible and to imagine walking to targets at various distances. Participants did not replicate the close time estimation they experienced during actual performance. Actual walking times were identical to those obtained in a previous study (Decety et al., Experiment 1), whereas duration increased significantly in the mental mode (by 30% or more). During the mental task, however, participants did not use the increase in encoded force to overcome resistance because they did not actually walk. Because participants were blindfolded during the experiment, their performance may have reflected changes in memory function or in visuospatial representation. Furthermore, Corcos (1994) indicated that if the weight was attached to participants’ limbs rather than placed on their backs, actual movement might be slowed down in the same way as imagined movements. That possibility should be confirmed experimentally. In a visually guided pointing task, Cerritelli et al. (2000) confirmed that the force and timing components of imagined movements were assembled independently and immediately in response to current task demand characteristics. That independence was also shown when a weight was attached to the limb that individuals imagined moving when performing a motor-sequencing task. The duration of imagined movements increased significantly (by 30%) as compared with the motor task. Contrary to the study by Decety et al.,
participants were not blindfolded for that experiment and were able to use visual feedback to adjust their MI effort. Thus, although Gottlieb, Corcos, and Argawal (1989) found that attaching additional inertial weight to the upper limb slowed down actual movements, Cerritelli et al. did not. The results of Cerritelli et al. reflected a change in force calculation, as was suggested by Decety et al.

**Duration of Rapid and Complex Attention-Demanding Movements**

Investigators attribute simulation of action and preparation before execution to the same motor representation system (Jeannerod, 1994). Despite that finding, in few studies have the durations of both simulated and actual movements been shown to be similar when participants imagined a complex attention-demanding movement as if they were actually performing it during a competition. In a golf-putting task, Coello and Orliaguet (1992) showed that MI duration was disproportionately overestimated in comparison with the time actually required to perform it. Participants also felt that the time taken increased with movement amplitude. Furthermore, the authors found that overestimation increased simultaneously with the ball–target distance, whereas actual movement time was constant. Those results confirm findings by Beyer, Weiss, Hansen, Wolf, and Seidel (1990). In their study, 8 swimmers sitting in a resting position were required to imagine their own swimming movements over a distance of 100 m in their preferred style. The duration of imagined swimming was shown to be dependent upon the swimming style but remained 25% longer than actual swimming time. Although Collet, Dittmar, and Vernet-Maury (1999) showed that elite weightlifters underestimated the complete duration of the snatch, they found that the duration of the execution phase was overestimated: When all successive stages of the movement (including its preparation) were mentally performed, preparation and concentration phases were underestimated. However, the results showed that the duration of execution phases was often overestimated in MI (up to 15%). Finally, Calmels and Fournier (2001) observed that MI durations of the most difficult gymnastics figures were 10% longer than those of actual movements. Their findings concurred with those of a number of previous studies showing that difficult actions take longer to image (Decety, Philippon, & Ingvar, 1988; Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989). Thus, in mental simulation of rapid and complex attention-demanding movements, athletes seem to have greater difficulty in preserving the temporal aspects of the movement. One may postulate that image accuracy is a more important aspect than is temporal invariance. C. L. Reed (2002) found, furthermore, that the temporal aspects of MI were not a uniformly shifted version of the temporal aspects of motor production, and hypothesized that one should also consider the processing constraints imposed by the visual and working memory systems.

**Underestimation of Movement Duration**

**Influence of Image Content**

Comparison of durations of mental and actual movements (tying a knot) have shown that mental representation was shorter than actual execution time (Annett, 1988). Vieilledent (1996) compared the durations of mental rehearsal and execution of a locomotion task in climbing. Imagined movement times were shorter than execution times; that finding differs from previous results (Decety & Boisson, 1990; Decety & Jeannerod, 1996; Decety et al., 1989). However, because participants had to imagine themselves moving as accurately as possible and at a constant speed, the study by Vieilledent revealed the difficulty of simulating movements that integrate difficult variations of postural constraints. Moreover, because participants simulated only the dynamic phases of the task and not the static phases, they underestimated the time spent on imagined movement. In shooting, the marksmen’s concentration phase is based on mental rehearsal of the shot; mental rehearsal has been found to determine the accuracy of the forthcoming shot (Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1991, 1992). Results showed that MI duration was shorter than actual movement time. It is a fact that participants imagine shooting parameters and all proprio- and exteroceptive information usually associated with them in successive stages, as if they were in a competition. It is advisable, however, to hold the arm and pistol steady during the concentration phase, but that steadiness cannot be maintained over a long period of time. That may explain why the sequence of stages is visualized faster during imagined shooting than during actual shooting. Time differences were also found in skydiving (Barthalais, 1998). During a set free-fall, the skydiving team had to perform a series of predetermined formations as quickly as possible. Although mentally simulated times were very close to those recorded during skydiving for the best competitors, the athletes visualized the series of figures faster. Again, those results reveal a relationship between expertise level and MI; elite athletes were the most accurate with respect to MI duration. We analyze that relationship later in this article.

**Perceived Difficulty of Task and Temporal Constraints**

In a review, Driskell et al. (1994) indicated that mental imagery might be affected by the intrinsic characteristics of the task being imagined. Difficult transformations of objects take more time to complete (Kosslyn & Koenig, 1992). Likewise, task difficulty is thought to influence the relative duration of mental representation of action (Decety et al., 1989; Jeannerod, 1995, 1999). Participants represent the easier parts even faster (Calmels & Fournier, 2001). Mental execution of an entire gymnastics floor routine performed by 12 elite female gymnasts was found to be shorter than the actual time required to perform the routine (Calmels & Fournier). Gymnasts frequently use imagery just before a competition (White & Hardy, 1998). It is no surprise that in
such conditions of time constraint, gymnasts accelerate the rhythm of routine imagery. Competition offers participants less time than training does. Munroe, Giacobbi, Hall, and Weinberg (2000) had previously shown that MI duration was especially underestimated during a competition. The gymnasts in Calmels and Fournier’s study also indicated that imagery helped them to relax. Participants endeavored to review the entire floor routine within a limited time to control competitive anxiety. Finally, MI duration was shorter than actual execution when the skill was perceived as being easy to perform. That finding favors the notion that one should determine participants’ levels of skill. Conversely, MI duration was longer than in actual performance for the more difficult figures. Those results confirm that skill complexity and time constraints influence MI duration.

Influence of Expertise Level

According to Unestahl (1983), top Swedish skiers were able to ski a course mentally in a time very close to the actual time taken. Deschaumes-Molinaro et al. (1991, 1992) found that the best marksmen’s timing of mentally simulated actions closely approximated actual concentration and movement times. Similarly, Barthalais (1998) and C. L. Reed (2002) observed that the best skydivers and springboard divers were the most accurate, from the time viewpoint, in imagining themselves, as accurately as possible, performing as if they were in a competition. Those results concur with the finding of Denis, Chevalier, and Elloi (1989) and Isaac (1992) that less experienced athletes had greater difficulty in representing accurate movement. The transfer between imagery and actual movement may be facilitated if movement durations are similar (Nideffer, 1985). However, the perceived difficulty of the task may be considered an important factor influencing imagined movement duration. Depending on their expertise level, athletes are to a greater or lesser degree aware of the technical complexity of a movement. The best competitors may perceive a movement as being easy to perform, whereas novice or intermediate level athletes may consider the same movement difficult. Thus, when instructed to represent the movement as accurately as possible, elite athletes appear to be the most accurate; they preserve the actual temporal organization of movement. In springboard diving, C. L. Reed explained, intermediate divers had considerable knowledge of how to perform, but their performance was not fully automatic. Thus, their time to assemble dive components for visualized performance could be relatively longer than that of expert divers, for whom component assembly was automatized. Novice divers clocked relatively shorter visualization times because they had less schematic knowledge about the dives to be assembled. Finally, variations in experimental procedures can explain differences between MI and motor-performance durations. Athletes can simulate actions as accurately as possible, as if they were actually in competition, or just imagine them without time constraints. Instructions to perform mental representation of action may thus influence the temporal organization of MI and should be very precisely stated.

Experiment: Duration of Mentally Simulated Movement in Tennis and Gymnastics

In our review of available literature dealing with durations of mentally simulated movement, we have found inconsistent results: Although MI duration closely mirrors duration of motor production in highly automatic (reaching, grasping) and cyclical movements such as walking or rowing, it can be under- or overestimated (perhaps with the exception of the best competitors). Many factors have been shown to influence the temporal organization of MI. Among those factors, skill complexity and environmental constraints seem to influence MI statistically. To complete the data, we compared durations of actual movements and MI in a tennis task and a gymnastics floor routine. We asked highly skilled tennis players (n = 10) and gymnasts (n = 10) to represent a series of movements in their own sports activity (10 trials). As references (10 trials), we recorded durations of actual movements. Tennis players were asked to serve in the left service area, then to place themselves close to the net and perform a volley. Gymnasts were asked to perform the most difficult series of figures they were able to do (at least round-off, flic-flac, and back acrobatics [tucked or stretched backward salto]).

We hypothesized that the time to put together the components of those rapid attention-demanding movements for visualized performance might produce relatively longer imagined than physical movement durations. To test that hypothesis, we required participants to imagine themselves performing movement during a competition, as closely and accurately as possible, without any actual body movement. Upon initiation of the first body movement and at the end of the MI sequence, the athletes pressed a button with the thumb of their dominant hand, to start and stop the timer, respectively. Durations were found to be systematically longer during MI sessions than during actual performance in both tennis and gymnastics (p < .01; Figure 1). Participants indicated that they tried to build images as accurately as possible. In accordance with Munroe et al. (2000), one can assume that in the absence of time constraints, more time was available to build up a clear representation of movement. One may therefore conclude that in complex skills, image accuracy is more important than temporal characteristics. Moreover, in our study, MI sessions were performed during training; whereas in the study by Calmels and Fournier (2001), the imagery took place just before the competition and mental image duration was therefore slowed down. Thus, the present results confirmed that chronometric differences between MI and action are affected both by time constraints and skill complexity. Moreover, in the absence of environmental constraints, when athletes are instructed to imagine themselves performing in competition, movement duration is not the predominant aspect.
ond experiment confirmed that verbal rehearsal of motor action at a fast rate is more difficult. The results of a second experiment showed a reduction in actual movement speed during the retention test. Similarly, participants who imagined a motor act at a faster speed showed an increase in speed during the retention test (although the effects were less pronounced because imagining a motor action at a fast rate is more difficult). The results of a second experiment confirmed that verbal rehearsal of motor action stages could not have caused the speed-specific interference effects. According to Rushall and Lippman, the procedures and elements of mental training and the participant’s intention may have caused the inconsistent results: MI may be performed during skill-learning or performance enhancement. Whereas the differences can, at least partially, be explained by that theory, other factors such as temporal characteristics of movement, task difficulty, environmental constraints, or accuracy of mental images should be considered. Hall, Mack, Paivio, and Hausenblas (1998) and Martin, Moritz, and Hall (1999) argued that, depending on the situation, athletes should be advised to use mental picture characteristics differentially (e.g., by reducing the speed of the mental picture to elicit retention of a mental component or a more accurate mental picture). Consequently, instructions referring to MI duration must be explicit so that mental work components can be adapted to athletes’ aims.

Contributions of Cognitive Neuroscience Data

Investigators have used mental chronometric tasks in cognitive neuroscience to study the mechanisms underlying cognitive processes (Menon & Kim, 1999). Understanding the neural correlates of goal-directed action, whether executed or imagined, has thus been an important domain of cognitive brain research since the advent of functional imaging studies in which functional magnetic resonance imaging (fMRI) and positron emission tomography were used (Decety et al., 1994; Lotze et al., 1999; Roth et al., 1996). Brain-mapping techniques bring precise anatomic localization of cerebral structures involved in both imagined and executed movements. Neurological data have provided converging evidence that imagined and executed movements share the same neural substrate (for reviews, see Mellet et al., 1998; Thompson & Kosslyn, 2000). Other studies emphasize particularly the involvement of several motor-related areas during MI, such as (a) supplementary, prefrontal, and premotor areas (Decety et al., 1994; Deiber et al., 1998; Naito et al., 2002; Porro, Cettolo, Francescato, & Baraldi, 2000); (b) cerebellum and basal ganglia (Decety, Sjoholm, Ryding, Stenberg, & Ingvar, 1990; Li, 2000; Naito et al.); and even (c) the primary motor cortex (Lotze et al., 1999; Porro et al., 2000; Roth et al.). However, the latter structure was not always found to be activated (Decety et al., 1988; Deiber et al.). There are also similarities between actual and imagined movements at the peripheral level: The same autonomic nervous system pattern has been observed during both MI and motor performance (Deschaumes-Molinaro et al., 1991, 1992), and autonomic activation increases in proportion to mental effort (Decety, Jeannerod, Durozard, & Baverel, 1993; Decety, Jeannerod, Germain, & Pautene, 1991; Wang & Morgan, 1992; Wuyam et al., 1995). MI and actual movement thus share many properties. Lafleur et al. (2002) showed that cerebral plasticity occurring during incremental acquisition of a foot-sequence learning task was reflected in the same brain structures.

Voluntary Modification of MI Duration

Participants or environmental constraints can modify the speed at which a movement or series of movements is voluntarily performed. A tennis player may have very fast images during a match because the time to engage is limited (Munroe et al., 2000). Conversely, the same tennis player may have very slow images during training sessions, when the time available to provide for more accurate movement control is longer. Slow-motion imagery has a negative effect on free-throw shooting performance in top female basketball players (Kobayashi, 1994). Rushall and Lippman (1998) confirmed that finding. Boschker (2001; Boschker et al., 2000) found that participants who imagined a sequential motor action at low speed (in comparison with a baseline test) showed a reduction in actual movement speed during the retention test. Similarly, participants who imagined a motor act at a faster speed showed an increase in speed during the retention test (although the effects were less pronounced because imagining a motor action at a fast rate is more difficult). The results of a second experiment confirmed that verbal rehearsal of motor images during a match because the time to engage is limited (Munroe et al., 2000). Conversely, the same tennis player may have very fast images during training sessions, when the time available to provide for more accurate movement control is longer. Slow-motion imagery has a negative effect on free-throw shooting performance in top female basketball players (Kobayashi, 1994). Rushall and Lippman (1998) confirmed that finding. Boschker (2001; Boschker et al., 2000) found that participants who imagined a sequential motor action at low speed (in comparison with a baseline test) showed a reduction in actual movement speed during the retention test. Similarly, participants who imagined a motor act at a faster speed showed an increase in speed during the retention test (although the effects were less pronounced because imagining a motor action at a fast rate is more difficult). The results of a second experiment confirmed that verbal rehearsal of motor actions.
regions during MI. That result provides additional evidence that actual execution and MI share a common neural substrate, and extends the relationship further to different levels of performance on a motor skill learning task. However, activation of many similar brain areas during MI and actual performance does not guarantee that all aspects of actual and imagined movements, for example, duration, are similar (Papaxanthis, Schieppati, et al., 2002). Thus, the relationship between actual and imagined movements is complex. In fact, the temporal equivalence between imagined

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<td>Barr &amp; Hall (1992)</td>
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<td>Motor imagery preserved the temporal characteristics of movement. Durations of simulated movements were similar to those recorded during actual performance. The timing of execution and mental simulation of highly automatic and cyclical movements were based on common mechanisms.</td>
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<td>Barthalais (1998)</td>
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<td>Although simulated movement was underestimated when compared with actual performance, the best athletes simulated the action mentally at a tempo very close to the actual time.</td>
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*Underestimation of actual movement duration during motor imagery*

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<td>Barthalais (1998)</td>
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<td>In accordance with results of previous studies by Denis et al. (1989) and Isaac (1992), the less experienced athletes had more difficulty in representing the movement accurately: They simulated the series of figures faster.</td>
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<td>Collet et al. (1999)</td>
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<td>Calmels &amp; Fournier (2001)</td>
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<td>Because participants often used motor imagery just before the competition, simulated movement duration was underestimated when compared with actual duration. That time constraint was the main cause invoked by participants to justify accelerating the rhythm of imagery.</td>
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and actual movements has not been consistently reported in the literature. Those distinctions are consistent with the findings of neuroimaging studies: Overlapping but also different neurophysiological substrates have been found in such studies. One limitation of many neuroimaging studies is that cerebral maps are static representations of the dynamic activity of the brain. Advances in single-event fMRI have now opened up possibilities for the study of temporal processing in the brain on the second and subsecond time scales and for the study of spatial processing of information on the submillimeter scale (Menon & Kim, 1999). Investigators may exploit the temporal dimension of fMRI for chronometric studies and use it to examine sequential neural substrates in various regions. Involvement of specific cortical areas and their relative order may thus be discerned during all successive stages of MI. The data may help us to advance hypotheses concerning differences between MI and motor-performance duration.

Conclusion

To summarize, according to the nature and temporal characteristics of the task, MI duration may closely approximate actual movement times. Therefore, in highly automatic activities such as reaching, grasping, and writing a signature, or in cyclical movements (such as walking, running, or rowing), MI duration is similar to that recorded during motor performance. However, participants may also under- or overestimate actual durations (Table 1). When movement representation is influenced by environmental constraints, such as performing MI during a competition, just before action, the duration is underestimated. Similarly, when athletes imagine long preparation and execution periods successively, such as in shooting, they have greater difficulty in representing actual duration. Underestimation of actual duration is also observed when athletes do not represent the entire sequence of movement but instead focus their representation on particular aspects of movement. However, the best athletes appear to be the most accurate with respect to duration in representing motor sequences. Conversely, MI duration was found to increase with skill complexity. Finally, in rapid and complex attention-demanding movements (golf-putting, gymnastics floor routine, and tennis serve), participants systematically overestimate MI duration. Overestimation may appear in the mental rehearsal of other similar rapid movements; however, that hypothesis should be experimentally tested.

The nature of instructions given to athletes is also an important factor that may influence MI duration. Depending on the instructions provided, the participant’s aims can explain the differences between MI and motor-performance durations. Athletes may thus simulate motor performance as if they were actually in a competition, thus preserving the temporal organization of movement, or they can decide to generate very accurate images without time constraints.
The present review can be considered a starting point for further, more extensive research on MI and motor-performance durations. Because elite athletes are the most accurate with respect to imagined motor sequence duration, it would be interesting to compare MI and motor-performance durations within larger groups of athletes in a longitudinal study; that comparison would enable us to evaluate the influence of learning and automatization phases on MI accuracy. In future work, investigators will also have to determine the components of mental training that could lead to improvements in image accuracy and preservation of the temporal equivalence between MI and actual durations. The equivalence between MI and actual durations should be useful for predictive aspects of mental rehearsal. However, underestimation of actual duration during MI may also reflect a learning stage of performance in which physical performance or the integration of cognitive and physical performance is still developing. In methods for training MI to fit actual performance time in those cases, one would need to accommodate the ongoing developments. Finally, experiments combining mental chronometry and fMRI may make it possible to compare imagined and actual duration, on the one hand, and to analyze intensity and spatial distribution of functional activation at a cortical and subcortical levels during MI, on the other. Knowledge of the order in which structures are activated may help to advance hypotheses concerning differences between imagined and actual durations.

REFERENCES


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