ARTICLE

Measuring Motor Imagery Using Psychometric, Behavioral, and Psychophysiological Tools

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COLLET, C., A. GUILLOT, F. LEBON, T. MACINTYRE, and A. MORAN. Measuring motor imagery using psychometric, behavioral, and psychophysiological tools. *Exerc. Sport Sci. Rev.*, Vol. 39, No. 2, pp. 85–92, 2011. *This review examines the measurement of motor imagery (MI) processes. First, self-report measures of MI are evaluated. Next, mental chronometry measures are considered. Then, we explain how physiological indices of the autonomic nervous system can measure MI. Finally, we show how these indices may be combined to produce a measure of MI quality called the Motor Imagery Index.* **Key Words:** motor imagery, mental imagery, psychometric measures, mental chronometry, autonomic nervous system, electrodermal and cardiac activities.

MOTOR IMAGERY

Motor imagery (MI), or the mental simulation of motor movement, is the cognitive rehearsal of an action without actually executing it (9,26). As the mental representation of a movement without the concomitant production of the muscle activity necessary for its implementation, MI has attracted increasing interest from researchers in sport science, psychology, and cognitive neuroscience (12,27).

During the past 15 years or so, we have conducted a number of studies on theoretical, practical, and rehabilitation issues involving MI. First, we have investigated the brain mechanisms underlying motor skill rehearsal and movement planning (11). Second, we have shown with others that the MI technique of *mental practice* ("seeing" and "feeling" a movement in one's imagination before executing it) can increase physical strength performance (30) and enhance skill learning (3) and technical performance in athletes (4,32). Finally, we confirmed that MI training can facilitate rehabilitation from physical injury or neurological damage ((5) see (22) for a review). Elsewhere, we have provided a detailed account of research findings on MI (12).

Considering that MI is a multidimensional construct (see model developed by Guillot and Collet (10)), we have measured its underlying processes using a combination of psychometric tests (18), qualitative procedures (19,25), chronometric methods in which MI processes are investigated by comparing the duration required to execute real and imagined actions (8), and psychophysiological techniques (1). Although these approaches have each yielded some interesting results (12), they have not yet been combined adequately to provide an aggregate index of MI quality. Therefore, the purpose of this review is to propose a rationale for our novel hypothesis that it is possible to calculate an index of MI quality by *quantitatively combining* psychometric, qualitative, chronometric, and psychophysiological measures. Our proposed *Motor Imagery Index* (MII) has significant implications for researchers and practitioners because it can be used to understand individual differences in MI and to assess the efficacy of MI interventions.

PSYCHOMETRIC APPROACH

For more than a century, researchers have used standardized self-report questionnaires to measure individual differences in imagery dimensions such as *vividness* (*i.e.*, the clarity or sensory richness of an image) and *controllability* (*i.e.*, the ease and accuracy with which an image can be manipulated mentally, see (24)). We have investigated both of these dimensions of imagery in sport settings. For example, we found that elite canoe-slalom competitors reported significantly greater use of MI than did less proficient counterparts when preparing for races (17). We investigated the effects of MI on the learning (through both physical and mental practice) of volleyball technique among intermediate performers of this sport (32). We found that a combination of MI and physical practice produced the most efficient

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training condition for the acquisition of a volleyball skill. We also measured individual differences in image controllability using the Group Mental Rotations Test (33), a measure that requires participants to complete *mental rotation* tasks (*i.e.*, spatial visualization puzzles that measure the ability to imagine what an object would look like if presented in a different orientation) that have correct or incorrect answers. In a novel application of this mental rotations test to athletes in field settings, we investigated the imagery controllability of elite canoe-slalomists who were competing in various World Cup races (18). Our results showed that, as expected, there was a significant moderate correlation between image controllability and race rank order for these athletes. This finding is interesting but perhaps not really surprising because canoe-slalomists routinely use imagery processes in an effort to mentally plan complex sequences of spatial routes under severe time constraints and in the absence of opportunities to navigate the course physically (25).

As it is difficult to create test items that objectively assess the ability to imagine physical movements, subjective measures of imagery vividness commonly are used in the measurement of MI ability (see (13) and (31) for the Motor Imagery Questionnaire–Revised version and the Vividness of Movement Imagery–Revised version, respectively). Unfortunately, these tests of MI have certain limitations. For example, the movements that participants are required to form in these tests are quite complex and time consuming, thereby making such tests administratively inconvenient (23). In addition, the construct validity of these MI measures is questionable. For example, in the original version of the VMIQ, participants are requested to rate a given action by either "watching somebody else" doing it (alleged to measure visual imagery of movement) or "doing it yourself" (alleged to measure kinesthetic imagery of movement). The problem with this instruction is that it is confounded by imagery perspective. Specifically, it does not specify whether one should watch oneself performing the action from a *third-person perspective* (*i.e.*, as if watching oneself on television) or from a *first-person perspective* (*i.e.*, as if one were performing the movement themselves (23)). In short, the VMIQ measures external *other* imagery rather than external *self-imagery* — a problem that, fortunately, has been addressed in the revised version of this scale (31). Given such problems, we have augmented the psychometric approach to imagery measurement with three other measurement paradigms — the next of which is the qualitative approach.

QUALITATIVE APPROACH

Qualitative methods enable researchers to investigate the meaning and richness of people's experiences. Although such methods have obvious weaknesses (*e.g.*, they depend on introspective access to conscious awareness), they can provide valuable insights into athletes' *meta-imagery* processes — or their knowledge of, and control over, their *own* mental imagery skills and experiences (26) — and their reported use of MI over time. We have used qualitative methods such as semi-structured interviews to study the MI experiences of canoe-slalom competitors (25), as well as of a multisport sample (19).

Using expert-novice comparisons, we investigated whether expert athletes have greater insight into and control over their use of imagery than their successful counterparts. First, we asked athletes about their knowledge of some common MI effects. Across the samples, our findings indicated that athletes were aware of *mental practice* effects (explained earlier). In addition, we found that most of our participants were aware of the *mental travel* effect — the fact that when one imagines a movement, it should last the same duration as the actual executed action. Second, we investigated athletes' ability to engage in *meta-imagery monitoring* or their capacity to check the content of their imagery representation. For instance, when athletes experience a debilitative image (*e.g.*, a missed putt) they, by monitoring their imagery content, can choose to stop the imagery, rewind it, and attempt to imagine the desired action or outcome (*i.e.*, a successful putt). Athletes in our studies gave accounts of this process of "rewinding" their images if they experienced debilitative imagery (19). Moreover, several participants reported that they deliberately engaged in imagery of undesirable outcomes (*e.g.*, an errant drive in golf) to facilitate the generation of an appropriate response, a type of "what-if" imagery. Finally, we studied *meta-imagery control* or any strategy that a person uses in attempting to regulate and/or improve his or her imagery. We discovered that athletes reported using a number of strategies to enhance their MI, including holding their implements (*e.g.*, golf club) during imagery and even moving physically during imagery. This latter point requires explanation as the respondents did not merely *describe* movements that simulated their actions (*e.g.*, moving your arms during imagery of kayaking, termed *synchronous imagery*), they actually engaged in *asynchronous* movements, where, for example, their hands would represent the movement of an imaginary kayak (20). Although few studies have tackled this apparent confusion between imagery and movement, preliminary research suggests that imagery content is more accurate when athletes perform visualization in contexts that resemble training or competition environments, rather than in laboratory conditions (10).

With this latter idea in mind, we required participants to engage in a task involving self-estimation of different aspects of their imagery experience immediately after engaging in MI. The key findings to emerge were that although imagery was multimodal, the most important aspects of imagery (and most commonly reported) were visual and motor. Of note was the fact that participants differentiated between two aspects of MI: the effort aspect and the sense of body position (25). The relative contribution of different senses to the imagery experiences of athletes in different sporting activities requires further exploration. Nevertheless, our studies highlight that qualitative methods may offer a fruitful pathway to illuminate the multidimensional nature of MI.

CHRONOMETRIC MEASURES

In the quest to understand links between voluntary movement and MI, it was discovered that they demonstrate similar temporal patterns, as shown by the seminal study of

Decety *et al.* (2). Since then, researchers have been interested in assessing an individual's ability to preserve the temporal characteristics of the movement during MI. Although measuring such temporal congruence is a simple and reliable method to evaluate the temporal features of imagery accuracy (8,9), the findings we have reported suggest that the relationship is a complex one. A number of factors seem to influence the temporal properties of motor images, and these issues are considered briefly in this section to provide a full overview of the critical role of chronometric measures.

Many studies have reported that the duration of mentally simulated actions ideally should be correlated with the time taken to execute the same movements (8). However, we have identified several external factors that influence athletes to either underestimate or overestimate the actual duration of MI (8). For instance, we provided evidence that distortion of mental durations can be caused by movement duration (7) (also see (6)), as well as movement difficulty (7,8). Practically, short durations are often overestimated, whereas long durations are frequently underestimated during MI. We also have found that imagery times increase linearly as a function of both task difficulty and intensity of the mental effort. The temporal constraints, expertise level, or the level of arousal might similarly alter MI times (15). Clearly, such distortions of MI times do not mean that MI is inaccurate systematically.

In another set of experimental studies, we have demonstrated that changing imagery speed seems to rapidly affect the actual speed, hence, highlighting the fact that the control of MI speed is a very important aspect of mental training. We investigated the effect of voluntarily changing imagery speed on complex motor tasks, as well as a highly automated motor task, for which the duration was set and controlled for many years (16). The data revealed that changes in MI speed modified the execution time of subsequent motor tasks. In short, a voluntary *increase* in imagery speed led to increases in the speed of motor performance. Conversely, a voluntary *decrease* in imagery speed led to decreases in the speed of the actual movement.

Practically, these data provide evidence that in research on MI, it is absolutely necessary to control the *duration* of imagined movements. Interestingly, voluntarily changing MI speed may have positive effects and therefore facilitate motor learning. For instance, decreasing the speed of MI might slow down the actual movement that would enable the athlete to make corrections and adjustments of fine visual motor tasks (28). Moreover, we also showed that accelerating MI can increase the speed of the subsequent actual performance — although we have no idea, as yet, whether such speed gains might affect the technical components of motor skill execution. Nevertheless, changes in MI speed may have some important negative effects. For example, the fact that the lack of control of MI speed may elicit unexpected changes in actual times could be detrimental to actual performance. Underestimating movement duration during MI can result in actual speed gains in which one could mix up speed with haste. The fact that athletes frequently use imagery at their own pace (regardless of its speed and congruence with its physical counterparts) makes them exposed to unexpected changes in actual speed, which means that MI could hinder subsequent motor performance.

Interestingly, the importance of evaluating the temporal congruence between MI and motor performance is confirmed by neuropsychological research on patients with brain damage. Such studies show evidence of patients' difficulty in preserving congruence between actual and imagined times during MI (21). In this regard, damage to cortical structures may interfere with the temporal organization of MI and accuracy of motor tasks (most especially for distal movements), thus emphasizing the importance of assessing the MI ability of patients before considering using mental practice as a therapeutic approach. When assessing MI processes, it may be important to consider the relationship between actual and imagined times using paradigms with *intermediate* time measures (*i.e.*, split times) instead of just total times. More generally, in most imagery research, it remains difficult to determine, when total times are identical, whether athletes imagined all the elements of their actual sequence in real time, or if there were some overestimations or underestimations that may have canceled each other out.

To summarize, we have shown that methods based on recording MI times and measuring the temporal congruence between imagery and actual times are powerful and versatile tools for the assessment of MI ability. However, although chronometric methods are easy to use and cost-effective, their interpretation is not always straightforward because several extraneous factors need to be considered before drawing conclusions about imagery ability (8). It also is evident that the temporal features of MI probably are less important when imagery is used to improve motivation, build confidence, and modulate anxiety, where athletes voluntarily use imagery speeds other than in real time (28), without being exposed to the same consequences as in actual practice. A final caution is that because imagery vividness is not considered at all when looking at imagery times, imagery duration recordings should ideally be combined with other paradigms (*i.e.*, qualitative, psychometric, and psychophysiological) when attempting to measure MI comprehensively (12,32).

PSYCHOPHYSIOLOGICAL MEASURES

Recent advances in measurement technology have led to converging evidence, indicating that some psychophysiological parameters change during MI and that these changes are generally shown to match those elicited during actual execution (1). To explain, brain mapping techniques provided evidence that imagined and executed movements activated almost the same neural networks. Results suggested a strong overlapping of brain structures controlling motor activity, including premotor cortex, supplementary motor area, and other subcortical centers during both actual execution and motor representation of the same movement. However, with a view to developing an index of MI quality, we must focus our methodological tools on ambulatory and noninvasive procedures. Furthermore, psychophysiological recordings are more suitable than direct measurement of brain activity for the provision of real-time data processing and instantaneous feedback.

At a more functional level of analysis, psychophysiological concomitants of MI have focused on two sources of evidence:

cardiovascular responses and electrodermal activity (for a review, see (1)). We shall now address each of these in turn.

In 1995, Wuyam *et al.* (35) recorded variations of the respiratory and cardiac functions during the representation of action that resembled what was observed during actual movements. Heart rate and respiratory frequency increased, whereas the imagined effort increased in parallel. These responses of the autonomic nervous system (ANS) clearly should be interpreted in terms of increasing arousal. MI also requires focusing attention on several important cues of movement execution to make them clearly represented in the mind. Cardiac deceleration has been linked closely with attention processes (29). Responses from the ANS recorded during MI thus provided at least two courses of reliable information: the first concerning variation of arousal and the second associated with more qualitative processes such as focusing attention. Although arousal is mainly under the control of the sympathetic branch of the nervous system (34), attentional processes remain under the management of the vagal nerve, that is, the parasympathetic system. With reference to Porges (29), the *nucleus ambiguus vagus* is associated with cognitive processes, including attention and orienting to changes in the environment.

The other variable of particular interest is electrodermal activity (EDA), which results from exocrine sweat glands activity and is under the unique control of the sympathetic system (34). As its function is to mobilize the energy of the organism, to help the individual who is facing constraints from the environment to process information efficiently, EDA could therefore give a close evaluation of arousal and its variation. An increase in arousal is evident in increased skin conductance (SC) (or decreased skin resistance) heart rate and blood pressure, for example. Furthermore, EDA is very sensitive to a stimulus, whatever its origin (*i.e.*, either from the environment or from internal processes). Electrodermal response (EDR) (phasic activity) is elicited as early as the participant is engaged in the mental representation of a movement. We thus have an objective index of the athlete's mental activity. Peripheral physiological indicators from the ANS are closely correlated with relevant cognitive processes (14).

Taken as a whole, we have shown that recording electrodermal and cardiac activities may provide a window on higher order brain functions (1). In the next section, we argue that these indices can contribute to the study of MI, along with other neurophysiological and psychological methods (9). In fact, we already have used them in certain situations both as a way to control MI in real time and to differentiate between good and poor imagers (11,32).

As we shall explain, the main principle underlying our MII is that autonomic response patterns recorded during MI should resemble those recorded during actual execution. Based on this principle, certain autonomic response indices may serve as psychophysiological markers of mental rehearsal. Consequently, ANS basal values as well as ANS responses, recorded during each MI trial, should match those recorded during actual execution. Based upon this principle, several criteria can be defined for psychophysiologically efficient mental work.

In summary, despite abundant evidence that ANS responses are elicited during the mental representation of movements, few researchers have used this phenomenon to control and evaluate the effectiveness of MI during learning or mental rehearsal. In this article, we fill this gap in the literature by proposing to link quantitative responses from the ANS to the qualitative mental process of MI. This novel approach allows us to link specific patterns of ANS responses with qualitative aspects of MI.

MII: A NOVEL HYPOTHESIS

In this section, we propose to integrate certain aspects of the various measures previously described into a single index of MI quality. Our postulated MII may be computed from six other subindices (numbered from SI_1 to SI_6), as follows:

$$MII = SI_1 + SI_2 + SI_3 + SI_4 + SI_5 + SI_6$$

To explain, SI_1 measures MI quality on the basis of the subjective approach (*i.e.*, via self-estimation). SI_2 is yielded from a psychological questionnaire specifically designed to evaluate MI ability (see (13), *e.g.*, the MIQ-R). SI_3 is computed from the principle of isochrony, with reference to the mental chronometry (MC) method. SI_4, SI_5, and SI_6 emerge from physiological recordings. SI_4 is related to the evaluation of arousal level by the mean of the EDA basal level. SI_5 and SI_6 are two indices from EDA and cardiac responses, respectively, each of them bringing useful information about attention allocated to the mental representation of movement. Taking into account the relative importance of each subindex, we could apply a weighting factor, numbered from c1 to c6, as follows:

$$MII = c1^* SI_1 + c2^* SI_2 + c3^* SI_3 + c4^* SI_4 + c5^* SI_5 + c6^* SI_6$$

Using the qualitative approach, MI vividness could be evaluated using a 7-point scale. The first point could represent a fuzzy image, meaning that the athlete encountered trouble in forming a vivid representation of the movement concerned. Conversely, a 7 could represent a very vivid and clear representation of this movement. Intermediate levels from 2 to 6 would correspond to a mixed evaluation of the representation. The first subindex could be computed by taking the average score into account, in case of several trials. As self-estimation is a subjective indicator, our proposal is to set the first coefficient c1 to 1. The average score should therefore be divided by 7 to finally have a maximal score of 1.

$$c1 * \frac{average\ score}{7}$$

The second subindex is based on the results of a well-validated psychometric test such as the MIQ-R. This index is made of 8 movements that should be imagined using both visual and kinesthetic imagery. This test also is aimed at evaluating the MI vividness using a 7-point scale with the same evaluation as that described in the previous paragraph (1 means very hard to imagine, whereas 7 means very easy to imagine). With reference to this estimation scale, the maximal score could be 56. Consequently, SI_2 could be computed as follows:

$$c2 * \frac{MIQ\_R \text{ score}}{56 \ (max \text{ score})}$$

Thus, the maximal score of SI_2 could be 1. As it also is computed from self-estimation, our proposal is to set the second coefficient c2 to 1.

The third subindex is related to MC and the principle of isochrony governing the relationship between imagined and actual movement duration. With some cautions caused by exceptions to this latter principle (see the previous paragraph), we postulate that the temporal equivalence between imagined and executed movement is a reliable criterion for MI quality. Thus, MI quality evaluated through MC could be:

$$c3 * \left(\frac{1 - |\text{MC } actual - \text{MC MI}|}{\text{MC } actual} \right)$$

As MI duration may be longer or shorter than that of actual execution, absolute values are used. The difference remains the same, however. The significant difference is found between the duration of the mental representation of movement and its actual duration. The maximal score could be 1, with, however, a higher weighted coefficient. As MC brings objective data, c3 could be set at 2. This coefficient could easily be decreased as a function of certain features of the task and/or participants (see previous paragraph again). For example, when the duration of actual task is very short or very long, the isochrony may be altered and, consequently, the weight of this subindex should be adjusted.

Regarding the physiological indicators, we should be able to evaluate both arousal and attention processes using a limited number of indicators. The EDA can be used to estimate the level of arousal because of its control by the sympathetic nervous system. We propose to quantify arousal with EDA tonic level using SC. Two other indicators serve to estimate the level of attention focused on the represented action: EDR and cardiac activity. These indices may be described as follows. First, the level of arousal at which MI is performed should be maintained at a constant level during the session. Theoretically, the arousal level at which MI is performed should be almost the same to that at which actual movement is performed. However, as the conditions of simulated movements are not identical to those of its actual execution, it seems better to verify whether the level of arousal is preserved during the imagery session. Consequently, the fourth subindex of MI quality should be computed as follows:

$$c4 - \frac{|SC \ end - SC \ start|}{|SC \ start|}$$

The difference between SC recorded when starting the session and at the end of the rehearsal period should be the weakest. When this difference is null, the maximal score is thus c4. A negative difference between SC_{end} and SC_{start} would correspond to a *decrease* in arousal. This would mean that the athlete relaxed during the session, which could impair MI quality (16). The opposite result also is possible and would mean that the athlete increased his or her level of arousal. This would correspond to overactivation, possibly elicited by overloaded conditions (*e.g.*, too many mental repetitions). When this difference is large, the resulting score may be less than 1 and could even be negative, thus altering the whole MII. This specific computation is made to emphasize the importance of this subindex. In the same way, to attest its importance, the value of c4 could be set at 2.

The two remaining indices are related to attentional processes as the person engaged in MI needs to remain focused on the fundamental movement cues required to perform well. These processes can be evaluated using EDR recorded as early as the athlete has informed the experimenter that he or she has begun the sequence mentally (32), and they also can be evaluated by the respiratory sinus arrhythmia. Typically, the EDR is generally recorded when a stimulus is provided to the athlete. This response suggests that the stimulus was perceived and processed. The duration of information processing is generally paralleled by the duration of EDR. This also may indicate that some cognitive activity actually occurred in the individual's mind, and hence, such EDR may be observed in the early stages of the person's attempt to form a mental representation of the experimental task. A way to quantify EDR is to measure its duration with the aim to compare its duration during actual execution to that observed during MI of the same movement. The criterion for MI quality is the isochrony between the two EDR. Thus, SI_5 should respect this requirement by being based on a computation of

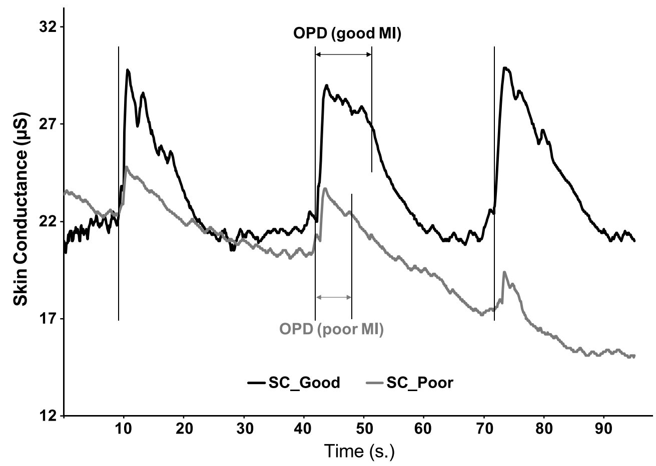

Figure 1. Skin conductance (SC) response during motor imagery (MI). Each *vertical bar* represents the starting of MI. It corresponds to the onset of electrodermal response. Whereas the Ohmic Perturbation Duration (OPD) is close to the duration of actual movement, thus indicating a good MI performance, a short OPD is correlated with poor imagery performance. In each case, the OPD is shorter when MI performance is weak. Furthermore, the slope related to good MI shows a constant SC level, thus indicating that the arousal level is constant during the MI session (SC value is around 22 μSiemens). Conversely, SC drastically decreased between the start and the end of the session, thus indicating decreased arousal. These data suggest that the participant is unable to keep his or her arousal at a level that is compatible with efficient cognitive processing. The SC level and behavioral responses could, thus, be integrated in the MI Index (MII) as a measure of MI performance.

the ratio of the two EDR, named Ohmic Perturbation Duration (OPD).

$$c5 * \frac{MI\ OPD}{Actual\ OPD}$$

As the EDR provides an objective and accurate indication of MI quality, we propose to set the weighting coefficient at 2. Figure 1 gives an example of EDR recordings during MI, showing OPD computation and comparison between poor and good MI performance.

The last subindex to be integrated within the MII is extracted from cardiac activity. As previously described, heart rate decrease (*i.e.*, bradycardia) usually is correlated with increased attention. When heart rate is rated in terms of instantaneous values, this bradycardia corresponds to a sudden drop of cardiac frequency that is observable easily. However, the duration of rehearsed movements generally is longer than this period of orienting attention. For this reason, a more accurate index is preferred to bradycardia as it could indicate that focused attention is maintained during the whole period of movement representation. Instantaneous heart rate shows spontaneous variations as a function of respiratory cycles, and so there is increased heart rate during the breathing in phase, whereas heart rate decreases during the expiration. This is *respiratory sinus arrhythmia* (RSA), which represents the mean amplitude of heart rate variability during the observation period. RSA is likely to decrease when attention is focused during a given period (29). Thus, this index could be considered as a measure of concentration during MI:

$$c6 * \frac{RSA\ rest - RSA\ MI}{RSA\ rest}$$

Figure 2 gives an example of heart rate recordings during MI, showing RSA computation and a comparison between poor and good MI performance.

The combination of EDR and sinus arrhythmia quantification brings complementary data to bear on the nature of the mental processes involved in MI, especially, focused attention. As this cardiac index has the same advantages as EDR, we propose keeping the same coefficient of weighting, that is, 2.

The resulting MII is made of the sum of all subindices previously described:

$$\begin{aligned} MII = {} & c1 * \frac{Self\ Estimation}{7} + c2 * \frac{score\ MIQr}{56} \\ & + c3 * \left(1 - \frac{|MC\ actual - MC\ MI|}{MC\ actual}\right) \\ & + c4 - \left(\frac{|SC\ end - SC\ start|}{SC\ start}\right) \\ & + c5 * \frac{OPD\ MI}{OPD\ actual} + c6 * \frac{RSA\ rest - RSA\ MI}{RSA\ rest} \end{aligned}$$

The two following examples of implementation are aimed at showing both a poor MII score and a good MII score, respectively, depending upon the sum of all subindices. The resulting implementations are summarized in the Table.

Values of poor MI performance are detailed as follows. The self-estimation score is 1 from 7. The MIQ-R score is 20 from 56. The duration of imagined movement is underestimated 5 s whereas the actual movement lasted 12 s, the SC value decreased from 25 to 6 μSiemens during the mental rehearsal session, meaning that the participant relaxed during the session without keeping his arousal at a level compatible with efficiency. The mean OPD values were under the actual movement duration, 3 s versus 12 s, and the RSA remained close to the reference value, 10 beats $\cdot$ min^{-1} versus 12 beats $\cdot$ min^{-1}.

The poor MII score was thus implemented as follows:

$$\begin{aligned} MII = {} & c1 * \frac{1}{7} + c2 * \frac{20}{56} + c3 * \left(1 - \frac{|12-5|}{12}\right) \\ & + c4 - \left(\frac{|6-25|}{25}\right) + c5 * \frac{3}{12} + c6 * \frac{12-10}{12} \\ = {} & 3.408. \end{aligned}$$

In the same way, values of good MI performance are detailed as follows. The self-estimation score is 7 from 7. The MIQ-R score is 50 from 56. The duration of imagined

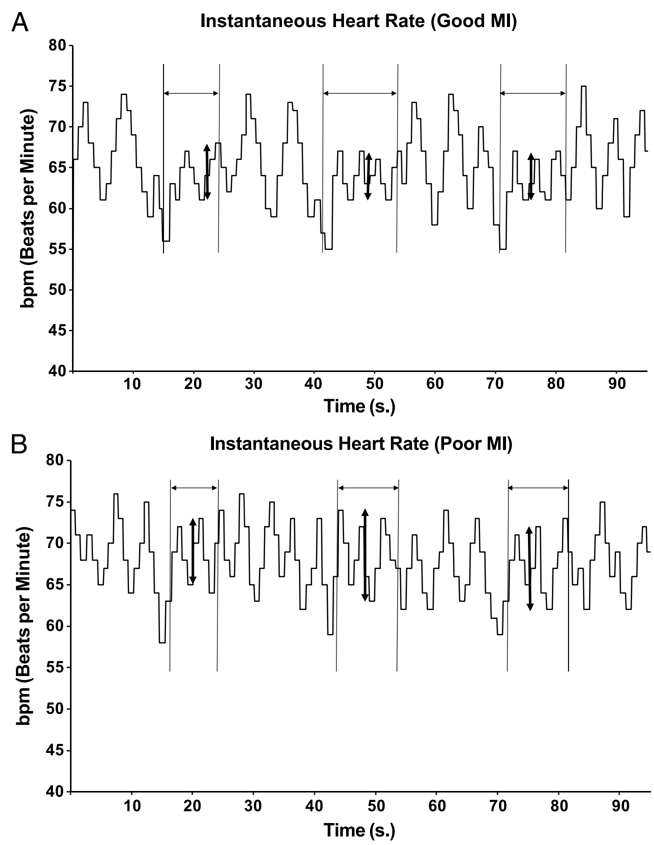

Figure 2. Instantaneous heart rate recordings during motor imagery (MI). Each *horizontal arrow* represents the period during which MI was carried out. MI is shown to elicit variation in the respiratory sinus arrhythmia (RSA) by decreasing the amplitude between maximal and minimal heart rate. However, *bold vertical arrows* show that this decrease is significantly higher during the mental rehearsal sequence of good MI performance (A) than during mental rehearsal sequence of poor MI performance (B). As it brings complementary information to electrodermal activity, RSA also should be integrated in the MI Index (MII) as a measure of MI performance.

TABLE. Two examples of MII implementation

Subindices	Weighting Factor	Poor MI Performance			Good MI Performance		
		Score	Implementation	Subindex Value	Score	Implementation	Subindex Value
Self-evaluation	1	1	1*1/7	0.143	7	1*7/7	1
Questionnaire	1	20	1*20/56	0.357	50	1*50/56	0.893
Mental chronometry	2	5 (Actual time is 12s)	$2*\left(1-\frac{\lvert 12-5\rvert}{12}\right)$	0.834	11 (Actual time is 12s)	$2*\left(1-\frac{\lvert 12-11\rvert}{12}\right)$	1.834
Electrodermal activity	2	6	$2-\left(\frac{\lvert 6-25\rvert}{25}\right)$	1.24	24	$2-\left(\frac{\lvert 24-25\rvert}{25}\right)$	1.96
Electrodermal response	2	3 (ref. time is 12s)	2*3/12	0.5	11 (ref. time is 12s)	2*11/12	1.832
Respiratory sinus arrhythmia	2	10 (ref. RSA is 12)	$2*\frac{12-10}{12}$	0.334	5 (ref. RSA is 12)	$2*\frac{12-5}{12}$	1.166
			MII	**3.408**		MII	**8.685**

The six subindices making the Motor Imagery Index (MII) appear in the first column. The weighting factors are in the second column. Implementation for poor MI performance is described in the three following columns. The same principle was applied for the good MI performance. Each MII score is made of the sum of each subindex. The MII clearly separated poor from good MI performance.

movement is more closely estimated, 11 s (actual duration, 12 s). The SC value remains almost at the same level (24 vs 25 μSiemens). The mean OPD values are close to actual movement duration, 11 s versus 12 s, and RSA decreases strongly by comparison with the reference value, 5 beats $\cdot$ min^{-1} versus 12 beats $\cdot$ min^{-1}, thus attesting focused attention.

The good MII is thus implemented as follows:

$$MII = c1*\frac{7}{7}+c2*\frac{50}{56}+c3*\left(1-\frac{|12-11|}{12}\right) + c4-\left(\frac{|24-25|}{25}\right)+c5*\frac{11}{12}+c6*\frac{12-5}{12} = 8.685$$

To summarize, the implementation of poor MII is 3.408, and this corresponds to a high MII, 8.685, a difference that is more than twofold. Based on this hypothetical example, it is evident that the MII can be used to distinguish between poor and good mental rehearsal (Table).

GENERAL CONCLUSIONS

In this article, we have argued that the multidimensional construct of MI (or the cognitive rehearsal of an action without actually executing it) is best measured using a combination of qualitative, psychometric, chronometric, and psychophysiological approaches. More precisely, we have postulated the novel hypothesis that an overall MII score may be calculated from six specific components that are themselves derived from self-estimation of imagery quality, psychometric assessment of imagery vividness, MC (estimation of the differences between actual and imagined duration of movement execution), and from three psychophysiological concomitants of imagery (based on electrodermal and cardiac activities).

Having explained our proposed formula for calculating the MII, we now turn to consider the advantages of this hypothetical index. To begin with, just like the Apgar index (which was the first standardized method for the calculation of an infant's chances of successfully living outside the womb), the MII is relatively easy to calculate because several of the component measures (specifically, the self-estimation, psychometric assessment, and chronometric recordings) do not require specialist equipment. Second, our proposed MII is a flexible metric because its weighting can be adjusted to take account of factors relating to specific features of the imagined movement, as well as of the characteristics of the participants. For example, if the principle of isochrony is violated because of the use of mental tasks whose estimated duration is too short or too long, the weight of the relevant subindex could be reduced. Conversely, if MI sessions are planned for enhancing self-confidence and relaxation, the weight of the electrodermal tonic level could be increased. Finally, we believe that because of its multicomponent origin, the MII overcomes the limitations associated with using only one approach to the measurement of MI. Clearly, the next step is to validate this new index empirically using a range of either athlete or patient samples. A step in this direction was taken by Roure *et al.* (32), but the next studies in this field require more precise measurement of the mental processes used by participants while they are engaged in MI. This also could be a limitation of our MII use: integrating indices from several different scientific fields requires a thorough knowledge of each tool and data processing method. It might be difficult for a researcher to control both the psychometric and physiological methods. For this reason, the calculation of the MI index will undoubtedly involve many skills to ensure its reliability.

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