Gaze Behavior in Golf Putting – A Review

Abstract

Gaze behavior in general, and the *quiet eye* (QE) in particular, are integral to the performance of closed, self-paced motor tasks. This review examines the relationship between the QE (and a number of other gaze properties) and golf-putting performance. An analysis of 26 studies revealed conflicting results. For example, while some studies showed that longer QE durations (QEDs) (e.g., 2-3 sec) characterize expert golfers, successful putting performance, and improved learning, several other studies reported no relationship between QEDs and putting performance. Four out of six studies (66.7%) showed that experts have longer QEDs on the ball, five out of eight studies (62.5%) showed longer QEDs in successful versus unsuccessful putts, four out of five studies (80%) found that QE may explain 14-43% of the variance in performance, and five out of six studies (83.3%) showed that QE can be trained and will lead to improved putting performance. We discuss some inconsistencies in the reviewed data, and outline a number of methodological concerns and research limitations associated with the reviewed studies, including (a) a lack of studies on different QE locations, (b) a lack of studies that directly manipulate QEDs, and (c) the failure of most studies to calculate QED for each phase of the putt. We also propose a number of applications for practitioners who teach golfers how to putt.

Keywords: **expert performance, visual attention, sport, quiet eye, visuomotor control**

Closed, self-paced motor tasks are those taking place in a relatively stable and predictable environment, where there is adequate time to prepare for their execution (Lidor, 2007; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018). Examples of closed, self-paced motor tasks are shooting in archery, free-throw shooting in basketball, dart throwing, and golf putting. In these tasks, performers can plan their actions in advance and activate task-enhancing physical and psychological routines/techniques. During the past 25 years a training regimen, termed *visual attention training*, has been developed specifically to assist athletes in performing closed, self-paced motor tasks.

All sports require optimal control of physical actions, and vision is essential in providing the performer (i.e., the athlete) with the relevant information required by the movement systems so that he or she can attain a high level of achievement (Vickers, 2016). According to Vickers (2016), "Vision and focus of attention play a critically important role as the ability to direct the gaze to optimal areas in the playing environment, at the appropriate time, is central to success in all sports" (p. 1). Therefore, visual attention training should be integrated into the physical and psychological training of athletes who aim at improving their skill level in closed, self-paced tasks.

In the current article, we review a series of studies (*N* = 26) focusing on gaze behavior in one closed, self-paced task – putting in golf (a golf stroke performed on a putting green that is meant to connect the putter head with the ball and cause it to roll into or near the hole). In golf, compared to other sports where athletes are required to hit a moving object (e.g., baseball, hockey, tennis), the golfer is asked to hit a stationary object – a small ball (mass = no more than 45.93 grams; diameter = not less than 42.67 mm) – short as well as long distances. In

putting, the distance between the golfer and the hole is relatively short, and therefore he or she can often see the hole and can follow the path of the ball towards the hole. When the hole cannot be seen (due to an uphill slope, for example), the golfer can still choose a spot on the green at which to aim. In other strokes in golf (e.g., the swing), it is more difficult to use vision the same way as in putting, due to the long distance between the position of the golfer and the target (the hole). While performing a swing, for example, the golfer should develop peripheral awareness (the ability to quickly and accurately identify objects in his or her peripheral vision; see Wilson & Falkel, 2004).

One perception-action variable that is important for the enhancement of the performance of closed, self-paced motor tasks, such as putting in golf, is the *quiet eye* (QE). QE has been defined as the final fixation or tracking gaze that is directed at a specific location or object in the task space within 3° of the visual angle (or less) for a minimum of 100 msec (Vickers, 2007, 2016). The onset of the QE occurs before the initiation of the critical final movement of the task, and the offset occurs when the gaze deviates from this specific location by more than 3° of the visual angle for at least 100 msec. Therefore, the QE can last beyond the final movement of the task. It has been reported that the QE of elite performers is significantly longer than that of near-elite performers or beginners (e.g., Vickers, 2007). More recently, with the advancement of eye-tracking technology, a number of researchers have narrowed the visual field from 3° to 1-1.5° (e.g., Klostermann, Kredel, & Hossner, 2018; Vine, Lee, Walters-Symons, & Wilson, 2017).

Those who have achieved a high level of proficiency in sport may have learned to fixate or track critical cues or locations earlier and for longer durations (Vickers, 2016). Indeed, long

QE durations (QEDs) have been shown to be related to expert performance in a number of sport skills, among them the basketball free-throw shot (Harle & Vickers, 2001), dart throwing (Vickers, Rodrigues, & Edworthy, 2000), goaltending in ice hockey (Panchuk & Vickers, 2006), rifle shooting (Janelle et al., 2000), and hitting the ball with the cue in billiards (Williams, Singer, & Frehlich, 2002).

In one meta-analysis review, it was reported that expert performers maintained QEDs that are longer by approximately 62% compared to less-skilled performers (Mann, Williams, Ward, & Janelle, 2007). A more recent meta-analysis review corroborated this by finding a large mean effect for differences in QED between experts and novices, as well as a moderate effect for QED differences for successful versus unsuccessful performances (Lebeau et al., 2016). Indeed, QED differences between successful and unsuccessful performances were found in simulated archery (Behan & Wilson, 2008), golf putting (Wilson & Pearcy, 2009), elite shotgun shooting (Causer, Bennett, Holmes, Janelle, & Williams, 2010), goaltending in ice hockey (Panchuk, Vickers, & Hopkins, 2017), and billiards (Williams et al., 2002).

One possible explanation for the positive effect of longer QEDs on performance (which stems from the information-processing framework) is that the QE allows for a pre-programming period, during which visual information is cognitively processed to meet the demands of the task and to produce the best movement (Vickers, 2009). Williams et al. (2002) showed an increase in QED with increased task complexity, and therefore provided support for the pre-programming hypothesis. During putting, this pre-programming period occurs prior to the initiation of the backswing, and allows the golfer to calculate the angle and speed needed for a successful putt. However, as Gonzalez and associates (Gonzalez et al., 2017) suggested, this

explanation may be a simplification of more complex processes. For example, it is also possible that longer QEDs improve the online control of movement, rather than – or in addition to – the period of pre-programming (Causer, Hayes, Hooper, & Bennet, 2017). During putting, online control refers to the period of time between the initiation of the backstroke and the time of the club-ball contact. During this time, longer QEDs allow for fine-tuning the pre-programmed club face angle and velocity. Another hypothesis – the inhibition hypothesis – suggests that longer QEDs allow the inhibition of less than optimal movement variants, so that only the optimal movement variant is used in both the preparation and the online execution (Klostermann, Kredel, & Hossner, 2014). Lastly, pupil dilation – as a measure of cognitive effort – was found to be higher during a putt compared to baseline (Campbell et al., 2019), suggesting that the possible explanations for the benefits of the QE may indeed lie within the cognitive domain.

Optometrists, golf consultants, and golf coaches have recommended that golfers devote time in their training to practicing vision skills, so that they can better control their actions on the golf course (see Farnsworth, 1997; Wilson & Falkel, 2004). However, in order to plan appropriate training regimens aimed at improving gaze behavior in athletes who perform closed, self-paced motor tasks, relevant information on different aspects of how athletes gaze during the execution of such tasks should be obtained by those professionals who regularly work with them. Among these professionals are sport psychology consultants, performance psychologists, and coaches. Having increased knowledge about QE will help them determine whether it would be beneficial to integrate such training into their athletes' schedule. It has been argued that the single most important determinant of earnings in professional golf is putting ability, and therefore golfers (i.e., professional golfers) should keep practicing their

putting , since improvement in this skill remains the quickest way to increase their earnings (Alexander & Kern, 2005). We assume that relevant information about different aspects of QE will help these professionals to better plan their short- and long-term training programs, as well as to appropriately assess the contribution of these programs to the improvement of the closed, self-paced motor task (i.e., the putt). In addition, information obtained on the gaze behavior of athletes should be evidence-based. The implementation of evidence-based knowledge regarding gaze behavior in golf putting has the potential to assist the golfer in holing more putts and improving his or her competitive performance.

Based on the reviewed studies selected for this article, we (a) discuss evidence-based knowledge about putting and gaze behavior – among the issues discussed are gaze behavior in both beginning and skilled golfers, gaze behavior in successful/unsuccessful putts, and slope and gaze behavior; (b) discuss the methodological concerns and research limitations associated with the reviewed studies; (c) propose a number of ideas for additional studies of gaze behavior in golf putting; and (d) present several practical implications for those professionals who work with golfers.

Literature Search

This narrative review was conducted using an electronic search of the literature in two databases – Scopus and EBSCO Discovery Service, by using the following search terms: *golf* OR *golf putting* OR *putting* AND *gaze* OR *quiet eye* OR *gaze behavior*. The search was limited to peer-reviewed articles published in the English language. Only studies where gaze was measured were included. Studies in which gaze instructions were given but gaze was not recorded were excluded. In addition, a more specific search was conducted in Google Scholar

for the term *quiet eye* in the title, as well as for one of the following words in the title: *golf, golfers, putting,* or *training*. In addition, lists of references from relevant studies were scanned for further sources. The initial search was performed in November, 2018, a second search was conducted in February, 2019, and a final search was conducted in May, 2019.

A flow diagram of the study selection process based on the PRISMA Statement (Liberati et al., 2009) is presented in Figure 1. The electronic search yielded 25 relevant studies (Binsch, Oudejans, Bakker, & Savelsbeg, 2009; Campbell & Moran, 2014; Campbell et al., 2019; Causer et al., 2017; Frank, Land, & Schack, 2016; Fulton, Ertz, Rohler, Fontana, & Mack, 2014; Klostermann et al., 2014; Mann, Coombes, Mousseau, & Janelle, 2011; Moore, Vine, Cooke, Ring, & Wilson, 2012; Moore, Vine, Freeman, & Wilson, 2013; Moore, Vine, Wilson, & Freeman, 2012; Moore, Wilson, Vine, Coussens, & Freeman, 2013; Panchuk, Farrow, & Meyer, 2014; van Lier, Kamp, & Savelsbergh, 2010; Vickers, 1992; Vine, Lee, Moore, & Wilson, 2013; Vine et al., 2017; Vine, Moore, Cooke, Ring, & Wilson, 2013; Vine, Moore, & Wilson, 2011; Vine & Wilson, 2010; Walters-Symons, Wilson, Klostermann, & Vine, 2018; Walters-Symons, Wilson, & Vine, 2017; Wilson & Pearcy, 2009; Wood, Vine, & Wilson, 2013; Ziv & Lidor, 2015). A manual search of the reference lists of the 25 studies revealed one more relevant article (Naito, Kato, & Fukuda, 2004), for a total of 26 articles that were included in our review.

All articles were reviewed independently by both authors to ensure that they met the selection criteria set for the current review. A full agreement was reached between the authors as to the inclusion of the reviewed studies.

Insert Figure 1 about here

Results

Results are presented for seven categories: (a) the effects of skill level on gaze behavior; (b) QE and performance; (c) slope and gaze behavior; (d) focus of attention and QE; (e) QE – pre-programming or online control?; (f) QE training; and (g) psychological manipulations. These seven categories were selected since they reflect the main themes that were examined in the reviewed studies. Most of the studies were placed in only one category, according to their main focus. Only a few were included in more than one category. A summary of the studies (*N* = 26) is presented in Table 1 (the order of the studies is by year of publication).

Insert Table 1 about here

In general, the level of expertise of the participants in the reviewed studies ranged from beginning learners to expert golfers. Putting distance ranged from 1.5 m to 5 m, but in most studies the distance was 2-3 m. In most of the studies in which QE was measured, QE location was the golf ball, with two studies defining the location as the ball or the putter head (van Lier et al., 2010; Ziv & Lidor, 2015). Only one study defined QE location as the top or back of ball, the putter head, or the area adjacent to the ball (Wilson & Pearcy, 2009). Recording of eye movements was performed using different types of mobile eye trackers, such as the Applied Science Laboratories mobile eye tracker (ASL; Bedford, MA, USA) or the EyeSeeCam mobile eye tracker (EyeSeeTec GmbH, Fürstenfeldbruck, Germany). Performance was measured by either counting the holed putts or calculating the mean distance from the hole. Lastly, the number of putts performed in each study varied greatly – from fewer than 10 to more than 300 putts.

The Effects of Skill Level on Gaze Behavior

Six studies that examined the effects of skill level on gaze behavior were found (Campbell et al., 2019; Klostermann et al., 2014; Mann et al., 2011; Naito et al., 2004; Vickers,

1992; Walters-Symons et al., 2017). The relationship between gaze behavior and putting performance was originally examined by Vickers in a study on 12 tournament golf players (Vickers, 1992). In this seminal study, Vickers reported that during the putt, compared to high-handicap (10-16) golfers, low-handicap (0-8) golfers made a smaller number of saccades, made fewer fixations on the surface and on the golf club, and had longer fixations on the ball and the target. Since the term “quiet eye” had not yet been defined, data on QE were not available in this study.

A number of subsequent studies replicated Vickers' (1992) findings, this time with the QE defined (e.g., Klostermann et al., 2014; Mann et al., 2011; Walters-Symons et al., 2017). Klostermann et al. (2014) found longer QEDs and better performance in experts (mean handicap = 6) compared to near-experts (mean handicap = 25.6) when putting from a distance of 3 m. In addition, larger negative correlations between QE offset and radial error and between QED and radial error were found in experts but not in near-experts (in which correlation coefficients were not statistically different than zero), suggesting that a late QE offset and longer QEDs benefited only the experts. Mann et al. (2011) reported that, compared to near-expert golfers (handicap = 10-12), expert golfers (handicap = 0-2) demonstrated significantly better putting performances and longer QEDs. Walters-Symons et al. (2017) reported significantly longer QEDs in expert golfers (mean handicap = 5.7) compared to novice golfers (no golfing experience).

In contrast to the findings that emerged from the above-mentioned studies, one study found no differences in QEDs between skilled (mean handicap = 7) and less-skilled (mean handicap = 7) participants (Campbell et al., 2019). In both groups, pupil dilation increased by

over 30% during the putt when compared to baseline and peak pupil dilation coinciding with QE onset, suggesting that cognitive effort is elevated during the period of the QE. Lastly, Naito and colleagues (2004) found that beginning golfers who rarely played golf tend to fixate on the ball for more time than expert golfers. The gaze behavior of the expert golfers involved fixating on the golf club prior to the backswing and the location on the green where the club was located during the swing, and shifting the gaze to approximately 4 cm ahead of the ball location just before contact. When the beginning golfers adopted a similar shift in gaze prior to ball contact, their putting performances improved. The authors of this study suggested that peripheral vision may play a role in expert golfers' putting performances. However, only three expert golfers participated in this study.

In summary, four out of the six studies (66.7%) indicated that expert golfers show longer QEDs on the ball compared to novices, with the fourth study showing the opposite. Therefore, while data are relatively scarce, it appears that longer QE directed at the ball is important for expert putting performance. However, it is possible that QE directed at the hole can be just as beneficial as QE directed at the ball. Additional studies that compare experts and novices using different QE locations in various putting distances and conditions are warranted.

QE and Performance

Sixteen studies examining the relationship between gaze and putting performance were found (Causer et al., 2017; Fulton et al., 2014; Mann et al., 2011; Moore, Vine, Cooke, et al., 2012; Moore, Vine, et al., 2013; Moore, Wilson, et al., 2013; Panchuk et al., 2014; van Lier et al., 2010; Vickers, 1992; Vine et al., 2011; Vine, Lee, et al., 2013; Vine & Wilson, 2010; Walters-Symons et al., 2017,2018; Wilson & Pearcy, 2009; Wood et al., 2013). These studies included a

comparison of successful and unsuccessful putts, correlation and regression analyses of QE and performance, or mediation analyses.

In one study, it was found that longer QEDs (mean 1,693 msec) accompanied holed putts, while shorter QEDs (mean 1,231 msec) accompanied missed putts (Wilson & Pearcy, 2009). Longer QEDs in successful putting performances were also reported by Panchuk et al. (2014) and Causer et al. (2017), who compared QEDs after calculating a median split of radial error. In addition, Vickers (1992) found an increased probability of hitting the hole with a steady fixation on the ball that lasted longer than 1,700 msec during the swing phase. Lastly, Vine, Lee, et al. (2013) calculated and compared QED as QE-pre (i.e., until initiation of the backswing), QE-online (i.e., from initiation of the backswing until ball contact), and QE-dwell (from ball contact until the gaze drifted off the green to the place where the ball was now located). In their study, experienced golfers participated in a shootout (i.e., holing as many consecutive putts until a miss) under pressure. Total QED, QE-online duration, and QE-dwell duration were higher in the first holed putts and the penultimate putts compared to the last (missed) putt. QE-pre was similar between putts.

In contrast to these studies, one study using a single-subject analysis found longer QEDs in holed putts compared to missed putts in five of 10 expert participants and in six of 10 near-expert participants (Mann et al., 2011). In another study, no differences in QEDs were reported (van Lier et al., 2010). In this study the participants, who were teaching golf professionals (mean handicap = 3.4), were divided into a successful and an unsuccessful group, based on the percentage of holed putts (>.62 and <.40 for the successful and unsuccessful groups,

respectively). Based on this division, the last fixation on the ball was similar in the successful group (1,100-1,300 msec) and the unsuccessful group (1,500-2,100 msec).

One possible explanation for the inconsistency in the findings on successful and unsuccessful putts was provided by Walters-Symons et al. (2017). In their study, expert and novice golfers putted until five hits and five misses were recorded. QEDs were calculated for random pairs of putts, miss-hit pairs of putts (a hit after a miss), and miss-miss pairs of putts (a miss after a miss). While no differences in QED were indicated in the random pairs, QED was longer for a hit after a preceding miss and shorter for a miss after a preceding miss. These findings suggest that it might not be enough to randomly compare pairs of hits and misses or to randomly average hits and misses, since the shot order influences QED. Indeed, longer QEDs allowed participants to recover from a previous miss – whether they were novice or expert golfers.

While the putting success order can be one explanation for these mixed results, another possible explanation may be the distance of the putt. For example, participants in van Lier et al.'s (2010) study putted from 1.8 m, and no differences in QE were found between successful and unsuccessful putts. In contrast, participants in the Wilson and Pearcy (2009) study putted from 3 m, and a difference in QE was found. Thus, it is possible that longer QEDs become important only when the difficulty of the putt passes a certain threshold. Other studies support this explanation by showing that QE increases with task complexity (e.g., Walters-Symons et al., 2018; Williams et al., 2002).

In a number of studies the relationship between QE and performance was measured using correlations, regression, or mediation analyses. Vine and Wilson (2010) and Vine et al.

(2011) found that QE predicted 36% and 43% of the variance in putting performance, respectively. A more modest value (14%) was found by Moore et al. (2013), and Fulton et al. (2014) reported a correlation of .48 (i.e., QE explains 23% of variance in performance). Finally, in several combinations of target size, putting distance, and putter size, Walters-Symons et al. (2018) found mostly weak correlations between QE and performance. A moderate correlation (r = .39) was found in one condition (large target, long length, small putter), suggesting that increased QED was related to larger radial error.

Mediation analyses were conducted in several studies as well. In one study (Moore, Vine, Cooke, et al., 2012), mediation analysis showed that experimental group affiliation (QE-trained versus technically trained in which the QE-trained group had longer QEDs) predicted putting performance through reduced y-axis acceleration of the golf club, but not when tested under increased anxiety. In a follow-up study with a subset of the participants from the abovementioned study, Moore, Vine et al. (2013) found that group affiliation (and hence, indirectly, QED) predicted performance under heightened anxiety through cognitive appraisal of the task (the ratio of perceived demands divided by perceived resources). In contrast to these studies, Moore, Wilson, et al. (2013) failed to find processes that mediate the relationship between experimental group affiliation (manipulated by a sense of threat or challenge) and performance.

In summary, five out of eight studies (62.5%) that examined successful versus unsuccessful putts found longer QEDs in successful versus unsuccessful putts (Causer et al., 2017; Panchuk et al., 2014; Vickers, 1992; Vine, Lee, et al., 2013; Wilson & Pearcy, 2009). One study found no differences (van Lier et al., 2010), one study found differences in half of the

participants (Mann et al., 2011), and one study found differences depending on shot timing (i.e., random pairs of shots or a successful shot after an unsuccessful shot; Walters-Symons et al., 2017). In addition, four out of five studies (80%) found that QE may explain 14-43% of the variance in performance. Lastly, it is not clear which processes mediate the relationship between QE and performance, therefore additional research is needed to clarify the processes mediating the relationship between QE and putting performance.

Slope and Gaze Behavior

Three studies examined the relationships between putting performances, gaze behavior, and the slope of the green (Campbell & Moran, 2014; van Lier et al., 2010; Wilson & Pearcy, 2009). In one study of six university team golfers, slope severity (i.e., flat, .9°, or 1.8°) did not influence QEDs (Wilson & Pearcy, 2009). However, participants used more aiming fixations when putts were executed on a sloped green (7.94) compared to a flat green (5.93). Putting performances did not differ among slope conditions. Similarly, van Lier et al. (2010) found no differences in putting performances between a flat green, a 1° slope, or a 2° slope. However, the participants – golfers with a mean handicap of 3.4 – showed a significantly smaller fixation percentage on the ball and on the putter in the 2° slope compared to both the 1° slope and the flat green. In addition, as the slope increased, a greater number of fixations were made towards the high side of the slope.

A different approach to studying slopes was adopted by Campbell and Moran (2014). Expert, near-expert, and least-expert golfers viewed a computer simulation of the green, filmed from six locations. The intention of this procedure was to simulate a common pre-shot routine, which included viewing the green from different directions in order to accurately assess the

slope. In three of the five locations (looking from the left side; halfway between the ball and the hole; while standing; standing up behind the hole and looking towards the ball; and, standing up behind the ball looking towards the hole), the least-expert golfers made more fixations compared to the expert and near-expert golfers (~ four extra fixations). In addition, for two locations (crouching low behind the ball looking at the hole and standing up behind the ball looking towards the hole), the mean fixation duration was shorter for the least-expert golfers compared to the expert and near-expert golfers (~200-350 msec difference). These differences did not lead to statistically significant differences in the percentage of correct verbal estimations of the aiming point. Despite the lack of statistical significance, the expert golfers had 76.5% of correct aims, while the near-expert and least-expert golfers had 57.1% of correct aims. However, since the putts were not actually executed, the relationship between gaze behavior and performance cannot be established.

In summary, the findings of these studies do not show a consistent relationship between gaze behavior and performance on different slopes. This observation is somewhat surprising, as the presence of slopes is assumed to increase the difficulty of the putting task, and may require the golfer to adopt different gaze strategies. Additional research on this topic is needed.

Focus of Attention and QE

Two studies examined the relationship between focus of attention and QED in golf putting (Klostermann et al., 2014; Ziv & Lidor, 2015). In general, external focus of attention (i.e., concentration on the effects of one's movements) facilitates motor performance to a greater extent than internal focus of attention (concentration on one's body movements) (for a review, see Wulf, 2013). In both reviewed studies, external focus instructions led to longer QEDs

compared to internal focus instructions. However, in one of these studies, the longer QEDs were not accompanied by improved putting performances in participants with no golfing experience (Ziv & Lidor, 2015). In the other study, of experts and near-expert golfers, late QE offset was related to improved performance, but the difference in QE offset between the expert and the near-expert golfers was more pronounced in the internal focus condition (Klostermann et al., 2014). Lastly, QE offset efficiency (i.e., the correlation between QE offset and performance) was significant only under the internal focus condition.

The results of both the abovementioned studies do not support a causal relationship between external focus of attention and longer QEDs, or vice versa, and therefore the authors of the Klostermann et al.'s (2014) study proposed an alternative hypothesis – the inhibition hypothesis. The inhibition hypothesis suggests that longer QEDs allow the inhibition of less than optimal movement variants, so that only the optimal movement variant is used in both preparation and online execution.

In summary, the current (limited) data do not show that external focus leads to improved putting performance by way of increasing QEDs. It is suggested that future studies examine the relationships between external focus of attention, QEDs, and performance at different putt distances and slopes. In addition, measuring club kinematics and/or muscle activation may reveal differences that are more subtle than the actual performance.

QE – Pre-programming or Online Control?

It is generally accepted that longer QEDs contribute to the enhancement of motor performance by allowing pre-programming of the upcoming motor action (e.g., Janelle et al., 2000; Mann et al., 2011; Williams et al., 2002; see also a review by Vine, Moore, & Wilson,

2014). Six studies discussed whether the underlying mechanisms behind the benefits of QE are related to pre-programming or to online control (Causer et al., 2017; Klostermann et al., 2014; Mann et al., 2011; Vine, Lee, et al., 2013; Vine et al., 2017; Walters-Symons et al., 2018).

In one study, putt difficulty was manipulated by changing three variables – distance (1.2 m vs. 2.4 m), hole size (5 cm vs. 10 cm), and putter-face size (.6 cm vs. 1.7 cm) (Walters-Symons et al., 2018). The interaction between putter-face size and putt distance revealed that the longest total QED and the QED prior to the initiation of the backswing were found in the more difficult condition (i.e., small putter-face, long distance). This result supports the pre-programming hypothesis, since the participants took more time to prepare for the more difficult putts. The pre-programming hypothesis was also supported by electroencephalogram data which showed that longer QEDs were related to greater Bereitschaftspotential (BP) negativity (r = ~.3) (Mann et al., 2011). The BP is a negative potential that begins 1-1.5 sec before a self-paced movement (Jahanshahi & Hallett, 2003), and represents movement preparation (Shibasaki & Hallett, 2006).

However, four studies included in the current review showed that, at least in golf putting, QE during online control – from the initiation of the backswing to the putter-ball contact – may be of equal importance to pre-programming (Causer et al., 2017; Klostermann et al., 2014; Vine, Lee, et al., 2013; Vine et al., 2017). For example, in one study, performance suffered when vision was occluded from the initiation of the backswing to putter-ball contact, compared to when it was not occluded (Causer et al., 2017). At the same time, online QED (from backswing to contact) and dwell QEDs (after contact) were shorter under occluded conditions, but pre-programming QED (from the ready position to the initiation of the

backswing) was longer. These findings emphasize the importance of QE during online movement execution. Specifically, the longer QED during pre-programming was not enough to overcome the shorter online QED. In a second study (Klostermann et al., 2014), late QE offsets were related to improved performance in expert and near-expert golfers. In a third study (Vine et al., 2017), compared to no occlusion or occlusion until the initiation of the backswing, occlusion after initiation of the backswing led to reduced performance. Lastly, in the fourth study, longer QE during online control (from backswing to contact) and QEDs after ball contact were related to improved performance (Vine, Lee, et al., 2013). The findings that emerged from the above-mentioned four studies suggest that a longer QED is important not only for pre-programming the optimal putting action, but also – and perhaps even more – for online control of the movement.

In summary, the results of two of the studies supported the pre-programming hypothesis, while the other four studies supported the online control hypothesis. It is plausible that longer QEDs enhance putting performance by optimizing both the planning of the putt and the online control of the putt.

QE Training

Six studies examined whether QE training can improve putting performances (Moore, Vine, Cooke, et al., 2012; Moore, Vine, et al., 2013; Panchuk et al., 2014; Vine, Moore, et al., 2013; Vine et al., 2011; Vine & Wilson, 2010). In one study, novice golfers were divided into a technical instruction group and a QE instruction group (Vine & Wilson, 2010). The participants in each group learned to putt, and then performed two retention tests with one pressure test in between (i.e., a test under elevated anxiety). While QED was longer in the QE-trained group,

the performance during the retention tests did not differ between groups. However, during the pressure test, the QE-trained participants maintained their level of performance, while the performance of the technical-trained participants deteriorated. One noteworthy limitation of this study is that both groups received technical instructions, with the QE-trained group receiving additional gaze instructions. Therefore, the increased volume of instructions in the QE-trained group may have contributed to the difference in performance.

Similar findings were obtained in a follow-up study, where participants in both the QE-trained group and the control (no-QE training) group viewed their own gaze as compared to a video of the gaze of an elite prototype (Vine et al., 2011). Only the participants in the QE-trained group were taught how to observe the differences between their gaze and the gaze of the elite prototype. The QE-trained group was also provided with specific gaze instructions. The QE-trained group holed more putts (60%) in a pressure test (by manipulating social comparisons and creating a competitive monetary incentive) compared to the control group (36%), but not in a retention test. Similarly, the QE-trained group had lower error values (i.e., mean distance from the hole) in both the retention test and the transfer test. The QE-trained group also had longer QEDs (2,794.31 msec) than the control group (1,404.74 msec). In an actual competition, unlike the control group, the QE-trained group reduced the number of missed putts per round of competition and increased the percentage of putts holed from distances of 1.8-3.05 m. The importance of this study is in showing that performance improvement after QE training is not limited to laboratory settings.

A third study included lengthy practice (320 putts), followed by two retention tests with a pressure test in-between (Moore, Vine, Cooke, et al., 2012). QE-trained undergraduate

students with no golfing experience had longer QEDs and outperformed technical-trained students in both putts holed and radial error, during both the retention and pressure tests. In addition, the QE-trained group showed lower putter lateral and vertical acceleration, allowing for hitting the golf ball with the club head's "sweet spot" and hitting the center of the ball, respectively. The QE-trained group also showed greater heart rate deceleration, which usually characterizes experienced golfers, as well as reduced muscle activity that – as the authors suggested – can be associated with external focus of attention, which has been shown to improve motor performance (Wulf, 2013).

In a follow-up study of a subset of the participants from the 2012 study of Moore and colleagues (Moore, Vine, Cooke, et al., 2012), a possible psychological mechanism that explains how QE training can improve performance under anxiety was proposed (Moore, Vine, et al., 2013). The QE-trained group appraised the putting task under pressure as a challenge, while the technical-trained group appraised it as a threat. It is possible, therefore, that the improved performance of the QE-trained group in this study was due to increased resiliency to the possible negative effects of anxiety. As the authors of this study explained, QE training can enhance the perception that coping resources are available, and may be used as a pre-performance routine that can alleviate the negative effects of anxiety.

In another study, QED was manipulated by either (a) placing a colored marker under the ball and asking the participants to say the name of the color (making them dwell on it after the ball is hit); (b) telling the participants to look towards the hole for 2-3 seconds, return their gaze to the ball, and swing immediately; or (c) using an apparatus that obscures the movement of the putter and obscures the view of the ball after contact (Panchuk et al., 2014). These QED

manipulations were compared to a control condition (a "just do it" group). While differences in QEDs and QE dwelling times (fixation on the ball after contact) were found, there were no differences in putting performance. It is possible that the short training session (30 putts) that took place between a pre-test and a post-test of 10 putts each did not bring about a change in performance. Another possible explanation for these findings is that the putting distances between the pre- and the post-test (1.83 m) differed from those in training (15 putts from 1.22 m and 15 putts from 2.44 m).

Lastly, differences between explicit (technical) training, analogy training, and QE training were assessed in both the retention and the pressure tests after practicing 320 putts (Vine, Moore, et al., 2013). Analogy training is a form of implicit training. In this study, the participants were asked to see themselves as a grandfather clock and to move their arms like the pendulum of that clock. The QE-trained group performed better than the analogy-trained group during retention, and better than both the analogy-trained and explicitly-trained groups during the pressure test. QED was also longer in the QE-trained group compared to both other groups. In addition, the explicitly-trained group accrued more explicit rules and reported more conscious processing compared to the QE-trained and analogy-trained groups. One limitation of this study was associated with the instructions given to the participants in the analogy group, namely to move their arms like a pendulum. Concentrating on moving one's arms may lead to internal focus, and this, in turn, could lead to poor performance (for a review, see Wulf, 2013). The authors suggested that in future studies it would be more beneficial to instruct participants to move the putter as a pendulum and not their arms. This would more likely lead to external

focus of attention, and any differences between a QE-trained group and an analogy group could be attributed solely to the differences in gaze behavior between the groups.

In summary, five out of the six reviewed studies (83.3%) suggest that QE can be trained and can lead to improved putting performance. Still, the effects of length of practice, the skill level of the participants, and the difficulty of the shot are relevant topics for future investigations.

Psychological Manipulations

Six studies examining the effects of psychological interventions on golf putting were found (Binsch et al., 2009; Frank et al., 2016; Fulton et al., 2014; Moore, Vine, Wilson, et al., 2012; Moore, Wilson, et al., 2013; Wood et al., 2013). Instructions to avoid a thought or an action can ironically lead to an increase in the tendency to engage in that specific thought or action (see Beilock, Afremow, Rabe, & Carr, 2001; Wegner, Ansfield, & Pilloff, 1998). For example, a golfer who is instructed not to putt the ball too short may do just that, especially if he or she is under a mental or physical load (Wegner et al., 1998). However, individuals can also overcompensate their response to specific instructions. For example, participants who were asked to avoid hitting the ball too far ended up hitting it too short (Beilock et al., 2001).

The relationship between gaze behavior and ironic or overcompensation effects was also examined by Binsch et al. (2009). In their study, undergraduate students were provided with the following instructions: (a) "make sure that the ball ends in the hole", (b) "end in the hole but be careful it does not end in front of the hole", or (c) "end in the hole but be careful it does not end past the hole". In general, longer gaze durations directed to specific areas were related to an increased likelihood that the ball would land in that area. In addition, individual

differences were found – while some participants maintained their good performance, some tended to gaze longer and hit the ball more often to the location they were told to avoid (ironic effects), and others gazed longer and hit the ball more often to the location opposite the location they were told to avoid (overcompensation).

Visual illusions can also affect putting performances (Chauvel, Wulf, & Maquestiaux, 2015). For example, hole size illusions were found to influence QED and putting performances (Wood et al., 2013). The illusions were provided by placing either smaller circles (perception of a smaller hole) or larger circles (perception of a larger hole) around the golf hole. QED, which was the only gaze variable reported, was longer (by 170 msec) and radial error was smaller (by 3.64 cm) when the hole was perceived as larger. A mediation analysis revealed that the illusion of a larger hole was a significant predictor of the longer QED. Based on these findings, the authors suggested that the illusion of a larger hole might have positively affected the pre-programming of the putt. However, it was also possible that the presence of large circles around the hole (which create the illusion of a smaller hole) might have distracted participants from fixating on the hole, and therefore interfered with the pre-programming of the putt. Additional research is needed to clarify this issue.

The effects of visual distractions (e.g., a camera flash) on performance in low- and high-pressure conditions were examined in one study (Fulton et al., 2014). The performance of the participants in this study was not affected by the high-pressure manipulation. In addition, no differences in putting performances were found between the visual distraction condition and the no-distraction condition. Still, QED was longer during the trials with visual distractions

(1,789 msec) compared to the trials without visual distractions (1,458 msec), and a moderate correlation was found between QE and performance (r = .48).

Manipulating the participants' sense of challenge or threat when facing a putting task may affect performance as well. In one study, for example, undergraduate students with no golfing experience were randomly assigned to a challenge condition (suggesting to the participants that they were equipped to deal with the task of putting) and to a threat condition (suggesting to the participants that they were ill-equipped to deal with the task of putting) (Moore, Vine, Wilson, et al., 2012). The main finding of this study was that QED was longer in the challenge group compared to the threat group, however QED did not mediate the differences in performance between the groups. In essence, the improved performance of the challenge group was mediated by various putting kinematic variables. The fact that QED did not mediate the differences in performance may be explained by the small difference in QED between the groups, and the generally short QED in both groups (1,527 and 1,195 msec for the challenge and threat groups, respectively). Indeed, QE training suggests a QED of 2-3 seconds as being optimal (Moore, Vine, Cooke, et al., 2012; Vine, Moore, et al., 2013).

An examination of the effects of challenge and threat states on golfers was conducted as well (Moore, Wilson, et al., 2013). Compared to participants who underwent threat manipulation, participants who underwent challenge manipulation had a smaller number of performance errors and longer QEDs. However, similar to the undergraduate students, a mediation analysis did not reveal a relationship between QE and performance.

Lastly, in one study putting performances, gaze behavior, and mental representations of the learned task in long-term memory were examined in three groups: (a) physical practice, (b)

combined physical and mental practice, and (c) no practice (Frank et al., 2016). Participants performed a retention test that took place three days after the last day of practice. The participants in the combined group, but not in the physical practice group, had more elaborate mental representations, longer QEDs, and better putting performances compared to the participants in the no-practice group. Differences between the combined group and the physical practice group failed to reach significance, even though the participants in the combined group trained both mentally and physically, and therefore had twice the amount of practice. Still, the idea that QED is related to the development of mental representations suggests that QE reflects some kind of cognitive processing.

In summary, motor imagery, visual illusions, the manipulation of challenge and threat, and specific putting instructions may either positively or negatively affect both gaze and performance. Such effects are consistent with the concept of psychological suggestion (a process by which an individual guides the thoughts, feelings, or patterns of behavior of another individual) and its influence on the way individuals think and behave (see Michael, Garry, & Kirsch, 2012, for a review).

Discussion

The purpose of the current narrative review was to examine the effects of gaze behavior in general, and of QE in particular, on golf-putting performance. The six main findings of this review are: (a) longer QED on the ball appears to characterize experts; (b) longer QEDs appear to be related to successful putts; (c) there is no clear relationship between slope and gaze behavior; (d) improved pre-programming, better online control, and the inhibition hypothesis may explain the effects of QE on putting performance; (e) QE can be trained and may lead to

improved putting performance; and (f) psychological manipulations such as promoting a sense of challenge rather than threat can improve putting performance.

Based on the 26 reviewed studies, five methodological concerns and research limitations are discussed.

The Lack of Studies on Different QE Locations

It was suggested that the QE period presents a window of time during which neural networks are organized before and during the execution of a motor task (Vickers, 2016). However, it is plausible that the same neural organization can occur – and perhaps to a greater extent – in different QE locations. In golf the QE can be, for example, on the ball, on the target, or on the steepest point of the slope.

Performing a motor task in two visuomotor spaces (e.g., the ball area and the hole area in golf) requires retaining a number of pieces of information in the player's memory. When focusing on the ball, the participant is required to commit to memory the location of the hole and the slope of the green. In contrast, when focusing on the hole, the participant is required to commit to memory the angle between the putter head and the ball, the putter velocity, and the height of the putter as it connects with the ball. In both of these cases, longer QEDs may provide an ample opportunity for neural organization. Therefore, there could be certain benefits to maintaining QE on the ball, other benefits to maintaining QE on the hole, and yet other benefits to maintaining QE on the most elevated part of a slope, which, if present, may add a third visuomotor space that competes for the golfer's attention.

In Vickers' (1992) seminal study, 60.5% of misses were due to distance errors and 39.5% to location errors. It thus is possible that maintaining a longer QED on the hole will allow for

more accurate club velocity calculations and lead to improved performance, since the ball-to-hole distance information remains in sight and the participant does not need to commit it to memory. This explanation and its association with the contrasting importance of gaze for online control during motor execution should be examined in future inquiries.

The Lack of Studies Manipulating QEDs in Golf Putting

In most studies of gaze behavior and putting performance, QED has been classified as a dependent variable. QED was observed in expert versus novice golfers, holed versus missed putts, or after QE training versus provision of only technical training. In most training studies, the instructions for QE training involve fixating on the ball for 2-3 seconds (e.g., Moore, Vine, Cooke, et al., 2012; Vine et al., 2011). More studies manipulating QEDs are warranted. These future studies have the potential to reveal, for example, the lower and upper thresholds of QED, below and above of which, respectively, performance can deteriorate.

Reporting Global QED rather than QED for Each Phase of the Putting Task

In most of the studies, only one value was calculated for the entire QED. This value included (a) the preparation phase that occurs before the initiation of the backswing, (b) the online control phase that occurs from the initiation of the backswing to the putter-ball contact, and (c) the dwell phase that occurs after putter-ball contact. This one QED value impedes our ability to ascertain whether longer QEDs are associated with improved performance by allowing more time for motor pre-programming, or by allowing more optimal online control of motor execution.

The importance of online putting execution was indeed described in four of the studies (Causer et al., 2017; Klostermann et al., 2014; Vine, Lee, et al., 2013; Vine et al., 2017).

However, we propose that future studies report total QED, pre-QED, online QED, and dwell QED. In addition, it could also be useful in future studies to separate QED during the backswing from QED during the foreswing, since it is possible that online control of movement occurs in the foreswing only (Craig, Delay, Grealy, & Lee, 2000).

Scarcity of Data on Gaze Behavior and Putting on a Slope

The relationship between gaze behavior and putting on a sloped green was examined in only three of the studies (Campbell & Moran, 2014; van Lier et al., 2010; Wilson & Pearcy, 2009). This finding is somewhat surprising, since putting in golf is rarely performed on a flat terrain. A slope introduces the golfer to a new performance variable (i.e., a physical change in the environment) that makes the task of holing a putt more difficult. The decision regarding where to aim the ball depends on the angle of the slope and its direction. Moreover, due to the effects of gravity, when hitting the ball slowly one should aim more into the slope, and when hitting the ball faster one can aim lower on the slope, since the force of gravity will not affect the ball to the same extent.

As indicated previously, a slope adds a third visuomotor space (in addition to the ball area and the hole area), and therefore it is plausible that the specific gaze behavior required to improve putting performance on a sloped terrain differs from that required on an even terrain. In this respect, the QE training protocol used in most of the training studies should probably be adjusted to meet the challenge of the slope. The instruction given to ”make no more than three fixations towards the hole” (see Vine, Moore, et al., 2013) may not be enough, and fixations towards the slope should be incorporated into the instructions. Moreover, fixations from

different locations are warranted in order to assess the angle of the slope as well (see Campbell & Moran, 2014).

Disregard of Inter-individual Variability

The studies included in the current review mostly failed to account for inter-individual variability (Mann et al., 2011 is an exception). In many of the studies, the mean QEDs are accompanied by rather large standard deviations (e.g., mean QED of ~3,000 msec and a standard deviation of 1,000 msec). Clearly, the QE phenomena can vary both between and within levels of performance. Indeed, one study analyzed variations in QE in expert and novice bowlers, and found considerable variability between the participants (Chia, Chow, Kawabata, Dicks, & Lee, 2017). It is suggested that future work should try to assess and report inter-individual variability in gaze behavior during putting.

Practical Implications for the Practitioner

In most of the QE training studies reviewed in our article, the participants were either beginning or experienced golfers, and not elite or professional golfers (see Table 1); therefore, we currently cannot be certain if such training would truly have a meaningful impact on elite-level golfers' putting performance. However, based on the findings that did emerge from our review, four practical tips are proposed for those professionals – golf coaches, sport psychology consultants, and performance psychologists – attempting to improve the results of their players' golf putting task;

(a) Research has shown that QE has been associated with a high level of proficiency in closed, self-paced motor tasks, such as putting in golf. Therefore, practitioners should obtain relevant information on different aspects of QE (e.g., QE in beginning/experienced golfers or QE

637 and focusing attention) as a visual variable that can assist their golfers in improving their
638 accuracy when aiming at the putting green;

639 (b) QE training should be an integral component of the physical/psychological training of
640 the golfer. Golfers should use eye-tracking systems in their on-green training regimes, in order
641 to gather information on their QEDs while putting. Based on Moore, Vine, Cooke, et al. (2012)
642 and Moore, Vine, et al. (2013), Table 2 summarizes the current instructions for golf putting. The
643 instructions include two stages for pre-training if eye-tracking equipment is available and six
644 instructions for training;

645 (c) Since putting in golf is classified as a closed, self-paced motor task, golfers can
646 include QE as part of their physical/psychological pre-performance routines (Lidor, 2007; Vine
647 et al., 2011);

648 (d) Since the slope of a green makes the task of holing a putt more difficult, it would
649 most likely benefit the golfer if the QE instructions take the slope into account.

650 **Conclusions**

651 The findings of the current review suggest that gaze behavior in general, and QE in
652 particular, are related to putting performance. QE appears to be longer in expert golfers
653 compared to less expert golfers and in successful putting performances compared to less
654 successful performances. In addition, QE can be trained, and such training can lead to improved
655 putting performance. However, it is still unclear whether the positive effects of QE on
656 performance are related to pre-programming of the putt, online control of the putt, or both.
657 Unfortunately, not enough data exists regarding the effects of QEDs when slopes are involved.
658 We encourage researchers to examine this issue, as golf putting is often performed in the

presence of slopes. Finally, we encourage practitioners to train golfers to adopt longer QEDs while aiming at the hole.

Conflict of Interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contribution

Both authors made a substantial and direct contribution to this manuscript, and approved it for publication.

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FIGURE CAPTION

Figure 1. The review selection process.

Table 1

A Summary of Studies (*N* = 26) Examining QE in Golf Putting (ordered by year of publication).

Study	Discussed in Sections	Participants	Putting Details and Procedure	QE Data (duration in msec)	Performance and Other Gaze Data (duration in msec)
Vickers (1992)	SK, PER	Tournament players: LH (*n* = 5) and HH (*n* = 7)	Distance: 3 m 10 hits and 10 misses compared	Location: ball Duration*: Preparation: LH 1,442 (msec), HH 926 Swing: LH 1,788, HH 911	Skill-level differences in performance: LH > HH
Naito et al. (2004)	SK	Expert golfers (handicap = 0, *n* = 3), intermediate golfers (handicap = 2-15, *n* = 3), and beginners (rarely play, *n* = 11)	Distance: 2 m 10 putts performed	NA	Fixation duration on ball: Beginners > experts Fixation duration on club head: Experts > beginners, intermediates Right before ball impact: Experts shifted gaze to 4 cm from the ball in the direction of the hole Possible use of peripheral vision in experts compared to beginners and intermediates In beginners: shifting gaze to direction of target at ball contact improved performance
Binsch et al. (2009)	PSY	Undergraduate students (*n* = 27, 14 females) No golfing experience	Distance: 1.8 m Three instruction conditions: "hole" – make sure ball ends in the hole, "not-in-front" – make sure ball ends in the	NA	Some participants showed ironic effects (gazing longer and hitting towards the place they were told to avoid), some showed overcompensation (gazing longer and hitting towards the location opposite

			hole, be careful it does not end in front of hole, "not-past" – make sure ball ends in the hole, be careful it does not end past the hole Three putts per condition under mental load (counting backwards)		the location they were told to avoid), and some showed good performance Negative instructions (e.g., avoid hitting to this area) can affect gaze behavior and lead to either overcompensation or ironic effects
Wilson & Pearcy (2009)	PER, SL	University team golfers (*n* = 6)	Distance: 3 m Five putts for each of 5 slopes: flat, .9° to both sides, 1.8° to both sides	Location: top or back of ball, putter head, or adjacent to ball Duration: Missed putts: 1,231 Holed putts: 1,693	Performance error between slopes: 1.8° slope > .9° slope > flat Number of aiming fixations: slope (7.94) > flat (5.93)
van Lier et al. (2010)	PER, SL	Teaching golf professionals (mean handicap = 3.4, *n* = 20, 2 women) divided into a successful group and a less-successful group based on proportion of holed putts	Distance: 1.8 m Fifteen putts for each of 3 slope conditions: flat, 1%, 2% (right-to-left)	Location: ball and putter head Duration[##]: successful 1,100-1,300 Unsuccessful 1,500-2,100 No differences between groups, slopes, or between holed and missed putts	Number of holed putts: Flat = 1% =2% Effects of slope on gaze: % time viewing ball and putter: 2% < 1%, flat Increased slope – shift in gaze to the high side of hole
Vine & Wilson (2010)	QET, PER	Male undergraduate students (*n* = 14) No golfing experience	Distance: 3.3 m Blocks: 1 pre-test, 8 acquisition, 1	Location: ball Retention A[#]: QE: 3,200, Technical: 1,400	Performance in pressure test: Technical (reduced performance) < QE (maintained performance)

		Two group: QE training, technical training	retention A,1 pressure test, 1 retention B Forty putts per block	Pressure test[#]: QE: 2,800, Technical: 900 Retention B[#]: QE: 3,200, Technical: 1,300 QE of top 3 performers (3,561) > QE of bottom 3 performers (1,372)	No other differences in performance between groups despite differences in QE QE predicted 36% of the variance in putting performance
Mann et al. (2011)	SK, PER, PPOC	LH (0-2, *n* = 10) and HH (10-12, *n* = 10) golfers	Distance: 3.7 m Ten practice putts Two blocks of 45 putts EEG measures (BP)	Location: not mentioned Duration[##]: LH > HH, hits = misses	Performance: LH > HH BP negativity: LH > HH BP negativity not related to performance QEDs correlated with BP measures (*r* = .28-.30)
Vine et al. (2011)	PER, QET	Golfers (mean handicap: 2.8, *n* = 22) Two groups: QE training, Control	Distance: 3.05 m Putts taken from 3 locations Recording 10 real competition rounds before and after lab training In the lab: practice and baseline putts, 20 training putts Retention and pressure tests	Location: ball Duration: in pressure test: QE-trained: 2,794 Control: 1,404 No differences in pre-test or retention	Lab putting performance error (distance from hole) during retention and pressure tests: Control > QE-trained QED predicted 43% of variance of performance error Competition performance: Putts per round: QE-trained < control Post-training < pre-training in QE – trained group only Percentage of holed putts from 1.8-3.05 m post-training: QE-trained > control. **QE predicted 43% of the variance in putting performance**

Moore, Vine, Cooke et al. (2012)	PER, QET	Undergraduate students (*n* = 40) with no golfing experience Two groups: QE training, technical training	Distance: 3.05 m Putts taken from 3 locations baseline (40 putts), training (320 putts), retention 1 (20 putts), pressure (20 putts), retention 2 (20 putts)	Location: ball Duration: during retention tests: QE (~3,400) > technical (~1,800) Pressure test: QE maintained duration, technical reduced duration	During retention and pressure: % putts holed: QE (26-27%) > technical (17-20%) Radial error: QE < technical Putting kinematics: Lateral and vertical club acceleration during downswing: QE < technical.
Moore, Vine, Wilson et al. (2012)	PSY	Undergraduate students (*n* = 127, 63 females) with no golfing experience Two groups: challenge, threat	Distance: 1.83 m Three different locations Six putts	Location: ball Duration: challenge (1,527) > threat (1,195)	Radial error: Challenge (~35) < threat (~47) Putter kinematics: Lateral, vertical, back-and-forth acceleration: Challenge < threat Muscle activity during foreswing: Challenge < threat QE did not mediate differences in performance between groups
Moore, Vine et al. (2013)	PER, QET	Undergraduate students (*n* = 30) with no golfing experience A subset from Moore, Vine, Cooke et al. (2012)	Same as Moore, Vine, Cooke et al. (2012)	Location: ball Duration: Retention and pressure tests[#]: QE-trained (~3,500) > technical (~1,700)	Mean performance error during retention and pressure tests: QE-trained < technical Appraisal of resources: QE-trained > technical Resource appraisal mediated relationship between training group and performance in pressure test
Moore, Wilson et al. (2013; Study 2)	PER, PSY	Golfers (mean handicap: 10, *n* = 60) Two groups: challenge,	Distance: 2.44 m Half-sized hole (5 cm) Six putts performed	Location: ball Duration: challenge (2,148) > threat (1,542)	Performance: Holed putts: challenge > threat Distance from hole: challenge < threat

		Threat			Mediation analysis revealed no relationship between QE and performance
Vine, Lee et al. (2013)	PER, PPOC	Golfers (mean handicap: 3.6, *n* = 50)	Distance: 1.52 m A shootout – holing as many consecutive putts without missing under pressure Comparing first, penultimate, and final putts	Location: ball QE-pre backswing, QE-online (from backswing to contact), QE-dwell (after contact) Duration: QE-total: First (2,284), penultimate (2,205) > last (1,601) QE-pre: ~1,000, no differences between putts. QE-online: First, penultimate (>800) > final (560) QE-dwell: First, penultimate (~400) > final (<100)	Longer QE-online and QE-dwell durations related to improved performance under pressure QE pre-programming role questioned
Vine, Moore et al. (2013)	QET, PSY	Undergraduate students (*n* = 45) with no golfing experience Three groups: Analogy training Explicit training QE training	Distance: 3.05 m Putts taken from 3 locations baseline (40 putts), training (320 putts), retention 1 (20 putts), pressure (20 putts), retention 2 (20 putts) Explicit rule accrual and conscious	Location: ball Duration: In both retention and pressure[#]: QE (~3,500-3,700) > analogy, explicit (~1,600-1,800)	Mean radial error: QE < analogy in retention QE < analogy, explicit in retention and pressure In pressure test: Explicit showed reduced performance, analogy and QE maintained performance Explicit rule accrual, conscious processing: Explicit > analogy, QE

			processing measured		
Wood et al. (2013)	PER, PSY	No golfing experience (*n* = 40, 10 females)	Distance: 1.75 m Ebbinghaus Illusion Target with either smaller (perceived large) or larger circles (perceived small) surrounding hole 10 practice putts, 10 putts under for smaller circles, 10 putts for larger circles	Location: ball Duration: Perceived small (1,481) < perceived large (1,651)	Perceived hole size: Perceived small < perceived large Performance error: Perceived small > perceived large
Campbell & Moran (2014)	SL	Touring golf professionals (expert, *n* = 17), elite-amateurs (near-expert, *n* = 14), club-level amateurs (least-expert, *n* = 14)	Computerized green-reading, slope perception task Simulated views of green from 6 positions Six sec view time allowed for each position No limit to decision making after "tour" of green Make decision on where to aim to hole a putt	NA	Viewing time for all groups: 51.4% on target area, 34.8% on 60 cm leading up to target, 13.7% on ball Mean number of fixations: Professional, elite amateurs < club-level for 3 of 6 locations (~4 extra fixations) Mean duration of fixations: Professional, elite amateurs (~720-970) > club-level (550-640) for 2 of 6 locations % correct verbal estimates of aim: Professional (76.5%) > elite and club (57.1%) but not significant

Fulton et al. (2014)	PER, PSY	Division-I collegiate golfers (*n* = 8)	Distance: 5 m Warmup (10 putts) Low pressure (50 putts) and high pressure (50 putts) with random camera flash as a distraction during QE	Location: ball Duration: Visual distraction (1,789) > no distraction (1,458)	Worries / tense / confident feelings: Low pressure = high pressure Putting performance: Visual distraction = no distraction QE and performance moderately correlated (*r* = .48)
Kloster-mann et al. (2014)	SK, FA, PPOC	Expert (*n* = 12, 4 females) and near-expert (*n* = 12, 5 females) golfers	Distance: 3.0 m Sixteen practice trails Five practice trials and 16 actual trials in 2 counterbalanced conditions: internal and external focus of attention	Location: ball Duration: Experts (2,235) > near experts (1,564) QE offset: experts (1,177) > near experts (634) Larger differences under internal focus conditions	Performance: external > internal, experts > near experts Late QE offsets related to improved performance in experts Late QE offsets related to improved performance under internal focus of attention
Panchuk et al. (2014)	PER, QET	Amateur golfers with various skill levels (handicap range = 1-41, *n* = 29) Four groups: Control, hole focus (look at hole for 2-3 sec, saccade to ball and swing immediately), marker focus (name color of	Distance: pre-test and post-test 1.83 m, practice 1.22 and 2.44 m Ten pre-test and post-test putts Intervention: 15 putts from 1.22 m and 15 putts from 2.44 m	Location: ball Duration: From pre- to post-test: Marker focus increased Hole focus decreased Hits (1,840) > misses (1,569) QE dwell time (after contact): +247 in marker focus group	Performance similar between all four groups and between pre- and post-test

		marker under ball after it is hit), PBoS			
Ziv & Lidor (2015)	FA	Undergraduate students (*n* = 72) with no golfing experience Three instructional groups: control, internal focus, external focus Two audio distraction groups: distraction, no distraction	Distance: 2.0 m One-hundred and twenty acquisition trials, 24 retention trials, 24 transfer trials Repeat 24 retention and transfer trials under audio distraction or no distractions	Location: ball or putter head Duration: Acquisition, retention, transfer: External (1,822-2,168) > control (1,214-1,286), internal (1,168-1,447)	Performance: No distractions: Control = internal = external With audio distractions: External, internal > control QE was not related to improved performance
Frank et al. (2016)	PSY	University students (*n* = 45, 27 females) with no golfing experience Three training groups: Physical practice, combined physical + mental (imagery) practice, no practice	Distance: 3.0 m Pre-test(day 1), acquisition (3 days), post-test (day 5), retention test (day 8) Combined group practiced mentally in addition to physically – practiced twice as much as physical only	Location: not mentioned Duration[#]: Pre-test, acquisition: equal for all groups (~900) 3-day retention: Combined (~ 2,500) > no practice (~900), but only a tendency to statistical difference from physical only (~1,400) QED increased in	Performance: Post-test: combined > no practice 3-day retention: combined, physical > no practice Mental representation structures in long-term memory: Combined > no practice QED related to mental representation structure (*r* = .29) Both QE and mental representation developed over the course of practice, especially in combined practice
Causer et al. (2017)	PER, PPOC	Undergraduate students (*n* = 21) with no golfing experience	Distance: 1.83 & 3.35 m	Location: ball Total duration: Low-RE (1,183) > high-RE (844),	Performance: Differences between low-RE and high-RE were greater under occluded vision

		A median split to create low-radial error (low-RE) and high-radial error (high-RE) groups	Two conditions: full vision, occluded vision (from initiation of backswing to ball contact) Twenty putts for each combination of distance and vision (80 putts total)	occluded (1,095) > full vision (933) Pre-programming duration (until backswing): Low-RE (860) > high-RE (621), occluded (962) > full vision (519) Online duration (from backswing to contact): Low-RE (192) > high-RE (151), occluded (84) < full vision (295) Dwell duration (after contact): Low-RE (130) > high-RE (71), occluded (17) < full vision (153)	Related to lower online and dwell QED in occluded condition Online control duration influences golf putting performance
Vine et al. (2017)	PPOC	Skilled golfers (mean handicap = 5.8, *n* = 27)	Distance: 3.05 m Six putts in 3 counterbalanced conditions: no occlusion, early vision (occlusion after initiation of backswing), late vision (occlusion until initiation of backswing)	Location: ball Duration[#]: No differences between conditions (~2,200-2,500)	Performance: Control, late vision > early vision Putting kinematics: Lateral acceleration: Control, late vision > early vision Vertical acceleration: Control < early vision

Walters-Symons et al. (2017)	SL, PER	Experienced golfers (mean handicap = 5.7, *n* = 18) and novices (*n* = 21)	Distance: 3.05 m Putting until 5 hits and 5 misses were recorded Comparing miss-hit and miss-miss pairs	Location: ball Duration: Golfers (1,920) > novices (1,240) Random pairs: no differences in QED Miss-hit pairs: hit (1,952) > preceding miss (1,389) Miss-miss pairs: miss (1,438) < preceding miss (1,561)	Reaching 5 hits and 5 misses: Golfers (14 putts) faster than novices (26 putts) Longer QE helps recover performance after a miss
Walters-Symons et al. (2018)	PER, PPOC	Golfers (mean handicap = 7.2, n = 34)	Distance: 1.2 vs 2.4 m Hole size: 5 vs 10 cm Putter-face size: 1.7 vs .6 cm After 5 warm-up putts, eight counterbalanced conditions of increasing difficulty. 10 putts in each condition	Location: ball Total duration[#]: 2.4 m (2,200 msec) > 1.2 m (1,900 msec) Interaction between putter-face size and distance – small putter-face and long distance led to longer QE duration. QE before backswing: no differences. Interaction between putter-face size and distance – small putter-face and long distance led to longer QE duration. QE after backswing: 2.4 m (900) > 1.2 m (830)	Performance: Distance: 1.2 > 2.4 m Hole size: 10 cm > 5 cm Putter-face size: 1.7 > .6 Weak correlations between QE and performance Significant correlation in one condition (large target, long distance): *r* = .39

Campbell et al. (2019)	SK	High-skilled (mean handicap = 6.9, *n* = 13) and less-skilled (mean handicap = 17, *n* = 11) golfers	Distance: 1.83 vs. 3.66 m Two blocks of 10 putts from the two distances	Location: ball Duration: 1.83 m: high-skilled (1,202) = less-skilled (1,155) 3.66 m: high-skilled (1,347) = less-skilled (1,243)	Pupillometry: Pupil dilation during putting > baseline (by over 30%) Peak pupil dilation coincides with onset of QE (*r* = .73) Performance: High-skilled = less-skilled at both distances

Sections: SK – Skill Level; PER – QE and Performance; SL – Slope; FA – Focus of Attention; PPOC – Pre-Programming or Online Control; QET – QE Training; PS – Psychological Manipulations.

BP – Bereitschaftspotential; EEG – Electroencephalogram; HH – High handicap; LH – Low handicap; NA – Not available; PBoS – Putting Box of Science (special putting apparatus that obscures movement of golf club and obscures ball after it is hit); QE – Quiet eye; QED – Quiet eye duration

* Note that QE was only defined four years later. Data represent fixations on the ball during the preparation and swing phases. During the contact phase, no fixations were directed to the ball

Values are approximated from a figure in the original study

QE calculated as last fixation until initiation of backswing

Table 2

A Summary of the Current Instructions for QE Training in Golf Putting.

Stage		Instructions	Comments
Pre-training*	1	Show a video of an elite golfer with optimal gaze behavior.	Point out key features and especially QE. Ask questions to ensure understanding.
	2	Show the trainee a video of his or her own gaze behavior.	Ask about and point out differences between gaze of trainee and gaze of elite golfer.
Training	1	Assume stance and ensure gaze is located on back of ball.	
	2	After setting up, fix gaze on hole.	
	3	Make one to three fixations towards the hole.	
	4	The final fixation is the QE to the back of the ball with an onset prior to the beginning of backstroke and a duration of 2-3 sec.	2-3 sec can seem like a long time to the participants. You can time them until they get it right.
	5	Do not look at the club head during the putt.	
	6	QE should remain on the green for 200-300 msec after the golf club contacts the ball.	Make sure the trainee understands that he or she needs to look at the green that is under the golf ball.

* If eye-tracking equipment is available.