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Evidence for biomechanics and motor learning research improving golf performance

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ABSTRACT

This review sought to determine the evidence for how biomechanics and motor control/learning may improve golf performance. To be eligible, the biomechanics and motor learning studies had to use direct (ball displacement, shot accuracy) or indirect (clubhead velocity, clubface angle) golf performance outcome measures. Biomechanical studies suggested that reducing the radius path of the hands during the downswing, increasing wrist torque and/or range of motion, delaying wrist motion to late in the downswing, increasing downswing amplitude, improving sequential acceleration of body parts, improving weight transfer and utilising X-factor stretch and physical conditioning programmes can improve clubhead velocity. Motor learning studies suggested golf performance improved more when golfers focused on swing outcome or clubhead movement rather than specific body movements. A distributed practice approach involving multiple sessions per week of blocked, errorless practice may be best for improving putting accuracy of novice golfers, although variable practice may be better for skilled golfers. Video, verbal, or a combination of video and verbal feedback can increase mid-short iron distance in novice to mid-handicap (hcp) golfers. Coaches should continue to critique swing technique but also consider how the focus, structure and types of feedback for practice may alter learning for different groups of golfers.

INTRODUCTION

A considerable amount of biomechanical research has been conducted on the golf swing as a golfer's technique has a large effect on golf performance where the aim is to hit the golf ball into a small hole in as few shots as possible (Hume, Keogh, & Reid,

2005). Golf performance (driving, chipping and putting) can be assessed via direct (ball displacement, shot accuracy) or indirect (e.g., clubhead velocity, clubface angle at contact) outcome measures. The magnitude and direction of the linear clubhead velocity at impact is determined by the angular velocity of the clubhead during the swing and the length of the club. Golfers must develop a consistent fundamental swing pattern to secure these qualities (Kwon, 2010). However, relatively few motor learning studies have been conducted to determine what constitutes optimal golf teaching strategies to obtain the fundamental swing pattern and how this may differ for golfers of varying standards. This relative lack of motor learning research is quite surprising when you consider the popularity of this sport worldwide, the large prize money and sponsorship deals that professional golfers attract and the considerable amount of biomechanical research on this sport. The purpose of this review was to determine the strength of the evidence and gaps in the literature for how biomechanics and motor control/learning may assist golfers improve their performance.

METHODS

Electronic databases (Web of Knowledge, Scopus, Medline, SportsDiscus, ProQuest Direct, Cinahl, Scirus Current Contents, ABI/INFORM Global and ProQuest Direct) from January 1975 to July 2011, and the internet (e.g. Journal of Biomechanics on line, Google Scholar) were searched using keywords golf, biomechanics, motor control, motor learning, dynamical systems, feedback, variable practice and performance. Keywords were used separately and in combination. Reference lists of retrieved articles were manually checked for additional studies. Initial exclusion criteria were that the

article was not: 1) available in English and in full text; 2) in a peer reviewed journal or conference proceedings with full papers rather than abstracts only; 3) previously referred to by other sources; or 4) adding knowledge to the aim of the review. After applying the initial exclusion criteria 329 articles were sourced.

Cochrane Collaboration (Higgins & Green, 2005) review methodology was used to evaluate the evidence for biomechanics and motor control/learning research improving golf performance. The quality of the papers that met the exclusion and inclusion criteria were reviewed to determine if they were controlled, had randomisation of subject allocation, blinding of subjects and assessors. Methodological limitations were associated with many of the studies initially reviewed such as a failure to clearly describe the characteristics of the cohort (e.g. no handicap – hcp provided), specifications of golf clubs used, the environmental conditions, or the p-value or effect size associated with the outcome measure. In addition the definition of variables was often not well described in studies. For example, the definition of the plane of the golf swing has been described as fundamental in golf research by Kwon (2010) but was not reported in many studies. In most cases data were provided for a few golfers only, with the exception of Nesbit (2005a) who reported kinematic and kinetic data for 84 male golfers.

There were 57 golf reviews identified in the search that were general in nature, and some reviews that had independently addressed biomechanics (e.g., Hume, Keogh, & Reid, 2005) or motor learning (e.g., Knight, 2004) with respect to golf performance. Our

paper builds on these reviews by integrating and critically evaluating the evidence from both biomechanics and motor control/learning research. The final selection of 30 biomechanics and 20 motor learning studies for the review was based on the study being descriptive or experimental in nature and having outcome measures of direct (ball displacement, shot accuracy) or indirect (clubhead velocity, clubface angle) golf performance for driving, chipping and putting during practice or competition. Motor learning studies conducted on the golf swing were classified under three general categories: 1) attention during practice; 2) structure of practice; and 3) feedback during practice. Brief definitions of the various motor learning theories that apply to each of these three broad categories and a critical review of the literature examining the benefits of these approaches for golf are provided.

BIOMECHANICAL CONCEPTS AND FINDINGS

How to measure golf performance via biomechanics methods

Biomechanics has a role in optimising the distance and accuracy of all golf shots by providing both qualitative and quantitative evidence of body angles, joint forces and muscle activity patterns. Common golf biomechanics concepts necessary to understand golf technique include stability, Newton's laws of motion (inertia, acceleration, action reaction), lever arms, conservation of angular momentum, projectile motion, the kinetic link principle, and the stretch shorten cycle (Hume, et al., 2005).

Golf, as a highly technical sport, has been assessed using two-dimensional (2D) or three-dimensional (3D) high-speed video or optoelectronic systems, 3D force plates,

pressure sensors, electromyography, and by computer simulations/modelling in an attempt to improve performance. For example, clubhead velocity has been measured using 2D (e.g., Bradshaw, et al., 2009) or 3D kinematic analysis systems (e.g., Egret, Vincent, Weber, Dujardin, & Chollet, 2003; Horan, Evans, Morris, & Kavanagh, 2010), and ball velocity has been measured using ball launch systems (e.g., Bertram & Guadagnoli, 2008; Wallace, Otto, & Nevill, 2007). From a technical perspective, 3D high-speed kinematic analyses are recommended for golf research studies, although the best method to accurately measure 3D trunk motion is still debated (Cole & Grimshaw, 2009; Wheat, Vernon, & Milner, 2007).

Most of the biomechanical research involving the golf swing has been conducted in laboratory-type situations. These laboratory-based studies have predominately measured clubhead velocity as a proxy measure of ball displacement since displacement cannot be measured indoors. An early exception was Burden, Grimshaw and Wallace (1998) who measured both golf ball displacement and driver clubhead velocity for eight sub 10-hcp golfers completing 20 shots off a tee towards a playing field. The over-emphasis of laboratory-based studies may change with recent advances in technology allowing comparable levels of analysis to be conducted on the golf course (Neal, Lumsden, Holland, & Mason, 2007), leading to greater ecological validity of these studies.

What predicts golf performance – biomechanical variables of interest

Many research studies have sought to understand the primary determinants of ball displacement (length of the shot) for the drive and long irons, given maximum ball displacement is often a primary outcome of these shots. Based on the laws of projectile motion, golf ball displacement is related to the clubhead's linear velocity at ball contact. Fletcher and Hartwell (2004) reported a correlation of 0.86 for full golf swing clubhead velocity with driving distance. The centeredness of contact, clubhead path, position of clubface and angle of approach (Wiren, 1990) may also affect the distance and/or direction components of the ball displacement.

There is less biomechanical research on golf ball striking accuracy than optimal ball displacement or clubhead velocity (Hurrion, 2009; James & Rees, 2008; Karlsen & Nilsson, 2008; Karlsen, Smith, & Nilsson, 2008). This is surprising due to the known importance of chipping and putting accuracy on overall golf performance (Alexander & Kern, 2005; Hellstrom, 2009), but can be explained in part by ball striking accuracy being a more complex variable to measure. In contrast to the swing characteristics of drives and the long irons, successful chipping and putting requires the golf ball to be hit accurately over a relatively short distance. However, success in putting and chipping is still related to the velocity of the ball after impact with the club, and the ball's direction. According to Wiren (1990) these two variables may be affected by grip type, the ability to read the green (aiming), magnitude and direction of clubhead velocity at impact, and point of contact between the ball and club.

Simulation studies utilising 2-D, three segment models with joint torque generators (Sprigings & Mackenzie, 2002b; Sprigings & Neal, 2000) or 3-D, full body models (Nesbit, 2005a) have demonstrated the important role of the wrist in the golf swing. These studies have shown that reducing the radius path of the hands during the downswing (Nesbit, 2005a), increasing wrist torque (Nesbit, 2005a; Sprigings & Mackenzie, 2002a; Sprigings & Neal, 2000), increasing wrist range of motion (Nesbit, 2005a) and delaying relative wrist motion to late in the downswing (Nesbit, 2005a) all increase ball displacement or clubhead velocity.

Ball displacement or clubhead velocity may also be improved by increasing downswing amplitude (Delay, Nougier, Orliaguet, & Coello, 1997), the sequential acceleration of body parts (Fletcher & Hartwell, 2004) and shaft flexibility (Nesbit, 2005a). Large inter-golfer differences have been reported, with Nesbit (2005a) recommending individual golfer analysis of work, power, force and torque to improve clubhead velocity. Differences in reported clubhead velocities in studies were probably a result of the experience and skill of the golfers (novice, high and low handicap players, and professional golfers), the clubs used (drivers, irons, putters), as well as analysis methodologies. Only a few well designed studies (e.g. Robinson, 1994) reported correlations of kinematic or kinetic variables of golf swings to golf performance outcome measures. Correlations with clubhead velocity were reported for total work ($r = 0.431$) (Nesbit, 2005a), handicap ($r = 0.132$) (Nesbit, 2005a), centre of pressure ($r = 0.46 - 0.58$) (Ball & Best, 2007a, 2007b) and ball impact locations higher on the club faces of drivers and 5-irons ($r = 0.65$) (Williams & Sih, 2002).

Due to the highly complex multi-joint motions in golf, kinematic studies have focused on both the clubhead and various body segments (e.g. Egret, et al., 2003; Evans, Refshauge, Adams, & Barrett, 2008; Neal & Wilson, 1985; Zheng, Barrentine, Fleisig, & Andrews, 2008). As a total body sequential movement, it would appear likely that the golf swing requires certain generic coordinative patterns to be effectively performed. Many studies examined the nature of the coordination between the pelvis, upper torso and upper limb during the golf swing (Burden, et al., 1998; Horan, Evans, & Kavanagh, 2011a; Horan, et al., 2010; Myers, et al., 2008), with a particular emphasis on clubhead velocity and ball displacement.

McHardy and Pollard (2005) reviewed studies that used electromyography to examine the amplitude and patterns of muscle activation during the golf swing (e.g. Abernethy, Neal, Moran, & Parker, 1990; Cole & Grimshaw, 2008; Horton, Lindsay, & MacIntosh, 2001; Pink, Jobe, & Perry, 1990; Pink, Perry, & Jobe, 1993). Electromyography studies support the view that skilled golf performance involves sequential muscle activation, with different muscles becoming more active in varying phases (e.g. downswing) (Glazebrook, Curwin, Islam, Kozey, & Stanish, 1994). Although the level of muscle activation depends on the swing phase, relatively high levels of hip and knee (Bechler, Jobe, Pink, Perry, & Ruwe, 1995) and trunk (Pink, et al., 1993; Watkins, Uppal, Perry, Pink, & Dinsay, 1996) muscle activity were observed, with less activation of the muscles around the shoulder girdle/joints (Kao, Pink, Jobe, & Perry, 1995; Pink, et al., 1990). There may also be some differences in muscle activity patterns between golfers of

various standards, with Farber, Smith, Kvitne, Mohr and Shin (2009) reporting more pronator teres muscle activity during the golf swing for professional and low handicap (<4 hcp) than amateur (10-20 hcp) golfers. Whilst many factors influence the force-EMG relationship and therefore our ability to understand the magnitude of muscle activation, further research is required to determine what may constitute the “optimal” sequencing and magnitude of muscle activation for a variety of golf shots.

Using common biomechanical concepts, kinetic determinants of the golf swing include the kinetic-link principle, angular impulse-momentum relationship, summation of forces (including ground reaction forces) and stretch-shorten cycle (Hume, et al., 2005). When a golfer wants to maximise the distance of their drives and long irons, relatively large ground reaction forces and joint torques would appear to be required (Barrentine, Fleisig, Johnson, & Woolley, 1994; Nesbit, 2005a; Worsfold, Smith, & Dyson, 2008). Within-swing changes in ground reaction forces, often referred to as weight transfer, may help in maximizing golf ball displacement (Ball & Best, 2007a, 2007b; Jenkins, 2008; Kawashima, Meshizuka, & Takaeshita, 1999). It has been advocated that during the backswing a greater proportion of the ground reaction forces be on the back foot, with transfer of the ground reaction forces onto the front foot during the downswing/acceleration phase. However, studies by Ball and Best (2007a, 2007b) and the perspective article of Jenkins (2008) suggest more research is needed to determine the role of weight transfer in maximizing golf ball displacement.

According to the kinetic link principle, rapid sequential stretching of the hip, trunk and upper limb muscles during the backswing would allow greater muscular forces and torques to be produced. The difference in hip and trunk angles at the top of the backswing was initially referred to as the X-factor by McLean (1992) with the increase in this angle early in the downswing called the X-factor stretch. Evidence for the benefit of the X-factor and X-factor stretch in increasing clubhead velocity (Cheetham, Martin, Mottram, & St Laurent, 2001; Cole & Grimshaw, 2009; McTeigue, Lamb, Mottram, & Pirozzolo, 1994) or ball displacement remains equivocal (Hellstrom, 2009). The equivalence may reflect methodological differences, with studies attaching markers to the acromium supporting the utilisation of the X-factor and X-factor stretch whereas studies using markers attached slightly medial to the spine showed no benefit (Hellstrom, 2009).

Simulation studies have provided an insight into the role of the kinetic link principle in the golf swing (Nesbit, 2005a, 2005b; Sprigings & Neal, 2000). Delaying the uncocking of the wrists to when the lead arm is about 30° below the horizontal takes advantage of the kinetic link principle which results in a greater summation of angular velocities, and likely more linear clubhead velocity at ball impact and ball displacement (Sprigings & Neal, 2000). Nesbit (2005a) provided a full-body model of the swing, correlations for golf swing mechanical variables and clubhead velocity, and comparisons between four subjects for swing mechanics. These simulation studies have demonstrated that golf swings involve highly coordinated motions (Nesbit, 2005a) and that forces and range of motion are equally important in developing clubhead velocity (Nesbit, 2005b).

Organismic constraints – Golfer characteristics (age, gender, ability, physical condition)

Studies comparing golfers of varying age, gender, ability and fitness may increase our understanding of the determinants of golf ball displacement and accuracy and provide golf coaches with additional information on how to coach a variety of clients. Several studies have reported gender-related differences in golf swing characteristics (Egret, Nicolle, Dujardin, Weber, & Chollet, 2006; Horan, et al., 2010; Zheng, et al., 2008). Egret et al. (2006) reported that although their five female golfers (20.4 \pm 4.2 years; 6.1 \pm 3.4 hcp) seemed to produce a wide swing with larger hip and shoulder joint rotation angles at the top of the backswing than their seven male golfers (23.1 \pm 2.9 years; 6.6 \pm 1.7 hcp), and the male golfers flexed their left knee more during the backswing, neither of these differences showed any significant relationships with clubhead velocity. Horan et al. (2010) reported that 19 male (26 \pm 7 years) skilled golfers (hcp <4) had different lateral and anterior posterior pelvis tilt than their 19 female (25 \pm 7 years) skilled golfers (hcp <4). The results of these two studies suggest that what might be considered optimal swing characteristics for male golfers may not necessarily apply to female golfers.

Age-related differences in golf swing characteristics have also been reported (Wiseman, Chatterjee, Wiseman, & Chatterjee, 1994). For example, older golfers reach their peak downswing force earlier in shots, exhibit a trend toward faster overall velocity or

tempo of shots and have greater changes and variability in applied force (Jagacinski, Greenberg, & Liao, 1997).

Fradkin et al. (2004) established that clubhead velocity was correlated ($r = 0.950$) with golf handicap (clubhead velocity = $4.065 - 0.0214 \times \text{hcp}$) for 45 male golfers (18-80 years, 2-27 hcp). Further, Keogh et al. (2009) found that low handicap golfers ($\text{hcp} = 1.3 \pm 0.5$) had significantly greater 5-iron accuracy and clubhead velocity and were stronger in the golf swing-specific cable woodchop than the high-handicappers ($\text{hcp} = 20.3 \pm 2.4$). Trends for greater bench press strength as well as longer arms (upper and total) and less right hip internal rotation were also observed for the low-handicappers. Several studies examined kinematic and kinetic differences between the swings of low and high handicap golfers. Abernethy et al. (1990) and Neal et al. (1990) compared the upper limb muscle activity and kinematics, respectively, of expert and novice golfers performing pitching wedge, 9-iron and 7-iron shots to targets located 20-m, 40-m and 60-m away. More consistent shoulder and wrist muscle activity patterns and temporal patterning of the different phases of chip shots have been reported for expert than novice golfers (Abernethy, et al., 1990). Lindsay, Mantrop and Vandervoort (2008) reported in a review of literature that skilled golfers exhibit increased force production, efficiency and performance consistency relative to less skilled golfers. However, variability even amongst skilled players indicated that there is more than one ideal swing method. The relative lack of understanding of the role of motor variability in golf lead Bradshaw et al. (2009) to examine differences in biological movement variability of the golf swing in low ($\text{hcp} = 0.3 \pm 0.5$) and high ($\text{hcp} = 20.3 \pm 2.4$) handicap golfers (18-

36 years). Another aspect of variability that has gained little attention is what differentiates good and poor shots in skilled golfers. To address this question, Neal et al. (2007) compared the sequencing and timing of body segment movements between well-timed and mistimed shots (based on each golfer's own judgement and the ball carry distance) for low handicap players. Interestingly, the mistimed and well-timed shots did not differ on any measured variables related to golf swing sequencing and timing, although mistimed shots were associated with a more off-centre ball strike.

Six studies compared golfers of varying ability when putting (Carnahan, 2002; Coello, Delay, Nougier, & Orliaguet, 2000; Delay, et al., 1997; Fairweather, 2002; Paradisis & Rees, 2000; Sim & Kim, 2010). Delay (1997) examined how ten golfers (<5 hcp) and ten non-golfers executed putts as accurately as possible to 1-m, 2-m, 3-m, or 4-m targets. In order to increase clubhead velocity at ball impact with increasing distance of the target, golfers increased the downswing amplitude while maintaining downswing movement time constant. Paradisis and Rees (2000) reported low handicap golfers had a proportionally smaller backswing and follow-through, less vertical displacement during the backswing and achieved maximum clubhead velocity more consistently at ball contact than high handicap golfers when putting a distance of 2.46-m. Five expert golfers achieved higher accuracy with lower impact velocity than five novice golfers when using two putter weights (500 g, 750 g) over three putt distances (1.7-m, 3.25-m, 6-m) (Sim & Kim, 2010). Novices showed symmetrical movements, while experts exhibited more asymmetry in their movements as a result of modulating their relative timing, relative amplitude and velocity of their putting stroke differently from novices.

There was no difference in time-to-contact between the novices and experts (Sim & Kim, 2010). Given the results of these studies, it is unclear whether the optimal way to modulate putt distance is via alterations in backswing length, downswing acceleration or some combination of the two.

Partly as a result of electromyography studies and of the growing acceptance of physical conditioning for golfers (Smith, 2007), a number of cross-sectional (Sell, Tsai, Smoliga, Myers, & Lephart., 2007; Smith, Callister, & Lubans, 2011; Wells, Elmi, & Thomas, 2009) and training (Doan, Newton, Kwon, & Kraemer, 2006; Fletcher & Hartwell, 2004; Hetu, Christie, & Faigenbaum, 1998; Jones, 1999; Lephart, J.M. Smoliga, J.B. Myers, T.C. Sell, & Tsai, 2007; Thompson, 2002; Thompson, Cobb, & Blackwell, 2007) studies have determined the effect of physical conditioning on golf performance. These studies which combined resistance training with balance and/or flexibility training demonstrated small, but positive effects on variables related to ball displacement. Doan et al. (2006) also demonstrated significant increases in distance control in putting (males only) and maintenance of clubface and launch angle consistency when driving. These results indicate that physical conditioning programs can improve variables related to ball displacement while maintaining or even increasing accuracy. It is however difficult to determine what aspect of these mixed conditioning programs contribute most to improvements in golf performance due to the variety of training approaches utilized in each study.

MOTOR LEARNING CONCEPTS AND FINDINGS

Motor control has been defined as “the study of the control of movement in humans” while motor learning has been defined as “the study of how movements are learned, that is how movements are produced differently as a result of practice or experience” (Schmidt and Lee, 2009, p. 4). Researchers in motor learning may utilise a variety of motor control theories to understand how humans initially acquire motor skills or re-learn these skills while rehabilitating from an injury or medical condition (Magill, 2011). Such a view is consistent with Schmidt and Lee (2009, p. 4) who stated that “we see no good justification however for separating the study of motor learning from the study of movement or of motor control in general as this is artificial separation that inhibits the understanding of both issues.” The term motor control has been used in this manuscript when referring to how a golfer controls their movement during specific tasks (e.g. during the golf swing), and the term motor learning when referring to how golfers change aspects of their movements and/or performance over a period of time.

Although the biomechanics of the golf swing has been well described, less is known about how the golf swing is best learnt and how practice conditions can facilitate this process (Farrally, et al., 2003). Using the constraints-led approach of dynamical systems theory as the theoretical viewpoint, Knight (2004) suggested that golfers may achieve a better and more reliable swing by exploring different swing parameters, rather than attempting to perform each swing with absolute invariance i.e. low movement variability. According to dynamical systems theory, movement output (performance) is intrinsically linked to the control strategy employed by the performer (Newell, 1996). In

turn, the coordinative pattern that emerges is a direct consequence of the interaction of the individual (organismic), task and environmental constraints (Newell, 1996) imposed on a particular movement. As the interaction of the constraints that a golf swing is performed under is likely to differ from swing to swing and person to person, the “optimal” coordinative pattern that emerges will exhibit some inter- swing and person variance. What coordinative parameters need to exhibit high degrees of invariance from swing to swing and which benefit from some degree of functional variability are yet to be clearly identified. These questions have led to a number of studies or letters dedicated to understanding the role of movement variability in the golf swing (Bradshaw, et al., 2009; Glazier, 2011). Horan et al. (2011) examined the role of functional variability in body and clubhead motion and inter-segmental coordination in 19 male (mean \pm SD: age = 26 \pm 7 yr, hcp = 0.6 \pm 1.1) and 19 female (age = 25 \pm 7 yr, hcp = 1.3 \pm 1.6) golfers. Both male and female golfers reduced the variability of their hand and clubhead motion nearing ball impact, a finding consistent with dynamical systems theory principles. According to dynamical systems theory, the functional variability in the earlier part of the downswing would allow skilled players to alter their movement patterns during this phase of the swing under different task and environmental constraints while still achieving consistent contact between the clubhead and ball at impact.

Attention during practice

Motor control and learning theories also provide insight into what aspects of performance the golfer should attend to during the practice session to facilitate optimal learning. Amongst golfers and golf professionals, there appears little consensus on

whether optimal learning is facilitated by concentrating on the timing and/or movement of the bodily segments or the clubhead. Such conjecture is not unexpected as the field of motor control and learning has debated these types of issues for many years. Eight studies compared the learning effects of altering the attention of golf practice session (see Table 1). These studies assessed the effect of implicit versus explicit learning (Bright & Freedman, 1998; Hardy, Mullen, & Jones, 1996; Kavussanu, Morris, & Ring, 2009; Masters, 1992; Maxwell, Masters, & Eves, 2000; Poolton, Masters, & Maxwell, 2005) or internal versus external focus of attention (Poolton, Maxwell, Masters, & Raab, 2006; Wulf, Lauterbach, & Toole, 1999) on golf performance.

INSERT TABLE 1 about here

Implicit versus explicit learning

Implicit learning can be viewed as a process that occurs without awareness of what is learned; whereas explicit learning focuses on specific aspects of the task such as required movement patterns (Magill, 2011). The implicit and explicit learning studies of the golf swing used novice golfers. The majority of the studies included several implicit and explicit sub-groups, some of which practiced and/or were tested while performing a dual-task. Dual tasks included tone counting or random number generation while putting and were used to give some insight into the potential of these learning approaches to be impervious to competition-related stresses. These studies varied somewhat on the duration of the acquisition phase (1-5 days) and on the number of days between acquisition to retention and/or transfer testing (same day to three days). Implicit and

explicit learning groups both improved their putting performance, with many of the studies showing no significant difference between any of these combinations of learning approach (Bright & Freedman, 1998; Hardy, et al., 1996; Kavussanu, et al., 2009; Maxwell, et al., 2000). Only two studies demonstrated significantly larger performance improvements from implicit learning. Masters et al. (1992) reported that the implicit learning groups and a non-stressed control group all made significantly greater improvements in the number of putts holed at a retention test one day post acquisition than the explicit groups. Poolton et al. (2005) reported that novice golfers in the explicit group had a significant reduction in the number of 2-m putts holed during the transfer test, whereas the implicit-explicit group significantly improved. Collectively these findings suggest that an implicit learning focus may produce significantly better results than explicit learning, especially when performance is assessed with a dual-task paradigm. This result would appear consistent with the motor learning literature whereby the major benefit of the implicit learning approach is that the improvements in performance are more likely to be retained under stressful or fatiguing situations in which cognitive function may be reduced (Magill, 2011).

Internal versus external focus of attention

An internal focus of attention involves concentrating on aspects of the body's movement patterns, whereas an external focus of attention directs the attention to outside the body (e.g. the clubhead) (Magill, 2011). The two studies (Poolton, et al., 2006; Wulf, et al., 1999) that compared the learning effect of an internal versus external focus of attention on golf performance both involved novice golfers, a one day acquisition phase and had

the retention and/or transfer tests on either the acquisition day or one day later. Wulf et al. (1999) reported that the external focus of attention group was significantly more accurate during the chipping tasks than the internal focus of attention group during retention. Poolton et al. (2006) also reported that the external focus of attention group significantly improved their putting accuracy during transfer testing, while the internal focus of attention group experienced a reduction in performance.

Structure of practice

Six motor learning studies (see Table 2) compared the learning effects of altering the structure of the golf practice session via massed versus distributed practice (Dail & Christina, 2004), block versus random practice (Goodwin & Meeuwsen, 1996; Guadagnoli, Holcomb, & Weber, 1999; Porter & Magill, 2010) as well as errorless versus errorfull practice (Lam, Maxwell, & Masters, 2010; Maxwell, Masters, Kerr, & Weedon, 2001).

INSERT TABLE 2 about here

Massed versus distributed practice

Massed and distributed practice differ based on the number of practice trials within a given time period, with distributed practice allowing greater rest periods within a practice session or involving more frequent shorter, practice sessions (Magill, 2011). Dail and Christina (2004) examined the effect of distributed practice (performing 60 putts of 3.7-m on each of four days) compared to performing all 240 putts on the same day (massed

practice) using a group of 90 novice golfers. At a 28 day retention test (which only involved 15 golfers from each group), the distributed practice group had significantly less 3.7-m putting error than the massed practice group.

Block versus random practice

Traditionally, golfers have used constant (blocked) practice where a golfer uses the same club and practices hitting golf balls to the same target for many consecutive shots before moving on to a different target or club (Farrally, et al., 2003). In contrast, random (variable) practice involves performing different golf shots each swing so that no two consecutive shots involve the same club, target or distance.

Three studies (Goodwin & Meeuwsen, 1996; Guadagnoli, et al., 1999; Porter & Magill, 2010) directly compared the learning benefits of blocked and random practice on golf putting by randomly allocating subjects to blocked or random practice groups. Additionally, Goodwin and Meeuwsen (1996) and Porter and Magill (2010) included combination groups that started their acquisition phase with block practice and finished with variations of random practice. The three studies involving block and random practice differed in the number of acquisition days (1-4), but all involved novice golfers performing putting tasks over three distances, with a retention and/or transfer test a day after acquisition. In general, Goodwin and Meeuwsen (1996) and Porter and Magill (2010) reported no significant difference in putting error between the block and random groups in the retention and transfer tests across all three assessed distances. There were however some exceptions to this generalisation. Specifically, Goodwin and

Meeuwssen (1996) found that during the transfer test, the random and block-random groups performed significantly better than the block group at the longer 6.23-m distance. Similarly, Porter and Magill (2010) found that the combination (Increasing) group performed significantly better than the block and random groups in retention testing and significantly better than the random group in transfer testing. Guadagnoli et al. (1999) reported a significant interaction between skill and type of practice, whereby novice golfers significantly improved their putting accuracy more through block practice, whereas experienced golfers improved significantly more through random practice.

Errorless versus errorfull practice

Errorless and errorfull practice are both examples of block practice (Magill, 2011). Errorless practice involves starting at the shortest distance and working up to the longest distances, whereas errorfull practice starts at the longest distance and finishes at the shortest distance. Errorless practice derives its name from the likelihood that the absolute errors in putting accuracy should be minimised due to starting with the shortest distance; with errorfull practice involving the greatest errors in the initial stage.

Two studies (Lam, et al., 2010; Maxwell, et al., 2001) examined the effect of errorless and errorfull practice on golf putting learning with Maxwell et al. (2001) also including a random group. Both studies involved novice golfers performing putts over eight distances and on the same day performing a retention and/or transfer test. The errorless groups in both studies had significantly greater putting accuracy in the retention and transfer tests than the errorfull and random groups. Maxwell et al. (2001)

also reported that when the retention tests were performed with a secondary task, there were further significant reductions in putting performance for the errorfull and random groups, but no significant changes for the errorless group. The secondary task used was tone counting and required the golfers to count the number of high but not low pitch sounds while putting.

Feedback during practice

Six motor learning studies compared the learning effects of altering the type or frequency of augmented feedback during golf practice session (see Table 3).

INSERT TABLE 3 about here

Golf coaches commonly provide augmented feedback to novice and elite golfers on their performance, with many using video analysis as one part of this process. A number of studies examined how a variety of these feedback approaches may facilitate golf learning. Of relevance to golf, the motor learning literature focuses on the relative benefits of the knowledge of results versus knowledge of performance and on the relative frequency at which the augmented feedback is given. Knowledge of results can be defined as feedback associated with the outcome of a movement (e.g. the landing or resting position of a golf shot), whereas knowledge of performance is defined as feedback relating to the movement patterns employed during the swing (e.g. the relative motion of the hips and shoulders) (Magill, 2011). Within the golf motor learning literature, some have compared the effect of video, verbal, video and/or verbal feedback

to self-guided learning (Guadagnoli, Holcomb, & Davis, 2002; Guadagnoli, McDaniels, Bullard, Tandy, & Holcomb, 2001; Thompson, 1969), with others examining the effect of altering the frequency of such feedback (Ishikura, 2008b; Masters, Maxwell, & Eves, 2009; Smith, Taylor, & Withers, 1997).

Video feedback

Of the studies examining the potential benefits of video feedback, there were differences in the expertise of the golfers (skilled, mid-handicap and novice), amount of acquisition (1-4 days) and time until the retention tests (same day to 14 days post-acquisition). None of the studies reported any significant learning benefits of video (or combined video plus verbal) feedback on direct or proxy measures of accuracy such as clubface angle. Bertram et al. (1969) also reported that video feedback did not significantly improve clubhead velocity, rather that novices significantly improved with verbal feedback whereas skilled golfers improved via self-guided practice. In contrast, two studies involving novice and mid-handicap golfers, respectively demonstrated that video or video and verbal feedback significantly improved driving distance more so than verbal or self-guided practice (Guadagnoli, et al., 2002; Guadagnoli, et al., 2001). Although Guadagnoli et al. (2002) found that mid-handicappers who were given video or video and verbal feedback significantly increased their driving distance two weeks post acquisition, they suffered small decrements in performance at retention 1 (two days post-acquisition). While these results are somewhat mixed, they do suggest that unskilled to moderately skilled golfers can increase driving distance from video

feedback, but such improvements may take a number of weeks to occur and may initially involve a small deterioration in performance.

Knowledge of results versus knowledge of performance

Three studies examined altering aspects of the knowledge of results given to novice golfers during the acquisition phase (Ishikura, 2008b; Masters, et al., 2009; Smith, et al., 1997). All these studies involved one day of putting practice and a retention or transfer test on the acquisition day or one day later. Masters et al. (2009) reported that objective and marginally perceptible (subjective) knowledge of results led to significantly better improvements in putting performance than supraliminal (fully perceptible) KR feedback (where the objective threshold of awareness was ~10-14 longer than the objective and subjective practice conditions). Ishikura (2008) and Smith et al. (1997) both observed that knowledge of results on only a sub-set of all putts produced significantly better learning than knowledge of results on all putts, be it every third putt (Ishikura, 2008) or every putt that was more than 10% away from the target (Smith, et al., 1997), respectively.

Smith et al.'s (1997) golfers who received the transitional information (consisting of a sequential series of seven golfing cues and no knowledge of results) improved significantly more than those who received a knowledge of results, with this especially apparent for shots landing more than 10% from the target. Of interest, the cues were generic and not specifically geared towards addressing any real or perceived issues with a golfer's putting technique or performance.

FURTHER RESEARCH

Biomechanics and motor control researchers may use dynamical systems theory principles to further examine the role of variance and invariance in a range of kinematic, kinetic and electromyographic variables in the golf swing. Such research would highlight the variables that need to be tightly controlled to ensure optimal performance and those that can benefit from functional variability. Experienced golfers and coaches could then integrate the findings of these movement variability studies into their coaching, focusing on providing feedback to their clients on those variables requiring relative invariance. Future studies should continue to examine how alterations to the focus and structure of practice, as well as the type of feedback given during practice alters the learning effect. In particular, these studies should examine how organismic (e.g. age, gender, kinanthropometry) as well as task (e.g. club type) constraints influence the learning effect for measures of accuracy and distance. More studies should be conducted that view learning and performance on an individual-specific basis, rather than comparing groups of golfers as in past research, as individuals differing organismic constraints may alter the “optimal” coordinative patterns and hence how golf coaches may best assist them improve their performance. Specifically, future research should focus on effectiveness of variable versus block practice, internal versus external focus of attention practice and types of feedback across various sub-groups of golfers.

PRACTICAL IMPLICATIONS FOR GOLF PRACTICE

Coaches should be able to use simple video analysis to obtain relevant biomechanical variables such as the radius path of the hands during the downswing, range of motion and timing of wrist motion in the downswing, downswing amplitude, and sequential acceleration of body parts, to help provide feedback to golfers that will improve clubhead velocity and golf ball distance. Coaches should consider the golfer's attention during practice, the structure of practice and the types of feedback provided in practice. Novice golfers may obtain larger and more transferable improvements in putting and chipping accuracy through the use of an external focus rather than internal focus of attention and perhaps from using an implicit rather than explicit learning approach. Golfers may also improve their ability more by distributing their golf practice over several sessions rather than one day per week. Novice golfers should perform block practice starting with short distance putts and increasing this distance through the practice session; whereas more experienced golfers may benefit more from random practice. Gaining knowledge of results from a sub-set of all shots provides better learning than knowledge of results from all shots. Golfing cues focusing on aspects of the swing may also produce significantly better learning than knowledge of results feedback alone.

CONCLUSIONS

Biomechanical studies have improved our understanding of the variables that characterise a successful golf swing. Motor learning studies have improved our understanding of the focus, structure and feedback useful for improving golf

performance. However, it must be acknowledged that the design of both the cross-sectional and experimental longitudinal studies described in this review may impact on the implications of this literature. Specifically, intra- and inter-participant cross-sectional and/or longitudinal studies offer varying degrees of insight into how the golf swing is controlled and learnt. Regardless of the design, the inclusion of more advanced measures of coordination such as continuous relative phase and vector coding in these studies may further contribute to our understanding of how to improve golf performance. If such studies utilise ecologically valid approaches, they will further improve our theoretical knowledge of golf performance determinants and increase our ability to translate this knowledge to improving golf performance.

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LIST OF TABLES

Table 1: Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the focus of the practice.

Table 2: Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the structure of the practice.

Table 3: Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the feedback given during practice.

LIST OF FIGURES

None.

- 1 **Table 1:** Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the **attention**
 2 **during practice.**

Study	Subjects	Intervention	Outcome measure methods	Accuracy (% Change)
Bright and Freedman (1998)	35 females and 13 male novice golfers with no golf in previous year. No age or golf hcp given.	<i>Implicit and Implicit Dual Task</i> (no instructions while doing dual task of random letter generation) and <i>Explicit</i> (specific written instructions) groups performed 4 sessions of 40 putts of 2-m.	Same day testing session of 40 putts of 2-m. <i>Implicit Dual Task</i> group assessed while doing random letter generation. Accuracy = number of 2-m putts holed.	All groups significantly increased the number of putts holed from first session to testing session: <i>Implicit</i> +228%; <i>Explicit</i> +165%; <i>Implicit Dual Task</i> +120%.
Hardy et al. (1996)	16 males and 16 females novice golfers, 21 yrs. No golf hcp given.	<i>Implicit and Implicit Dual Task</i> (no instructions while doing dual task of random letter generation), <i>Explicit</i> (specific written instructions) and <i>Control</i> (no written instructions or dual task) groups performed 8 blocks of 50 trials of 1.5-m putts over 4 learning sessions on consecutive days.	Testing session 1 day after 4 learning sessions, involving 2 blocks of 50 putts of 1.5-m. <i>Implicit Dual Task</i> group assessed while doing random number generation. Accuracy = number of 1.5-m putts holed.	All groups significantly increased the number of putts holed from first learning session to testing session: <i>Implicit</i> +80%; <i>Explicit</i> +95%; <i>Implicit Dual Task</i> +100%; <i>Control</i> +41%.
Kavussanu et al. (2009)	39 male and 63 female novice golfers. No age or golf hcp given.	Explicit specific instructions were given to all groups (<i>Mastery</i> , <i>Performance</i> or <i>Performance-Avoidance</i>), but no instructions related to task goal of the putting task which consisted of 4 blocks of 10 putts of 2-m.	Same day transfer task. Accuracy = putting radial error of 20 3-m putts.	All groups significantly reduced radial error during learning phases. No significant difference between <i>Mastery</i> (33-cm), <i>Performance</i> (30.5-cm) or <i>Performance-Avoidance</i> (32.5-cm) in radial error during transfer.

Masters et al. (1992)	40 novice golfers, 27 yrs. No gender or golf hcp given.	<i>Implicit and Implicit Control (no instructions while doing dual task of random letter generation), Explicit (specific written instructions) as well as Stressed Control and Non-Stressed Control (no instructions) groups performed 8 blocks of 50 trials of 1.5-m putts over 4 learning sessions on 4 consecutive days.</i>	Testing session 1 day after learning sessions, involving 2 blocks of 50 putts of 1.5-m. <i>Implicit Control and Stressed Control groups</i> assessed while doing random letter generation. Accuracy = number of 1.5-m putts holed.	<i>Non-stressed control (+21%), Implicit (+17%) and Implicit control (+38%) groups significantly improved from Acquisition 4 to Test; whereas Stress control (-8%) and Explicit (-6%) had non-significant reductions in putts holed.</i>
Maxwell et al. (2000)	27 novice golfers, 23 ±2 yrs. No gender or golf hcp given.	<i>Implicit and Implicit Control (no instructions and dual task of tone counting) and Explicit (specific written instructions) groups practiced 12 blocks of 50 putts of 3-m across 5 days.</i>	Retention test of 50 putts 3 days later. <i>Implicit Control</i> group assessed while doing tone counting. Accuracy = number of 3-m putts holed.	All groups significantly improved number of putts holed: <i>Explicit +114%; Implicit +300%; Implicit control 318%.</i>
Poolton et al. (2005)	11 male and 24 female novice golfers, 21 ±1 yrs. No golf hcp given.	<i>Explicit (specific written instructions) or Implicit-Explicit (no instructions followed by specific written instructions) groups performed 8 blocks of 50 trials 0.25-4m putts.</i>	Retention and transfer blocks of 50 putts of 2-m. Transfer involved secondary task of tone counting. Accuracy = number of 2-m putts holed.	No significant difference (12%) in putts holed by both groups in retention tests. Transfer test revealed a significant effect where <i>Explicit</i> reduced (-13%) while <i>Implicit-Explicit</i> holed more (+13%) putts.
Poolton et al. (2006)	7 male and 23 female novice golfers, 24 ±6 yrs. No golf hcp given.	<i>Internal (hand) or External (clubhead) focus of attention groups performed 10 blocks of 30 putts over 2-m.</i>	Retention and transfer blocks of 30 putts of 2-m on same day as learning. Transfer involved secondary task of tone counting. Accuracy = number of 2-m putts holed.	<i>Internal (+70%) and External (+67%) significantly improved number of putts holed compared to Retention. Transfer test revealed a significant effect where Internal reduced (-24%) while External holed more (+20%) putts from retention to transfer block.</i>
Wulf et al. (1999)	13 male and 9 female novice golfers, 21-29 yrs. No golf hcp given.	<i>Internal (arms) or External (clubhead) focus of attention groups performed 8 blocks of 10 chips with a 9-iron over 15-m in session 1.</i>	One day later retention assessed with 3 blocks of 10 chips with a 9-iron over 15-m. Accuracy = landing position of ball relative to hole via concentric circles.	<i>Internal (+62%) and External (+24%) significantly improved accuracy of chips from session 1 (Blocks 1-2) to retention session. External (21.2) had significantly improved accuracy than Internal (13.8) at retention session.</i>

4 **Table 2:** Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the structure of
5 the practice.

Study	Subjects	Intervention	Outcome measure methods	Accuracy (% Change)
Dail and Christina (2004)	25 male and 65 female novice golfers, 22.3 yrs. No golf hcp given.	<i>Massed Practice</i> (240 putts in one day) and <i>Distributed Practice</i> (60 putts on each of 4 days) groups of 3.7-m putts.	1, 7 and 28 day Retention test. Accuracy = putting errors score (distance to hole).	At 28 day retention, error score for <i>Massed Practice</i> (35.3-cm) significantly more than <i>Distributed Practice</i> (27.8-cm). Only 15 in each group did retention tests.
Goodwin and Meeuwssen (1996)	30 novice females, 26.2 ±8.0 yrs. No golf hcp given.	<i>Blocked, Random or Block-Random</i> practice over 2 days, each day involving 99 putts (33 each from 2.43-m, 3.95-m and 5.47-m).	1 day later Retention and Transfer test. Retention test of 10 putts of 2.43-m, 3.95-m and 5.47-m in a blocked order. Transfer test 1 day later of 10 putts of 1.67-m, 3.19-m and 6.23-m in blocked order. Accuracy = absolute error distance from target line.	Retention: No significant difference in absolute error for all three groups. Transfer: No significant difference between the three groups at 1.67 and 3.19-m. <i>Random</i> (0.60-m) and <i>Block-Random</i> (0.70-m) had significantly less absolute error than <i>Block</i> (0.86-m) for 6.23-m putts.
Guadagnoli et al. (1999)	30 males, 23.1 yrs and 28 females, 21.9 yrs. Subdivided into novice and experienced putters. No golf hcp given.	<i>Blocked or Random Practice</i> involving 36 putts on each of 4 days of 1.8-m, 3.1-m and 4.9-m.	1 day later Retention test of 12 putts of 1.8-m, 3.1-m and 4.9-m in a random order. Accuracy = 5 point scale based on ball's final position.	Significant improvement in putting accuracy for <i>Experienced Random</i> (+29%) and <i>Novice Block</i> (+51%) but not for <i>Novice Random</i> (+6%) or <i>Experienced Block</i> (+8%) practice groups.
Lam et al. (2010)	22 male and 14 female novice golfers, 21 ±2 yrs. No golf hcp given.	<i>Errorless</i> (0.25-4-m) and <i>Errorfull</i> (4-0.25-m) putting of 8 blocks of 50 putts.	Same day retention test of 2 blocks of 50 putts of 2-m and transfer test of 2 blocks of 50 putts of 2-m with a different putter. Accuracy = 5 point scale based on ball's final position.	<i>Errorless</i> (81.2%) had significantly better putting accuracy than <i>Errorfull</i> (72.2%) during Retention and Transfer tests.

Maxwell et al. (2001)	27 novice golfers, 23 ±2 yrs. No gender or golf hcp given.	<i>Errorless</i> (0.25-2-m), <i>Errorfull</i> (2-0.25-m) and <i>Random</i> putting of 8 blocks of 50 putts.	Same day retention test of 3 blocks of 50 putts. 1st block 2-m retention test, 2nd block 2-m retention test with secondary task. 3rd block 3-m transfer test. Accuracy = number of putts holed.	<i>Errorless</i> (41.4) significantly more putts holed in Retention than <i>Errorfull</i> (36.6) and <i>Random</i> (34.6). <i>Errorless</i> (41.6) significantly more putts holed in Retention with Secondary Task than <i>Errorfull</i> (32.8) and <i>Random</i> (30.9). <i>Errorfull</i> (36.6) and <i>Random</i> (34.6) performed significantly worse in Retention test with Secondary Task than Retention test, but <i>Errorless</i> (41.4) showed no significant change. <i>Errorless</i> (35.2) had significantly more putts holed in Transfer Task than <i>Errorfull</i> (32.0) and <i>Random</i> (28.9). Retention: <i>Increasing</i> significantly better accuracy than <i>Random</i> (+26%) and <i>Blocked</i> (27%). Transfer: <i>Increasing</i> significantly better than <i>Random</i> (+20%) but not <i>Blocked</i> (11%).
Porter and Magill (2010)	18 male and 42 female novice golfers. No age or golf hcp given.	<i>Blocked</i> , <i>Random</i> or <i>Increasing</i> practice group involving 81 putts from 0.9-m to 1.82-m.	Retention test 1 day later of 20 putts of 0.9 and 1.82-m. Transfer test 1 day later of 20 putts of 1.52-m and 1.6-m. Accuracy = position of ball in concentric circles	

7 **Table 3:** Summary of studies examining changes in golf putting and/or chipping performance as a result of varying the feedback
 8 given during practice.

Study	Subjects	Feedback intervention	Outcome measure methods	Accuracy / Distance / Velocity (% change)
Bertram et al. (2007)	12 males and 12 female novice golfers, 27 yrs. No golf hcp given.	<i>Verbal</i> feedback, <i>Video+Verbal</i> (with feedback of performance) or <i>Self-Guided</i> groups performing 30 shots with a 6-iron.	Same day retention test with clubhead velocity and clubface angle measured by swing monitor across 12 shots with a 6-iron.	Clubface angle: Significant decrease for <i>Verbal</i> (-140%). Significant increase for <i>Video+Verbal</i> (+70%). No significant change for <i>Self-Guided</i> (+2%). Clubface velocity: Significant increase for <i>Verbal</i> (+9%). No significant change for <i>Video+Verbal</i> (-2%) and <i>Self-Guided</i> (+2%).
Bertram et al. (2007)	12 males and 12 female skilled golfers, 27 yrs, hcp = 0-10.	<i>Verbal</i> feedback, <i>Video+Verbal</i> (with feedback of performance) or <i>Self-Guided</i> groups performing 30 shots with a 6-iron.	Same day retention test with clubhead velocity and clubface angle measured by swing monitor across 12 shots with a 6-iron.	Clubface angle: No significant change for any group (no data reported). Clubface velocity: Significant increase for <i>Self-Guided</i> (+4%). No significant change for <i>Verbal</i> (+1%) and <i>Video+Verbal</i> (-1%).
Guadagnoli et al. (2001)	45 novice golfers, age 21-36 yrs. No gender or golf hcp given.	<i>Video</i> , <i>Verbal</i> and <i>Video+verbal</i> feedback (with feedback of performance) groups practiced 7-iron to target line extending 200-m for 4 sessions of 100 shots, each separated by 1 day.	Retention test one day after practice involving 15 shots with 7-iron to target line extending 200-m. Accuracy = total distance and error distance.	Error distance: No significant change for <i>Video</i> (+4%), <i>Video+Verbal</i> (+2%) or <i>Verbal</i> (0%). Total distance: Increase for <i>Video</i> (+31%) and <i>Video+Verbal</i> (+37%) was significantly greater than for <i>Verbal</i> (+6%).
Guadagnoli et al. (2002)	30 golfers, 29-50 yrs, hcp 7-16. No gender given.	<i>Video</i> , <i>Verbal</i> (with feedback of performance) and <i>Self-guided</i> groups practiced 7-iron to target line extending 185-m for 90 minutes for 4 sessions, each separated by 1 day.	Retention tests two and 14 days after practice involving 15 shots with 7-iron to target line extending 185-m. Accuracy = total distance and error distance.	Error distance: No significant change for <i>Video</i> (-9%), <i>Verbal</i> (-18%) or <i>Self-guided</i> (+11%) at Retention 2. Total distance: Significant increase for <i>Video</i> (+9%) and no significant change for <i>Verbal</i> (+5%) and <i>Self-guided</i> (-2%) at Retention 2.

Ishikura (2008)	19 male and 15 female novice golfers, 21 ±1 yrs. No golf hcp given.	Knowledge of results given after every putt (<i>KR100</i>) or after every third (<i>KR33</i>) of 60 putts of 3.5-m.	10 min later (Retention 1) and 24 hr later (Retention 2) tests involving 5 putts of 3.5-m. Accuracy = absolute distance from 3.5-m target line.	Absolute error: <i>KR33</i> (20-cm) significantly less than <i>KR100</i> (42-cm) during Retention 2.
Masters et al. (2009)	48 novice golfers, 20 yrs. No gender or golf hcp given.	<i>Subjective</i> , <i>Objective</i> or <i>Supraliminal</i> feedback of 5 blocks of 100 putts of 2.7-m.	Same day transfer test of 50 putts that ended in target circle.	Accuracy: No significant difference between <i>Subjective</i> (43), <i>Supraliminal</i> (41) and <i>Objective</i> (33) during Retention. Significant reduction from Block 5 to Retention for <i>Supraliminal</i> (-17%) and significantly improved for <i>Subjective</i> (+79%) and <i>Objective</i> (+320%).
Smith et al. (1997)	24 male and 24 female novice golfers, 22 ±3 yrs. No golf hcp given.	Knowledge of results (<i>KR0%</i> , <i>KR5%</i> and <i>KR10%</i>) was given. All groups also performed with or without knowledge of performance information for 5 blocks of 10 chips of 10-m.	Retention assessed one day later in 10 chips. Accuracy = variable error of landing position of chip relative to hole.	<i>KR10%</i> (2.41-m) significantly less variable error than <i>KR5%</i> (2.70-m) and <i>KR0%</i> (2.91-m) group. All KR groups (3.04-m) had significantly more variable error than Transitional feedback (2.32-m).

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