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ARTICLE

PaR (Plan-act-Review) Golf: Motor Learning Research and Improving Golf Skills

Timothy D. Lee
McMaster University

Richard A. Schmidt
Human Performance Research

In this paper we review the motor learning literature concerning the effects of conditions of practice and methods of providing augmented feedback on the acquisition of motor skills. Specific attention is provided to research that concerns the learning of golf skills. We interpret the results of this research with particular recommendations and implications for conducting golf practice. The term "PaR golf" refers to a recommendation that practice should emphasize the *P*lanning and *R*eview components of the golf swing during practice, and *de-emphasize* the importance of the repetitious *a*ct of executing golf swings. These recommendations are consistent with the principle that golf practice that best simulates play on the course will optimize learning.

Keywords: motor learning, motor performance, golf practice, movement planning, movement evaluation

Change is ubiquitous in the golf industry. Equipment that allows the golfer to hit the ball farther and straighter; clothing to provide comfort and protection; nutrition to replenish energy; various kinds of gadgets that are intended to promote skill development; course design to improve play and enjoyment; and so on—all of these changes are developed with the purpose of enhancing the golf experience. But, despite these efforts, one estimate of the current state of the game is that average levels of *skill* have not changed, and remain essentially the same today as they were decades ago (Pennington, 2005). In other words, skill improvement, the ultimate payoff for many of these changes in golf, has failed to change.

We agree with Christina and Alpenfels (2002) that the failure to make significant advances in overall levels of skill, despite the enormous advances in golf

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Lee is with Department of Kinesiology, McMaster University, Hamilton, ON, Canada. Schmidt is with Human Performance Research, Marina del Rey, CA. Address author correspondence to Tim Lee at scapps@mcmaster.ca.

technology, can be attributed to a fundamental lack of knowledge about *how* to make changes that transfer from the practice range to the golf course. Christina and Alpenfels put the blame squarely on traditional training methods for this lack of skill development. These traditional methods encourage a style of practice that emphasizes successful performance by means of swing repetition. In our view, as we discuss in the next major section, this style of practice is ineffective for a number of reasons. Perhaps a lack of attention to what the research has to offer is one culprit in the failure to advance change in golf skill.

Our view is that typical golfer's (and also that of the typical "person on the street") fundamental viewpoint about how learning works is fundamentally flawed. One way this general viewpoint can be expressed often uses a metaphor that is unfortunate. A common metaphor involves a standard hammer-driven die that makes an imprint on raw metal. In this metaphor, practice is equivalent to hammer blows, and learning is the product of that—a lasting imprint on the metal. We all know that striking the hammer on the die repeatedly makes the imprint deeper, stronger, and more visible. If we imagine that skill at some task is related in some way to the "vividness" of the image on the metal, then the way to make the image stronger and more visible is to repeat hammer blows to the die over and over and over. Doing this "stamps in" the desired image, making it more vivid and resistant to fading with time (in this metaphor, fading of the image is thought to be equivalent to forgetting).

The problem is, if we use this metaphor for learning as being "stamped in" by repetitions, then more repetitious practice would always produce a stronger image and more skill. This may not always be so. For example, we suppose that most of us would think (correctly) that more practice is, in some sense, "better" for skill improvement and the resistance to forgetting. But, when we take the matter further and imagine the effect of a particular kind of practice on learning (a good example would be rote practice through repetitions), this leads to errors in terms of what would happen in the golfer. This metaphor would insist that repetitious practice of the same skill over and over and over (e.g., "Make 100 free throws after basketball practice"), should lead to more learning, as this repetitious practice would "stamp in" the learning, consistent with the metaphor. The problem is that repetitious practice does not have this effect at all. We will talk about the evidence for this contention later in this article. But, for now, imagine how you would conceptualize the products of learning. If one conceptualizes learning as a "stamping-in" process, this would lead to the wrong recommendations concerning how to practice.

As opposed to a "stamping-in" activity, we agree with the metaphor that golf is a "problem-solving" activity. After all, the basic problem for the golfer is to move the golf ball from point A to point B; and taking a swing at the ball represents an attempted solution to the problem. More specifically, such a problem-solving process would involve three steps, which we refer to as PaR (Planning, acting, and Reviewing). In our view, golfers (and those who provide advice to golfers) tend to overemphasize the process of swinging the club during practice (the "acting" part), just as one might overestimate the importance of repetitious practice swings. Based on our examination of the literature from the perspective of factors known to influence motor learning, we believe that the more effective type of practice emphasizes the *planning* and *review* of actions, instead of repeating practice swings at the driving range.

In separate sections of this paper we review the research evidence regarding factors that influence how learners plan and review actions. These two general sections are each subdivided into three research factors, and each of these factors is further subdivided into three sections, in which we present: 1) a brief review of the literature, followed by 2) an interpretation of the evidence relevant for learning golf skills, and 3) recommendations for golf practice. The paper concludes with a discussion of learning specificity—why one should practice as they play—and some specific recommendations for golf practice.

The Distinction Between Learning and Performance

Those new to the motor-skills research may find it strange that the study of learning seems to go against many common-sense ideas, as the metaphor discussed earlier does. In a typical, simple learning experiment, separate groups of subjects might be presented with two different practice conditions, and the scientist's job is to discover which of these conditions produces the most learning. Learning-scientists often divide such activities into two distinct phases, as discussed next.

Phase I

The first of these phases is called the *acquisition phase* (in which the factor of interest is varied between two groups of randomly assigned subjects). Here, participants in each group practice the task under one value of the particular variable of interest, and performance changes that occur with practice are noted. For some, this is about all there is to an experiment on learning—the condition that produces the "best " performance gains during practice, or which results in the most effective performance overall, is taken as the condition that has generated the most learning. But, the problem is that the effects of some variables on performance in phase I can have characteristics that appear and disappear very easily with time and/or a change in conditions. We discuss a number of these variables here. As an example, one of these factors involves the concept of guidance, wherein the learner is essentially guided (either physically or verbally) so that s/he is prevented from making errors. Such procedures—almost by definition—produce magnificently skilled performances while the guidance is present during practice. However, as one might perhaps expect, these gains in performance do not survive a change in conditions. Here the simple idea is that one must remove the guidance so that the "real" effect of the guidance during practice can be evaluated and separated from the effects of guidance, per se. That is, one searches for a test of the *permanence* of what was learned earlier.

Phase II

Extending this example, in phase II of the typical motor-learning experiment the guidance conditions must be removed to determine what, if anything, the learner has achieved while practicing with them. Conditions of skill acquisition often have effects on performance while a skill is being practiced that may be positive (e.g., guidance devices) or negative (e.g., fatigue). This, then, gives the basis for the second phase of the learning experiment—the *retention (or transfer) phase*. Here, all participants in the experiment are tested without the guidance after a period of no practice (a retention interval), to determine how much performance has changed internally for the person. Performance in the retention (or transfer) phase is the *ultimate criterion* for learning. Just as one may conduct practice with guidance on the range, the true "test" of learning is how it affects performance later on the course. Typically, in order for us to study the effects of some factor on learning, one must evaluate performance in a retention or transfer test in which the variable of interest is removed. Here, the condition during acquisition leading to the best retention performance is judged as the condition that produces the most learning. That eliminates the temporary factors affecting performance, so that one can see what the permanent effects might be.

This is essentially the problem facing the golfer who practices his swing on the driving range. The golfer cannot be certain that the changes in performance on the range are merely temporary, or whether these changes represent "real," permanent changes that we would call learning. The only solution is to perform a retention (or transfer) test; these tests could be done on the golf course during a round of play. Of course, the retention tests need not be actually on a golf course. As long as one can argue that the temporary effect of the variable being studied have been eliminated by the time of the retention test, one could regard performance in a situation in which the variable interest has been removed as being indicative of learning.

With these thoughts about the distinction between performance and learning in mind, we now turn our attention to a discussion of factors that influence the acquisition of golf skills. The discussion is divided into two major sections—factors known to influence (primarily) the planning for action and reviewing of the results of action.

Planning (Preparing for Action)

Preparation and planning to move is a key component of the golf shot, perhaps as important (or even more important) as the execution of the swing itself. Therefore, it is not surprising that practice is a key component in learning to plan and prepare for movement. In this section we describe three areas of motor-learning research concerning movement planning that are affected greatly by practice: a) the organization and scheduling of practice (i.e., blocked vs. random practice), b) the focus of attention (i.e., internal vs. external focus) during practice, and c) the duration of gaze fixation that is adopted immediately before action.

a) Blocked vs. Random Practice Research

One of the most extensively-researched topics in motor learning during the past 30 years concerns the effects of practice scheduling, which asks the following question: if you intend to practice different tasks during a session (say, Tasks A, B, and C), is it more advantageous to concentrate practice on each one of these skills in isolated episodes (practicing A, B, and C in an order such as: A, A, A. . . , B, B, B,. . . , C, C, C), versus interleaving practice attempts among all the tasks (A, B, C, B, C, A, C, A, B. . .)? This latter type of practice, often termed random (or interleaved) practice, occurs when no task is repeated on two consecutive attempts. The opposite of random practice is concentrated practice, often called *blocked* *practice*; this type of practice fits well with the common-sense view of learning embodied in the die-stamping metaphor discussed earlier. Believing in this metaphor for learning, blocked practice has made good sense to many, for several reasons: (a) the action's representation (sometimes, erroneously, considered to be "muscle memory,") is thought to be more effectively "stamped in," (b) feedback from a given performance should be more easily associated with the task being practiced at any given time, and (c) the learner can focus on practicing small details of the skill without having to focus on what happened during the other tasks. Because blocked practice generally results in very effective performance, the supposed benefit of blocked practice is also consistent with the concept of errorless practice, in which making errors during performance is viewed as being detrimental to learning, as if errorful practice promoted "learning to make errors."

But, while the research evidence does support the notion that blocked practice produces great performance while it is present, the research also shows that performance deteriorates markedly on subsequent tests of retention that are indicative of learning. The first, and most revolutionary of the many studies that examined these practice schedules was undertaken by Shea and Morgan (1979). Two groups of research participants practiced three different arm movement patterns, attempting to respond to an associated light stimulus with a movement made as rapidly as possible. In blocked practice, all of the practice trials were concentrated on one task at a time, just as the common-sense, metaphorical viewpoint would have it. Alternatively, in so-called *random practice*, the practice trials for the three tasks were given in a nearly random order, so that a given task was (almost) never followed by the same task. The same number of practice trials was given for these two groups, so the only difference between groups was the order in which the tasks were practiced. Tests of retention (which, we argue, represent the measures of learning here) were conducted after brief (10-minutes) and much longer (10-day) retention periods. In addition, for various subgroups, the retention trials were conducted under either random- and blocked-orders of retention testing.

The results of the Shea and Morgan (1979) study are shown in Figure 1. The performance data during the practice trials are presented in the left side of the figure, with improvements resulting from practice revealed by faster performances (lower total times in the figure). The data reveal clearly that blocked (concentrated) practice resulted in lower performance times than did the random practice. In an earlier tradition, we would have concluded: Clearly, the blocked condition was more effective for learning than the random condition, because the gains in performance were larger, and the blocked group condition performed more skillfully overall. However, as we have already mentioned, the critical test of *learning* involves performance in retention, and holds the view that the performance during acquisition is not critical for understanding learning. (Of course, we are not completely disinterested in performance differences during the acquisition phase, as a complete understanding of practice variables needs these practice data; but, those differences do not tell us much about the differences in learning, which is the goal.) These performances in retention, with the immediate effects of the variable on performance removed, are analogous to performing the golf round at some point in the future; it is considered to be the "best" measure of learning—the criterion test of learning.

For simplicity, the retention data have been averaged over the two intervals and presented in the right side of Figure 1. The results demonstrate a dramatic

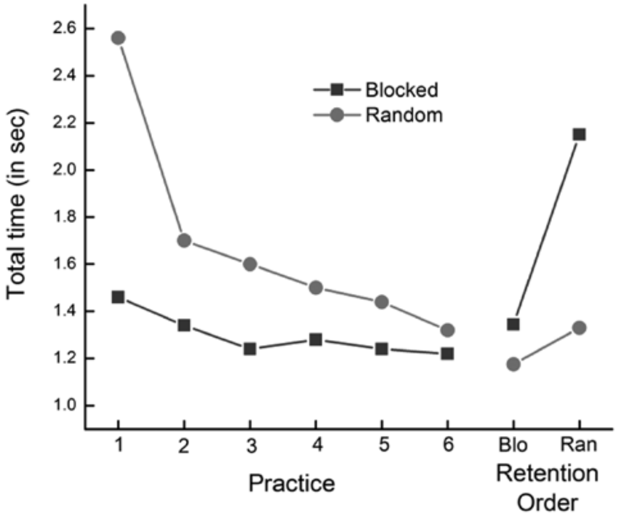

Figure 1 — Effects of blocked and random practice during practice trials and in retention (adapted from Shea & Morgan, 1979).

reversal of performance by both groups. Random practice in retention, which had previously been detrimental to performance in acquisition, revealed more skilled performance in both the blocked- and randomly-ordered retention tests compared with the retention performances following blocked practice in acquisition. This effect was most dramatically seen in the retention test conducted under random conditions in retention. In sum, blocked practice facilitated temporary changes in performance during practice; but random practice facilitated learning. The metaphor discussed earlier is unable to account for these effects.

The Shea and Morgan (1979) study was a landmark in the motor-learning literature for at least three important reasons. The study: 1) demonstrated that performance during practice is not always indicative of the underlying quality of learning, 2) revealed that introducing interference (from the other tasks) to the practice context can be a desirable feature in learning—not a negative influence, and 3) demonstrated that making errors during practice does not always degrade learning. Many studies have since replicated these findings, and the principles have been extended to a number of different task situations (see reviews by Barreiros, Figueiredo, & Godinho, 2007; Lee, 2012; Magill & Hall, 1990; Merbah & Meulemans, 2011). Indeed, these blocked-random findings are some of the strongest effects in the motor-learning literature.

Of importance to the present paper, the blocked-random findings have been replicated also in golf. For example, in a study by Porter, Landin, Hebert, and Baum (2007) learners were asked to make pitching and putting shots in either an alternating order (pitch, putt, pitch, putt, etc.) or in a blocked order (all pitches, then all putts, or vice versa) for the same number of practice trials overall. Although blocking the order of pitches and putts did facilitate performance during practice, the authors found that the blocked condition produced less skillful performances than the random condition on a retention test; and further, this was true for three different retention conditions (in random, blocked, or alternating-order schedules in retention). Moreover, this beneficial effect was seen in outcome scores (closeness of the shot to the target) as well as in analyses of the movement patterning scores (scored by golf experts from retention-test videos).

We caution the reader however, that there is a potential mistake in attributing too much to a literal interpretation of "random practice." A study by Lee, Wishart, Cunningham, and Carnahan (1997) illustrates this point clearly. They used a timing task, in which subjects learned the correct rhythm for a multiple key-press task, with three different timing patterns. Two groups performed practice trials in random and blocked orders, and, as expected, their results were quite similar to the findings of Shea and Morgan. However, of most interest was a third group, which received random practice, but was, during the acquisition phase, given an auditory model (a "demonstration") of the timing pattern just moments before making each practice attempt. These auditory models were very effective in helping the subjects in this group—in fact, their performance was even more accurate than that of the blocked group during the practice trials. Apparently, providing the subjects with the temporal model for the task just before execution gave them a good idea of how to control timing. However, in the retention test with this information withdrawn, this random + model condition was not only *less* accurate than the "standard" random group's performance, but was even less accurate than the blocked group's retention! Clearly, it was not the "randomness," per se, of the standard random group's practice order that was important, because these learners practiced in the identical order as did the random + model group. Rather, there was something about the *planning* for performance during practice in the standard random group that facilitated learning—and which had been made unnecessary by the presentation of the model in this random + model group—that was the key ingredient to the learning advantage over blocked practice.

Interpretation of the Research. We wish to be very clear and reiterate an important issue arising from the blocked- vs. random-practice literature: random practice does not facilitate learning because "randomness" or even frequent switching of tasks somehow produces magical properties for learning. Rather, random practice "works" because it encourages the learner to plan the movement in the interval just before the practice attempt; blocked practice eliminates this necessity, allowing the performer to reuse planning from the previous trial(s). Random practice introduces a "new" task, requiring a new movement plan, on each trial. Therefore, any planning information retained from performing the previous task would be inappropriate for the current task. In contrast, with blocked practice, since the same task is practiced repeatedly, the same plan can be used for the next performance attempt. Blocked practice in golf, which is a type of mindless, repetitious type of practice, is what Nilsson, Marriott, and Sirak (2005) describe as "scrape and hit" practice, because, in this condition, the learner need only "scrape" the ball into position before hitting it, without changing the grip on the club, altering the stance, establishing a target, etc.

This emphasis on movement planning does not, in itself, require "random" practice, per se; there is nothing "magical" about randomness here. In this view, the only requirement is that the process of planning the next shot be distinct from the plan for the previous shot—not necessarily that practice orders be purely random. This kind of practice creates a requirement or impetus to plan for each subsequent task as a "new" movement problem that requires a unique solution, in contrast to the just-completed movement's problem/solution; just as it would be when playing on a golf course.

Put another way, blocked practice seems to involve executing the movement (a golf stroke) without requiring (very much) dedicated planning on every attempt. Thus, in this view, the act of planning is critical for learning: blocked practice minimizes planning, and random practice encourages it. Consequently, by this view, there should be other ways to encourage planning than simply by introducing a new task on each practice attempt, as discussed in the next section.

Implications for Golf Practice. On the surface, one implication of this research for golf is that range practice needs to be done in such a way as to maximize the planning that occurs during the preparatory interval before each shot. For example, on the actual golf course, a drive might be followed by a bunker shot, and then followed by a putt. But, this recommendation would, strictly speaking, require that the golfer relocate to a different area of the practice facility for each shot—a very inefficient and impractical practice style. How can this be done within the confines of "standard" practice?

The implication of the research is that every effort ought to be made to encourage the golfer to maximize the planning of each shot during practice. Selecting different targets for each practice shot, choosing a different club, or even keeping the same club and attempting a different flight path (e.g., fade or draw) or type of shot (e.g., full or partial swing), would encourage the learner to abandon the plan developed for the previous shot and plan differently for the "new," and upcoming shot. Indeed, as long as the learner makes the effort to perform a complete reanalysis of the movement plan for each shot, then there is no reason why the very same task (shot) would not benefit from this kind of practice. Random practice requires a new plan on each shot, and thus optimizes the learning of *how to plan*, which is a skill requirement for play on the course.

We agree with a recommendation from Nilsson et al. (2005), that for putting practice, the golfer should take only one ball to the putting green, making putts from various locations on the green—not putting several balls from the same location, as is commonly done. Using only one ball would encourage the learner to plan the next practice putt from a new position, requiring a completely new assessment of the distance, line, etc.—more like the way in which one would plan for a putt in a round of golf—assessing the distance, line, and anticipated force required of the stroke would be paramount. Clearly there are many different strategies that a clever golfer or instructor could devise that would achieve the goal of maximizing the planning process during golf practice.

b) Focus-of-Attention Research

Have you ever heard an instructor say something like, "Concentrate on what your right elbow is doing during your swing?" What effect does such an instruction have? The attentional focus refers to the target to which a performer directs his or her attention during the execution of an action. Often, but certainly not always, attention is directed to the place in the environment where we are looking. We all know that one could be looking at one thing and attending to another (e.g., looking at the ball while thinking about the motions of the arms during a golf swing). For golf, the issue concerns the location to which one “pays attention” during a swing. One fundamental question in this work is what type of *attentional* target location would be the most effective for the learner who is practicing a golf swing?

Scientists in this area have defined two general targets for attentional focus: an internal focus means that the performer is attending to what some part of the body is doing—internal referring to something inside the body (a sensory or motor signal). An external focus means that attention is directed toward the product of the action—a focus that is an external to the performer. Reviews of this research (e.g., Lohse, Wulf, & Lewthwaite, 2012; Wulf, 2013) present a consistent conclusion: practice with an external focus produces an advantage during both performance and learning. That is, the gains are shown in both the practice period and in a retention test.

For example, Wulf and Su (2007) manipulated the learner’s attentional focus while they were practicing a golf-chipping task. Novice golf participants were assigned to one of three groups: a) an internal-focus group was told to pay close attention to the movement of the *arms* during the chip, b) an external-focus group was instructed to pay attention to the motion of the *clubhead* during the chip, and c) a control group was provided no instructions. Performance was measured by points accumulated over blocks of 10 shots, in which more points were awarded to shots that landed closer to a 15-m target.

The findings, illustrated in Figure 2, were straightforward—the external group achieved a performance advantage within the first 10 chip shots, and this advantage was maintained throughout the practice period and in a retention test conducted one day later. An external attentional focus facilitated both performance and learning.

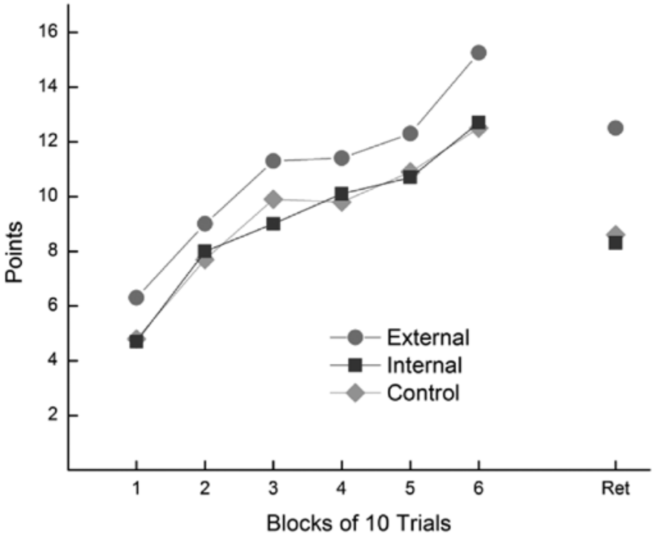

Figure 2 — Effects of internal, external and no (control) attentional focus instructions during practice and in retention (adapted from Wulf & Su, 2007).

Interpretation of the Research. There are numerous research results indicating that training with instructions to focus on the product of movement (an external focus), rather than on the movement itself (an internal focus), produces superior performance and learning. What remains unclear from this research however, is whether (a) the external-focus instructions boost performance and learning or (b) the internal-focus instructions are somehow detrimental to performance and learning. One possibility is that an external focus of attention allows the movement to be controlled more or less "automatically," with the performer devoting more attentional resources to achieving the outcome goal. Another possibility is that an internal focus directs the performer's attention to monitoring the motor commands and sensory feedback involved in movement production, which is typically seen primarily in early stages of motor learning [the "cognitive stage", in one view (Fitts, 1964)].

It is too early in the development of this research area to state precisely why attentional focus instructions affect performance and learning so strongly. However, the consistent findings in the research support continued efforts to uncover the processes at work here. For us, the most important findings are that external focus of instructions encouraged during practice facilitates performance both during practice performance *and* in retention. Clearly, learning is facilitated when planning processes are practiced with an external focus of attention.

Implications for Golf Practice. A popular, but captivating picture, readily available from an Internet image search for "1.5 seconds of thought," depicts a golfer in midswing with more than 60 different thoughts presumably going through his mind. Although fictitious, the image does represent a common fault in thinking about the swing during a golf shot. To us, the most interesting aspect of this picture is the fact that just about every one of the thoughts represents an internal focus of attention—only a very few of the thoughts might qualify as an external focus of attention.

Nilsson et al. (2005) describe a simple preshot routine designed to deal with the issue of attentional focus. They advocate breaking the preshot routine into a "think box" and a "play box." The idea is that regardless of the thoughts that occur while in the think box, these should all be set aside when one prepares to strike the ball while in the "play box." The attentional-focus literature would suggest that instead of clearing these thoughts altogether, that one should focus instead on an external attentional target, such as the ball, the intended shot path, or final location, etc.

c) Gaze-Duration Research

Another line of research concerns the golfer's focus immediately *before* performing an action. This research reveals that individuals with sport expertise tend to focus their eyes on a specific environmental target for a longer period of time immediately before movement onset than do nonexperts. Labeled the "quiet-eye effect" (Vickers, 2007), the finding has been replicated among skilled athletes in a variety of different sport events and movement contexts, including golf (Vickers, 1992). Moreover, research suggests that increasing the gaze duration can be trained, which, in turn, results in improved performance.

An example of the training effect was seen in a golf study by Moore, Vine, Cooke, Ring, and Wilson (2012). Nongolfers practiced a putting task for 320 trials, conducted over three sessions of practice. Two groups were compared at baseline (before practice) and after practice in two retention tests and a "pressure test" (a transfer situation that included a monetary incentive plus negative-efficacious comments, designed to elevate the stress level of the test). One group was provided technical putting instruction regarding eye, head, arm/shoulder and putter clubhead position during the putt. The other group viewed an expert golfer who demonstrated the "quiet-eye" technique—subjects were instructed to fixate their gaze on the back of the ball before the stroke began, not to change gaze for at least 2–3 seconds, and to continue to gaze at the spot below the ball after having made the ball-strike (see Table 1 in Moore et al., 2012, for full details). Instructions for both groups were repeated before each block of 40 trials.

Performances of the two groups in the pretest and three posttests are illustrated in Figures 3a and 3b. The top graph (Figure 3a) illustrates the duration of the last eye fixation on the ball before the putting stroke began. The two groups were essentially equal in gaze duration in the pretest, but the quiet-eye-trained group lengthened their gaze duration significantly as the result of focused training, resulting in much longer last-gaze ("quiet-eye") durations than the technical group in both retention tests and in the pressure-transfer test. A concomitant effect was seen in final distance of the putt from the hole, measured in absolute radial error (holed putts were assigned a score of zero error). Although the two training groups performed similarly in the pretest, all posttests performed by the "quiet-eye"-trained group were more accurate (less errorful) than the technically-trained group.

Interestingly, Vine, Moore, and Wilson (2011) replicated these findings (longer "quiet-eye" durations and lower radial error scores in retention and pressure tests) in a group of skilled golfers (mean handicap = 2.8). Moreover, this training advantage carried over from the laboratory to the course for the "quiet-eye"-trained group—resulting in almost 2 fewer putts per round in on-course performance following the practice period.

Interpretation of the Research. Although the term "quiet eye" might lead one to suspect that extraneous eye movements in the period directly preceding a putt have an influence on performance, we see no clear understanding of the mechanisms that result in improved performance with the training protocol. Vine et al. (2011) speculated that longer gaze fixations facilitated more precise eye-hand coordination during the motions of the putter, thereby producing more accurate ball strikes. However, an alternative possibility is that "quiet-eye" instructions influence the performer's focus of attention—focusing on the ball produces an external focus of attention, which facilitates performance, as described in the previous section. More work is clearly needed in this area to disentangle the theoretical significance of this effect.

Implications for Golf Practice. Regardless of the mechanism that underlies the "quiet-eye" effect, one implication might be that the period immediately before the start of movement is critically important for movement preparation. This view holds that the "quiet-eye" effect could have a positive impact on the planning process that occurs just before the initiation of the golf swing. Alternatively, the "quiet-eye" effect might have its basis in movement production. Moreover, since positive findings revealed following focused training with "quiet-eye" instructions are beneficial for both retention and pressure tests (and for both novices

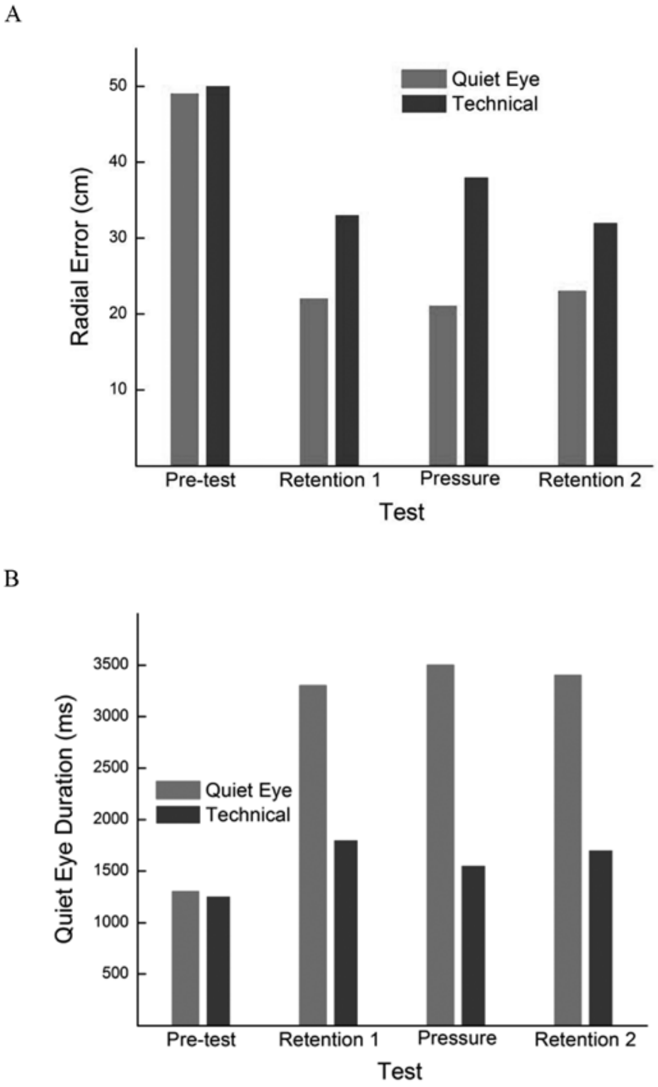

Figure 3 — Effects of “quiet-eye” and technical instructions on gaze duration (a) and outcome scores (b) in a pretest, two retention tests and a pressure (transfer) test (adapted from Moore et al., 2012).

and experts), this evidence tends to support our view of the planning process as a key determinant of success in golf performance. And both gaze-duration and focus-of-attention training appear to be effective mechanisms for developing a consistent preshot routine. As seen in the “pressure-test” results of Moore et al. (2012) and Vine et al. (2011), such training might help to offset the negative consequences that seem to accompany performance anxiety.

Summing Up: Planning (Preparing for Action). In the above section we have discussed three lines of evidence suggesting that the period of time before action is a significant determinant of successful practice. The lines of research evidence were quite different—examining practice schedules (blocked vs. random practice), the direction of attention before action (external vs. internal focus of attention), or the stability of one's eye-focus just before movement initiation. The findings were quite clear in each line of evidence that: a) movement planning has a very critical impact on performance of the golf swing, and b) that optimal movement planning is not a process that "just happens"—it requires practice to be learned and applied in play on the golf course.

Reviewing (Evaluating the Action)

If golf is, indeed, a problem-solving activity, then evaluating the success of that problem-solving activity, or simply, the *review*, represents an important component of the learning process. For many people, the main point of the review is to accumulate as much information about the swing as possible, as soon after the completion of the swing as possible. As we will discuss, such a goal misses a major learning feature of the review process. In this section, we consider the lines of evidence regarding the effects of externally-provided information on skill learning: a) guidance research, b) immediate-feedback research, and c) reduced-feedback research.

a) Guidance Research

Consider the multitude of training aids that are advertised on television, in golf magazines, and the Internet. Some are simple, inexpensive pieces of wood or plastic, whereas others involve very sophisticated and expensive computerized technology. A common feature among many of these aids is that they are designed to provide corrective, sometimes physically-restrictive feedback, as instantaneously as possible after an error occurs. We suspect that most of these aids are very effective during practice (i.e., they have a performance effect). But, do they result in effective learning?

A study by Armstrong (1970b) illustrates how physical guidance can impact motor performance and retention. The learners' task was to produce a horizontal arm movement according to a prescribed spatial and temporal pattern (e.g., changes in movement direction at specific times, etc., which, in some ways, is similar to learning a golf swing, except that there was no object to strike). Participants practiced the task for 75 trials on each of three consecutive days. Armstrong found that, for individuals to learn this task they needed extra information to assist in producing the movement accurately; he tested three methods of delivering this information. One group of learners was provided haptic (sensations that contribute to touch) guidance from a computer-driven, torque motor to assist in producing the movement, such that if the ongoing movement was too slow or too fast the assistive device would work like a spring to speed up or slow down the movement as appropriate. The device also reversed direction for the learner at appropriate temporal landmarks. Essentially, this group was physically *guided* to produce "correct" movements on each trial, over a three-day practice period. Another group of learners was presented a visual representation of the prescribed directional and temporal information on a computer monitor, together with a feedback trace of the action as the movement was unfolding. These traces (the goal or template trace along with the feedback the trace of the subject's ongoing movement) were presented to the learner in real time on each trial during practice; this type of feedback is usually called "concurrent feedback" (Schmidt & Lee, 2011). A third (control) group of learners was provided only a quantitative summary of the error accumulated [i.e., the amount of error deviation of the produced trace from the goal trace—called root-mean-squared (or RMS) error] after each trial. In addition, this error-feedback group was presented a visual representation of the goal trace together with the trace they produced, after the completion of the last trial of each block of trials during practice.

The performance during these three sessions of practice is plotted in Figure 4. As expected, the guidance group performed essentially perfect repetitions of the pattern on each trial—which is illustrated in the figure by the very small amounts of error when comparing the produced movement to the target movement. The concurrent feedback group also performed very well, although they never achieved the level of accuracy as the individuals who were physically guided during practice. The least accurate performance was found for the group that received only error feedback after each trial. This latter group was the slowest to improve, and, only at the end of the third session, did they achieve the level of performance that the concurrent feedback group achieved almost immediately on day 1.

The right side of Figure 4 shows the retention "test" trials performed by all three groups conducted immediately after the third practice session. All groups were treated the same way in these test trials, with no guidance, visual feedback, or post-movement RMS error being available. As is evident in the figure, the performance of both the guidance and concurrent feedback groups was degraded dramatically in these test trials as compared with the earlier performance in the acquisition phase.

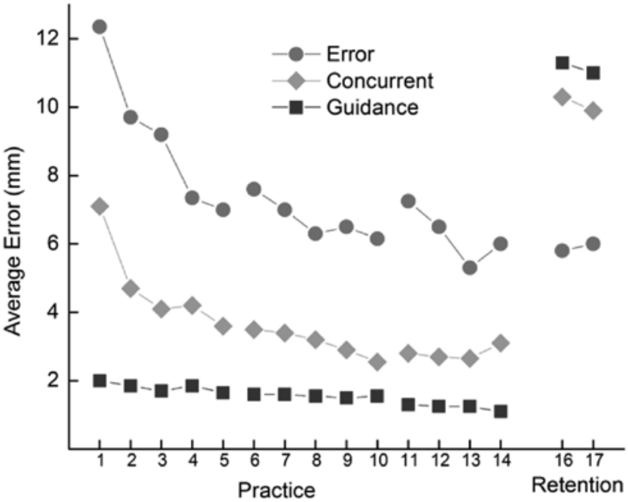

Figure 4 — Effects of physical guidance, immediate feedback and delayed feedback on performance over three days of practice and in a retention test (adapted from Armstrong, 1970b).

In fact, their performance was about the same as the error feedback group's performance at the *very start* of practice on day 1. Performance in these retention-test trials suggested that these groups had actually learned essentially nothing at all in terms of producing the action. In contrast, although the terminal feedback group did not make as large a performance gain during practice, this group retained the improvements well into the retention-test trials, and performed much more skillfully than the guidance and concurrent feedback groups as a result.

The poor performance of the physical guidance group is certainly damaging to a view that promotes the advantages of "errorless" practice and the potential advantages of physical-guidance devices in general. Indeed, these types of findings have been replicated often in motor-learning experiments (recently reviewed by Hodges & Campagnaro, 2012). With just a few exceptions (Bertram, Grosser, & Guadagnoli, 2008; Skrinar & Hoffman, 1978) and despite their prominence in golf industry, the potential effects of physical guidance golf aids have not been investigated rigorously. Based on these results (see Armstrong, 1970a; Hodges & Campagnaro, 2012), one should not expect such guidance techniques to be very effective for learning golf.

However, a recent, notable "twist" to the guidance literature was contributed by J. Lee and Choi (2010). Their subjects learned three patterns of a pursuit-tracking task under different conditions of haptic "interference." One group was provided haptic guidance, which was similar, in essence, to Armstrong's guidance condition except that the computer gradually became progressively less constraining with practice. The other two haptic conditions were designed to *disturb* (or interfere with) performance rather than to *guide* it. In one condition the computer made the learner's task *more* difficult as tracking performance became more accurate by applying a repulsive, force resistance. In the other condition, a noise-like disturbance was introduced such that attractions toward the target-course and repulsions away from the course were introduced by the computer at random during performance. A fourth condition (control group) received no haptic interference and relied only on visual feedback to make adjustments.

The performances of these four groups during the nine training trials of the three different tracking patterns are presented in the left side of Figure 5. As expected, the guidance group performed with minimal error in the early trials, and then gradually became more errorful as the constraints of the haptic guidance were progressively relaxed over trials. In contrast, the repulsive disturbance conditions resulted in the most errorful performance. The noise-like disturbance condition, in which the learner's limb was either randomly repelled away from the target or attracted toward it, performed similarly to the control group, and moderate to the performances of the guidance and repulsive groups.

Same-day and next-day retention tests are plotted in the right side of Figure 5. Similar to Armstrong (1970b), the guidance conditions resulted in the least skilled retention performance, despite the progressive relaxation of the guidance constraints over training trials. Interestingly, the control and the two disturbance groups performed similarly in the immediate retention test, but it was the noise-like disturbance group that performed most skillfully in the delayed retention test. Other studies have confirmed the positive influence on motor learning of assistive devices that *generate* error, rather than reduce it (Domingo & Ferris, 2010; Milot, Marchal-Crespo, Green, Cramer, & Reinkensmeyer, 2010).

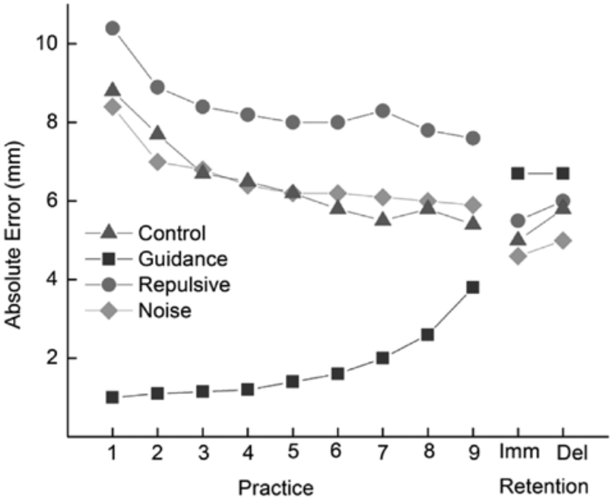

Figure 5 — Effects of no guidance, full guidance and two types of disturbed guidance (repulsive and noise) on practice performance and retention (adapted from J. Lee & Choi, 2010).

Interpretation of the Research. It is clear from the work just reviewed, plus the majority of findings in the literature (for reviews see Armstrong, 1970a; Hodges & Campagnaro, 2012), that guidance does not promote motor learning. In fact, guidance is more likely to lead to detrimental effects on learning compared with many other conditions of practice. We interpret this evidence quite literally, as suggesting that learners need to actively learn (rather than passively performing) movement control—to acquire the capability to control the spatial and temporal dynamics of moving effectors requires active practice. Artificial assistance that provides ongoing support to help understand the control of these dynamics tends to impede, rather than enhance learning—the learner treats the guidance as kind of "crutch," such that performance benefits when it is present, but fails when the "crutch" is removed. In contrast, enhanced effortful processes under active movement control conditions (noise and repulsive groups) support retention when augmented forms of support, such as guidance, are no longer available. Making practice *more difficult* for the learner seems to have benefits, within limits, of course. This is a similar idea to Bjork's (1994) notion of creating "desirable difficulties," wherein various ways of increasing the "difficulty" for the learner (rather than making it easier for the learner) has been shown to have beneficial effects on learning.

We do not dismiss the possibility that *some* guidance could be useful in the acquiring an understanding of the movement goal, especially so when the learner is at a stage where s/he is unable to produce anything remotely approximating the task. However, there is little research to suggest how much, or when, guidance might be useful in this regard and when such positive effects would inevitably become a negative influence on learning (Marchal Crespo, McHughen, Cramer, & Reinkensmeyer, 2010).

Implications for Golf Practice. For the very beginner, the golf swing might seem like a very strange and awkward series of motions, involving a difficult-to-understand type of coordination pattern. Although verbal and visual feedback, together with demonstrations, can be a powerful tool for learning, Button, Cundaris, and Lamb (2010) suggest that there may be a good case for some types of guidance aids to help the learner to develop a golf swing that is "in the ball-park". An assistive device might also help to direct the learner's attention to specific, internal movement cues that would help to better understand the spatial and temporal goals of the swing. However, it would be very easy to overdo one's reliance on guidance. Given that most golfers have the capability to roughly approximate the golf swing as beginners, this suggests that guidance, although it might be useful in early practice, could be easily overdone, leading to the "crutch-like" effects that guidance produces.

Given that the golfer has a limited amount of time to devote to golf practice, the instructor is motivated to make the time spent in practice as efficient as possible. Minimizing the time spent using a guidance aid seems to be consistent with optimizing practice effectiveness.

b) Immediate Feedback Research

Let's return now to the earlier discussion of the Armstrong (1970b) study, which was presented in Figure 4. We focused our earlier attention on the effects of physical guidance, which eliminated error almost entirely during the acquisition trials, and resulted in virtually no learning at all as revealed in the retention test. Look again at Figure 4, and now focus on the group that received concurrent feedback during practice. In this condition, the computer provided a feedback trace of the spatial-temporal characteristics of the movement produced by a learner, overlaying the goal trace. Although this concurrent feedback condition did not eliminate error entirely (which the guidance condition had done), the feedback did result in very rapid improvements on the task, and certainly it facilitated performance compared with the group that received only error feedback information after the trial was completed. Nevertheless, the effects of this concurrent feedback condition on learning, as shown in the right side of Figure 4, were similar to those of the guidance group—compared with the beginning levels of performance, this method of providing augmented feedback produced virtually no learning at all. Similar findings have been also generated by Schmidt and Wulf (1997) using a task of much shorter duration (1 second), which is more like the duration of a golf swing. Apparently, adding the concurrent visual feedback gave the learner too much help, and they used it as a "crutch."

Consider also the findings of Swinnen, Schmidt, Nicholson, and Shapiro (1990), where participants learned a task that involved moving the arm to intercept a moving light pattern (more or less like hitting a moving ball), and were provided with feedback about the result only upon movement completion. Two groups were compared which differed only in terms of *when* the feedback was provided: (a) almost instantaneously after completing the movement, or (b) after a short delay period of a few seconds. Two days of practice were followed by retention tests (performed without feedback) after 10 minutes, two days, and four months of no intervening practice. These results are shown in Figure 6. The group given a short delay before receiving the feedback learned the task much more effectively than the group that had received the feedback essentially instantaneously after movement

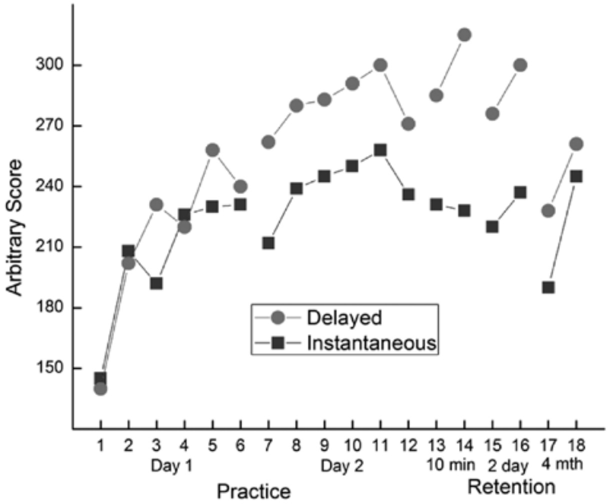

Figure 6 — Effects of immediate (instantaneous) and delayed augmented feedback on performance and three tests of delayed retention (adapted from Swinnen et al., 1990).

completion. This effect did not show up on the first day of practice performance, but was present on subsequent days and in the retention tests. That is, immediate feedback did not have the benefits that are traditionally ascribed to it.

Interpretation of the Research. Schmidt (1991; Salmoni, Schmidt, & Walter, 1984) provided an interpretation of these findings that has received considerable support in the literature—the ineffectiveness of concurrent feedback is likely due to its having a "guiding effect" on the learner. That is, when augmented feedback conditions influence behavior in such a strong manner that they "guide" the learner to making error corrections as specified by the feedback, then the learner fails to learn other important information—as we discussed in the section on guidance and learning. Critically, one of the key sources of information that seems to be "blocked" by the concurrent or instantaneous augmented feedback concerns inherent feedback—the information that our senses typically provide us about performance. When augmented feedback is presented in such a guiding manner, it essentially distracts learners from processing their own sources of feedback.

Implications for Golf Practice. An obvious, but sometimes neglected difference between "golf practice" (on a range) and "golf play" (on a course) is the availability of "artificial" (augmented) feedback. We use the term artificial simply to mean that some forms of feedback used in practice are not normally available (or not legal) to use by the golfer when they are on the course, such as instructors (usually) and computer-aided technology that tell the golfer immediately what went wrong, and why. If practice conditions are established such that the learner has become reliant on such artificial feedback to determine what went wrong and why, the golfer will be not be in a strong position to determine this information without those feedback sources present (on the course). Ironically, the immediacy of feedback appears to be a prominent feature in the advertisements for many of these modern, computerized feedback devices—the very feature that research has determined probably makes them *less* effective.

c) Reduced Feedback-Guidance Research

As reviewed in the previous section, research has shown that some methods of providing augmented feedback can have strong, negative (guidance-like) effects on learning. However, research also suggests that other methods of providing feedback can eliminate, or even reverse these negative effects. For example, Winstein and Schmidt (1990) found that simply reducing the frequency by which feedback is provided (from feedback following every trial to feedback on half of the trials) can reverse the negative, guiding influences of augmented information.

Another method, termed "bandwidth feedback," uses a systematic method to reduce feedback (Sherwood, 1988). Smith, Taylor, and Withers (1997) provided a good example of the bandwidth-feedback method in a golf chipping task. In this study, learners were provided with augmented feedback about their chipping style whenever the shot ended at a location greater than a predetermined distance from the hole. The distance to the hole was 10 m; error bandwidths were defined as: a) a ball location within a 5% radius of the hole (here, being 0.5 m), or b) locations within a 10% radius (1.0 m). The rationale was that "relatively successful" shots do not require augmented feedback; if only "poor" shots were followed by feedback, then this method would provide a way to reduce the frequency of feedback presentations, as practice tends to make the shots land closer to the hole, thus resulting in less frequent feedback. Similar to other bandwidth-feedback studies, and consistent with the Winstein and Schmidt (1990) evidence, Smith et al. (1997) found that the 10% bandwidth condition produced the most stable performance (minimum variable error) in the retention test, possibly because the withdrawn feedback did not give the learner an impetus to change the behavior on each trial.

Contrary to the common thinking, the bandwidth and reduced-frequency feedback research suggest that there can be a boost to learning on those trials for which performance is *not* followed by augmented feedback. One potential reason is that the learner might be trying to understand the meaning of inherent (or intrinsic) feedback (generating a kind of "error-detection mechanism") that can be used when augmented feedback from an instructor is not available (e.g., on the golf course). By this rationale, attempts to facilitate the processing of inherent feedback after a movement should enhance learning.

This idea was examined in another experiment in the set of studies by Swinnen et al. (1990). As they had done in their previous experiment (and presented in Figure 6), these authors compared two groups that were given augmented feedback either instantaneously or after a short delay following movement completion. A third condition was added in this subsequent experiment by Swinnen et al. (1990), in which the learners were asked to *estimate* their own errors *before* the augmented feedback was provided. The goal of this additional group was to assess the effect of having an empty delay filled with error-detection processing of the inherent feedback before augmented feedback is given. Indeed, Swinnen et al. found that generating subjective estimation of the anticipated feedback resulted in enhanced learning, as seen in a delayed-retention test (see also Liu & Wrisberg, 1997).

Interpretation of the Research. In the previous section we suggested that methods of providing augmented feedback can be so powerful ("attention attracting") that they "block" the processing of inherent sources of feedback. While we realize that augmented feedback plays an extremely important role in motor learning, the findings discussed in the present section suggest that promoting the processing of *inherent* feedback can have a positive effect on learning, probably because of the generation (and learning) of error-detection mechanisms.

In this section, we have discussed research showing that (a) reducing the frequency of augmented feedback, and/or (b) encouraging the processing of inherent sources of feedback, can enhance learning effectiveness. One of the critical reasons for the effectiveness of these methods is because augmented feedback typically is not provided in retention tests. Therefore, the learner is required to perform using only the available sources of inherent feedback in conjunction with his/her learned error-detection mechanism. An important advantage provided by these methods is that they encourage the processing, and presumably learning to interpret, the only sources of information that will be available in a retention test—a situation that is very much like what the golfer faces on the golf course.

Implications for Golf Practice. Inherent visual feedback tells the golfer where the ball went, but s/he must rely on other sources of information to provide knowledge about *why* the ball went where it did. For example, proprioceptive information informs about the swing path and timing; haptic information provides clues about contact between the grip and the club and between the clubhead and the ball/ground; vestibular information informs about balance; and auditory information provides some clues about the nature of the ball contact. Performance on the course can be facilitated if the golfer understands and uses these information sources (after the shot). However, learning to understand and use these information sources is a process that requires practice, as we have seen. Withholding augmented feedback from an instructor or a piece of technology, or even delaying that information until after the golfer has attempted to estimate his/her own performance, provides an opportunity for such learning. Although encouraging this style of review might not aid the golfer's performance during practice, it should facilitate performance in the future on the course, where those "artificial" sources of feedback are not available.

Summing Up: Reviewing (Evaluating the Action). In the above section, we have discussed evidence that *how* learners evaluate actions during practice will have a determining effect on skill in evaluating actions during actual play. Although external sources of augmented feedback, which includes information from artificial devices as well as from instructors, can serve as significant contributors to improved play, the information they provide should not be a substitute for learning the skill of self-detection of errors.

We leave the last words in this section to Jack Nicklaus, who recognized the value in understanding one's own swing: "Jack Grout (Nicklaus's teacher) taught me from the start. He said I need to be responsible for my own swing and understand when I have problems on the golf course how I can correct those problems on the golf course myself without having to run back to somebody." (Nicklaus, 2012). We believe that the key to learning about one's own swing is developing a subjective error-detection mechanism—learning that occurs during practice.

Specificity of Learning—Practice as You Play

We recognize that much, or perhaps all, of what we have said in this review of motor learning and golf has probably been said before in various ways, and in various forms and forums. In our view, there is one fundamental feature of PaR practice that makes it effective for play on the golf course—it encourages the same information-processing activities during practice that will be required during performance on the course. This feature of learning, known as *specificity of learning*, has a long tradition in the motor-skills research literature (discussed in detail in Schmidt & Lee, 2011, chapter 11).

In the first section of this review we considered features of practice that influenced preshot planning behaviors. In each of the three research areas, the most effective practice conditions for learning turned out to be the conditions that most closely resembled the behaviors required in play on the course. For example, each golf shot on the course presents a different problem to solve than the previous shot. Therefore, practice that encourages the treatment of each shot as a unique problem to solve represents a style of practice that resembles real play; in our view, this method enhances these skills for play on the course. Consequently, blocked practice and other forms of repetitive activities that minimize active problem-solving activities in practice, produce the least play-specific behaviors for the course. Similarly, we reviewed research that demonstrated the beneficial effects of external focus of attention and prolonged gaze-durations immediately before and during action. According to the same argument as presented above, one needs to practice these behaviors on the range to best prepare to use these strategies in play.

A similar argument for play-specific practice was made in the second section of our review. Guidance, whether the result of a physically-restrictive device or by a source of augmented feedback, impedes learning because it encourages a style of performing that is not specific for play on the course. We considered these guidance effects to be "artificial" for this reason—they are available only during practice. The only sources of feedback that are not "artificial" are the sensory sources that are always available to the golfer on the course, during play. However, the information provided by these sensory sources need to be understood, and acquiring these error-detection processes, we feel, should be the primary goal of the reviewing process during practice.

We have been fairly derisive about driving-range practice in this paper. One reason is that performing on many driving ranges is so different than performing on the golf course. As Christina and Alpenfels (2002) and Nilsson et al. (2005) point out, shots on the range are taken often from smooth, flat, clean fairway lies, which may be unlike some, if not most, of the shots encountered in a round of golf. The concept of practice specificity is that what you learn tends to be what you practice. In our view, an "optimal" driving range would have a number of deliberately nonflat lies, with varying turf, with targets on the range that mimic both greens and nongreen targets (for playing lay-up shots), with objects placed in front of the golfer to encourage shots to be played over, under, and around them, and so on. The idea is to make the driving range as similar to the actual play-on-course as possible.

Final Thoughts on Implications for Golf Practice

A rather simplistic, yet effective, strategy for implementing PaR practice would be to simply ask a leaner to reduce (not increase!) the number of balls struck during practice in a particular time period. For example, if one asked a learner to distribute a bucket of 20 balls over a 20-minute time period, our guess is that striking each ball would become more "important." The golfer would likely take far more time to plan and review each shot because of the spaced practice conditions, and the increased importance of each shot. Similarly, we would ask the learner to take only one practice ball to the putting green (rather than 2, 3, or more), so that each practice putt required a distinct, and different, solution.

Finally, we understand that golf practice can be boring. Therefore, a good technique to make practice more interesting is to play practice games—specifically, ones that simulate the types of behaviors required on the course (e.g., Wearner, 2006). Playing 18 "holes" of up-and-down from around the green, in various lies (e.g., tight lies, rough, sand) and from various distances could be a game for which the scoring record is maintained from practice session to session. Mentally simulating your home course on the range is another game-like activity. If you normally use a driver from the tee on hole #1, then play your first shot with this club. And depending on the outcome of that shot, the next club would be selected accordingly. And so on. These types of games not only simulate play on the course, but encourage the practice of the planning and review of behaviors that we discussed in this review to benefit learning.

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