Journal of Experimental Psychology:
Learning, Memory, and Cognition
2012, Vol. 38, No. 6, 1759–1764

0278-7393/12/$12.00 DOI: 10.1037/a0028065

RESEARCH REPORT

Imagined Actions Aren't Just Weak Actions: Task Variability Promotes Skill Learning in Physical Practice but Not in Mental Practice

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Early research on visual imagery led investigators to suggest that mental visual images are just weak versions of visual percepts. Later research helped investigators understand that mental visual images differ in deeper and more subtle ways from visual percepts. Research on motor imagery has yet to reach this mature state, however. Many authors have implicitly subscribed to the view that motor images are just weak versions of physical actions. We tested this view by comparing motor learning in variable practice conditions with motor learning in constant practice conditions when participants either physically or mentally practiced golf-putting. We found that physical and mental practice both resulted in significant learning but that variable practice was only better than constant practice when participants practiced physically. This outcome was not predicted by the hypothesis that motor imagery is just a weaker form of real-action experience.

Keywords: motor imagery, sensorimotor representations, mental practice, skill learning, task variability

Motor images, which can be defined as mental states in which motor representations are performed without overt movements (Decety, 1996), share many features with real actions. Durations of motor images often mirror durations of overt actions (Guillot & Collet, 2005), and neural areas activated during motor imagery—premotor cortex, supplementary motor area, and primary motor cortex—are similar to areas activated during actual performance (Leonardo et al., 1995; Lotze et al., 1999; Porro et al., 1996; Roth et al., 1996). Moreover, muscle activity generated during motor images resembles muscle activity observed during physical movements (Suinn, 1972, 1997). Similarities like these have been taken to suggest that representations for motor imagery and for overt motor behavior are one and the same (Decety, 1996; Decety & Grezes, 1999; Jeannerod, 1995).

A challenge to this view comes from the finding that mental practice, which can be defined as motor imagery used for the sake of motor learning (Corbin, 1972), typically leads to less learning than physical practice (Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983; Richardson, 1967a, 1967b). There may be a straightforward reason for this difference, however. It could be that motor images called up during mental practice entail weaker or less vivid sensorimotor representations than do overt actions.

An analogy can be made to the relation between mental visual images and real visual percepts. Perky (1910) suggested in her groundbreaking work on this topic that mental visual images are essentially like visual percepts, just less vivid. Consistent with this hypothesis, Perky found that people who were instructed to have images in their minds needed less light to see the imagined objects when those images were projected onto a screen than did people who were not instructed to have the images in their minds. Although methodological limitations of Perky's work came to light in later years, and the work was questioned by concerns about response bias, her claim was not, on its face, suspect. By extension, it is plausible that motor images are weaker or less vivid than the experience borne of physical activity.

It was not just by virtue of concerns about Perky's (1910) methodology but also by virtue of other, later experiments that students of mental visual imagery came to realize that mental visual images are not just weak versions of real visual percepts. Instead, they saw that the two forms of experience differ in deeper and more subtle ways. The most sophisticated way of characterizing these differences was offered by Shepard and Cooper (1982), who suggested that mental visual images bear not a first-order (direct) isomorphic relation to visual percepts but a higher order (less direct) relation to the visual percepts they represent. For reviews, see Anderson (2005); Bartolomeo (2008); and Kosslyn, Ganis, and Thompson (2001).

This article was published Online First April 30, 2012.

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This research was supported in part by a National Science Foundation grant to the Spatial Intelligence and Learning Center at the University of Chicago. The authors thank Pierre Perruchet and Tim Lee for helpful comments on the article.

Can the lesson learned from visual imagery research extend to motor imagery research? Is the relation between motor imagery and real physical experience isomorphic beyond the first order? The alternative—that the relation is first-order—is, again, possible. That is the null hypothesis for the present study.

Some previous research is at least broadly consistent with the null hypothesis that motor imagery has a first-order isomorphic relation to sensory experience from real action. Support for this idea can be found in a study that had participants either physically or mentally practice a special walking task in a specificity-of-practice paradigm (Krigolson, Van Gyn, Tremblay, & Heath, 2006). In this paradigm, transfer is thought to depend on the similarity of visual or kinesthetic feedback available during acquisition and transfer. Transfer is usually best when the available feedback matches the feedback available during training (Proteau, Marteniuk, & Levesque, 1992). During training, Krigolson et al.'s (2006) participants walked along a 2.5-cm-wide, 12-m-long line and tried to stop directly over the end of the line. Participants practiced in one of three conditions: full vision, no vision, or motor imagery. In the transfer test, which used no vision, the no-vision group did best. Of primary importance, the full-vision and motor imagery groups did not differ. Based on this result, the authors suggested that full visual feedback from actual practice and imagined visual feedback from motor imagery are very similar.

Toussaint, Robin, and Blandin (2010) reached a similar conclusion. In their experiment, participants in the physical practice group adopted a knee position and then attempted to reproduce that position after a short rest in another posture. Participants practiced either with or without vision. In a no-vision transfer test, the group that practiced without vision performed better. Toussaint et al. found a similar result in the mental practice group; participants in that group imagined themselves performing the positioning task while focusing on either the imagined visual aspects of mental practice, the imagined kinesthetic aspects, or both. In a no-vision transfer test, participants who focused on imagined kinesthetic information performed best. Because the effects of imagined feedback mirrored the effects of actual feedback, Toussaint et al. suggested that both mental and physical practice rely on similar sensorimotor representations. These results accord with the view that motor imagery and actual performance give rise to internal representations that enjoy a first-order isomorphic relation.

In the present study, we sought to further test the hypothesis that motor imagery and sensorimotor representations derived from actual performance have a relation that is first-order isomorphic. We reasoned that if imagined and actual feedback have such a relation the manipulation of a high-level psychological variable, far removed from the form of sensory representation used in the task, should not interact with the form of sensory representation that is used, imagined or experienced. The high-level psychological variable we focused on was task variability.

Our reasoning was as follows. It has been shown many times that long-term motor learning is generally better following variable training than constant training. In variable training the possible ways of performing a task are presented in mixed fashion, whereas in constant training the possible ways of performing a task are presented in blocked fashion. The mixed, or variable, method is generally better than the blocked, or constant, method. The benefit of task variability has been demonstrated in a variety of tasks, such as throwing, aiming, kicking, and hitting moving objects; for reviews, see Shapiro and Schmidt (1982) and Schmidt and Lee (2005). The reason for the benefit has been ascribed, variously, to the chance to form schemas for skilled performance (Schmidt, 1975), the opportunity to derive more precise estimates of statistical values relevant to performance (Rosenbaum, 2010), and the opportunity to develop strategies for task-switching (Shea & Morgan, 1979).

Regardless of the exact reason for the general benefit of variable over constant practice, the manipulation of this factor provides a new way of testing the null hypothesis that the sensorimotor information from motor imagery is simply weaker than the sensory feedback from actual performance. It does so because variable practice and constant practice are defined with respect to the history of training, not with respect to the properties of immediate sensory information. If motor imagery, used for mental practice, is simply less vivid than sensory feedback from actual performance, one would expect the difference between variable practice and constant practice to be similar when people use motor imagery for practice and when people get full feedback from physical practice.

Method

We asked novice golfers to physically perform series of golf putts (one group to which 32 participants were randomly assigned) or to imagine themselves performing the same putts while they held the same putter (another group to which 32 participants were randomly assigned). Within these two groups, a random half of the participants were asked to practice several different putts; the other half were asked to practice just one putt.

Participants

Eighty-one right-handed volunteers at the University of Chicago participated for financial compensation or course credit. No participants reported any competitive golf experience or previous professional instruction. One participant was excluded from the analyses for having a pretest score 3.5 standard deviations beyond the mean of all participants.

Materials

The experiment used a synthetic putting green, 317.5 cm by 365.76 cm. Small (4 cm^2) squares were placed on the green to demarcate the starting positions ($n = 5$) and targets ($n = 4$). The squares ranged in colors, which allowed the experimenter to indicate the starting location and target on each trial (see Figure 1). Participants used a standard right-handed putter and standard golf balls.

Procedure

We used a 2 (physical vs. mental practice) $\times$ 2 (variable vs. constant practice) between-subjects design. All participants completed a 10-putt pretest and posttest before and after training. During these tests, participants completed 10 unique putts to two test targets (see Figure 1). Each of the five starting points was used twice (once for each of the two test targets). These test targets were not used during training for any of the groups. Putt order during pretest and posttest was randomized for each participant.

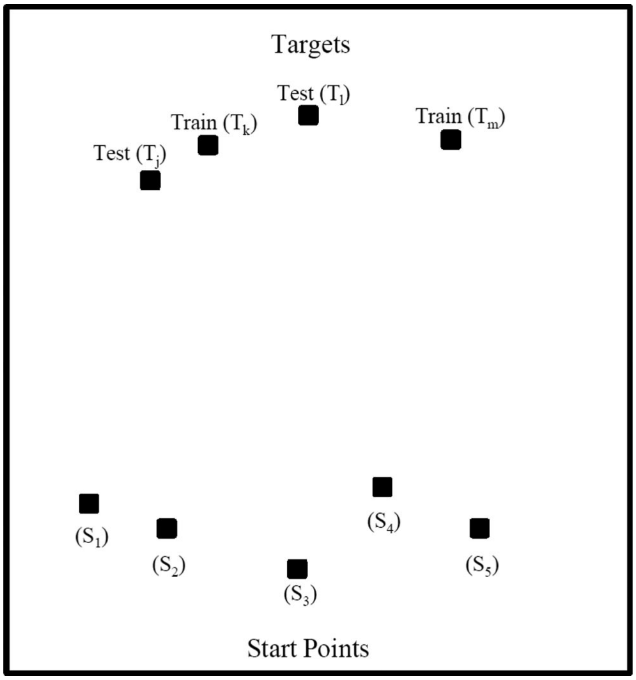

Figure 1. Overhead schematic of experimental setup (not drawn to scale). Putt distances and angles are shown in Table 1.

Training consisted of 50 trials for each group, but the distribution of putts varied by group. The variable groups received training on 10 distinct putts. Each putt was done 5 times, for a total of 50 training putts. The order of trials was arranged such that each block of 10 putts included the full set of 10 distinct training putts, but putt order within each block was random. All training putts used the two targets that were not used during testing, so all putts were different from the test putts. The distances and putt angles were similar to the test trials, but the actual putts were different (see Table 1). Training in the constant groups entailed repeating the same putt 50 times. The variable groups also performed this putt five times during training.

On each trial, the experimenter rolled a ball to the participant and indicated the starting point and target. Participants in the physical practice group attempted to putt the ball so it landed directly on the specified target. Otherwise, participants were not given any instructions about how to putt the ball. In the mental practice conditions, participants stood by the starting point, held the putter, and were instructed to imagine themselves putting the ball to the target. Participants had an unlimited amount of time to putt. Performance on each actual putt was measured by the distance the ball landed from the target. Thus, a lower score indicated better performance. The mental practice group performed a final actual putt to provide an objective measure of performance.

In addition to the four experimental groups, a mental practice control group was tested to ensure that any improvement in the mental practice groups could not be explained by performing the pretest. Control participants completed the same pretest and posttest as the experimental groups, but instead of imagining themselves putting the ball, they imagined themselves kicking the ball to the target. All participants in the mental practice groups completed the revised Movement Imagery Questionnaire (MIQ-R; Hall & Martin, 1997) prior to the experiment.

Results

To measure learning, we calculated the change in performance from pretest to posttest, taking into account each individual's baseline performance. Because a higher score indicated more error, we quantified learning by subtracting the average error during posttest from the average error during the pretest.

We performed a two-way analysis of variance (ANOVA) on the difference scores with physical modality (physical vs. mental) and task variability (variability vs. constancy) as between-subjects factors. As seen in Figure 2, performance improved for all experimental groups. There was a main effect of physical modality, $F_{(1, 60)} = 6.7$, $p = .012$, such that physical practice resulted in greater performance improvement than did mental practice. The size of this effect, as estimated by partial eta-squared (η_p^2), was .100. There was also a significant interaction between variability and physical modality, $F_{(1, 60)} = 5.7$, $p = .020$, $\eta_p^2 = .087$, but no main effect of variability alone, $F_{(1, 60)} = 1.7$, $p = .204$. Planned comparisons showed that improvement (decrease in error from pretest to posttest) in the physical practice group that had variable training ($M = 17.8$ cm, $SE = 2.6$ cm) was significantly greater than improvement in the physical practice group that had constant training ($M = 9.2$ cm, $SE = 2.5$ cm), $t_{(30)} = 2.3$, $p = .026$. The size of this effect, as estimated by Cohen's d statistic (Cohen,

Table 1
Distances and Angles Between Putt Start Points and Targets

	Start point (S_n)	Target (T_x)	Distance (cm)	Angle (deg)
		Test putts		
	S_1	T_j	135	70
	S_1	T_l	167	57
	S_2	T_j	135	83
	S_2	T_l	166	59
	S_3	T_j	153	99
	S_3	T_l	171	80
	S_4	T_j	141	124
	S_4	T_l	137	96
	S_5	T_j	168	130
	S_5	T_l	150	105
Mean			152	90
SD			14	25
		Practice putts		
	S_1	T_k	149	64
	S_1	T_m	185	45
	S_2	T_k	145	65
	S_2	T_m	166	54
	S_3	T_k	160	90
	S_3	T_m	163	70
	S_4	T_k	140	105
	S_4	T_m	124	88
	S_5	T_k	163	120
	S_5	T_m	127	96
Mean			152	80
SD			19	24

Note. Angles were measured with respect to a horizontal line drawn through the middle of each start point.

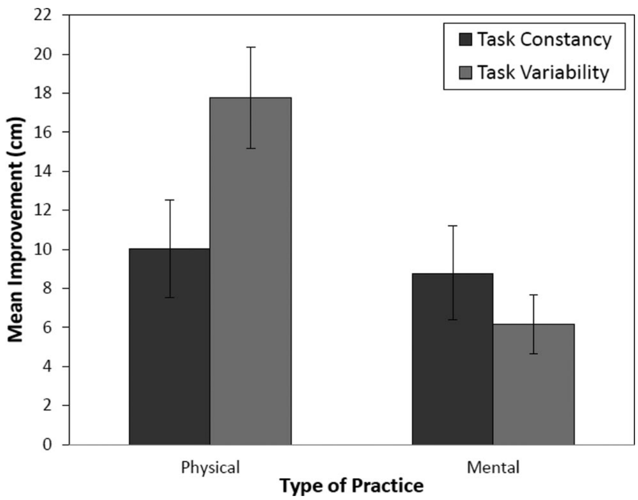

Figure 2. Amount learned measured as the difference from pretest to posttest ($\text{Mean}_{\text{pretest}} - \text{Mean}_{\text{posttest}}$) for each group. Error bars represent ± 1 standard error of the mean.

1992), was .857. However, the difference between the improvement shown by the mental practice groups that had variable practice ($M = 6.2$ cm, $SE = 1.5$ cm) or constant practice ($M = 8.8$ cm, $SE = 2.4$ cm) was not statistically significant, $t_{(30)} = 0.89$, $p = .383$. Learning in the constant physical practice group did not differ from learning in the constant mental practice group, $t_{(30)} = 0.13$, $p = .897$, or in the variable mental practice group, $t_{(30)} = 1.03$, $p = .315$. Last, to ensure that the benefits of practice were specific to practice that involved the same motor activity as the test, we conducted a one-sample *t* test on the average improvement for the control group. Mean improvement in this group was only 2.5 cm ($SE = 2.4$ cm), a value that did not significantly differ from zero, $t_{(15)} = 1.04$, $p = .314$.

To ensure that these effects were not the result of differences in baseline performance, we performed another two-way ANOVA with physical modality and variability on pretest scores. This analysis yielded no main effects and no interactions ($F\text{s} < 2.5$, $p\text{s} > .119$), indicating that differences in improvement were not attributable to differences in preexisting skill.[1]

It was important to assess differences in imagery ability, as measured with the MIQ-R, for kinesthetic imagery and visual imagery among the three groups. A one-way ANOVA showed that there were no significant group differences in kinesthetic imagery, $F_{(2,\ 45)} = .46$, $p = .634$, although there was a significant group difference in visual imagery, $F_{(2,\ 45)} = 3.6$, $p = .037$, $\eta_p^2 = .142$, such that visual imagery ability in the variable mental practice group ($M = 23.3$, $SE = 0.73$) was greater than in the constant mental practice group ($M = 20.1$, $SE = 1.2$), $t_{(29)} = 2.29$, $p = .030$, $d = 0.679$. There were no other significant differences in visual imagery ability ($p\text{s} > .05$).

Discussion

Early research on visual imagery led investigators to think that mental visual images were like actual visual percepts, just dimmer (Perky, 1910). Later research dispelled the idea that mental images and visual percepts bear such a simple, first-order isomorphic relation (Shepard & Cooper, 1982). Here we asked whether the same sort of difference might apply to the relation between motor imagery and actual motor performance. We reasoned that the same sort of difference might apply because imagined actions seem to entail less intense sensorimotor information than overt actions. This, in turn, might explain why mental practice generally pales in comparison to actual practice.

To pursue this question, we focused on a factor that is known to benefit motor learning—task variability. We reasoned that if motor images and overt actions bear first-order isomorphic relations, then variable practice should facilitate motor learning regardless of whether practice is mental or actual. We found that mental and physical practice both produced significant learning. However, we also found—and this is the most important result of the current study—that variable practice aided learning more than constant practice only in the physical practice condition. In mental practice, variable practice and constant practice helped learning to the same extent. This outcome would not be expected if real and imagined actions were only quantitatively different.

A possible objection to the argument just given is that the difference between variable and constant training could be nullified if the overall level of learning was very poor, in which case a floor effect could lead to a spurious rejection of the experimental hypothesis. The data do not support that interpretation. As seen in Figure 3, the improvement in the mental practice condition was better when mental practice concerned putting the ball to the target (the task relevant to the posttest) than when mental practice concerned kicking the ball to the target (the task irrelevant to the posttest). In addition, there was a trend for improvement to be somewhat better for the constant condition than for the variable condition in the mental practice groups, a result we did not anticipate and that can be pursued in future research. Although this latter difference might have arisen by chance alone, it shows that there was room for difference between the variable and constant conditions in the mental practice groups. Accordingly, the fact that variable practice aided learning more than did constant practice only in the physical practice condition need not be viewed as an artifact stemming from a floor effect in the mental practice condition. Based on this line of reasoning, we take our results to indicate that there is some qualitative difference between motor imagery and the experience of actual performance. Our results are inconsistent with the claim that motor representations for acting and for imagining are one and the same (Decety, 1996; Decety & Grezes, 1999; Jeannerod, 1995).

The current findings add to a growing body of research that has begun to expose differences between imagined and real actions. It has been shown that the times to complete different phases of a gymnastic vault vary across imagined and real conditions even though the overall times to complete the imagined and real versions are similar (Calmels, Holmes, Lopez, & Naman, 2006), and it has been shown that the temporal congruity between imagined and real actions varies with task complexity and performer expertise (Reed, 2002). Another result that suggests there is a problem

[1] For the sake of clarity, we separately report a two-way ANOVA on the pretest scores and another two-way ANOVA on the posttest scores. We confirmed that the alternative—including scores as a within-subject factor in a single three-way ANOVA—yields essentially the same results.

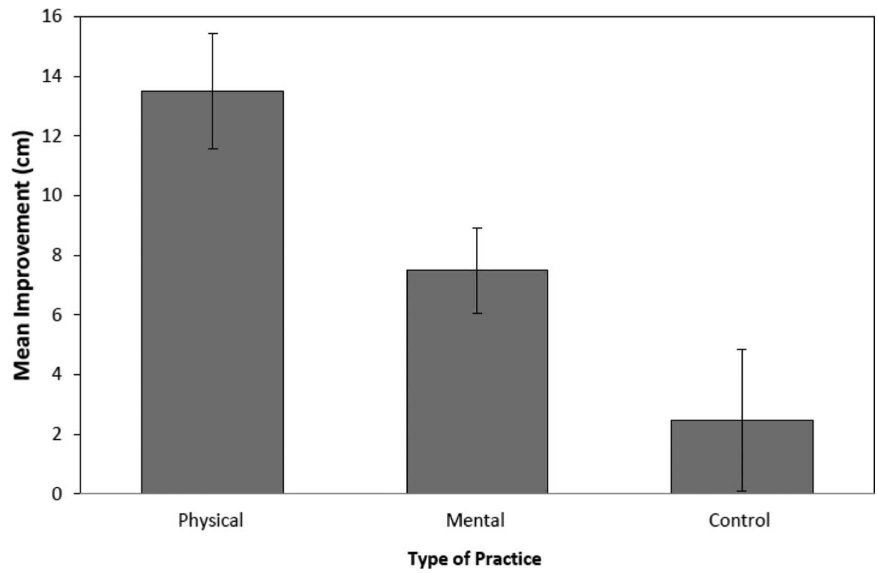

Figure 3. Amount learned measured as the difference from pretest to posttest ($\text{Mean}_{\text{pretest}} - \text{Mean}_{\text{postest}}$) for the physical practice groups, mental practice groups, and the control group. Data are collapsed across task variability. Error bars represent ±1 standard error of the mean.

with the first-order isomorphism view is that action selections differ across conditions when people either choose a preferred action by performing it or indicate which action they would prefer after mentally simulating the available options (Walsh & Rosenbaum, 2009). All of these results came from studies that were not concerned with learning. By contrast, the study reported here was concerned with skill acquisition. This difference made the present study necessary; it was not a priori obvious that conclusion, which came from studies that did not involve learning, would apply to learning itself. Beyond this point, the fact that a similar view has emerged in both kinds of studies is heartening because one might expect the motor representations subserving performance at any level of skill to depend on the motor representations that were used to reach that level of skill.

Our skill-centered approach affords specific opportunities for future research. It does so because other factors—not just task variability—are known to aid learning. Two such factors concern practice schedules. It is well known that distributed schedules—series in which practices and intervening rest periods have similar durations—benefit learning more than massed schedules in which practices are longer than intervening rest periods; see Donovan and Radosevich (1999) for a review. It is also well established that schedules in which different skills are randomly practiced on successive trials aid learning more than schedules in which each skill is practiced in its own block of trials (see Schmidt & Lee, 2005, for review). If real and imagined actions do, in fact, bear a second- or higher order isomorphic relation, then these effects should also differ across physical and mental practice conditions.

Future work can also investigate the specific reasons that mental task variability did not promote learning. One possible reason is that imagined actions cannot be updated with critical information about action outcomes. Physical practice affords both information about the movement parameters used to produce actions and knowledge of results (KR) about action efficacies. In the present study, participants who physically practiced saw how far the ball landed from the target and could therefore try to correctly modify the force and direction of subsequent putts. Without KR, the ability of the mental practice group to minimize error may have been impaired. Future work could test this possibility by replicating the current study with an additional group that does not receive KR during physical practice. If mental task variability is ineffective because there is no KR in mental practice, then one would expect similar performance between a no-KR group that physically practices and groups that mentally practice.

Although a lack of KR for imagined actions might explain why task variability did not enhance learning, it should be noted that mental practice also lacks proprioception. Sensory feedback is important because it helps the learner link errors in action outcomes with the movement parameters used to produce them. Indeed, a lack of proprioception likely limits the amount of learning attainable through mental practice; see Willingham (1998) for a discussion. This conclusion would be consistent with the finding mentioned at the outset of this section, that mental practice often pales in comparison to physical practice (Driskell et al., 1994; Feltz & Landers, 1983), and would suggest that our findings may have been due to both a lack of KR and a lack of sensory feedback.

Apart from these more theoretical implications of our results, our findings may also have practical consequences. Athletes often use mental practice to improve performance (Suinn, 1997), and there is evidence to suggest that stroke patients can use mental practice to regain motor function (Sharma, Pomeroy, & Baron, 2006). Our results suggest that there is no reason to go to special lengths to use variable rather than constant training in these contexts.

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Received December 22, 2010
Revision received February 21, 2012
Accepted February 28, 2012 ■