Measuring motor imagery ability: A review

Laura P. McAvinue and Ian H. Robertson
Psychology Department, Trinity College Dublin, Ireland

The internal nature of motor imagery makes the measurement of motor imagery ability a difficult task. In this review, we describe and evaluate existing measures of motor imagery ability. Following Jeannerod (1994, 1997) we define motor imagery in terms of imagined movement from the first person perspective. We describe how explicit motor imagery ability can be measured by questionnaire and mental chronometry, and how implicit motor imagery ability can be measured through prospective action judgement and motorically driven perceptual decision paradigms.

Future research should be directed towards a theoretical analysis of motor imagery ability, the improvement of existing questionnaires and the development of new ones, and the standardisation of existing paradigms.

Motor imagery has become an important topic in the areas of rehabilitation, for example in promoting the recovery of motor function following stroke (Page, 2000; Sharma, Pomeroy, & Baron, 2006), sport psychology, where athletes use motor imagery to improve their skills and strength (Janssen & Sheikh, 1994) and action control, where the neural bases and temporal characteristics of motor imagery can be explored to aid our understanding of action (Jeannerod, 1997). However, it has long been known that imagery ability is subject to wide individual differences (Galton, 1883; Kosslyn, 1980, 1999; Richardson, 1994), a fact that makes the measurement of imagery ability prior to an imagery experiment or imagery training programme imperative. In this paper, we describe and evaluate the measures that are available to measure motor imagery ability, beginning, first of all, with a definition of motor imagery.

Correspondence should be addressed to Laura P. McAvinue, Psychology Department, Aras an
Phiarsaigh, Trinity College Dublin, Dublin 2, Ireland. E-mail: laura.mcavinue@gmail.com

Thank you to the Irish Research Council for the Humanities and Social Sciences and the
National Disability Authority of Ireland for supporting this research.
EUROPEAN JOURNAL OF COGNITIVE PSYCHOLOGY
2008, 20 (2), 232_251

http://www.psypress.com/ecp DOI: 10.1080/09541440701394624
Downloaded By: [Canadian Research Knowledge Network] At: 15:28 13 March 2008

DEFINING MOTOR IMAGERY

Motor imagery has been at the centre of many theoretical discussions and has been conceptualised in terms of motor representations (Jeannerod, 1994, 1995, 1997), action prototypes coupled with memory processes (Annett, 1996) and forward models (Grush, 2004; Schwoebel, Boronat, & Coslett, 2002; Wilson, 2003; Wolpert & Flanagan, 2001). A quick and basic definition of motor imagery equates it with imagined movement of the body but imagined movement of the body can be realised in several different ways. Furthermore, within cognitive neuroscience and sport psychology, imagined movement has been discussed under many headings, including motor imagery, mental imagery, movement imagery, mental practice, imagery rehearsal, visualisation, kinaesthetic imagery, and visuomotor behavioural rehearsal. Not surprisingly, the use of these terms is underpinned by several slightly different concepts of ‘‘imagined movement of the body’’.

Sport psychologists made the first attempt at clarifying concepts of imagined movement. They pointed out that movement could be imagined from internal or external perspectives. The internal perspective involved imagining movement from the first person perspective, as if one was actually performing the movement. It was considered to contain a large kinaesthetic component causing the participant to feel him- or herself performing the imagined movement. The external perspective involved seeing oneself performing the movement from the third person perspective, as if watching oneself on television. This perspective was considered to be mainly visual in nature (Hall, Rodgers, & Barr, 1990; Janssen & Sheikh, 1994; White & Hardy, 1995).

Annett (1995) reserved the term ‘‘motor imagery’’ for imagery that required some degree of ‘‘voluntary control on the part of the imager as agent’’ (p. 1395). With this key ingredient in mind, he suggested that imagined movements of the body from the internal and external perspectives and dynamic visual images, which required imagined manipulation of external objects, deserved to be called motor images.

Jeannerod (1995, 1997) explained motor imagery in the context of a hierarchical model of action control. He put forward a centralist viewpoint of action control, arguing that action involved the covert stages of intending, planning, and programming the action, and the overt stage of execution. At each stage, a motor representation, specifying the goal of the action, was created. Action was controlled by comparing the represented goal of the action with the current state of the system.

Jeannerod suggested that motor representations were involved in a variety of other cognitive activities besides action control (Jeannerod, 2001; Jeannerod & Frak, 1999). He argued that motor representations participated in cognitive activities in conscious and nonconscious form. For example,

action in dreams and imagined action involved conscious motor representations (explicit motor imagery), whereas prospective action judgements and motorically driven perceptual decisions involved nonconscious motor representations (implicit motor imagery). Intended action and observation of action performed by others could involve conscious or nonconscious

motor representations.
According to Jeannerod's conceptualisation, then, explicit and implicit forms of motor imagery were underpinned by motor representations created in the motor system. They, therefore, necessarily, reflected the biomechanical constraints of the body and the kinematic rules that govern action. On a phenomenological level, Jeannerod (1994) described explicit motor imagery as imagined movement from the first person perspective, akin to the internal perspective movement imagery described by sport psychologists. Jeannerod differentiated motor imagery from dynamic visual imagery and external perspective movement imagery, considering these as examples of visual imagery. An important component of motor imagery, according to Jeannerod, was kinaesthetic sensation, which allowed the imager to feel him- or herself performing the movement. However, he was careful to point out that motor imagery could not be reduced to kinaesthetic imagery.
A motor image was a simulation of an action, which unfolded in a bodycentred and visuospatial context. It therefore contained the kinaesthetic, visual, and spatial aspects of the corresponding action. Smyth and Waller (1998) provided evidence for the existence of visual, kinaesthetic, and spatial aspects of motor imagery, showing that the predominance of each varied with the kind of action being imagined and the situation in which the action was being imagined.
In the sections that follow, the measures available to assess explicit and implicit motor imagery ability will be reviewed. The main difference between measures of explicit and implicit motor imagery ability is the degree of awareness of motor simulation that the participant has when performing the tasks. The measures of explicit motor imagery to be reviewed below are selfreport questionnaires and Mental Chronometry paradigms. In each of these measures, the participant is asked to engage in motor imagery and during the task, he/she consciously imagines performing movements. The measures of implicit motor imagery to be reviewed below are Prospective Action Judgement and Motorically Driven Perceptual Decision paradigms. In each of these paradigms, the participant is asked to make a decision regarding a visually presented stimulus. Examples of decisions to be made are a decision regarding the laterality of a visually presented hand and a judgement regarding the most comfortable kind of grip to use when grasping a wooden bar. During these tasks, the participant is not asked to engage in motor imagery. However, analyses of responses and reaction times during these tasks suggest that the participant is engaging in motor imagery, without

being aware of it. (Please note that the participant could solve these tasks using explicit motor imagery, if his/her attention was drawn to this strategy.)

MEASURING EXPLICIT MOTOR IMAGERY ABILITY

Explicit motor imagery ability can be measured through self-report questionnaires and mental chronometry.

Self-report questionnaires

Hall (1998) identified two kinds of questionnaire: those that measure movement imagery ability and those that measure movement imagery use.
Movement imagery ability. Isaac, Marks, and Russell (1986) developed the Vividness of Movement Imagery Questionnaire (VMIQ) to fill a void in the literature relating movement imagery to motor performance. This was one of the first questionnaires developed to measure movement imagery ability. Another example of a questionnaire developed around this time is the Movement Imagery Questionnaire (Hall & Pongrac, 1983), which is reviewed below. Prior to the development of these movement imagery questionnaires, studies on imagery and motor performance were forced to rely on general vividness questionnaires, such as the Questionnaire Upon Mental Imagery (QMI; Betts, 1909; Sheehan, 1967) or questionnaires relating to visual imagery only, such as the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973). The VMIQ was designed to assess the vividness of the visual and kinaesthetic aspects of movement imagery. Its format was based on that of the VVIQ. It included 24 items, each of which was a description of a common movement, varying from basic body movements, such as walking, to movements demanding precision and control, such as swinging on a rope. The participant imagined each item and then rated the vividness of his image along a 5-point scale with the anchor points, 1_‘‘Perfectly clear and as vivid as normal vision’’ and 5_‘‘No image at all, you only ‘know’ that you are thinking of the skill’’. The participant imagined each item first with respect to somebody else moving and then with respect to himself moving.
Isaac et al. (1986) claimed that the instrument was reliable and stable based on a 3-week test_retest reliability of r_.76 and the finding that there were no significant differences between multiple administrations of the questionnaire over a period of 6 months. Based on a correlation of r_.81 with the VVIQ, the authors concluded that the VMIQ was a valid instrument measuring the visual imagery of movement. In a factor analysis

of the questionnaire items, Campos and Perez (1990) found one underlying factor for the questionnaire, which they defined as ‘‘vividness of visual movement imagery’’. Isaac (1992) provided some evidence of the predictive validity of the VMIQ when she found that trampolinists with high imagery ability (classified on the basis of their VMIQ scores) showed greater improvements in their trampolining skills following an imagery training programme, than low ability imagers. Eton, Gilner, and Munz (1998) found that athletes in three athletic categories, namely, NCAA Division 1 athletes, Recreational athletes, and Nonathletes, could be differentiated on the basis of their VMIQ ‘‘self ’’ scale scores but not on the basis of their VMIQ ‘‘other’’ scale scores or their VVIQ scores. Eton et al. reported good internal consistency of the VMIQ (Cronbach’s alpha_.97). They reported an acceptable 2-week test_retest reliability for the ‘‘self ’’ scale (r_.8) but a low one for the ‘‘other’’ scale (r_.64).

The major problem with the VMIQ is that it is measuring visual imagery of movement rather than motor imagery. Certainly, the subscale that requires the participant to imagine somebody else moving is tapping into a visual rather than a motor image. Motor imagery may be employed for the second subscale in which the participant imagines performing the movement him or herself but the instructions given to the participant are so vague that one cannot be sure whether he/she is using an internal or external perspective. Even though Isaac et al. (1986) claimed that the questionnaire was designed to assess both visual and kinaesthetic aspects of movement imagery, there is no mention of kinaesthetic sensations in the instructions and the rating scale is anchored in terms of vision (i.e., 1_''Perfectly clear and as vivid as normal vision''). The high correlation between the VMIQ and VVIQ supports this interpretation and indeed, even Isaac et al. concluded on the basis of this result that the VMIQ was measuring the visual imagery of movement. Overall, then, while the studies on the reliability and validity of the VMIQ suggest that it is a promising measure, in its present format it appears to be measuring the vividness of visual imagery of movement rather than motor imagery.

The Movement Imagery Questionnaire (MIQ; Hall & Pongrac, 1983) was developed for the same reason as the VMIQ. Hall, Pongrac, and Buckolz (1985) blamed the failure to find a relationship between imagery ability and motor performance on the lack of questionnaires measuring movement imagery ability. Similar to the VMIQ, the MIQ was designed to measure the visual and kinaesthetic components of movement imagery. However, this time, the MIQ incorporated two scales referring to visual and kinaesthetic imagery, with visual movement imagery being defined as ''the formation of a mental (visual) image or picture of a movement in your mind'' and kinaesthetic movement imagery being defined as ''attempting to feel what performing a movement is like without actually doing the movement''. The

questionnaire comprised 18 movements, which ranged from movement of a single limb, such as raising and lowering the right knee, to movements of the entire body, such as performing a front roll on a mat and finishing in a standing position. In order to ensure that participants were imagining the same movement, the questionnaire incorporated a four-step programme for each item. First, the participant was provided with a written description of a starting position, which he was instructed to take up. Next, he read a description of a movement, which he performed once. Third, he returned to the starting position and imagined the movement using either visual or kinaesthetic movement imagery and finally, he rated the ease with which he performed the mental task using the appropriate scale, i.e., Visual: 1_''Very easy to picture'' to 7_''Very hard to picture'', and Kinaesthetic: 1_''Very easy to feel'', to 7_''Very hard to feel''.

Hall et al. (1985) reported acceptable levels of internal consistency (with Cronbach's alpha being .87 for the visual subscale and .91 for the

kinaesthetic subscale) and stability (with a 1-week test_retest reliability of r_.83). Subsequent studies have yielded similar estimates of internal consistency and test_retest reliability. These studies have also confirmed the bifactorial structure of the questionnaire, with items from the visual and kinaesthetic subscales loading onto separate factors during factor analysis (Atienza, Balaguer, & Garcia-Merita, 1994; Lorant & Gaillot, 2004).
As regards the validity of the questionnaire, there is some evidence that scores on the MIQ can predict the number of trials it takes to learn movements (Goss, Hall, Buckolz, & Fishburne, 1986) and the accuracy with which movements are reproduced (Hall, Buckolz, & Fishburne, 1989).
The main problem with the original MIQ was that it involved complex movements, such as the front roll,which some participants refused to perform. It was also considered quite lengthy, taking some time to complete. Hall and Martin (1997) revised the MIQ, shortening and simplifying it by leaving out difficult movements and redundant movements (i.e., if two trials pertained to movement of the same part of the body, one was deleted). They also reversed the rating scale so that a higher score indicated greater ease of imagery. The resulting MIQ-R contained four movements, each of which was imagined from the visual and kinaesthetic perspectives. Hall and Martin reported significant correlations between the corresponding scales on the MIQ and MIQ-R, (r__.77, n_50, pB.001, for each scale), and concluded that the MIQ-R was an acceptable revision of the MIQ. One advantage of the original and revised versions of the MIQ is their specificity. They ensure that all participants are imagining the same movements. Of course, the disadvantage is that even with the simpler movements in the MIQ-R, participantsmust be healthy and able-bodied in order to perform them.
The MIQ comes closer to measuring motor imagery, as defined in this paper, than the VMIQ. The VMIQcorrelates more highly with the MIQ visual

subscale (r_.65) than with the MIQ kinaesthetic subscale (r_.49) (Hall & Martin, 1997), suggesting that the first two scales tap into visual images of movement whereas the latter scale is measuring something different. At first glance, the visual and kinaesthetic scales seem to correspond to the external and internal perspectives of motor imagery. The correspondence is not perfect however. For the visual items, participants are instructed to form a visual image or picture of the movement in their minds. They are not told whether they should see themselves performing the movement from the third person perspective as if they are watching themselves on TVor if they should see the movement unfolding from the first person perspective, as if they are performing it themselves. The kinaesthetic subscale, for which participants are instructed to feel the movement without performing it, appears similar to motor imagery, but motor imagery, as defined earlier, includes both kinaesthetic and visual aspects of movement, the defining feature being that the movement is imagined from the first person perspective. The problem, then, is one of vagueness in the definitions of the visual and kinaesthetic subscales. They could be measuring ease of movement imagery from the external (third person) and internal (first person) perspectives but alternatively, both could be measuring movement imagery from the internal perspective, separating its visual and kinaesthetic aspects. This issue could easily be cleared up by adding more detailed definitions and instructions at the beginning of the questionnaire.

The Florida Praxis Imagery Questionnaire (FPIQ) is an interesting questionnaire but it has not been used widely to measure imagery ability. Ochipa et al. (1997) introduced this questionnaire as a measure of praxis imagery, meaning imagery for learned skilled movements. The FPIQ presented the participant with 12 actions to imagine, one at a time. The participant was asked four questions about each action. The first question related to the movement of the joints during the action (Kinaesthetic subscale). The second question related to the spatial position of the hands during the action (Position subscale). The third question related to the motion of the limb during the action (Action subscale). The fourth question related to a detail about the object employed in the action (Object subscale). Here is an example of an action to be imagined and questions from each of the subscales:

. Imagery: ‘‘Imagine you are using a key to unlock a door’’

. Kinaesthetic: ‘‘Which joint moves more, your finger joints or your elbow?’’

. Position: ‘‘Are your fingers straight or bent?’’

. Action: ‘‘Does your thumb move up and down or rotate?’’

. Object: ‘‘Is the part of the key you insert into the lock longer or shorter than the part you hold?’’

So far, no psychometric evaluation of the questionnaire has been attempted and it has only been used for the detection of impairments in motor imagery ability (see Maruff, Wilson, & Currie, 2003; Ochipa et al., 1997), rather than in an individual differences setting.

Movement imagery use. Craig Hall and his colleagues developed a series of questionnaires to measure the use of imagery by athletes in sport and exercise. These were the Imagery Use Questionnaire (Hall et al., 1990; recently altered by Weinberg, Butt, Knight, Burke, & Jackson, 2003), the Sport Imagery Questionnaire (SIQ; Hall, Mack, Paivio, & Hausenblas, 1998), and the Exercise Imagery Questionnaire (EIQ; Hausenblas, Hall, Rodgers, & Monroe, 1999). In general, these questionnaires present a series of statements about imagery use during sport or exercise and the participant responds by rating the frequency with which he or she engages in the specified kind of imagery.

The SIQ and EIQ have excellent psychometric properties, having been submitted to rigorous psychometric testing both during and after their development. The SIQ was designed to assess the use of imagery by athletes according to the functions of imagery specified by Paivio (1985). Paivio suggested that imagery had both cognitive and motivational functions in influencing behaviour. He further specified that these functions could operate at a general or specific level. Cognitive imagery focused on performance, with ‘‘specific cognitive imagery’’ relating to particular perceptuomotor skills and ‘‘general cognitive imagery’’ involving imagery strategies related to a competitive event. Motivational imagery pertained to emotion-arousing situations with ‘‘motivational specific imagery’’ focusing on goals and ‘‘motivational general imagery’’ relating to general physiological and emotional arousal. The items in the SIQ were created in order to reflect imagery use in each of these four categories. It included 30 statements about imagery use, which were rated along a 7-point frequency scale. The psychometric properties of the questionnaire were evaluated in two studies. First, 161 kinesiology students engaged in a sorting task, sorting the items of the SIQ by grouping similar items together under appropriate headings. Factor analyses of their classifications revealed five factors underlying the questionnaire: The three original, cognitive specific (CS), cognitive general (CG), and motivational specific (MS), factors were revealed and the motivational general factor was split into arousal (MG-A) and mastery (MG-M). A subsequent factor analysis based on the responses of 271 track and field athletes and 91 ice hockey players confirmed the existence of these five factors. Estimates of internal consistency, based on this latter sample, ranged from .70 to .88 for the five scales and when the characteristics of individual items were examined, all but one item were within the tolerance levels for assumptions of normality. Hall et al. (1998) claimed that this

questionnaire had some predictive validity on the basis of a finding of a relationship between imagery use and performance level. There was some evidence that elite athletes engaged in imagery more for motivational purposes, whereas lower level athletes used imagery for cognitive purposes, which makes sense if one assumes that elite athletes have acquired all the necessary skills and their mental preparation must instead involve managing motivation or anxiety at competitions.

Hausenblas et al. (1999) were interested in whether exercisers use imagery. They asked 144 aerobic exercisers if they use imagery and, if so, when they use it, why they use it, and what they image. They found that 75.7% of their sample reported using imagery with an average frequency of 4.19 (SD_1.58) on a 7-point scale. They used the exercisers’ responses to form a questionnaire designed to assess the frequency of imagery use by exercisers. The questionnaire contained nine statements relating to imagery use, which were answered along a 9-point frequency scale, ranging from 1_‘‘never engaging in this type of imagery’’, to 9_‘‘always engaging in this type of imagery’’. The psychometric properties of the final questionnaire were evaluated in two samples of exercisers (N1_144; N2_267). Factor analyses revealed three underlying factors, which were named: Energy, containing items relating to psychological management, Appearance, containing items to do with improving one's appearance or health, and Technique, containing items evoking imagery of the steps or movements involved in each exercise. The test_retest reliability was established at .88 and internal consistency estimates for the three factors for the two final samples ranged from .71 to .85, with one exception being Cronbach's alpha for Technique in the first sample of .65. Some claims of concurrent validity were made on the basis of the finding that low frequency exercisers reported significantly less imagery use than high frequency exercisers. The authors pointed out that the main disadvantage of the questionnaire was its focus on aerobic exercise only.

The main difficulty with these questionnaires is that they relate to the use of imagery in sport and so, are not applicable to a general or rehabilitation population. No questionnaire has been developed to assess the use of motor imagery in daily life. One could assume that it would not be as prominent as visual imagery but it is possible that people engage in motor imagery before or during daily tasks, such as moving a piece of furniture or mowing the lawn. We simply don't know.

Mental chronometry

Mental chronometry paradigms have been used to investigate the properties of motor imagery. These paradigms analyse the timing of a motor image, relying on the assumption that the time it takes to perform a mental task reflects the

cognitive processes underlying that mental task (Jeannerod, 1997; Milner, 1986). Decety and his colleagues have conducted a number of studies showing that imagined and executed actions take similar amounts of time (Decety, 1996). For example, they showed that it takes a similar amount of time to write or imagine writing a sentence (Decety &Michel, 1989) and to walk or imagine walking to previously inspected targets, arranged at avariety of distances from the participant (Decety, Jeannerod, & Prablanc, 1989). Furthermore, they showed that Fitts's Law, which governs executed actions, also holds in motor imagery (Decety, 1991; Decety & Jeannerod, 1996). Fitts's Law describes the fact that there is an inverse relationship between the difficulty of a movement and the speed with which it is performed: More difficult movements take longer to perform. In one experiment, Decety and his colleagues asked participants to walk or imagine walking along beams that varied in width, beam width being taken as a factor of task difficulty. They found a clear effect of task difficulty in both actual and imagined walking times, with participants taking longer to walk down narrower beams in both conditions (Decety, 1991). This effect of task difficulty was reproduced in a second study in which participants imagined walking through gates of different widths. Not only did participants' mental walking times increase with task difficulty (i.e., decreasing gate width) but mental movement time was linearly related to gate width (Decety & Jeannerod, 1996). The results of these studies form part of the evidence supporting the view that motor imagery shares the same central mechanisms as action.

The mental chronometry paradigm could be a useful measure of explicit motor imagery ability. So far, it has not been used to assess individual differences in motor imagery ability in a normal population. It has been used to assess impairments of motor imagery ability in clinical populations (Danckert et al., 2002; Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995; Maruff & Velakoulis, 2000; Maruff, Wilson, Trebilcock, & Currie, 1999; Sirigu et al., 1995, 1996). This line of research seems to be based on an assumption that, in ''normal'' participants, imagined and actual movement times will be very similar, and therefore, that any deviation between actual and imagined movement times in patient populations indicates a motor imagery impairment. However, it is possible that participants will vary in the similarity of their actual and imagined movement times, depending on their motor imagery ability.

MEASURING IMPLICIT MOTOR IMAGERY ABILITY

Prospective action judgements

Prospective action judgements are judgements about how one expects to perform an action. Research has shown that prospective action judgements

are made on the basis of simulations of actions. Johnson (2000b) investigated the properties of prospective action judgements using the Grip Selection Task. This task required participants to make judgements about how they would grasp a dowel (a wooden bar), and then, to actually grasp the dowel. First, the participant was presented with a series of pictures of the dowel, rotated into various positions (e.g., horizontal, vertical, rotated 45 in a clockwise direction), on computer screen. Without using his/her hands, the participant made a judgement about how he/she would grasp this dowel (e.g., whether he/she would use an overhand or underhand grip). The second half of the task involved the presentation of the dowel in actuality. The dowel was presented in a wooden box, which had its front and top panels removed so that the participant could reach in and grasp the dowel. The dowel was suspended in the centre of the box by a rod, which also enabled the dowel to be rotated by the experimenter. Using this simple device, the series of pictures of the dowel in various orientations presented on computer could be recreated in actuality. The participant actually grasped the dowel in each of its various orientations and the experimenter noted the grip (e.g., overhand/ underhand) that he/she used. The experimenter could then compare the participant's prospective grip selections, given during the computer presentation, with his/her actual grip selections, given during the actual presentation.

In a series of experiments involving the Grip Selection Task, Johnson (2000b) found evidence that prospective judgements about grip selection were based upon simulations of grasping. The results showed that prospective grip selections were very similar to actual grip selections and that the timing of prospective grip selections was influenced by factors known to influence the timing of real actions (Johnson-Frey, 2004). Specifically, Johnson found that: Prospective judgements about the limits of comfortable hand rotation when grasping and rotating a dowel were very similar to the limits reached when participants actually grasped and rotated the dowel; prospective judgements about the awkwardness of particular grips were very similar to awkwardness ratings obtained when grips were actually made; prospective judgements about which type of grip to choose (i.e., overhand or underhand), and which hand to use in order to adopt the most comfortable grip, were highly similar to choices made during actual grasping; both prospective and actual grip selection were determined by the awkwardness of the grip.

Throughout the experiments, participants' reaction times to make a prospective action judgement varied according to the awkwardness and extent of movement, two factors known to influence the timing of real actions. The time needed to make a prospective grip selection increased with the level of awkwardness that the selected grip would induce and with the extent of the movement that would be necessary to move the hand fromits current position

to a position amenable to gripping the dowel (Johnson, 2000b). These findings suggested that in order to make a prospective judgement about grip selection, participants were simulating the grasping act.

Frak, Paulignan, and Jeannerod (2001) also found evidence that prospective action judgements involvemotor simulation, using a Grasping Task. They asked participants to judge the feasibility of grasping and pouring from a container, given certain contact points on the rim of the container, which defined an opposition axis for a precision grip involving the index finger and thumb. The results showed a significant effect of orientation of the opposition axis on feasibility judgements and response times. Participants judged as most difficult, those contact points that would require biomechanically awkward or impossible grasping movements. Furthermore, participants took longer to make the judgement about these contact points. Response times during a control experiment, in which participants actually grasped and poured from the container, were similar to those obtained during the prospective judgement experiment. These findings suggested that participants were simulating grasping and pouring from the container in order to make the feasibility judgement during the prospective judgement task.

De'Sperati and Stucchi (1997, 2000) found evidence that participants used implicit motor imagery when making a judgement about the motion of an affordable object using the Rotating Screwdriver Task. They presented participants with a series of motion pictures, displaying a rotating screwdriver, which appeared in different orientations on screen. Participants had to judge whether the screwdriver was screwing or unscrewing. In a first experiment, de'Sperati and Stucchi (1997) found that reaction times were greater for those trials in which the screwdriver was presented with its handle pointing further away from the observer, and for those trials in which the orientation of the screwdriver would require an awkward grip. These findings suggested that participants were making their decision by simulating reaching out and grasping the screwdriver.

In a second experiment, de'Sperati and Stucchi (2000) compared the pattern of reaction times obtained during the Rotating Screwdriver Task with those obtained during a second task, the Clock Task, which employed exactly the same stimuli but was designed to evoke visual rather than motor processes. In the Clock Task, participants were also presented with the motion picture of a rotating screwdriver but they were asked to think of the screwdriver as being the pivot pin of an imagined clock, driving its hand from the back. Their task was to determine if the imaginary clock hand would be moving in a clockwise or counterclockwise direction, given the direction of motion of the screwdriver. The reaction times for the Rotating Screwdriver Task followed the same pattern found in the previous study, with reaction times increasing for orientations of the screwdriver that would require a further reach and an awkward grip. For the majority of

participants (13 out of 20), this pattern of reaction times was not present in the Clock Task, suggesting that these participants were relying on a different strategy, possibly relying on visual processes, to perform the task. In a minority of participants (7 out of 20), a similar pattern of reaction times emerged in both tasks, suggesting that these participants were also solving the Clock Task by simulating grasping, which, the authors argued, was also a valid way of solving the task.

Each of these tasks was designed to investigate the processes involved in making prospective action judgements. The results suggested that participants were engaging in implicit motor imagery during the tasks. So far, these tasks have not been used in an individual differences setting, even though the Grip Selection Task has been used to assess motor imagery ability in clinical populations (Buxbaum, Johnson-Frey, & Bartlett-Williams, 2005; Johnson, 2000a). It is possible that individual differences in implicit motor imagery ability would affect participants' abilities to make prospective action judgements. These tasks could be useful measures of implicit motor imagery ability.

Motorically driven perceptual decisions

Motorically driven perceptual decisions are decisions about perceptual stimuli that are made using motor processes. An example of a motorically driven perceptual decision is judging the laterality of a visually presented body part. Parsons has done a lot of research into how laterality decisions are made and has collected a lot of data showing that laterality decisions about a body part are made on the basis of motor simulations (1987a, 1987b, 1994). Parsons (2001) put forward the following process model for deciding whether a visually presented hand is a left or right hand: A rapid, initial and preconscious perceptual analysis of the hand shape provides a first estimate as to the laterality of the hand. The participant then engages in an implicit simulation of this hand moving from its current orientation into the orientation of the stimulus for comparison. This simulation follows the biomechanical constraints specific to the actual movement. The participant is unaware of this implicit movement. The participant then engages in an exact match confirmation strategy, comparing the simulated hand and the visually presented one. The results of this comparison inform an explicit judgement about the handedness of the stimulus.

Psychophysical, neuroimaging, and neurological data support this process model. Using psychophysics, Parsons (1987a, 1987b, 1994) showed that the time required to make a handedness judgement about a visually presented hand is proportional to the time required to actually move the hand from its current position into the stimulus orientation and the time required to imagine moving the hand from its current position into the stimulus

orientation. These results were found even though participants were not instructed to imagine moving their hands to make the laterality judgement and were often not aware of using motor imagery to solve the task. Functional neuroimaging data and studies of split-brain patients have shown that the handedness judgements engage brain areas known to be involved in motor planning and control, specifically the sensorimotor areas contralateral to the simulated hand (Parsons et al., 1995; Parsons, Gabrieli, Phelps, & Gazzaniga, 1998). Overall, this evidence strongly supports the idea that hand laterality judgements are made on the basis of motor simulations, which are mediated by the brain areas involved in motor planning and control of the hand in question.

Similar to the mental chronometry paradigm and the Grip Selection Task, the Hand Laterality Task has not been used widely to detect individual differences in motor imagery ability in normal populations. A number of studies have used the task to detect motor imagery deficits in clinical populations (e.g., Coslett, 1998; Dominey et al., 1995; Funk & Brugger, 2002; Moseley, 2004; Nico, Daprati, Rigal, Parsons, & Sirigu, 2003; Roelofs et al., 2001; Schwoebel et al., 2002; Schwoebel, Friedman, Duda, & Coslett, 2001; Tomasino, Rumiati, & Umilta, 2003). It is possible that people will vary in their ability to make motorically driven perceptual decisions depending on their ability to engage in implicit motor imagery.

THE RELATIONSHIP BETWEEN MOTOR IMAGERY MEASURES

In a recent study (McAvinue & Robertson, under review) we investigated the relationship between motor imagery measures by administering a selection of the measures reviewed above to a sample of 101 participants and performing a principal components analysis on the resulting correlation matrix. The analysis revealed three components underlying the battery of measures. Component 1, Self-Report of Movement Imagery, consisted of the kinaesthetic subscale of the Questionnaire Upon Mental Imagery (Sheehan, 1967), measuring vividness of kinaesthetic imagery, and the visual and kinaesthetic subscales of the MIQ, measuring the ease of visual and kinaesthetic movement imagery. Component 2, Explicit Motor Imagery Ability, consisted of mental chronometry performance for the dominant and nondominant hands and the kinaesthetic subscale of the MIQ. Component 3, Implicit Motor Imagery Ability, consisted of speed and accuracy in making prospective action judgements and accuracy in making motorically driven perceptual decisions. These results supported the distinction made by Jeannerod between implicit and explicit aspects of motor imagery, portraying these aspects as separate imagery abilities.

CONCLUSIONS

Most of the measures reviewed above were evaluated favourably. Most of the self-report questionnaires were reported to have good psychometric properties. However, at present, the MIQ and VMIQ may not measure motor imagery exactly and the imagery use questionnaires are restricted to sport and exercise. Future research with questionnaires should be clear about the concept of motor imagery that is being employed and could focus on the expansion of imagery use questionnaires to everyday life, the validation of the FPIQ and the creation of new questionnaires to measure different aspects of motor imagery, such as those identified in the FPIQ.

The Mental Chronometry, Prospective Action Judgement, and Motorically Driven Perceptual Decision paradigms have all been shown to involve motor imagery. However, these tasks have not been widely used to measure individual differences in motor imagery ability. They have mainly been employed to detect motor imagery impairment in clinical populations. There appears to be an assumption in this line of research that ‘‘normal’’ performance involves good motor imagery ability (e.g., similar reaction times during imagined and actual movements; accurate prospective action judgements and motorically driven perceptual decisions and response times that reflect biomechanical constraints). Evidence of poor motor imagery in patient groups is taken as motor imagery impairment. Individual differences in ‘‘normal’’ motor imagery ability have been largely neglected. Future research should focus on investigating the range of individual differences in ‘‘normal’’ motor imagery ability. A further critique of these paradigms is that they are laboratory measures, created by individual experimenters as the need arises. What is really needed is the development of standardised measures of implicit and explicit motor imagery ability. Another possible avenue for further development of measures is to assess imagery of the different dimensions of skills, such as sequencing, timing, configural actions, and coordination.

In this review, we classified measures as assessing either explicit or implicit imagery ability. This distinction was made on the basis of a theoretical proposition (Jeannerod, 2001; Jeannerod & Frak, 1999). It was supported by the principal components study, reported at the end of the paper, in which three componentswere found to underlie a battery of motor imagery measures (i.e., Self-Report ofMovement Imagery, Explicit Motor Imagery Ability, and Implicit Motor Imagery Ability). However, it must be kept in mind that it is unclear why awareness of using motor imagery should affect one’s ability to use it. Furthermore, in the principal components study, the ‘‘explicit’’ and ‘‘implicit’’ measures may not have differed due to the presence or absence of awareness, but may have loaded on separate components because of the nature of the tasks. For example, each of the implicit imagery tasks involved a decision regarding a visual stimulus whereas there was no visual stimulus

present in the explicit imagery tasks. The distinction between explicit and implicit imagery ability should be further examined.

This being said, the principal components analysis suggests that motor imagery ability is not a unidimensional ability. So far, each of the questionnaires and tests described above have been hailed as measuring ‘‘motor imagery ability’’, even though the tests are all very different from one another. Given the distinction between explicit and implicit imagery and the results of the principal components analysis, future research should recognise the possibility that motor imagery ability is multidimensional.

Finally, a further puzzle concerning motor imagery ability relates to the distinction between internal, first person perspective imagery and external, third person perspective imagery. First person perspective imagery is often considered as a form of motor imagery, whereas third person perspective imagery is considered as a formof visual imagery (Jeannerod, 1994). However, a number of findings and observations blur this distinction. For example, Jeannerod (2001) classified both motor imagery and action observation as simulation states, involving motor representations. Recently, Anquetil and Jeannerod (2007) presented evidence that imagined movement from first and third person perspectives involved the same representations. Mirror neurons, which respondwhen the agent is performing a goal-directed action andwhen it observes another agent performing a goal-directed action, have been identified (DiPellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). It seems that the distinction between first and third person perspective movement imagery requires further investigation.

Individual differences in imagery ability make it imperative to assess imagery ability prior to any study involving motor imagery.Anumber of good measures are available to do so. However, there is still much scope for further development of these measures, for the investigation of the relationship between them and the investigation of the nature of motor imagery ability.

Original manuscript received July 2006
Revised manuscript received February 2007
First published online August 2007

REFERENCES

Annett, J. (1995). Motor imagery: Perception or action? Neuropsychologia, 33, 1395_1417.
Annett, J. (1996). On knowing how to do things: A theory of motor imagery. Cognitive Brain
Research, 3, 65_69.

Anquetil, T., & Jeannerod, M. (2007). Simulated actions in the first and in the third person
perspectives share common representations. Brain Research, 1130, 125_129.
Atienza, F., Balaguer, I., & Garcia-Merita, M. L. (1994). Factor analysis and reliability of the
Movement Imagery Questionnaire. Perceptual and Motor Skills, 78, 1323_1328.

Betts, G. H. (1909). The distribution and functions of mental imagery (Contributions to Education,
No. 26). New York: Columbia University, Teachers College.
Buxbaum, L. J., Johnson-Frey, S. H., & Bartlett-Williams, M. (2005). Deficient internal models for
planning hand-object interactions in apraxia. Neuropsychologia, 43, 917_929.
Campos, A., & Perez, M. J. (1990). A factor analytic study of two measures of mental imagery.
Perceptual and Motor Skills, 71, 995_1001.
Coslett, H. B. (1998). Evidence for a disturbance of the body schema in neglect. Brain and
Cognition, 37, 527_544.
Danckert, J., Ferber, S., Doherty, T., Steinmetz, H., Nicolle, D., & Goodale, M. A. (2002).
Selective, non-lateralized impairment of motor imagery following right parietal damage.
Neurocase, 8, 194_204.
Decety, J. (1991). Motor information may be important for updating the cognitive processes
involved in mental imagery of movement. European Bulletin of Cognitive Psychology, 4,
415_426.
Decety, J. (1996). Do imagined and executed actions share the same neural substrate? Cognitive
Brain Research, 3, 87_93.
Decety, J., & Jeannerod, M. (1996). Mentally simulated movements in virtual reality: Does Fitts's
law hold in motor imagery? Behavioural Brain Research, 72, 127_134.
Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions.
Behavioural Brain Research, 34, 35_42.
Decety, J., & Michel, F. (1989). Comparative analysis of actual and mental movement times in two
graphic tasks. Brain and Cognition, 11, 87_97.
De'Sperati, C., & Stucchi, N. (1997). Recognizing the motion of a graspable object is guided by
handedness. Neuroreport, 18, 2761_2765.

De’Sperati, C., & Stucchi, N. (2000). Motor imagery and visual event recognition. Experimental
Brain Research, 133, 273_278.
DiPellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor
events: A neurophysiological study. Experimental Brain Research, 91, 176_180.
Dominey, P., Decety, J., Broussolle, E., Chazot, G., & Jeannerod, M. (1995). Motor imagery of a
lateralized sequential task is asymmetrically slowed in hemi-Parkinson’s patients. Neuropsychologia,
33, 727_741.
Eton, D. T., Gilner, F. H., & Munz, D. C. (1998). The measurement of imagery vividness: A test of
the reliability and validity of the Vividness of Visual Imagery Questionnaire and the Vividness
of Movement Imagery Questionnaire. Journal of Mental Imagery, 22, 125_136.
Frak, V., Paulignan, Y., & Jeannerod, M. (2001). Orientation of the opposition axis in mentally
simulated grasping. Experimental Brain Research, 136, 120_127.
Funk, M., & Brugger, P. (2002). Visual recognition of hands by persons born with only one hand.
Cortex, 38, 860_863.
Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor
cortex. Brain, 119, 593_609.
Galton, F. (1883). Inquiries into human faculty and its development. London: Macmillan.
Goss, S., Hall, C. R., Buckolz, E., & Fishburne, G. (1986). Imagery ability and the acquisition and
retention of movements. Memory and Cognition, 14, 469_477.
Grush, R. (2004). The emulation theory of representation: Motor control, imagery and perception.
Behavioral and Brain Sciences, 27, 377_396.
Hall, C. R. (1998). Measuring imagery abilities and imagery use. In J. L. Duda (Ed.), Advances in
sport and exercise psychology measurement (pp. 165_172). Morgantown, WV: Fitness Information
Technology.
Hall, C. R., Buckolz, E., & Fishburne, G. (1989). Searching for a relationship between imagery
ability and memory of movements. Journal of Human Movement Studies, 17, 89_100.

Hall, C. R., Mack, D. E., Paivio, A., & Hausenblas, H. A. (1998). Imagery use by athletes:

Development of the Sport Imagery Questionnaire. International Journal of Sport Psychology,
29, 73_89.
Hall, C. R., & Martin, K. A. (1997). Measuring movement imagery abilities: A revision of the
Movement Imagery Questionnaire. Journal of Mental Imagery, 21, 143_154.
Hall, C. R., & Pongrac, J. (1983). Movement Imagery Questionnaire. London, Ontario, Canada:
University of Western Ontario.
Hall, C. R., Pongrac, J., & Buckolz, E. (1985). The measurement of imagery ability. Human
Movement Science, 4, 107_118.
Hall, C. R., Rodgers,W.M., & Barr, K. A. (1990). The use of imagery by athletes in selected sports.
The Sport Psychologist, 4, 1_10.
Hausenblas, H. A., Hall, C. R., Rodgers, W. M., & Monroe, K. J. (1999). Exercise imagery: Its
nature and measurement. Journal of Applied Sport Psychology, 11, 171_180.
Isaac, A. (1992). Mental practice*does it work in the field? The Sport Psychologist, 6, 192_198.
Isaac, A.,Marks, D. F., & Russell, D. G. (1986). An instrument for assessing imagery of movement:
The Vividness of Movement Imagery Questionnaire (VMIQ). Journal of Mental Imagery, 10,
23_30.
Janssen, J. J., & Sheikh, A. A. (1994). Enhancing athletic performance through imagery: An
overview. In A. A. Sheikh. & E. R. Korn (Eds.), Imagery in sports and physical performance (pp.
1_22). Amityville, NY: Baywood Publishing Company.
Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery.
Behavioral and Brain Sciences, 17, 187_245.
Jeannerod, M. (1995). Mental imagery in the motor context. Neuropsychologia, 33, 1419_1432.
Jeannerod, M. (1997). The cognitive neuroscience of action. Oxford, UK: Blackwell Publishers.
Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition.
NeuroImage, 14, S103_S109.
Jeannerod, M., & Frak, V. (1999). Mental imaging of motor activity in humans. Current Opinion in
Neurobiology, 9, 735_739.
Johnson, S. H. (2000a). Imagining the impossible: Intact motor representations in hemiplegics.
NeuroReport, 11, 729_732.

Johnson, S. H. (2000b). Thinking ahead: The case for motor imagery in prospective judgements of
prehension. Cognition, 74, 33_70.
Johnson-Frey, S. H. (2004). Stimulation through simulation? Motor imagery and functional
reorganization in hemiplegic stroke patients. Brain and Cognition, 55, 328_331.
Kosslyn, S. M. (1980). Image and mind. London: Harvard University Press.
Kosslyn, S. M. (1999). Image and brain: The resolution of the imagery debate. Cambridge, MA: MIT
Press.
Lorant, J., & Gaillot, L. (2004). Validation de la version francaise du Movement Imagery
Questionnaire (MIQ). Canadian Journal of Behavioral Science, 36, 30_35.
Marks, D. F. (1973). Visual imagery differences in the recall of pictures. British Journal of
Psychology, 64, 17_24.
Maruff, P., & Velakoulis, D. (2000). The voluntary control of motor imagery. Imagined movements
in individuals with feigned motor impairment and conversion disorder. Neuropsychologia, 38,
1251_1260.
Maruff, P.,Wilson, P., & Currie, J. (2003). Abnormalities of motor imagery associated with somatic
passivity phenomena in schizophrenia. Schizophrenia Research, 60, 229_238.
Maruff, P., Wilson, P., Trebilcock, M., & Currie, J. (1999). Abnormalities of imagined motor
sequences in children with developmental coordination disorder. Neuropsychologia, 37,
1317_1324.
McAvinue, L. P., & Robertson, I. H. (under review). Principal components analysis of motor
imagery measures. Manuscript under review.

Milner, A. D. (1986). Chronometric analysis in neuropsychology. Neuropsychologia, 24, 115_128.
Moseley, G. L. (2004). Graded motor imagery is effective for long-standing complex regional pain
syndrome: A randomised controlled trial. Pain, 108, 192_198.
Nico, D., Daprati, E., Rigal, F., Parsons, L. M., & Sirigu, A. (2003). Left and right hand
recognition in upper limb amputees. Brain, 127, 120_132.
Ochipa, C., Rapcsak, S. Z., Maher, L. M., Gonzalez Rothi, L. J., Bowers, D., & Heilman, K. M.
(1997). Selective deficit of praxis imagery in ideomotor apraxia. Neurology, 49, 474_480.

Page, S. J. (2000). Imagery improves upper extremity motor function in chronic stroke patients: A
pilot study. Occupational Therapy Journal of Research, 20, 200_215.
Paivio, A. (1985). Cognitive and motivational functions of imagery in human performance.
Canadian Journal of Applied Sport Sciences, 10, 22S_28S.
Parsons, L. M. (1987a). Imagined spatial transformation of one's body. Journal of Experimental
Psychology: General, 116, 172_191.
Parsons, L. M. (1987b). Imagined spatial transformation of one's hands and feet. Cognitive
Psychology, 19, 178_241.
Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally
simulated action. Journal of Experimental Psychology: Human Perception and Performance, 20,
709_730.
Parsons, L. M. (2001). Integrating cognitive psychology, neurology and neuroimaging. Acta
Psychologica, 107, 155_181.
Parsons, L. M., Fox, P. T., Hunter Downs, J., Glass, T., Hirsch, T. B., Martin, C. C., et al. (1995).
Use of implicit motor imagery for visual shape discrimination as revealed by PET. Nature, 375,
54_58.
Parsons, L. M., Gabrieli, J. D. E., Phelps, E. A., & Gazzaniga, M. S. (1998). Cerebrally lateralized
mental representations of hand shape and movement. Journal of Neuroscience, 18, 6539_6548.
Richardson, A. (1994). Individual differences in imaging: Their measurement, origins and
consequences. New York: Baywood Publishing Company.
Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of
motor actions. Cognitive Brain Research, 3, 131_141.
Roelofs, K., Naring, G. W. B., Keijsers, G. P. J., Hoogduin, C. A. L., van Galen, G. P., & Maris, E.
(2001). Motor imagery in conversion paralysis. Cognitive Neuropsychiatry, 6, 21_40.
Schwoebel, J., Boronat, C. B., & Coslett, H. B. (2002). The man who executed ''imagined''
movements: Evidence for dissociable components of the body schema. Brain and Cognition, 50,
1_16.
Schwoebel, J., Friedman, R., Duda, N., & Coslett, H. B. (2001). Pain and the body schema:

Evidence for peripheral effects on mental representations of movement. Brain, 124, 2098_2104.
Sharma, N., Pomeroy, V. M., & Baron, J. C. (2006). Motor imagery: A backdoor to the motor
system after stroke? Stroke, 37, 1941_1952.
Sheehan, P.W. (1967). A shortened form of Betts's Questionnaire Upon Mental Imagery. Journal of
Clinical Psychology, 23, 386_389.
Sirigu, A., Cohen, L., Duhamel, J. R., Pillon, B., Dubois, B., Agid, Y., & Pierrot-Deseilligny, C.
(1995). Congruent unilateral impairments for real and imagined hand movements. Neuro
Report, 6, 997_1001.
Sirigu, A., Duhamel, J. R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental
representation of hand movements after parietal cortex damage. Science, 273, 1564_1568.
Smyth, M. M., & Waller, A. (1998). Movement imagery in rock climbing: Patterns of interference
from visual, spatial and kinaesthetic secondary tasks. Applied Cognitive Psychology, 12,
145_157.
Tomasino, B., Rumiati, R. I., & Umilta, C. A. (2003). Selective deficit of motor imagery as tapped
by a left-right decision of visually presented hands. Brain and Cognition, 53, 376_380.

Weinberg, R., Butt, J., Knight, B., Burke, K. L., & Jackson, A. (2003). The relationship between the
use and effectiveness of imagery: An exploratory investigation. Journal of Applied Sport
Psychology, 15, 26_40.
White, A., & Hardy, L. (1995). Use of different imagery perspectives on the learning and
performance of different motor skills. British Journal of Psychology, 86, 169_180.
Wilson, M. (2003). Imagined movements that leak out. Trends in Cognitive Sciences, 7, 53_55.
Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. Current Biology, 11, R729_R732.