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Putting in the mind versus putting on the green: Expertise, performance time, and the linking of imagery and action

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Does manipulating the time available to image executing a sensorimotor skill impact subsequent skill execution outcomes in a similar manner as manipulating execution time itself? Novice and skilled golfers performed a series of imaged golf putts followed by a series of actual golf putts under instructions that emphasized either speeded or nonspeeded imaging/putting execution. Novices putted less accurately (i.e., higher putting error score) following either putting or imagery instructions in which speed was stressed. Skilled golfers showed the opposite pattern. Although more time available to execute a skill enhances novice performance, this extra time harms the proceduralized skill of experts. Manipulating either actual execution time or imagined execution time produces this differential impact on novice and skilled performance outcomes. These results are discussed in terms of the functional equivalence between imagery and action and expertise differences in the attentional control structures governing complex sensorimotor skill execution.

Keywords: Expertise; Attention; Imagery; Embodied cognition; Speed-accuracy trade-off.

A growing body of work spanning across skill domains, research techniques, and even species has demonstrated a close relationship between perceptual and motor processes (e.g., Beilock & Holt, 2007; Brass, Bekkering, & Prinz, 2001; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Holt & Beilock, 2006; Zwaan & Taylor, 2006). The discovery of overlapping neural regions (e.g., premotor and motor cortex) involved in the observation and production of action (Decety & Grezes, 1999; Gallese et al., 1996) has been taken to suggest that our motor system not only supports action execution, but subserves action perception and representation as well (Garbarini & Adenzato, 2004). Moreover, this relation between perception and action does not seem to be limited to online action observation, but rather can be seen with respect to recalling, hearing, and even imagining stimuli with strong action associations. For instance, when individuals

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skilled in writing Kanji characters retrieve these characters from memory, they show neural activation in brain areas associated with actually writing the characters (e.g., premotor cortex, pre-SMA, where SMA is the supplementary motor area, and bilateral intraparietal sulcus)—even when there is no intention to write (Kato et al., 1999). And, when individuals hear sentences such as "I bit an apple", they show neural activation in brain areas implicated in the movements of sentence-related body parts (e.g., mouth areas; Tettamanti et al., 2005). Connections between the perceptual and motor systems have also been highlighted in the investigation of motor imagery (i.e., simulating movements without overt execution; Decety, 1996a). Many investigators have reported similarities between imagined and actual movements at both behavioural and neural levels (Guillot & Collet, 2005). This is the focus of the current work.

The relation between motor imagery and motor execution has received a significant amount of attention across a wide variety of research areas—ranging from sport psychology and motor learning to cognitive neuroscience. While the former literature primarily asks questions concerning the ability of motor imagery to enhance performance outcomes (Feltz & Landers, 1983), the latter area has focused on the similarities and differences (at both a cognitive and a neural level) between imagined and actual movements (Fischer, 2005; Guillot & Collet, 2005; Lotze et al., 1999; Stevens, 2005). In isolation, these areas of research do advance the knowledge base in their respective fields. Together, however, they have the additive power to fundamentally improve our understanding of skill learning, skill representation, and skill execution—both on and off the playing field.

Imagery/action equivalence

What is the relationship between imagined and executed actions? According to psychophysiology and neuroscience work of the past several decades, there is a functional equivalence between action execution and motor imagery (e.g., see Decety & Grezes, 1999; Jeannerod, 1994). That is, motor imagery and execution share common neural substrates (Decety, 1996a; Jeannerod & Frak, 1999). When individuals are asked to imagine themselves writing, increases in Regional cerebral blood flow (rCBF) are seen in prefrontal regions, SMA, and the cerebellum—similar to the activation patterns found during actual writing movements (Decety, Philippon, & Ingvar, 1988). Moreover, imaging and actually producing sequential foot movements results in similar changes in motor system activation across the learning continuum (Lafleur et al., 2002).

Added support for the notion of imagery/action equivalence comes from work demonstrating that the duration of mentally performed movements often does not significantly differ from physically executed movements. In a recent chronometric comparison of actual and imagined movements in elite gymnasts, Calmels, Holmes, Lopez, and Naman (2006) found that the overall time to perform and image a complex gymnastic vault did not significantly differ. This was true whether the vault was imaged from an internal (first person) or external (third person) perspective. Temporal congruence between imagined and executed actions has been shown across other skill domains and skill levels as well (see Decety, 1996a). For example, mentally performing graphic tasks such as drawing a cube or writing a sentence have been shown to have similar temporal organizations to actually performing such actions (Decety & Michel, 1989), and the time used to mentally simulate moving one's hand or arm to match the orientation depicted in a presented hand stimulus has been shown to mimic actual execution time (Parsons, 1994).

Despite the above-mentioned similarities between imagined and executed movements, it should be noted that there are differences as well. For example, in the chronometric comparison of imaged versus executed springboard dives, Reed (2002) found differences between motor imagery and physical performance that were dependent on dive complexity and skill expertise. Overall, imagery time increased relative to physical time as dive complexity increased, and, unlike novices and experts, intermediate divers imaged significantly slower than they performed. Moreover, in the above-mentioned comparison of imagined and executed vault performances, although Calmels et al. (2006) found that the time to image an entire vault sequence did not significantly differ from the time to perform this entire sequence, the temporal organization of the action differed across the imagery and execution conditions. When the vault was divided into component actions (e.g., the run phase, the flight phase, etc.), temporal congruence between imagery and action was drastically altered—again, suggesting that the correspondence between imagery and action is not as straightforward as one might initially believe. Finally, in the previously mentioned handwriting study, Decety et al. (1988) found primary motor area activation in actual but not imagined writing. In fact, several studies have found that motor imagery and actual performance show overlapping activity in premotor and supplementary motor areas, but not in primary motor cortices (see Guillot & Collet, 2005). These findings have been taken to suggest that actual and imaged movements overlap most specifically in terms of planning and programming behaviour, rather than behaviour instantiation (Decety, 1996a). This is consistent with the notion that motor imagery and physical performance share common processes at higher, cognitive levels of the motor control hierarchy, but differ at the level at which performance outcomes actually occur (MacKay, 1989).

Nonetheless, to the extent that motor imagery recruits at least some of the same cognitive and neural processes involved in actual execution, then just as manipulating the way in which one executes a task can impact performance outcomes, so too should manipulating the way in which individuals image execution. Previous behavioural work has addressed the impact of movement imagery practice on subsequent skill performance (Beilock, Afremow, Rabe, & Carr, 2001; Feltz & Landers, 1983). However, to our knowledge, little work has explicitly tried to link the types of skill level dissociations evident in performance outcomes (e.g., golf putting accuracy) following the manipulation of execution conditions to similar manipulations of the conditions under which imagery takes place. For example, expert performance accuracy in skills ranging from golf putting to baseball batting benefits from manipulations that prevent or discourage explicit attentional control of skill execution. These same manipulations harm novice performance outcomes (Beilock, Carr, MacMahon, & Starkes, 2002; Gray, 2004; Jackson, Ashford, & Norsworthy, 2006). If imagined and executed actions do share overlapping cognitive and neural processes, then just as manipulating execution conditions can have different effects on novice and expert performance, the performance outcomes associated with manipulating imagery should differ as a function of skill level as well. Toward this end, in the current work we looked to a literature where clear double dissociations between execution conditions and performance were evident (i.e., the skill acquisition and expertise literature). We then attempted to demonstrate one such double dissociation in performance via both the manipulation of the imagery that preceded execution and the manipulation of execution itself.

Expertise, attention, and time

Theories of skill acquisition and automaticity suggest that the cognitive substrates governing skill execution change as learning progresses (Anderson, 1993; Fitts & Posner, 1967; Keele & Summers, 1976). Although novice execution is thought to be attended online in a step-by-step fashion, well-learned skills are believed to be based on procedural knowledge that runs largely outside of explicit attentional control (Beilock & Carr, 2001; Jackson et al., 2006; Maxwell, Masters, & Eves, 2000). These skill level differences carry implications for how limitations in the time available for the set-up and execution of one's skill will impact performance. For example, because attention takes time to deploy (Posner & Snyder, 1975; Shiffrin & Schneider, 1977), limiting the ability to prepare and attend to skill processes and procedures should harm novice execution in comparison to situations with unlimited execution time. The opposite effect should be seen for skilled performance that is best left unattended (Beilock et al., 2002).

In support of the above idea, Beilock, Bertenthal, McCoy, and Carr (2004) had novice and skilled golfers execute a series of golf putts under speeded conditions in which individuals were told to putt as fast as possible (while still being accurate) or under conditions in which time constraints were not an issue. Although novices performed better under unlimited execution time than under speed conditions, skilled golfers showed the opposite pattern—a double dissociation of speed instruction and skill level.

One might be puzzled by the idea that well-learned skills may benefit from limited performance time given the well-established speed–accuracy trade-off (Fitts, 1954; Woodworth, 1899). However, the speed–accuracy trade-off has most often been demonstrated in cognitive and motor skills in which individuals have little previous experience with the task at hand (Schmidt & Lee, 2005). If the cognitive control structures governing performance differ as a function of skill level, then the notion that the more rapidly a skill is performed the less accurate it becomes may not generalize across all skill levels, and, to the extent that at least somewhat common neural substrates underlie motor imagery and execution (Decety, 1996a), then manipulating motor imagery time should have differential effects on skilled and novice golf putting performance—just like manipulating execution time. We now turn to several recent studies examining the correspondence between action observation and production as a basis to strengthen our predictions regarding the relationship between expertise, performance time, and the linking of imagery and action.

Action observation and production

In general, it has been demonstrated that observing an action interferes with the performance of conflicting actions and facilitates performance of similar actions. For example, Kilner, Pauligan, and Blakemore (2003) found that viewing an individual making arm movements incompatible with the arm movements one was to be making interfered with movement execution. Moreover, Brass et al. (2001) had individuals execute specific finger movements in response to viewing either compatible or incompatible finger movements. A marked reaction time advantage was found for compatible in comparison to incompatible trials. Direct, feed-forward connections between perceptual and motor processes are hypothesized to underlie such effects (Hamilton, Wolpert, Frith, & Grafton, 2006). If such connections also apply to the relation between motor imagery and action, then just as performing an action under optimal execution conditions has an impact on performance accuracy (e.g., an expert golfer performing under speeded putting conditions; Beilock et al., 2004), imaging an optimal action (e.g., an expert golfer imaging performing a putt under speeded conditions) should improve subsequent performance accuracy in comparison to imaging a less optimal action (e.g., an expert golfer imaging performing a putt under nonspeeded conditions). How might this occur? If similar to action observation, imagery serves the function of recruiting and fine-tuning the motor programmes required for performance (Hamilton et al., 2006; Prinz, 1997), then imaging an action under optimal conditions should serve to strengthen the cognitive and motor processes by which that action will eventually run off. Thus, measurable performance outcome changes should result from the manipulation of imagined execution just as they may result from the manipulation of execution itself. The impact of imagery time and execution time on performance outcomes may be separable in that both should have an impact independent of the other.

Current work

To test the above predictions, novice and skilled golfers first imaged and then executed a series of golf putts under both speeded and nonspeed imagery and putting instructions. Subsequent putting accuracy was then assessed as function of imagery condition (i.e., speed vs. nonspeed images) as well as a function of actual execution condition (i.e., speed vs. nonspeed putts). Although previous research has examined the impact of movement imagery practice on subsequent skill performance (Beilock et al., 2001; Feltz & Landers, 1983; Murphy, Nordin, & Cumming, in press), such work has rarely attempted to tease apart the unique impact of imagery and execution instructions on performance outcomes within a single performance as we do here. This is an important, and until now missing, behavioural correlate of the above-mentioned functional equivalence work. To the extent that imagined and executed actions do share somewhat overlapping neural substrates (Decety, 1996a), then manipulating imagery and manipulating action should have similar and possibly independent effects on performance outcomes.

Novice and expert golfers took part in the same 2 (imagery instruction: speed, nonspeed) × 2 (putting instruction: speed, nonspeed) experimental design. Imagery always preceded putting so that putting outcomes could be measured as a function of image condition as well as a function of actual execution condition. Imagery and putting instruction conditions were completely crossed such that all participants took part in all four combinations of imagery and putting instructions: (a) imagery speeded, putting speeded; (b) imagery speeded, putting nonspeeded; (c) imagery nonspeeded, putting speeded; (d) imagery nonspeeded, putting nonspeeded. Combination order varied across individuals.

Given our previous work demonstrating that novices putt more accurately under nonspeed than under speed conditions, with experts showing the opposite pattern (Beilock et al., 2004), we expected to find that, regardless of imagery instructions, novices would perform at a higher level (i.e., putt more accurately) under the nonspeed putting instructions than under the speed putting instructions. In contrast, experts should putt more accurately under the speed than under the nonspeed putting instruction condition. In terms of imagery instructions, if imaging an action and performing that action recruits similar cognitive and neural processes (Decety, 1996a), then manipulating imagery speed should have the same impact on subsequent putting accuracy as manipulating putting execution itself. Moreover, if similar to action observation, imagery serves the function of recruiting and fine-tuning the cognitive and motor programmes required for performance (Prinz, 1997), then measurable performance outcome changes should result from both the manipulation of actual execution and the manipulation of imagined execution. That is, the impact of imagery time and execution time on performance outcomes should be separable in that both should have an impact independent of the other.

Method

Participants

Participants were undergraduate students. Novices golfers ($n = 15$) had no previous golf experience. Skilled golfers ($n = 13$) had a PGA handicap of 8 or less ($M = 5.8$, $SE = 0.46$) and, on average, 10 years of golf playing experience ($M = 10.15$, $SE = 0.98$).

In addition, novice and skilled golfers did not differ in their reports of visual imagery ability (novice, $M = 23.60$, $SE = 0.86$; skilled, $M = 23.00$, $SE = 0.97$), $F < 1$, or kinaesthetic imagery ability (novice, $M = 19.40$, $SE = 1.25$; skilled, $M = 22.92$, $SE = 1.23$), $F(1, 26) = 3.97$, *ns*, as assessed by the Movement Imagery Questionnaire–Revised (MIQ-R; Hall & Martin, 1997). The MIQ-R consists of participants physically performing a series of motor movements followed by instructions to either “see” or “feel” themselves performing each movement. Participants then rate (on a 7-point Likert scale) the ease or difficulty of imaging the movements. Scores on each scale can range from 4 (lowest possible score) to 28 (highest possible score). As seen above, both novice and skilled golfers scored relatively high on these scales. Thus, any expertise differences seen below cannot be accounted for by skill-level differences in imagery ability.[1]

Procedure

After providing informed consent, reporting previous golf and sport experience, and completing the MIQ-R, individuals were informed that they would be performing two tasks: a golf putting task and a golf putting imagery task.

Golf putting task. The putting task was performed on an indoor putting green using a standard putter and ball. Individuals putted a golf ball as accurately as possible to a target, marked by a square of red tape, on which the ball was supposed to stop. One might wonder whether the task of putting to a target rather than to a regulation size hole might impact performance. However, previous work has demonstrated that the impact of the speed manipulations used in the current work do not differ as a function of whether one is measuring mean distance that a ball stops from a target versus number of "hits" for a regulation size hole (Beilock et al., 2004). Moreover, given that the expert golfers should have more experience putting to a regulation size hole than a target, while our novice golfers should not be experienced with either, using a target rather than a hole only works against finding expertise differences.

Participants putted from five different spots, 120–150 cm from the target. All participants followed the same random order of putting from the five locations. Before each putt, a light indicated the location from which participants were to execute their next putt. After each putt, the experimenter rolled a new ball to the appropriate starting location. While the participant set up for their next putt, the experimenter measured the previous putt's accuracy (i.e., the distance that the ball stopped from the centre of the target). Each putt was timed by the experimenter—beginning when the ball was stationary on the starting location until ball contact. Participants completed 10 initial putts to familiarize themselves with the putting task.

Imagery task. Next, individuals were introduced to the golf putting imagery task. Specifically, participants were told that they would be imaging themselves performing a number of golf putts (similar to the putts they just executed). They were informed that the experimenter would roll them a ball and illuminate a light next to the appropriate starting location. Participants were instructed to place the ball on the starting location (as in the previous putting task) and, rather than executing an actual putt, image themselves executing the golf putt in their mind. In order to obtain a measure of imagery time, participants were provided with a golf club that had a wireless mouse button attached to the shaft. Participants were instructed to hit the wireless button when they began their image (from the time the ball was placed on the starting location) and again when they imaged ball contact. A computer interfaced with the mouse recorded imagery time. These particular imagery timing instructions were designed to mimic, as closely as possible, the assessment of actual putt time described above. Participants were only instructed to image through club contact with the ball (rather than up until the ball's stopping point) as the speed with which one executes a putt during actual execution can only be controlled up to this point. This served to equate, as much as possible, the speed manipulation in the putting and imagery conditions. Participants completed 10 initial imagery trials to familiarize themselves with the imagery task.

Individuals then began the main portion of the experiment, which consisted of four experimental blocks. Each experimental block consisted of 10 imaged putts followed by 10 actual putts—that is, four blocks of 10 imaged and 10 actual putts, for a total of 80 trials. Imaged putts were always performed first so that putting outcomes could be measured as a function of image condition as

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[1] Moreover, using imagery ability as a covariate in the central analysis examining the impact of imagery instructions and putting instructions on putting accuracy (seen below) did not alter the pattern of results in any way.

well as a function of actual execution condition. Prior to each set of 10 trials (and once in the middle of each 10 trial series, as a reminder), participants were given instructions that emphasized either (a) imaging/putting as fast as possible while still being accurate (speed instructions) or (b) imaging/putting using as much time as needed while still being accurate (nonspeed instructions). See below for instruction wording. Each participant completed both images and putts under all possible combinations of the speed and nonspeed instructions in a 2 (imagery instruction: nonspeed, speed) × 2 (putting instruction: nonspeed, speed) design. Participants were randomly assigned to one of four different block orders.

Prior to each of the four imagery/putting blocks, individuals were given a short break during which time they were asked to verbally count backwards from 100 by 3s. This manipulation was designed to limit the influence of persisting thoughts about the previous block on subsequent skill performance. At the end of the experiment, participants were fully debriefed. Instructions were as follows:

Speed instructions. In this set of putts/images I want you to try to make/image the ball stop(ing) on the target. I have one additional instruction. I want you to try and execute/image your putt as quickly as possible, but make sure you are being as accurate as you can. Timing begins when the ball is stationary on the starting position and ends when you make contact with the ball.

Nonspeed instructions. In this set of putts/images I want you to try to make/image the ball stop(ing) on the target. You can take as much time as you need to do this. Timing begins when the ball is stationary on the starting position and ends when you make contact with the ball.

Results

Putting accuracy

The central result of our experiment comes from the examination of the impact of imagery instructions and putting instructions on actual putting performance outcomes—a Putting Instruction × Imagery Instruction × Expertise analysis of variance (ANOVA) with the last factor between subjects. The distance (cm) away from the centre of the target that the ball stopped after each putt was measured, and the mean distances from the target of the 10 putts in each of the four imagery instruction/putting instruction combinations were compared. This distance (or error) outcome score served as the measure of putting accuracy.

A 2 (putting instruction: speed, nonspeed) × 2 (imagery instruction: speed, nonspeed) × 2 (expertise: novice, skilled) ANOVA on putting accuracy revealed a main effect of expertise, $F(1, 26) = 48.87$, $p < .01$, $MSE = 58.15$. As expected, skilled golfers were more accurate putters overall than novices. This main effect was qualified by a Putting Instruction × Expertise interaction, $F(1, 26) = 49.19$, $p < .01$, $MSE = 26.08$, and an Imagery Instruction × Expertise interaction, $F(1, 26) = 5.30$, $p < .03$, $MSE = 16.04$. No other main effects or interactions reached significance—including the Expertise × Putting Instruction × Imagery interaction, $F(1, 26) = 0.017$, *ns*.[2] The lack of a three-way interaction between putting instruction, imagery instruction, and expertise does not seem to be due to a lack of power given an F essentially equal to

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[2] We also performed the same Putting Instruction × Imagery Instruction × Expertise analysis on putting accuracy while covarying out putting time and imagery time. The Imagery Instruction × Expertise interaction was maintained when putting time was covaried out of the analysis, and, likewise, the Putting Instruction × Expertise interaction was maintained when imagery time was covaried out of the analysis (ps $< .05$, respectively). This ensures that our two-way interaction of Imagery Time × Expertise was maintained even when putting time was held constant, and our two-way interaction of Putting Time × Expertise was maintained even when imagery time was held constant. There was no three-way Putting Instruction × Imagery Instruction × Expertise interaction in any of the above analyses (Fs $= 0.01$). Taken together with the main analyses reported in the text, these results add further support to the notion that putting instructions and imagery instructions had independent effects on putting accuracy.

0. Moreover, this lack of an interaction is important as it suggests that the impact of imagery instructions on accuracy as a function of golf putting expertise was not dependent on the putting instruction that an individual received for a particular putt and vice versa (i.e., the impact of putting instruction on accuracy as a function of expertise was not dependent on prior imagery instructions). We return to this point below.

In order to interpret the Putting Instruction × Expertise interaction, we looked separately at performance under speed versus nonspeed putting instructions for both novice and skilled golfers—collapsing across the type of imagery instruction that had preceded putting. As seen in Figure 1, regardless of imagery instruction, novice golfers putted less accurately under speed than under nonspeed putting instructions, $t(14) = 4.05, p < .01$. Skilled golfers showed the opposite pattern, $t(12) = 8.17, p < .01$. This finding replicates Beilock et al.'s (2004) work demonstrating that faster execution time does not harm, and may actually aid, the performance of well-learned skills that run largely outside of working memory.

Similarly, in order to interpret the Imagery Instruction × Expertise interaction, we looked separately at performance following speed versus nonspeed imagery instructions for both novice and skilled golfers—collapsing across the type of putting instruction that individuals had received. As seen in Figure 2, regardless of putting instruction, skilled golfers performed significantly better following speed imagery than following nonspeed imagery, $t(12) = 2.24, p < .05$. In contrast, novice golfers tended to putt less accurately following speed than following nonspeed imagery, $t(14) = 1.55, p = .14$. Although not significant at conventional levels, it is worth pointing out that this is the opposite pattern of that seen in the experienced golfers. The fact that the impact of imagery on putting accuracy was not as striking for the novice golfers is consistent with previous work demonstrating that mental practice is most successful when a significant amount of actual practice precedes imagery attempts (Feltz & Landers, 1983). If one does not have extensive putting experience, then the ability to recruit appropriate cognitive and motor execution processes during imagery seems less likely to occur (Beilock et al., 2001).

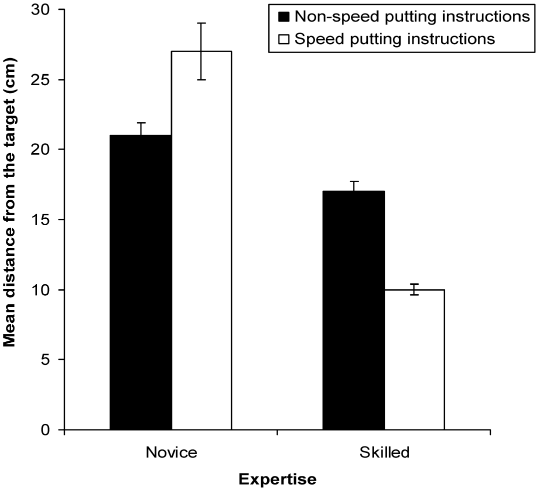

Figure 1. *Mean distance (cm) from the centre of the target that the ball stopped after each putt following the nonspeed and speed putting instructions for the novice and skilled golfers. Error bars represent standard errors.*

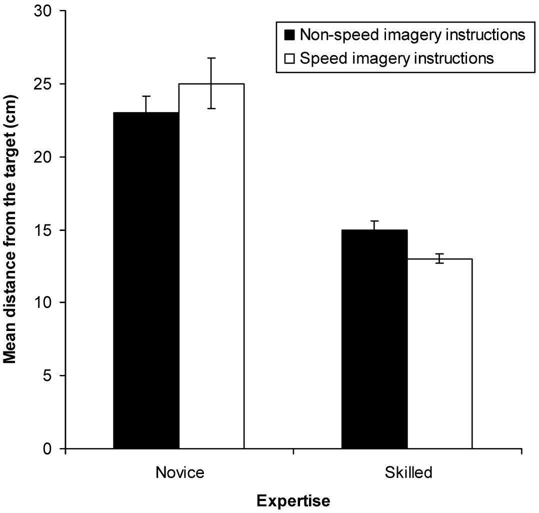

Figure 2. *Mean distance (cm) from the centre of the target that the ball stopped after each putt following the nonspeed and speed imagery instructions for the novice and skilled golfers. Error bars represent standard errors.*

As seen in Figure 1 and Figure 2, the impact of imagery time on performance was not as large as the impact of execution time on performance. Nonetheless, the fact that imagery impacted putting performance outcomes independent of the specific putting instructions individuals were exposed to (as supported by the nonsignificant Putting Instruction × Imagery Instruction × Expertise interaction) shows the unique impact that motor imagery can have on performance outcomes. If similar to action observation, imagery serves the function of recruiting and fine-tuning the motor programmes required for performance (Hamilton et al., 2006; Prinz, 1997), then imaging an action under various conditions should serve to alter the cognitive and motor processes by which that action will eventually run off. As a result, measurable putting outcome changes result from both the manipulation of imagined execution and the manipulation of execution itself.

Imagery and putting time manipulation checks

We next assessed imagery and putting time. The goal of these analyses was to ensure that individuals followed our instructions, imaging and executing their putts faster when speed was stressed. We also examined whether putting time differed as a function of imagery instruction in order to ensure that the impact of imagery on putting performance seen above could not simply be accounted for by imagery-induced alterations in putting time.

Imagery time. A 2 (expertise: novice, skilled) × 2 (imagery instruction: speed, nonspeed) ANOVA on imagery time revealed only a main effect of instruction, $F(1, 26) = 58.21$, $p < .01$, $MSE = 0.53$. There was no main effect of expertise, $F < 1$, nor an Instruction × Expertise interaction, $F(1, 26) = 1.42$, *ns*. Consistent with the imagery instructions, individuals imaged faster when instructed to do so (Table 1).

Table 1. *Mean imagery time following nonspeed and speed imagery instructions for novice and skilled golfers*

	Expertise			
	Novice		*Skilled*	
Imagery instructions	*Time*	*SE*	*Time*	*SE*
Nonspeed	2.91	0.32	3.25	0.39
Speed	1.65	0.20	1.53	0.19

Note: Time in s.

Putting time. A 2 (expertise: novice, skilled) × 2 (putting instruction: speed, nonspeed) ANOVA on putting time again revealed only a main effect of instruction, $F(1, 26) = 183.17$, $p < .01$, $MSE = 0.58$, in which putts were performed faster under the speed than under the nonspeed instructions (Table 2; putting instruction means). Again, there was no significant main effect of expertise, $F < 1$, nor an Instruction × Expertise interaction, $F(1, 26) = 2.14$, *ns*.

Finally, we looked at the impact of imagery instruction on putting time in order to rule out the possibility that the impact of imagery on putting performance outcomes seen above was merely due to an imagery-induced change in putting time. To do this, we performed a 2 (expertise: novice, skilled) × 2 (imagery instruction: speed, nonspeed) ANOVA on putting time. There was no main effect of instruction, $F(1, 26) = 2.08$, *ns*, or expertise, and

Table 2. *Mean putting time following nonspeed and speed imagery instructions and nonspeed and speed putting instructions for novice and skilled golfers*

		Imagery instruction					
		Nonspeed		*Speed*		*PI means*	
Golfers	*Putting instruction*	*Time*	*SE*	*Time*	*SE*	*Time*	*SE*
Novice	Nonspeed	3.66	0.27	3.61	0.29	**3.64**	**0.28**
	Speed	1.19	0.08	1.15	0.08	**1.17**	**0.08**
	II means	**2.43**	**0.16**	**2.38**	**0.17**		
Expert	Nonspeed	4.20	0.41	4.19	0.40	**4.19**	**0.40**
	Speed	1.18	0.11	1.08	0.07	**1.13**	**0.09**
	II means	**2.69**	**0.25**	**2.63**	**0.23**		

Note: Time in s. II = imagery instructions. PI = putting instructions.

no Expertise × Instruction interaction, $Fs \leq 1$, respectively. Putting time did not differ as a function of whether putts occurred after a set of speed images or a set of nonspeed images (Table 2; imagery instruction means). Thus the unique impact of motor imagery on performance seen above cannot be accounted for by imagery-induced alterations in putting time, as putting time did not significantly differ as a function of imagery instruction.

Discussion

Although novice execution is thought to be attended online in a step-by-step fashion, well-learned skills are believed to be based on procedural knowledge that runs largely outside of explicit attentional control (Beilock & Carr, 2001; Beilock et al., 2002; Jackson et al., 2006, Maxwell et al., 2000). These skill level differences carry implications for how situations that limit the time available for the set-up and execution of one's skill will impact performance. Specifically, the more time available to attend to and execute a skill should enhance novice sensorimotor skill performance (Schmidt & Lee, 2005). These same time parameters, however, may actually harm the proceduralized skills of experts if they afford experts the opportunity to explicitly control skill processes and procedures that are better left outside of conscious control (Beilock et al., 2004; Beilock et al., 2002; Gray, 2004; Jackson et al., 2006).

In the current work we demonstrate the above-mentioned skill level dissociation not only via directly manipulating execution time, but by manipulating imaged execution time as well. Novice and skilled golfers performed a series of imaged golf putts followed by a series of actual golf putts under instructions that emphasized either speeded or nonspeeded imaging or putting execution. Novices putted less accurately following either putting or imagery instructions in which speed was stressed. Skilled golfers showed the opposite pattern. Although more time available to execute a skill enhances novice performance, this extra time harms the proceduralized skill of experts. Manipulating either actual execution time or imagined execution time produces this differential impact on novice and skilled performance outcomes.

Perhaps most striking in the current work is the fact that imagery instructions and putting instructions had independent effects on performance accuracy as a function of skill level. As seen in Figures 1 and 2, the impact of the imagery instructions and putting instructions on accuracy were similar, yet these effects were not dependent on each other. We believe such independent effects are probably the result of imagery processes that serve to recruit and fine-tune the motor processes used during actual action execution—in much the same manner that observing another person's actions can impact one's own behaviour (Brass et al., 2001; Hamilton et al., 2006; Prinz, 1997). As a result, both imaging manipulations and execution manipulations show an impact on behavioural outcomes (in this case, putting accuracy).

One might imagine that imagery's impact on putting accuracy in the current work was merely achieved via imagery-induced alterations of putting time (e.g., after imaging under speed instructions, individuals putt faster). However, given that putting time did not differ as a function of the imagery instructions that preceded it, this does not seem to be the case. Rather, it seems as if motor imagery (similar to action observation) can serve to change the execution parameters that are instantiated during the actual unfolding of execution—cognitive and motor parameters that are likely to modulate the attentional control that individuals are able to evoke during the step-by-step unfolding of performance. Nonspeed imagery allows for the strengthening of a motor programme that incorporates explicit control of skill processes and procedures in a way that speed imagery does not. As a result, novices putt better after nonspeed than after speed imagery while experts show the opposite pattern. Such work not only lends insight into optimal practice and performance conditions for real-world sensorimotor skill execution (in this case, golf putting), but provides an explicit test of the necessary perception–action link implied by theories of function equivalence by demonstrating that the manipulation of offline execution simulation has an impact on actual performance outcomes in a manner similar to that seen when manipulating online execution itself.

Some might wonder whether one would predict anything other than the pattern of results found in the current work. Although there is a considerable amount of evidence in support of the notion that imagery (whether visual, auditory, or motor) involves a modal simulation of external events (Wilson, 2002), arguments in favour of the propositional nature of imagery still exist (see Pylyshyn, 1986). Under this view, manipulating the imagery of an action and manipulating the action itself should not necessarily impact subsequent performance outcomes in a similar and independent manner as the representation underlying imagery and action need not overlap. Moreover, even if one readily adopts a functional equivalence viewpoint (i.e., imaged actions are ground in the same systems that actually produce such actions), to our knowledge this is the first demonstration that manipulating imagery time produces similar and independent effects (i.e., regardless of the manipulation of actual execution time) on subsequent performance outcomes. This finding is an important, and until now missing, behavioural correlate to work examining the chronometric and neural equivalence between imagery and action (Decety, 1996a; Jeannerod, 1994).

Because only the total time to execute or image a putt (including both preparation and movement time) was assessed in the current work, precisely where in the execution process (whether imagined or actual) speed instructions exerted their impact in unknown. However, given the similar and independent impact of putting and imagery instructions on performance, and the notion that actual and imaged movements overlap most specifically at the level of planning and programming behaviour (Decety, 1996a; MacKay, 1989), it seems likely that speed instructions exerted their effects most strongly at the level of compiling and fine-tuning the motor programme to be executed rather than during movement instantiation. This might also explain why the effects seen in the manipulation of imagery time were not as robust as those seen in the manipulation of actual execution itself. That is, to the extent that imaging an action only activates a subset of the neural substrate needed to actually execute the imagined action, the impact of an imagery manipulation on performance outcomes should not be as great as the impact of manipulating performance itself.

The findings of the current work are similar to research demonstrating that observing an action facilitates performance of similar actions (Brass et al., 2001). However, rather than having individuals watch another person act on an object or in an event, we moved inward, asking individuals to imagine performing actions themselves. This work demonstrates that differences in the types of attentional control manipulations that impact performance as a function of skill level can be manifested via motor imagery manipulations as well. Such findings have important implications both on and off the playing field—or, in this case, putting green. For example, our findings demonstrate that not all types of imagery have similar effects on performance outcomes. For skilled performances based on proceduralized knowledge structures, the benefit of a lack of explicit attention to performance processes and procedures can be realized not only via speeded execution, but via speeded images as well.

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