MOTOR SKILL CONTROL AND LEARNING IN AIMING SPORTS: A PSYCHOPHYSIOLOGICAL ACCOUNT OF THE NEURAL EFFICIENCY AND QUIET EYE PHENOMENA

by

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ABSTRACT

This thesis aimed to increase our understanding of the psychophysiological correlates of superior motor performance in target sports by providing an integrated account of the models of *neural efficiency* (Hatfield & Hillman, 2001) and *quiet eye* (Vickers, 2007). To this end, I conducted a series of four studies adopting a multi-measure approach to record brain activity – using electroencephalography (EEG) – eye movements – using electrooculography (EOG) – and movement kinematics – using motion sensors – in a golf putting task. The findings of these studies led me to propose an integrated neural efficiency-quiet eye model arguing that superior motor performance is achieved through refinement of cortical activity – reflected in regional gating of alpha oscillations – whereby movement-related information processing is promoted and at the same time insulated from other psychomotor processes that are unrelated with, or detrimental to, fine motor control. The findings of my studies indicate that visual perception is inhibited during the final stages of preparation for action, and suggest that the quiet eye phenomenon reflects a general psychomotor quiescence that facilitates clean and smooth movements. This thesis demonstrates the utility of psychophysiology in human movement science and builds some methodological and conceptual foundations for interdisciplinary research on the correlates of superior motor performance.

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LIST OF PAPERS

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CHAPTER ONE

General Introduction

What determines superior motor performance? Researchers from the field of human movement science have adopted various approaches to address this question. An approach that has contributed greatly to the development of theoretical models is based on the analysis of the activity of multiple biological systems during the performance of skilled movements, such as those required in target sports (Tenenbaum & Eklund, 2007). Some researchers have examined neural activity to uncover the mechanisms of mental concentration. Other researchers have focused on eye movements to track visual attention. These 'neural' and 'ocular' branches have provided extraordinarily detailed descriptions of the correlates of motor performance, the former culminating with the discovery of the *neural efficiency* phenomenon (Hatfield & Hillman, 2001) and the latter with the discovery of the *quiet eye* phenomenon (Vickers, 1996, 2007). Crucially, these neural and ocular branches have grown separately from each other, developing distinct research methods and procedures. To date, there has been very little contact between these two branches, mostly consisting in the recognition of the incompatibility of the neural efficiency and quiet eye accounts of motor performance (Mann, Wright, & Janelle, 2016).

This thesis adopts a multi-measure, psychophysiological approach designed to bring together the neural efficiency and quiet eye phenomena into an integrated model of motor control and learning. Here, golf putting is examined as a model for closed-loop aiming skills. This is for various reasons. First, golf putting is complex enough to allow substantial performance improvements with practice, founding the basis for longitudinal mechanistic research. Second, the popularity of golf as sport grants access to a population of expert individuals who, through years of consistent and deliberate practice, have developed exceptional golf putting ability. Third, differently from other non-sport laboratory-based motor tasks, golf putting has high ecological validity as it is representative of a purposeful action. Finally, the relative postural stillness before and during the execution of the golf putt allows researchers to examine small amplitude physiological signals, such as those generated by the brain and the eyes, that would otherwise be overshadowed by the production of large body movements.

This chapter introduces the concepts of neural efficiency and quiet eye and reviews research that led to the discovery of these phenomena. The following section stresses the need for an integrated neural efficiency-quiet eye account and highlights the utility of psychophysiology to this end. The final part of this chapter provides aims and rationales for the research studies described in the following empirical chapters of this thesis.

Neural Efficiency

Researchers who are interested in the mental processes underlying superior motor performance have relied predominantly on electroencephalography (EEG). The EEG records time-varying voltages from an array of electrodes applied to the scalp of an individual. The electrical activity that can be measured by the EEG is largely due to post-synaptic potentials that are synchronous within regional neuronal populations of the cerebral cortex (Nunez & Srinivasan, 2006). Rhythmic fluctuations of these potentials generate electro-magnetic activity oscillating at various frequencies – commonly known as brain rhythms – which have distinct neurophysiological properties and which are associated with distinct cognitive processes (Buzsáki, 2006). Among these brain rhythms, alpha – oscillating at a frequency around 10 Hz – has attracted considerable attention from researchers due to its proposed inhibitory function and ubiquitous dominance across the entire cerebral cortex (Klimesch, Sauseng, & Hanslmayr, 2007; Klimesch, 2012). Alpha power – the magnitude of alpha oscillations – can be examined as an indirect marker of regional cortical activation: higher power in a specific region of the cortex reflects inhibition of neuronal excitability in that region (Romei, Gross, & Thut, 2010; Sauseng, Klimesch, Gerloff, & Hummel, 2009).

One of the first documented studies of alpha in target sports was conducted by Hatfield, Landers, Ray, and Daniels (1982) who examined the EEG of 15 elite rifle marksmen as they performed 40 shots to a 50-foot distant target. Hatfield et al. (1982) found that alpha power increased in the left-temporal region in the 7.5 s preceding shooting, compared to a resting baseline. Due to the involvement of the left-temporal region with language processing, this finding was interpreted as decreased reliance on verbal / analytic processes. In the intervening years following this pioneering study the literature on EEG and target sports has grown considerably (for reviews of studies see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004).

Around two decades later, Hatfield and Hillman (2001) published an influential report reviewing about ten studies of EEG alpha power in target sports including rifle shooting, archery, and golf putting. Crucially, Hatfield and Hillman (2001) made sense of the wealth of study findings by framing the extant knowledge within the concept of psychomotor efficiency. Efficiency was described as an adaptive process to repeated physical and mental challenges – such as those inherent to target sports – consisting in the maximization of the ratio between outcome and effort. According to this model, one could achieve greater efficiency in three ways: by increasing the outcome while decreasing the effort, by increasing the outcome while maintaining the same effort, or by maintaining the outcome while decreasing the effort. In their review, Hatfield and Hillman (2001) highlight how differences in expertise can be explained as a function of greater efficiency: through extended practice, the psychomotor processes responsible for the execution of a certain skill are refined through pruning of unnecessary activity. As a result of this process, individuals perform better while concomitantly diminishing their psychomotor effort. The concept of improved efficiency applies to the somatic level – for example, as improved coordination of agonist and antagonist muscles – as well as to the neural level – for example, as improved movement outcome with decreased neural activity. EEG alpha was the ideal candidate to study neural efficiency due to its role of neural quietening and cognitive relaxation, as described in the then state-of-the-art ‘idling’ model of brain activity (Pfurtscheller et al., 1996).

Since its introduction, the concept of neural efficiency was able to explain multiple EEG alpha findings (for a review of studies and interpretation in light of the neural efficiency concept see Hatfield et al., 2004 and Hatfield & Kerick, 2007). For example, Haufler, Spalding, Santa Maria, and Hatfield (2000) tested expert and novice rifle marksmen at a simulated 50-foot rifle shooting task. Haufler et al. (2000) found that, compared to novices, experts performed better while exhibiting greater EEG alpha power in regions of the left (but not right) hemisphere, in the 6 s preceding shooting. Another example is the study by Kerick, Douglass, and Hatfield (2004) that tested novice pistol shooters before and after a training period of 12-14 weeks. Kerick et al. (2004) observed that participants improved their performance by increasing the percentage of target hits as a function of practice time. The analysis of EEG alpha power revealed that left (but not right) temporal alpha power increased from pre to post training. The findings of Haufler et al. (2000) and Kerick et al. (2004) strengthened those of earlier studies regarding the deactivation of the left-temporal region of the cerebral cortex during superior motor performance (e.g., Hatfield et al., 1982). Taken together, these findings implied that improved performance was achieved with less cortical activation and, therefore, fit very well within the neural efficiency model.

Later findings, however, seemed to challenge the predictions of neural efficiency by indicating that, during superior motor performance, some cortical activity is enhanced rather than inhibited. For example, Babiloni et al. (2008) recorded the EEG from expert golfers performing golf putts to a 2.1-m distant hole. Babiloni et al. (2008) found that alpha power recorded from frontal and central regions decreased as function of time in the 4 s preceding the putt, indicating increased cortical activation. Importantly, they also found that compared to missed putts, holed putts were preceded by lower alpha power. Another such example is provided by the study by Cooke et al. (2014) that tested expert and novice golfers as they putted golf balls to a 2.4-m distant hole. Cooke et al. (2014) reported that, compared to novices, experts exhibited a greater reduction of alpha power for frontal and central regions prior to putting. Additionally, alpha power was lower ahead of holed than missed putts for the same regions. Taken together, the findings of Babiloni et al. (2008) and Cooke et al. (2014) provided evidence that skill proficiency was achieved with greater – and not less – cortical activation, in stark opposition with the concept of neural efficiency.

In order to reconcile the divergent results of decreased and increased cortical activation in target sports, the neural efficiency model needs to be revised in light of recent findings. A later section of this chapter argues for an extension of this model (which is presented fully in the General Discussion, Chapter 6) that can potentially take into account the full breadth of the findings of greater alpha power in some regions and lower alpha power in some other regions of the cerebral cortex.

Quiet Eye

The main function of the eyes is to acquire images of the outer world and transfer them to the brain to permit the generation of a percept informing our actions (Walls, 1962). In essence, ocular activity can be abridged into placing or maintaining an image of interest within the fovea, a small region placed at centre of the retina corresponding to less than 2° of the visual field. Due to the fact that the fovea exhibits the largest ratio of optic fibres per photoreceptors within the retina, images that fall into this area are processed in a privileged way by the visual regions of the brain (Guyton & Hall, 2006). Saccades (i.e., movements of the eyes), fixations (i.e., relative stillness of the eyes), and pursuit movements (i.e., slow movements of the eyes to track a moving object) revolve around orienting and keeping the eyes aligned with an object of interest (Krauzlis, Goffart, & Hafed, 2017). On this basis, shifts of the gaze can be monitored to infer the time-varying allocation of attentional focus onto spatial locations within the visual field (Posner, 1980). Researchers interested in the visuo-spatial attentional processes occurring during the execution of aiming tasks have relied predominantly on camera-based pupil-reflection methods to track eye movements.

The first analysis of eye movements in target sports dates back to Vickers (1992) who used camera-based eye tracking to monitor duration and spatial location of ocular fixations during the golf putt. Vickers (1992) found that, compared to less-skilled counterparts, skilled golfers made fewer fixations of longer duration on critical locations of the visual scene – particularly on the ball – before, during, and after the execution of the putt. Vickers (1992) interpreted this finding as evidence that movement proficiency was characterized by a maximization of the time spent focusing on critical elements related with the execution of the skill. A milestone for subsequent research was the definition of the ‘quiet eye’ period as the final ocular fixation on a critical location for the execution of a certain motor skill (e.g., the ball in golf putting), starting prior to movement initiation (Vickers, 1996).

Following this seminal research, a large number of studies have used eye-tracking methods to measure quiet eye duration in various sports and other fine motor skills (e.g., surgery), as a function of expertise and performance (for reviews of studies see Lebeau et al., 2016; Mann, Williams, Ward, & Janelle, 2007; Rienhoff, Tirp, Strauß, Baker, & Schorer, 2016; Vickers, 2007; Wilson, Causer, & Vickers, 2015). These studies have provided a very consistent picture whereby, compared to novices, experts exhibit a longer quiet eye duration. For example, Walters-Symons, Wilson, and Vine (2017) studied the eye movements of experienced and novice golfers as they performed golf putts. Walters-Symons et al. (2017) observed a longer quiet eye duration for experienced than novice golfers. Other studies found that better performance is accompanied by a longer quiet eye. For example, Wilson and Pearcy (2009) co-examined quiet eye duration and golf putting outcome (holed or missed) in a sample of experienced golfers. Wilson and Pearcy (2009) found that, compared to missed putts, holed putts were characterized by a longer quiet eye duration. The association of long quiet eye with superior performance has been replicated in so many studies that researchers have reached an almost unanimous consensus on the authenticity of the relation between long quiet eye and superior performance. Some researchers have ventured beyond descriptive research into the designing of training programmes aimed to improve performance by teaching individuals to produce a longer quiet eye (for a review of studies and methods of quiet eye training see Vine, Moore, & Wilson, 2014). This exciting application has already produced promising results and is likely to become increasingly popular in the next years.

Despite the consensus on the existence of the quiet eye-performance effect and the promising expectations of quiet eye training, there is an ongoing, major debate on the mechanism(s) by which a long quiet eye confers performance advantages. Informed by the findings of experimental manipulations aimed to alter the quiet eye phenomenon, researchers have proposed various mechanisms (for a comprehensive review see Gonzalez et al., 2017a). Common to most of these mechanisms is the almost undisputed thesis that visual processing plays a major role in determining the quiet eye-performance effect (Vickers, 2012). However, to date there is no direct empirical evidence that visual processing is enhanced during the quiet eye period. In order to improve our understanding of this phenomenon, researchers have advocated more mechanistic research testing the predictions derived from the mechanistic accounts that have been put forward to explain the quiet eye-performance effect (Causer, 2016; Williams, 2016; Wilson, Wood, & Vine, 2016).

The next section of this chapter includes a discussion on potential methodological drawbacks that have held back progress on the mechanistic understanding of the quiet eye phenomenon. Crucially, it presents a theoretical controversy, labelled the ‘efficiency paradox’ that highlights the incompatibility between the quiet eye and the neural efficiency accounts of superior motor performance. Finally, it proposes a method to solve this paradox.

Summary and Limitations of Literature

Scientists interested in understanding the biological correlates of superior motor performance have predominantly studied the neural and ocular activity that accompanies the execution of motor skills. Research that focused on the neural correlates have been heavily influenced by the model of neural efficiency (Hatfield & Hillman, 2001), whereas research that focused on the ocular correlates can be framed almost entirely within the model of quiet eye (Vickers, 2007).

The neural efficiency model links superior motor performance with decreased activity in regions of the brain involved with cognitive processes that are deemed irrelevant for precise motor control (Hatfield & Hillman, 2001). This model has received mixed support by empirical studies of EEG alpha power in target sports. On the one hand, various studies have supported the neural efficiency model by reporting greater alpha power (i.e., diminished neural activity) in experts compared to novices (e.g., Haufler et al., 2000) and following than preceding extended skill practice (e.g., Kerick et al., 2004). On the other hand, the findings of other EEG studies challenged the neural efficiency model by reporting lower alpha power (i.e., elevated neural activity) in experts compared to novices (e.g., Cooke et al., 2014) and ahead of successful than unsuccessful performance (e.g., Babiloni et al., 2008; Cooke et al., 2014). An extension of the neural efficiency model should take into account that some neural activity is inhibited while, concomitantly, some other neural activity is enhanced.

For this purpose, the gating-by-inhibition model of alpha activity (Jensen & Mazaheri, 2010) provides a useful theoretical framework for the analysis of alpha power in multiple regions of the cortex. This model is based on the notion that alpha indicates regional inhibition of the cortex: elevated alpha power indicates increased inhibition whereas diminished alpha power indicates greater release from inhibition (Klimesch, Sauseng, & Hanslmayr, 2007; Klimesch, 2012). Importantly, the alpha gating model contends that cortical processing is diverted away from regions exhibiting greater alpha power and routed towards regions exhibiting lower alpha power (Jensen & Mazaheri, 2010). While the exact mechanisms governing the generation of alpha activity and its propagation across the brain tissues are still debated, it is generally accepted that regional distribution of alpha oscillations within the cortex is influenced by thalamo-cortical and cortico-cortical interactions (Klimesch, 2012). For example, a shift of focus from visual to acoustic processing is associated with an in increase in alpha power in the occipital regions involved with visual processing, whereas a shift from acoustic to visual processing is associated with a decrease in the same regions (e.g., Foxe, Simpson, Ahlfors, 1998; Mazaheri et al., 2014).

The adoption of the gating-by-inhibition framework within the neural efficiency model of superior motor performance can help make sense of the complex, often divergent, regional patterns of alpha power observed in expert and novice performers. Namely, neural efficiency can be re-defined as the extent by which neural processes that are functional to the task at hand are enhanced while those that are irrelevant for task performance, or even detrimental, are inhibited. Regions that are inhibited should exhibit relatively greater alpha power whereas regions that are active should exhibit relatively lower alpha power.

The quiet eye model associates superior motor performance with longer ocular fixations on locations that are relevant to task performance (Vickers, 2007). A compelling body of research has demonstrated the validity of the quiet eye model for a variety of sports (Lebeau et al., 2016). There are minimal doubts on the existence of the quiet eye phenomenon, however, there is a major debate on the mechanisms accounting for the quiet eye-performance effect (e.g., Wilson, Wood, & Vine, 2016).

The uncertainty surrounding the mechanisms may be due to a number of factors. First, most research has measured the quiet eye period by aggregating the duration of the fixation in the period before movement initiation, during movement execution, and even after movement completion into one compound measure (Vickers, 2007). Although it is sensible to aggregate these periods as they refer to the same ocular fixation – hence, a single attentional focus unit – the lack of distinction makes it difficult to relate this compound measure with the different stages of movement execution. For example, it is hard to conceive that the quiet eye period recorded after movement initiation has anything to do with the planning of movement parameters such as force and direction. It is more plausible that, after movement initiation, other processes, such as online control or postural quiescence, play a more important role. For the sake of interpretability, mechanistic research on the quiet eye phenomenon should examine pre and post-movement initiation quiet eye periods separately.

Second, the definition of a quiet eye period appears ambiguous because, even during a fixation, the eyes are never completely still. In fact, small high-frequency movements occur constantly during fixations to make sure that the retinal image does not dissipate (Krauzlis et al., 2017). For this reason, the selection of a threshold criterion below which the eyes are deemed quiet sounds arbitrary (Williams, 2016). An alternative and complementary approach is to measure the amount of eye quietness and observe its changes as a function of time, relative to different phases of the movement. The development of an ‘eye quietness’ index can provide a totally new perspective on the study of ocular activity occurring during the execution of motor skills and, therefore, has to potential to improve mechanistic understanding of the quiet eye.

Third, the almost exclusive reliance on camera-based eye tracking to score the quiet eye period has contributed to the isolation of the quiet eye literature from related fields that examined superior motor performance using alternative methods. For example, if the quiet eye reflects mental processes, a critical research question would be to examine what happens in the brain during the quiet eye period. Unfortunately, the technical difficulty to co-record and synchronize measurements of ocular and brain activity has held back progress on this matter. While researchers have advocated that a multi-measure approach would be highly beneficial to the debate on the mechanisms of the quiet eye (Causer, 2016; Williams, 2016; Wilson et al., 2016) only a handful of studies have managed to do so (Janelle et al., 2000; Mann, Coombes, Mousseau, & Janelle, 2011; Moore, Vine, Cooke, Ring, & Wilson, 2012).

Considered separately, the models of neural efficiency and quiet eye explain well how individuals can achieve superior motor performance. However, the predictions of each model are in sharp contrast with each other. Namely, if the concept of efficiency applied to eye movements in precision sports, one could deduct that, compared to novices, experts should require less – and not more – time focusing on critical spatial locations of the visual scene. As Foulsham (2016) notes, longer fixations generally indicate more difficult or less efficient information processing: for example, dyslexic individuals need longer ocular fixations compared to non-dyslexic individuals. The ‘efficiency paradox’, formally described by Mann et al. (2016), constitutes a substantive theoretical challenge for the quiet eye model and, moreover, it highlights the relative isolation of quiet eye research from other related fields interested in motor expertise.

In a response to Mann et al. (2016), Vickers (2016) argued that the thesis that experts process visual information more quickly than novices is illusory, citing quiet eye findings as proof of her argument. However, this argument does little to solve the efficiency paradox as no independent (non-quiet eye) evidence is provided. The need for a new model that reconciles the divergences between the neural efficiency and quiet eye phenomena is necessary if we wish to advance our understanding of what determines superior motor performance in target sports. A solution of the efficiency paradox requires the adoption of a multi-measure approach where indices of neural and ocular activity are combined and examined concomitantly. To this end, psychophysiology can provide methods for the objective, unobtrusive, and simultaneous registration of activity from multiple biological systems during the execution of movements. Specifically, on the one hand, patterns of brain activity can be examined by recording EEG alpha power, and visual processing can be inferred by analysing the activity of the visual areas of the brain (e.g., Loze et al. 2001; Janelle et al., 2000). On the other hand, ocular activity in target sports can be recorded through electrooculography (EOG), a technique that measures changes in the electro-magnetic potentials produced by eye movements (Gonzalez et al., 2017b; Mann et al., 2011). Interestingly, EEG studies typically include EOG recordings. This is due to the fact the electrical activity generated by the cerebral cortex is orders of magnitude smaller than that generated by eye movements. Typically, EEG researchers consider the EOG signal an artefact and use it almost exclusively to de-noise the EEG signal. A paradigm shift for the integrated analysis of neural and ocular activity is the acknowledgement that the EOG encompasses meaningful information about eye movements and that this information can be extremely valuable to understanding psychomotor processes. Accordingly, bridging the ‘neural’ and the ‘ocular’ branches of research in superior motor performance requires the development of procedures to exploit the complexity of integrated EEG and EOG signals.

Aims of Thesis and Outline of Empirical Chapters

The overarching aim of this thesis is to provide an integrated account of the neural efficiency and quiet eye model in target sports, by using psychophysiological methods. My thesis has four aims. The first aim is to evaluate the utility of the gating-by-inhibition model for the interpretation of changes in regional EEG alpha induced by practice of a closed-loop aiming skill. This aim is addressed in the empirical study described in Chapter Two. In this study, the EEG was recorded from recreational golfers before and after a practice period of approximately 1 week including three sessions. Changes in regional alpha power were explored as mediators of performance improvements as a function of time.

The second aim is to test the explanatory power of the model of neural efficiency as alpha gating by manipulating the need to re-parameterize movement features, such as force and direction, across the repeated execution of a motor skill. This aim is addressed in the empirical study described in Chapter Three. In this study, recreational golfers putted golf balls to the same target in a blocked design whereas others putted to a target varying randomly on each trial in terms of distance and extent, while their EEG was recorded. This study examined whether the need to re-parameterize features of the movement affected neural efficiency defined as the extent and intensity of alpha gating.

The third aim is to develop analytic procedures based on the EOG signal to examine eye movements during the execution of a motor skill. This aim is addressed in the empirical study described in Chapter Four. In this study the EOG was used to score the quiet eye period separately for the pre and post-movement initiation phases and using multiple thresholds. Importantly, this study presents a novel index to measure eye quietness as a function of time.

The fourth aim is to triangulate measures of neural activity, ocular activity, and movement kinematics while recreational golfers performed golf putts to a target. This aim is addressed in the empirical study described in Chapter Five. This study exploits the methods developed in the preceding empirical chapters to test two main mechanisms deemed responsible for the quiet eye phenomenon.

Chapter Six summarizes the findings described in each of the previous empirical chapters and integrates them into a model combining the neural efficiency and quiet eye accounts of superior motor performance. Then, it highlights the limitations of this model and suggests directions for future research. Finally, it presents practical applications that can be useful for athletes to improve their performance.

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CHAPTER TWO

Practice makes efficient: Cortical alpha oscillations are associated with improved golf putting performance

Abstract

Practice of a motor skill results in improved performance and decreased movement awareness. The *psychomotor efficiency* hypothesis proposes that the development of motor expertise through practice is accompanied by physiological refinements whereby irrelevant processes are suppressed and relevant processes are enhanced. The present study employed a test-retest design to evaluate the presence of greater neurophysiological efficiency with practice and mediation analyses to identify the factors accounting for performance improvements, in a golf putting task. Putting performance, movement-specific conscious processing, electroencephalographic (EEG) alpha power and alpha connectivity were measured from 12 right-handed recreational golfers (age: M = 21 years; handicap: M = 23) before and after three practice sessions. As expected, performance improved and conscious processing decreased with training. Mediation analyses revealed that improvements in performance were partly attributable to increased regional gating of alpha power and reduced cross-regional alpha connectivity. However, changes in conscious processing were not associated with performance improvements. Increased efficiency was manifested at the neurophysiological level as selective inhibition and functional isolation of task-irrelevant cortical regions (temporal regions) and concomitant functional activation of task-relevant regions (central regions). These findings provide preliminary evidence for the development of greater psychomotor efficiency with practice in a precision aiming task.

Introduction

Practice of a motor skill typically results in improved movement execution and performance. According to the psychomotor efficiency hypothesis (Hatfield & Hillman, 2001), such improvements are accompanied by the suppression of task-irrelevant processes (e.g., diverting resources away from cortical regions that have limited relevance for the task) and the enhancement of task-relevant processes (e.g., redirecting resources to the most important cortical regions for task-performance). At the neurophysiological level, a compelling body of research has found indirect support for this hypothesis by revealing that, while performing precision skills such as golf putting, shooting, and archery, expert athletes manifest greater neural efficiency than novices (for review see Cooke, 2013; Hatfield et al., 2004). By adopting a test-retest design, the aim of the current study was to test the psychomotor efficiency hypothesis. Specifically, we examined (a) whether practice of a motor skill over time leads to neurophysiological adaptations compatible with increased psychomotor efficiency, and (b) whether such adaptations account for improvements in movement performance.

Most research relating to neural efficiency in precision sports has examined electroencephalographic (EEG) activity in preparation for action and during movement execution. The EEG measures time-varying changes in voltages from an array of scalp electrodes and reflects post-synaptic potentials in the pyramidal neurons of the cerebral cortex (Nunez & Srinivasan, 2006). The interplay of these potentials generates oscillations at different frequencies, including alpha oscillations (around 8-12 Hz), which are thought to play a major role in shaping the functional architecture of the cortex due to their proposed inhibitory function (Klimesch, 2012). Specifically, the magnitude of alpha oscillations – i.e., alpha power – can influence regional activation in the cortex through a gating mechanism whereby resources are diverted away from regions showing higher alpha power (i.e., more inhibition) and towards regions showing lower alpha power (i.e., lower inhibition) (Jensen & Mazaheri, 2010).

The study of alpha oscillations in precision sports has revealed that experts display higher alpha power over the temporal regions (e.g., Haufler et al., 2000; Janelle et al., 2000) and lower alpha power over the central regions (e.g., Cooke et al., 2014) of the cortex compared to novices while preparing for movement execution. Additionally, experts and novices show different time dynamics of alpha power. For example, Cooke et al. (2014) observed a biphasic pattern of alpha oscillations that was stronger for experts than novices: alpha power showed an initial increase followed by a sudden drop in the last second preceding movement initiation. Taken together these findings suggest the presence of a pattern of cortical activity across the scalp where the timely inhibition of some cortical regions (e.g., temporal) and the lack of inhibition of other regions (e.g., central) can be related to the development of motor expertise.

Complementing the study of the regional and temporal dynamics of alpha power, a few studies have examined the functional connectivity among alpha oscillations across different regions of the cortex. Alpha connectivity between two regions represents the extent to which the alpha activity of those regions is functionally connected (i.e., frequency-specific cortico-cortical communication between different regions). Based on the assumption that alpha reflects inhibition (Klimesch, 2012), alpha connectivity indicates the strength of the functional connection between the inhibition of one region and the inhibition of another region. For example, greater alpha connectivity could be interpreted to reflect two regions engaging in similar and consistent inhibition, whereas lower connectivity may indicate distinct inhibition profiles.

Research in precision sports has revealed that, compared to novices, experts display lower left temporal:frontal alpha connectivity, reflecting a functional disconnection between alpha oscillations of the left temporal region and alpha oscillations of the frontal region (e.g., Gallicchio et al., 2016). Building upon the notion that the left temporal and the frontal regions are involved in language and movement planning respectively, reduced left temporal:frontal alpha connectivity has been interpreted as a marker of the selective inhibition of the left-hemisphere and decreased cognitive/verbal interference during preparation for movement execution (Deeny et al., 2003).

More recently, a series of studies has associated left temporal:frontal alpha connectivity with the propensity to consciously monitor and control one's movements – i.e., movement-specific conscious processing – during golf putting (Gallicchio et al., 2016; Zhu et al., 2011). Three lines of evidence support these views. First, lower left temporal:frontal alpha connectivity in preparation for putting as well as lower putting-related conscious processing were found for expert golfers compared to novices (Gallicchio et al., 2016). Second, individuals who were dispositionally less prone to engage in conscious processing displayed lower left temporal:frontal alpha connectivity prior to putting compared to individuals more prone to engage in conscious processing (Zhu et al., 2011). Third, novice golfers who were trained implicitly, which was associated with lower conscious processing, showed decreased left temporal:frontal alpha connectivity when putting compared to novice golfers who were trained explicitly (Zhu et al., 2011).

Taken together, these findings suggest that decreased left temporal:frontal alpha connectivity and decreased movement-specific conscious processing are features of expertise. This is in line with classic theories of motor skill learning that argue that the development of motor expertise is accompanied by a gradual withdrawal of cognitive analysis and decreased awareness of one's movements (e.g., Fitts & Posner, 1967). These theories suggest that, following extensive practice, individuals can progress from a cognitive stage, characterized by deliberate and conscious analysis of movement, to an autonomous stage, characterized by automatic control of movement.

While the extant literature argues for greater neural efficiency as expertise develops, some potential limitations still need to be overcome. First, the putative link between expertise and neural efficiency is mostly based on expert-novice differences seen in cross-sectional designs. These findings do not provide a direct test of the hypothesis that practice leads to greater neural efficiency because of the unfeasibility of randomly allocating participants to either the expert or the novice group. For example, it could be that, irrespectively of practice, individuals who show greater neural efficiency are more likely to become experts compared to individuals who show lower neural efficiency. To date, only two studies have examined the effects of practice on neural efficiency using a longitudinal design (Kerick et al., 2004; Landers et al., 1994). These studies found that performance improvements in archery (Landers et al., 1994) and pistol shooting (Kerick et al., 2004) after three months of training were associated with increased alpha power over the left temporal region of the cortex. However, they did not examine any practice-induced changes in cortical connectivity. Second, no study to date has examined the neurophysiological factors accounting for the development of expertise. Within-subject mediation analyses (Judd, Kenny & McClelland, 2001) can be used to examine changes in neural efficiency as a function of performance improvements and thereby shed some light on the mechanisms responsible for the improvements associated with practice.

Third, most studies have employed global measures of performance (e.g., hits versus misses, distance from the target) that can potentially obscure the individual contribution of distinct parameters involved in movement planning and execution. For example, the movement of a golf ball putted on a flat surface can be conceptualized as a vector having a certain direction and force. Indeed, there is good evidence that there are different neuronal populations that respond selectively to changes in movement direction and force (e.g., Riehle & Requin, 1995). Accordingly, the examination of angle and length errors, respectively associated with movement direction and force, can provide more refined measures of performance that may be differentially sensitive to changes in neural efficiency.

The present exploratory study was designed to address these limitations. Our aims were threefold. First, to describe the neurophysiological adaptations that accompany the development of expertise through practice. Second, to identify neurophysiological mediators that account for changes in performance and movement-specific conscious processing with practice. Third, to evaluate the differential impact of movement direction and force planning on neurophysiological activity. Data were collected in the context of a study designed to examine the efficacy of a neurofeedback training protocol on golf putting performance (Ring et al., 2015). Here we report new analyses that were conducted on the data of the control group who underwent putting training sessions while receiving sham neurofeedback (i.e., who did not receive genuine feedback of cortical activity). We expected that performance would improve with practice and that these improvements would be mediated by increased regional gating of alpha power, reduced cross-regional alpha connectivity, as well as reduced movement-specific conscious processing, in accord with the predictions of the psychomotor efficiency hypothesis.

Method

Participants

Twelve right-handed male recreational golfers took part in this study (age: *M* = 21.00, *SD* = 2.52 years). The participants reported a mean golf experience of 4.63 years (*SD* = 2.89) and a mean golf handicap of 23.33 (*SD* = 4.62). All participants provided informed consent.

Putting task

Golf balls (diameter 4.7 cm) were putted on an artificial flat putting surface (Turftiles) to a hole (diameter 10.8 cm) at a distance of 2.4 m, using a blade-style putter (length 90 cm). The participants were instructed to get each ball "ideally in the hole, but if unsuccessful, to make them finish as close to the hole as possible."

Training

In each 1-hour training session participants practiced putting. Participants wore a cap with one frontal scalp electrode and reference and ground electrodes placed on the left and right mastoids respectively. They were instructed to try to regulate the pitch of a tone by changing their brain activity while preparing for putting and then to putt the ball when the tone was silenced. Specifically, they would stand over the ball and hear the pitch of a tone increase and decrease, and occasionally go silent for 1.5 seconds, which was a cue to putt. In reality, the tone was independent of their brain activity (i.e., sham neurofeedback), and was yoked to an experimental participant who received genuine neurofeedback: thus the sham feedback participants acted as controls in Ring et al. (2015). Each training session comprised twelve 5-minute blocks.

Procedure

A test-retest design was employed, with participants visiting the laboratory on five different days: putting task on day 1 (i.e., test); training on days 2-4; putting task on day 5 (i.e., retest). On average, the test-retest interval was 8.17 (*SD* = 5.24) days and the final training session to retest session interval was 2.00 (*SD* = 2.59) days. In the test and retest sessions, participants were instrumented for EEG recording, instructed, then completed 20 familiarisation putts followed by 50 test putts. In each of the three training sessions separating the test and retest sessions, participants completed a mean of 181.25 (*SD* = 52.25) practice putts. Thus, the total number of putts in training was 543.75 (*SD* = 127.01). The study protocol was approved by the local research ethics committee.

EEG Recording

In the test and retest sessions 32 active electrodes were positioned on the scalp, according to the 10-20 system, at: Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2. In addition, four active electrodes were placed at the bottom and at the outer canthus of both eyes. Common mode sense and driven right leg electrodes were used to enhance the common mode rejection ratio of the signal. The signal was amplified and digitized at 512 Hz with 24-bit resolution, using the ActiveTwo recording system (Biosemi, Netherlands). Signals were down-sampled offline to 256 Hz, 1-35 Hz band-pass filtered (FIR, order 512), and re-referenced to the average of all EEG channels. Channels with bad signals were removed and interpolated prior to averaging. Non-neural activity was minimized using the Artifact Subspace Reconstruction plugin for EEGLAB (Delorme & Makeig, 2004). Epochs were extracted from –3.25 to +1.25 s relative to the initiation of the backswing, which was triggered when the putter head broke the beam of an optical sensor interfaced with the ActiveTwo recording system.

Time-frequency decomposition was performed through short-time Fast Fourier Transform (FFT) on 33 overlapping segments each of the duration of 0.5 s and linearly spaced with centre points ranging from –3 to +1 s. Prior to FFT, each segment was also Hanning-windowed to taper both ends to 0 and then 0-padded to reach 2 s duration. This procedure generated complex-valued FFT coefficients in the time-frequency plane with a precision of 0.125 s and 0.5 Hz. Six Regions Of Interest (ROIs) were identified: left temporal (FC5, T7, CP5), left central (FC1, C3, CP1), frontal (F3, Fz, F4), right central (FC2, C4, CP2), right temporal (FC6, T8, CP6), and occipital (O1, Oz, O2). Signal processing was performed using the EEGLAB toolbox (Delorme & Makeig, 2004) and MATLAB

(MathWorks, USA).

Measures

Putting performance. The number of holed putts out of 50 was recorded in the test and retest sessions. Additionally, three performance errors – radial (cm), angle (degrees), and length (cm) errors (Supplemental Material of Chapter Two, Figure S1) – were computed for each putt using a camera system (Neumann & Thomas, 2008) and averaged (geometric mean) to yield measures for the test and retest sessions.

Alpha power. Power (μV^2) was computed in the time-frequency plane separately for each channel and trial (i.e., putt) as the product between each FFT coefficient and its complex conjugate (i.e., equivalent to amplitude squared). Importantly, no baseline was employed. Instead, skewness and inter-individual differences in the power density distributions were dealt with by employing a median-scaled transformation: each participant's values were scaled by their median and then log-transformed (10·log10). This procedure meant that power was normally distributed with a mean of zero for each participant, without altering within-subject relations. Power was then averaged across time (–3 to –2 s, –2 to –1 s, –1 to 0 s,0 to +1 s, where zero represents initiation of the backswing), channels (ROIs), putts, and frequency (10-12 Hz) to yield estimates of alpha oscillatory power in each session (test, retest). Alpha is typically around 8-12 Hz, however, we focused on the upper portion of this range, (i.e. 10-12 Hz) on the basis of spectral features that were evident in the current data (see Supplemental Material of Chapter Two, Figure S4).

Alpha connectivity. Inter Site Phase Clustering (ISPC) was computed as the length of the complex-valued resultant of cross-trial clustering of unitary complex vectors having as angle the phase difference between channel pairs for each point of the time-frequency plane (M.X. Cohen, 2014; Lachaux et al., 1999). ISPC measures the phase lag consistency across trials (i.e., putts) between two channels independently from their power and reflects the functional connectivity between the oscillatory activity of two underlying cortical regions, with values ranging from 0 (no connectivity) to 1 (perfect connectivity). The impact of volume conduction on connectivity was examined by taking the absolute imaginary part of the Inter Site Phase Clustering (imISPC) (cf. Nolte et al., 2004). Like ISPC, imISPC reflects functional connectivity with values ranging from 0 to 1, however, imISPC is insensitive to instantaneous connectivity (i.e., 0- or π- lagged) and therefore values are much smaller than ISPC. No baselines were used. Instead, to normalize their density distributions, ISPC and imISPC were Fisher Z-transformed (inverse hyperbolic tangent); values could range then from 0 to ∞. Values were then averaged (arithmetic mean) across time (–3 to –2 s, –2 to –1 s, –1 to 0 s, 0 to +1 s), channel (ROI) pairs, and frequency (10-12 Hz) to yield estimates of alpha connectivity in each session (test, retest).

Conscious processing. Self-reported conscious processing was measured immediately after completing the putting task in the test and retest sessions using a putting-specific version (Cooke et al., 2011; Vine et al.,2013) of the conscious motor processing sub-scale of the Movement Specific Reinvestment Scale (Orrell, Masters, & Eves, 2009). This scale consists of six items scored on a 5-point Likert scale (1 = *never*, 3 = *sometimes*, 5 = *always*) related to the feeling of awareness of the kinematics involved in execution of the putt and thoughts about putt outcome. The six items were averaged to generate a single scale score. Past research (Cooke et al., 2011; Vine et al., 2013) has established the reliability (α = .81-.88) and validity of the putting-specific version of the conscious motor processing sub-scale of the Movement Specific Reinvestment Scale.

Statistical Analyses

Performance and conscious processing. Changes from test to retest in putting performance and conscious processing were examined by paired-sample t-tests. Within each session the relation between the number of holed putts and the three performance errors was examined through Pearson's correlations.

Alpha power and connectivity. Power was subjected to a 2 Session (test, retest) × 6 ROI (left temporal, left central, frontal, right central, right temporal, and occipital) × 4 Time (–3 to –2, –2 to –1, –1 to 0, 0 to +1 s) ANOVA. In addition, contrast analyses were performed to examine changes in power over time. ISPC and imISPC were each subjected to 2 Session × 4 Time ANOVAs, conducted separately on each of two ROI pairs (left temporal:frontal, right temporal:frontal), chosen on the basis of previous literature (Deeny et al., 2003, 2009; Gallicchio et al., 2016; Zhu et al., 2011). The multivariate solution was reported in the ANOVAs where appropriate (Vasey & Thayer, 1988). Significant main effects were interrogated using post hoc testing. Partial eta-squared (η^2_p) and r^2 are reported as measures of effect size: values of .02, .13, and .26 were taken to reflect small, medium, and large effects, respectively (J. Cohen, 1992).

Mediation. Mediation analyses were conducted to test whether changes across sessions in the number of holed putts could be accounted for by changes in performance errors, conscious processing, alpha power, and alpha connectivity. We also tested whether changes in conscious processing could be attributed to changes in alpha power and connectivity. We used the procedure described by Judd et al. (2001) for repeated-measures designs: multiple regression was used to predict the test to retest change in the dependent variable based on the test to retest change in the potential mediator variable, while controlling for its mean-centred sum. Full mediation can be inferred when the regression coefficient associated with the change in the mediator variable is significant (i.e., $p < .05$), and partial mediation is inferred when the coefficient associated with the intercept is also significant. The following strategy was adopted to reduce the likelihood of type-I errors: we first assessed whether the change in the number of holed putts was mediated by changes in any of the potential mediator variables, and only if this was the case were mediation analyses conducted on the changes in the performance errors and conscious processing.

Results

Putting performance

Overall, every putting performance measure improved with training from test to re-test (Table 2.1). However, there were considerable individual differences: not all participants improved equally and in fact a few got worse (Supplemental Material of Chapter Two, Figure S2). The number of holed putts was highly negatively correlated with the three performance errors (rs = –.77 to –.92, ps < .003), with angle error the highest (Supplemental Material of Chapter Two, Table S1).

Table 2.1. Descriptive statistics of putting performance as a function of session together with the results of the paired-sample t-tests.

	Test *M (SD)*	**Retest** *M (SD)*	***t*(11)**	***p***	***r*²**
holed putts (0-50)	12.17 (2.39)	16.25 (2.97)	2.18	.05	.301
radial error (cm)	10.95 (1.59)	8.05 (1.23)	2.26	.04	.317
angle error (degrees)	1.39 (0.12)	1.17 (0.14)	1.74	.11	.215
length error (cm)	8.80 (1.27)	6.42 (0.95)	2.22	.05	.310

Alpha power

The 2 Session × 6 ROI × 4 Time ANOVA conducted on EEG power revealed a large main effect of ROI, $F(5,7) = 105.49$, $p < .001$, $\eta^2_p = .987$. Post-hoc Scheffé tests indicated ($p < .001$) that power was higher in the occipital than left/right temporal and frontal regions, which, in turn, were higher than left/right central regions (Figure 2.1A). Power tended to be lower in the retest session than the test session (Figure 2.1B), *F*(1,11) = 0.78, *p* = .40, η^2_p =.066, in all regions (left temporal Δ = –0.55; left central Δ= –0.40; frontal Δ= –0.28; right central Δ = –0.23; right temporal Δ = –0.66) except the occipital region (Δ = 0.40). Although no clear omnibus time effect was evident, *F*(3,9) = 2.93, *p* = .09, η^2_p = .494, the effect size was large, and, therefore, we performed contrast analyses to characterize the a priori predicted changes in power in the moments surrounding movement; a series of 4 Time ANOVAs (contrast codes: 0, 1, –2, 1) were conducted separately for each session and ROI. This quadratic trend was not displayed in the test session, *F*s(1,11) = 0.02-0.74, *p*s = .41-.89, η^2_ps = .002-.063,with the sole exception of the left temporal region, *F*(1,11) = 4.10, *p* = .07, η^2_p = .271, but was clearly evident in all regions in the retest session, *F*s(1,11) = 12.57-4.01, *p*s = .005-.07, η^2_ps = .267-.533. This implies a practice-induced time-varying change in alpha power, characterized mainly by a reduction in power during the final second before movement following practice during the retest session (Figure 2.1B).

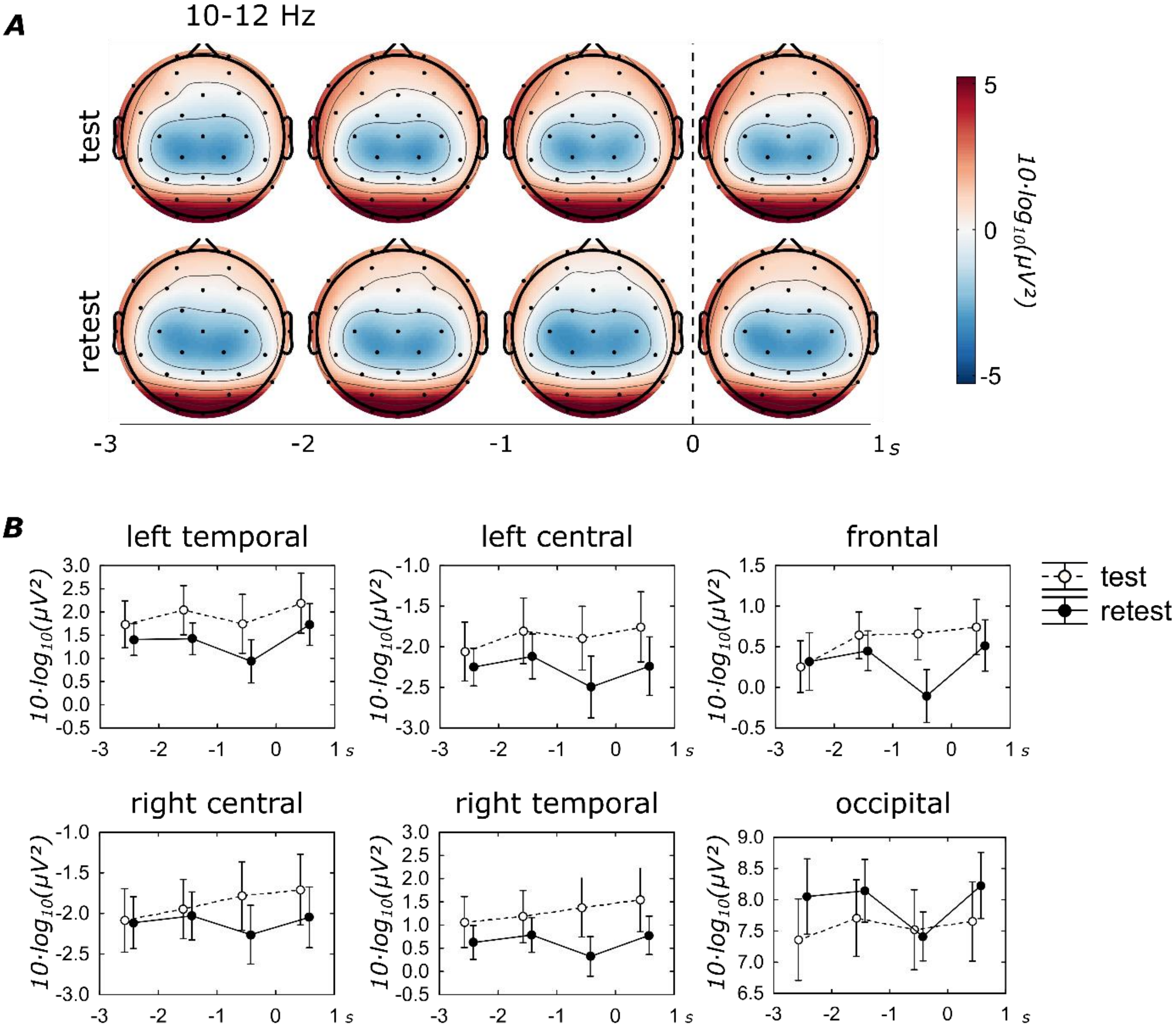

Figure 2.1. (A) Scalp maps representing alpha power (10·log10(μV²)) averaged across participants, as a function of session (test, retest), time (–3 to +1 s), and channel. (B) Alpha power (10·log10(μV²)) averaged across participants, as a function of session (test, retest) and time (–3 to +1 s) in the six regions. Error bars represent the standard error of the mean.

Alpha connectivity

The 2 Session × 4 Time ANOVAs on the left temporal:frontal connectivity indices (Figure 2.2) revealed no main effects for session (ISPC: Δ = 0.01, $F(1,11) = 1.02$, $p = .34$, $\eta^2_p = .085$; imISPC: Δ = –0.004, $F(1,11) = 0.35$, $p = .57$, $\eta^2_p = .031$) or time (ISPC: $F(3,9) = 0.77$, $p = .54$, $\eta^2_p = .203$; imISPC, $F(3,9) = 3.46$, $p = .06$, $\eta^2_p = .536$). Similarly, no effects emerged with right temporal:frontal connectivity (Figure 2.2) as a function of session (ISPC: Δ = 0.01, $F(1,11) = 0.75$, $p = .41$, $\eta^2_p = .064$; imISPC: Δ = 0.008, $F(1,11) = 2.512$, $p = .14$, $\eta^2_p = .186$) and time (ISPC: $F(3,9) = 0.63$, $p = .61$, $\eta^2_p = .174$; imISPC: $F(3,9) = 0.69$, $p = .58$, $\eta^2_p = .187$). No session by time interactions emerged. Finally, the results from all ROI pairs are reported in the Supplemental Material of Chapter Two (Figure S5) for interested readers.

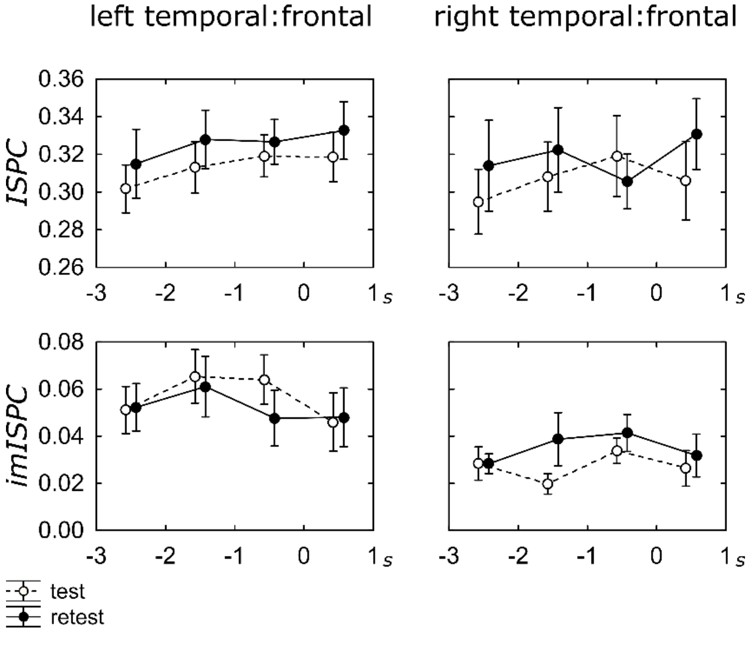

Figure 2.2. Left / right temporal:frontal alpha ISPC and imISPC averaged across participants as a function of session (test, retest) and time (–3 to +1 s). Error bars represent the standard error of the mean.

Conscious processing

Overall conscious processing decreased from test (M = 3.88, SD = 0.20) to retest (M = 3.36, SD = 0.24), $t(11)$ = 2.59, p = .03, r^2 = .378. Again, there were large individual differences in the extent of this change, with four participants opposing the trend by reporting the same or greater conscious processing after training (Supplemental Material of Chapter Two, Figure S3).

Mediators of the change in putting performance

Putting performance improved with practice. On average, participants holed 4.08 more balls (i.e., an 8.2% improvement) in the retest session compared to the test session. Judd et al.'s (2001) regression-based within-subject mediation analyses indicated that this improvement was fully mediated by the reduction in angle error from test to retest (b = –9.82, p = .008); the intercept (a = 1.89, p = .21) indicated that, had angle error not changed from test to retest, the improvement would have been reduced to only 1.89 additional holed putts, which represents a non-significant change in performance. Neither radial error (b = –0.88, p = .06) nor length error (b = –0.81, p = .17) mediated performance improvement. Further, conscious processing did not mediate the change in performance (b = –1.23, p = .70).

In terms of alpha power, the improvement in putting performance was partially mediated by the change in left temporal power in the seconds surrounding backswing initiation (–1 to 0 s: b = 2.46, p = .04; 0 to 1 s: b = 2.07, p = .04; see Figure 2.3). Since power tended to decrease with practice (Figure 2.1B), smaller reductions in left temporal power from test to retest were associated with larger improvements in performance. Based on the associated intercepts (–1 to 0 s: a = 6.07, p = .005; 0 to 1 s: a = 5.04, p = .01), this means that an individual who increased their left temporal power from test to retest in the second before backswing initiation would be predicted to hole at least two more putts whereas someone who increased power from test to retest in the second after initiation would be predicted to hole at least one more putt. Furthermore, left temporal power within the –1 to 0 s interval also partially mediated the reduction in angle ($b = –0.19$, $p = .03$) but not radial ($b = –1.72$, $p = .06$) or length ($b = –1.33$, $p = .09$) errors (Supplemental Material of Chapter Two, Figure S6).

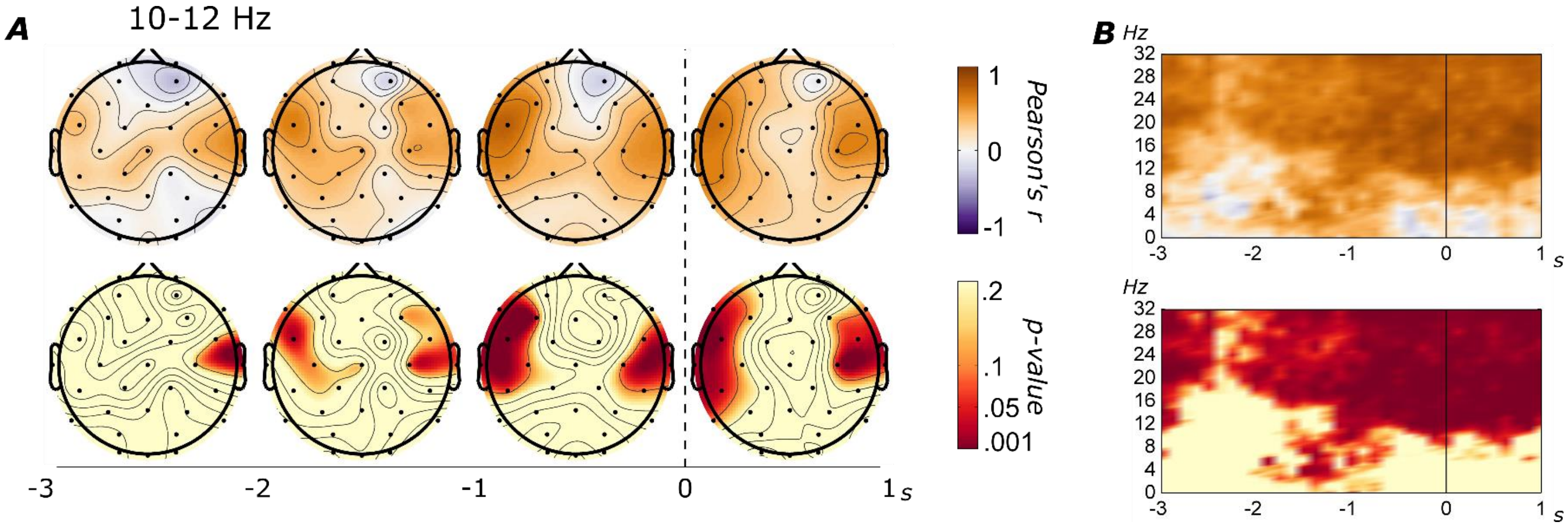

Figure 2.3. (A) Scalp maps representing Pearson's correlations conducted on the inter-session change scores between the number of holed putts and alpha power, as a function of time (–3 to +1 s) and channel. (B) Time-frequency plots representing Pearson's correlations conducted on the inter-session change scores between the left temporal alpha power ($10 \cdot \log10(\mu V^2)$) and the number of holed putts, as a function of time (–3 to +1 s) and frequency (0 to 32 Hz).

In terms of alpha connectivity, putting performance was partially mediated by the inter-session change in left temporal:frontal ISPC within the –2 to –1 s interval (*b* = –120.60, *p* = .01). Since ISPC tended to increase with practice (Figure 2.2), smaller increases in left temporal:frontal connectivity from test to retest were associated with larger improvements in putting performance. Based on the intercept (*a* = 5.88, *p* = .004), performance would be predicted to improve by at least two more holed putts if left temporal:frontal ISPC decreased within this time interval. The same analysis conducted on imISPC also revealed a negative relation, (*b* = –53.02, *p* = .28). Furthermore, left temporal:frontal ISPC within the –2 to –1 s interval also partially mediated the reduction in angle (*b* = 6.35, *p* = .05), but not radial (*b* = 56.97, *p* = .13) and length (*b* = 35.52, *p* = .28) errors.

Right temporal:frontal ISPC and imISPC did not mediate the improvement in putting performance (*p*s = .19-.93). Lastly, mediation analyses on all ROI pairs (Supplemental Material of Chapter Two, Figure S7A, B) indicated that the relation between smaller increases in left temporal:frontal ISPC and greater performance improvement extended to a network linking the left temporal region to the other cortical regions.

Mediators of the change in conscious processing

On average, participants reported less conscious processing (Δ = –0.52) from test to retest. This reduction in conscious processing was fully mediated (*a* = –0.34, *p* = .09) by the change in left temporal:frontal ISPC within the –2 to –1 s interval (*b* = –11.87, *p* = .03), whereby decreases in conscious processing were associated with increases in ISPC. Finally, the mediation analyses involving all ROI pairs (Supplemental Material of Chapter Two, Figure S7C, D) showed that changes in conscious processing were related to changes in connectivity across a broad network of cortical regions.

Discussion

Performance improved from test to retest. That retention was assessed a couple of days after the end of training provided evidence for motor learning (e.g., Salmoni, Schmidt & Walter, 1984). The primary aim of this exploratory study was to identify the neurophysiological factors that mediate changes in motor performance with practice. Improvements in golf putting performance from before (test) to after (retest) completing three training sessions were mediated by EEG alpha power and alpha connectivity in preparation for putting but not by self-reported conscious processing.

Alpha power

Spectral analyses revealed a distinct 10-12 Hz peak compatible with the alpha rhythm (see Supplemental Material of Chapter Two, Figure S4), and therefore activity within this frequency range was interpreted as reflecting cortical alpha oscillations. Alpha activity was displayed across the different regions of the cortex in a focal pattern: power was lowest over the central regions, medium over the temporal regions, and highest over the occipital region. In line with the gating-by-inhibition hypothesis (Jensen & Mazaheri, 2010) the observed regional pattern suggests that neuronal resources were taken away from occipital and temporal regions (i.e., highest inhibition) and diverted towards the central regions (i.e., lowest inhibition) during movement preparation. This focal pattern, which was evident in both test and retest sessions, could reflect the prior practice history of our participants, who were all experienced golfers, and therefore had already developed a degree of psychomotor efficiency related to the putting movement.

Efficiency-based changes in alpha power due to training can be inferred from our mediation analyses. Importantly, they suggested that participants who were able to sustain a relatively higher power in the temporal regions from test to retest in the seconds surrounding movement improved their putting performance the most. This effect was localized to the left (and to a lesser extent, the right) temporal region and can be interpreted in terms of alpha gating: increased inhibition in regions not directly involved in putting-relevant processing is beneficial to putting. That this effect was absent in the occipital region is most likely because occipital inhibition was already the strongest among the regions examined and tended to strengthen further with training. In other words, likely there was a ceiling effect for occipital alpha, whereby further increases did not benefit performance.

It is also worth noting that while a relatively higher level of temporal alpha power was beneficial, practice also prompted a decrease in power, especially at the frontal region, in the final second preceding movement. This quadratic trend for time-varying alpha power in the retest session could be interpreted as reflecting the timely allocation of resources to putting-relevant processing (Cooke et al., 2015). Indeed, this quadratic pattern is consistent with previous research and has been associated with expertise and successful performance in experts (Babiloni et al., 2008; Cooke et al., 2014). However, as this quadratic decrease in alpha power at retest did not mediate changes in performance, the inhibition of irrelevant cortical regions seems to have been more important for performance improvement than the timely activation of relevant ones. This remains a topic for future research, which may consider variables such as task and experience as potential moderators of any effects.

Alpha connectivity

Functional connectivity was examined between the temporal and frontal regions using two indices based on the consistency of cross-regional phase lag across trials: ISPC and imISPC.

The latter is a conservative version of the former that is not biased by volume conduction. The fact that 10-12 Hz imISPC was non-zero (Figure 2.2) indicated the likely presence of genuine alpha connectivity. Neither connectivity index changed across the time intervals or from test to retest. However, mediation analyses suggested that greater improvements in performance from test to retest were achieved by participants displaying relatively lower left temporal:frontal connectivity a couple of seconds before putt initiation. Low left temporal:frontal alpha connectivity has been associated with expertise and successful putting performance in experts (Babiloni et al., 2011; Gallicchio et al., 2016). At the neurophysiological level, lower connectivity represents a stronger disconnection between the two signals – i.e., left temporal alpha and frontal alpha – provided that the two signals are not projections of the same source generator because of volume conduction within the head.

The additional analyses performed on a wider network of regions (Supplemental Material of Chapter Two, Figure S7) revealed that performance improvements were not exclusively associated with a stronger disconnection of alpha activity between left temporal and frontal regions. Rather, it is evident that improved performance was associated with a functional isolation of left temporal alpha from many other regional alpha activities. Taken together, these analyses provide preliminary support for our hypothesis that improvements in performance with practice would be mediated by reduced connectivity (i.e., less cortico-cortical communication) between alpha oscillations in the left temporal region and other regions of the cortex, including the frontal region (cf., Deeny et al., 2003; Gallicchio et al., 2016; Zhu et al., 2011).

Conscious processing

Movement-specific conscious processing decreased and performance improved with practice, in line with the classic theories of motor skill learning (e.g., Fitts & Posner, 1967).

However, mediation analyses did not support the putative link between decreased conscious processing and performance improvement. Similarly, Malhotra et al. (2015) also found no relation between improvements in putting performance and changes in conscious processing with training. It should be noted that these two null findings reflect the absence of a linear relation; however, our analyses indicate a curvilinear relationship: participants who reported a moderate decrease in conscious processing improved more than those who reported a large decrease, no change, and even a small increase in conscious processing (Supplemental Material of Chapter Two, Figure S8). It has been increasingly recognized that conscious processing does not always negatively impact performance but can foster performance improvements in experts (Toner & Moran, 2014) and novices (Malhotra et al., 2015). Given these findings it would be fruitful for future research to seek to identify optimal levels of conscious processing as a function of factors such as task, expertise and personality. Such research should also consider sub-components of conscious processing, for instance, distinguishing conscious monitoring and conscious control (Toner & Moran, 2011), particularly when they are about to putt, which should be able to paint a better picture of what individuals attend to in the moments before movement initiation.

Mediation analyses suggested that decreases in conscious processing from test to retest were associated with increases in alpha connectivity across a network involving all cortical regions examined (Supplemental Material of Chapter Two, Figure S7). Higher connectivity represents a stronger connection between the alpha oscillations, and therefore suggests that decreased movement-specific conscious processing or awareness of one’s movements is associated with multiple cortical regions engaging in similar and consistent inhibition (cf. Baars, 2002). This interpretation awaits confirmation.

Performance errors

The analyses of the three performance metrics – i.e., radial, angle, and length errors – revealed that improvements in the number of holed putts with practice was largely due to reductions in angle error rather than radial or length errors. This finding suggests that a more precise alignment of the putter head with the ball at the moment of impact is more beneficial to putting outcome than appropriate impact velocity (Cooke et al., 2010). Additionally, all of the significant associations observed between EEG activity and putting performance errors were found for angle error, suggesting that programming of movement direction is better reflected in alpha activity than movement force. Although there is evidence that movement direction and force are selectively coded by different neuronal populations (e.g., Riehle & Requin, 1995), future research is needed to clarify the relationship between alpha oscillations, on the one hand, and programming of movement parameters, on the other hand.

Limitations and future research

The current study yielded some novel and important findings regarding the causal relations among practice, cortical efficiency, conscious processing and performance. However, their interpretation should be considered in light of potential limitations. First, although the putting task was completed under ecologically valid conditions, the training cannot be considered a form of discovery learning because participants received sham neurofeedback. Moreover, we did not employ a control group who did not receive any form of neurofeedback. We cannot determine the impact of the current training protocol and therefore future research should consider replicating our findings using other forms of training, including discovery learning, and appropriate control groups.

Second, we refrained from interpreting activity in different cortical regions in terms of specific cognitive processes because we did not measure nor manipulate cognition directly. We acknowledge that the presence of a certain regional activation makes some cognitive processes more likely to be involved than others, however, we avoided reverse inference (Poldrack, 2006) and postponed interpretation. Indeed, it would be worth studying the relation between regional activation and cognitive processes using experimental designs where cognition is manipulated (rather than simply measured) in the context of precision aiming.

Third, the use of spectral decomposition on (inherently non-stationary) EEG signals implies that power is likely to be greater than 0 at any unfiltered frequency, irrespectively of the presence of actual neural generators oscillating at that frequency. The distinct 10-12 Hz power peak in the group-averaged frequency plots (see Supplemental Material of Chapter Two, Figure S4) supported the likely presence of cortical oscillations within this frequency band. However, the use of a fixed range did not account for individual variations. Future studies could individually adjust these ranges to obtain greater specificity and sensitivity (cf. Klimesch, 1999).

Fourth, we considered measures of alpha as candidates to mediate the main effect of session on performance despite having non-significant main effects themselves. This strategy is in line with current guidelines recommending that mediation only requires the existence of an effect to be mediated (i.e., change in performance) for that effect to be indirectly influenced by the mediator variables (e.g., alpha power) (Preacher & Hayes, 2004). Our approach satisfies these criteria, nonetheless, we did not manipulate any of the mediator variables, and therefore the outcome variable (i.e., performance) may have influenced the mediatior variables (Cooke et al., 2015). It would be useful to replicate these analyses in larger samples with more statistical power where the mediators are manipulated independently of the outcome variables, using, for instance, brain stimulation or neurofeedback training.

Fifth, the greater relative importance of the angle error over radial and length errors is potentially biased by the presence of an actual hole, which may have influenced our performance measurements, particularly in regards to length error. For example, balls can be redirected by the hole (e.g., a lip out) and most balls that dropped into the hole would otherwise have rolled past the hole had the hole not been present, introducing variability that cannot be accounted for by the measurements. Future studies could use a mark on the mat instead of a hole to overcome this limitation.

Finally, we only tested experienced golfers that arguably lay somewhere between the cognitive and the autonomous stage of learning (cf. Fitts & Posner, 1967). Given that the particular stage of learning that the individual is in may moderate the adaptations in alpha gating and connectivity with training, future research could examine these learning-related adaptations in novices and experts as well as experienced individuals.

Conclusions

This exploratory study provides preliminary evidence that practice of a motor skill leads to neurophysiological adaptations compatible with the psychomotor efficiency hypothesis (Hatfield & Hillman, 2001). Efficiency was manifested as selective inhibition and functional isolation of task-irrelevant cortical regions and concomitant functional activation of task-relevant regions. Our findings suggest that processing in broadly central regions (cf., Andersen & Buneo, 2002; Desmurget et al., 2009) is more important than processing in temporal regions (cf., Kerick et al., 2001) while performing a precision aiming task, such as golf putting. These findings imply that larger improvements in precision aiming performance with practice may be achieved by employing training protocols that foster suppression of task-irrelevant processes.

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CHAPTER THREE

Don't look, don't think, just do it! Towards an understanding of alpha gating in a discrete aiming task

Abstract

Prior to and during movement, oscillatory alpha activity gates cognitive resources towards motor areas of the cortex by inhibiting neuronal excitability in non-motor areas. The present study examined the effect of manipulating target variability on this alpha gating phenomenon. Using a baseline-test-retention design, we measured EEG alpha power, performance accuracy and task difficulty in 32 recreational golfers as they putted golf balls (20 per target) to one central target (baseline, retention) and four targets of different directions and extents (manipulation). For participants in the random group (n = 16) target location varied with each repetition in a random fashion whereas for participants in the blocked group (n = 16) it was kept constant within blocks. Regional analyses revealed a focal pattern of lower central alpha and higher occipital and temporal alpha. This topography was specific to preparation for movement and was associated with performance: smallest performance errors were preceded by decreased central combined with increased occipital alpha. The random group performed worse than the blocked group and found the task more difficult. Importantly, left temporal alpha prior to movement onset was lower for the random group than the blocked group. No group differences were found at baseline or retention. Our study proved that alpha gating can be altered by manipulating inter-trial variability and thereby demonstrated the utility of the alpha gating model. Our findings

underscore the importance of inhibiting occipital and left temporal areas when performing movements, and provide further evidence that alpha gating reflects neural efficiency during motor tasks.

Introduction

The willful and repeated execution of an action induces a series of psychomotor adaptations consistent with increased efficiency (Brener, 1986). At the neurophysiological level, the brain becomes better at discriminating processes that are functional to optimal execution from those that are not; with repetition, the former are enhanced and the latter suppressed (Hatfield & Hillman, 2001; Hatfield, 2018). The execution of an action is characterized by a distinctive spatiotemporal pattern in the electroencephalogram (EEG), involving oscillatory activity within the alpha frequency (i.e., around 10 Hz) band. Specifically, prior to and during movement, alpha decreases over motor areas of the cortex while concurrently increasing over non-motor areas (Neuper & Pfurtscheller, 2001; Pfurtscheller, 1992). The function of alpha is to exert inhibitory control across the cerebral cortex whereby higher alpha indicates stronger neuronal inhibition and less alpha indicates greater release from inhibition (Klimesch, Sauseng, & Hanslmayr, 2007; Klimesch, 2012). Based on this evidence, the *gating-by-inhibition model* (Jensen & Mazaheri, 2010) proposes that neuronal excitability is diverted away from regions showing higher alpha power (i.e., greater inhibition) and routed towards regions showing lower alpha power (i.e., less inhibition). Consequently, the alpha gating model describes a mechanism that explains how the brain accomplishes the activation of motor areas alongside the inhibition of non-motor areas to achieve psychomotor efficiency.

Research on skilled motor performance requiring precise motor control, such as target sports like golf putting and gun shooting, has revealed temporal and spatial dynamics of the alpha rhythm that account for inter- and intra-individual variations in performance and expertise (for review of studies see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004). Two recent studies have explored the utility of the alpha gating model as framework to study the phenomenon of psychomotor efficiency. First, Gallicchio, Finkenzeller, Sattlecker, Lindinger, and Hoedlmoser (2016) examined alpha in a biathlon shooting task. They analyzed the topography of alpha in the second preceding each shot and described a focal pattern of simultaneous lower alpha in the central regions and higher alpha in temporal and occipital regions. Importantly, this pattern was associated with performance: lower central alpha and higher temporal alpha preceded improved shooting accuracy. Gallicchio and colleagues interpreted their findings as evidence that stronger alpha gating redirected neural resources more efficiently towards processes that supported performance and away from those unrelated to performance. Second, Gallicchio, Cooke, and Ring (2017) examined changes in alpha gating before and after practice of a golf putting task. They recorded alpha from recreational golfers as they putted balls to a hole before and after three training sessions. Their findings confirmed a shift in the topographical pattern that was consistent with the gating of resources away from temporal and occipital regions and towards central regions following motor learning. Importantly, they found that the largest improvements in performance following practice were associated with increased alpha power (indicative of greater inhibition) over the temporal regions.

The abovementioned studies provide preliminary evidence that a movement-related alpha gate is associated with motor performance and that its intensification – higher alpha in movement-unrelated regions (i.e., temporal and occipital) and lower alpha in movement-related regions (i.e., central) – can reflect improvements in psychomotor efficiency with practice. Accordingly, practicing a skill under conditions that strengthen the gating phenomenon may be expected to improve motor performance. However, there is currently no evidence that the movement-related alpha gate can be modulated by the structure of the practice conditions. The present study was designed to fill this gap in our understanding of the alpha-gating phenomenon and represents the first attempt to manipulate the strength of the alpha gate by varying the nature of the practice schedule. Specifically, we manipulated the trial-by-trial variability of the target in a golf putting task and compared the effects of variable practice and blocked practice (cf. Porter & Magill, 2010) on alpha oscillations. For some individuals the location of the target varied with each repetition in a random fashion whereas for others it was kept constant within blocks of consecutive repetitions.

Repeating a movement under a schedule of random variability increases cognitive load during motor preparation by requiring that parameters, such as force and direction, are re-specified for each movement (Lee & Magill, 1985) and by fostering comparisons of these parameters among the different movements (Shea & Morgan, 1979). If alpha gating reflects improved neural efficiency acquired through repetition, then random variability across repetitions should curb the development of psychomotor efficiency and interfere with the focal distribution of alpha across the cortex.

The aims of the present study were threefold. Our first study aim was to confirm the existence of the movement-related alpha gating phenomenon and establish its behavioral relevance. Specifically, we expected to see a regional pattern of lower alpha power over central regions and higher alpha power over temporal and occipital regions that was specific to motor preparation. Furthermore, we expected that a stronger gate (i.e., higher alpha power over non-motor areas and lower alpha power over motor areas) would be associated with better task performance.

Our second study aim was to examine the impact of target variability on motor performance, task difficulty, mental effort, and alpha gating. We hypothesized that, compared to blocked repetition, random repetition would result in worse performance, greater perceived difficulty and effort, and a weaker alpha gate (reflected in blunted enhancement of task-relevant central regions and/or suppression of task-irrelevant temporal and occipital regions).

Our third study aim was to evaluate the extent of any carry-over effect of practicing a skill under a random repetition condition when reverting back to a blocked repetition condition. Based on theories of motor learning arguing for enhanced performance following practice under a random, compared to a blocked, schedule (e.g., Schmidt, 1975), we expected that random practice compared to blocked practice would produce better performance and a stronger alpha gate (indicative of increased neural efficiency) at a blocked retention test.

Method

Participants

Thirty-two right-handed male recreational golfers were randomly allocated to a blocked practice group (age: *M* = 19.94, *SD* = 2.29 years; number of golf putting practice events in the last 12 months: *M* = 13.06, *SD* = 16.25) or to a random practice group (age: *M* = 20.25, *SD* = 1.81 years; number of golf putting practice events in the last 12 months: *M* = 11.06, *SD* = 9.01). None had a formal golf handicap. Participants were asked to refrain from alcohol, caffeine and nicotine 3 hours prior to testing, and were compensated with £10 and research credits. All provided signed consent to take part in the study. The study protocol was approved by the local research ethics committee.

Putting task

Participants putted golf balls (diameter 4.7 cm) with a blade-style putter (length = 91 cm) to a series of five targets — adhesive paper markers (diameter = 0.6 cm) — positioned on a flat putting surface (Turftiles, length 5 m, width 1.5 m; Stimpmeter value: 2.27 m). One central target was at a distance of 2 m and in straight line from the putting position. The four peripheral targets varied in terms of distance (far, near) and side (left, right). The two far and the two near targets were at distances of 2.5 and 1.5 m from the starting position, respectively. The two left and the two right targets were 0.15 m perpendicular to the line drawn from the ball to the middle target. The putting setup is illustrated in the Supplemental Material of Chapter Three (Appendix 1).

Participants were instructed to putt at their own pace (i.e., with no time pressure) and as accurately as possible in order to "*get the final position of the ball as close as possible to the target*". Prior to each putt, participants were instructed to stand in a relaxed position and maintain their gaze on a fixation cross placed at eye-sight on the facing wall (c. 1.5 m away), until an acoustic tone (duration: 200 ms; frequency: 1200 Hz) prompted them to look at a stimulus box. The box was positioned on the putting surface 15 cm away from to the ball. The box informed them about the location of the upcoming target by illuminating one of five light emitting diodes (LEDs) for the duration of the trial. The arrangement of the five LEDs represented the spatial location of the targets on the putting surface. The tones and LEDs, which served as cue stimuli, were controlled by an Arduino Micro board (Arduino, Italy) interfaced with a computer running MATLAB (MathWorks, USA).

Procedure

Participants attended one 2-hour session. After briefing and instrumentation for physiological recording they performed 10 familiarization putts: one putt to each target; this sequence was repeated twice. Then, participants completed the putting task. They putted 120 balls in three conditions: *baseline*, 1 block of 20 putts; *test*, 4 blocks of 20 putts; and *retention*, 1 block of 20 putts. After each block, participants completed some self-report measures assessing task difficulty and mental effort (see below for details).

In the baseline and retention conditions, the target was always the middle target. In the test condition, the target varied among the four peripheral targets, in either a blocked or random fashion according to group allocation. For participants in the blocked group, each putting block included only one of the four peripheral targets (i.e., 20 consecutive putts to the same target), and the sequence of blocks was randomized. For participants in the random group, each block included a pseudo-random sequence of the four peripheral targets; namely, all four targets were presented within each set of four consecutive putts, with the constraint that the same target could not be presented twice in a row. After each putt the experimenter took a photograph of the target area using a ceiling-mounted camera, repositioned the ball on the starting position, and then pressed a key to initiate the next trial. The time between the onset of the audiovisual cue and backswing initiation was 7.08 s (*SD* = 2.66 s) with a minimum of 3.04 s. The time between consecutive putts was 25.6 s (*SD* = 16.8 s) and the time between consecutive blocks was approximately 2 min. Upon completion of the putting task the participant was debriefed and paid.

2.4 Physiological signals

Thirty-two active electrodes were positioned on the scalp at Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2 (10-20 system, Jasper, 1958) to record the EEG. Two active electrodes were positioned on each mastoid. Four active electrodes were placed at the outer canthus and below each eye to record horizontal and vertical EOG. And finally, two electrodes were placed on the right clavicle and left lower ribs to record the ECG (chest-configuration lead-II montage). All channels were recorded in monopolar. Common mode sense and driven right leg electrodes were used to enhance the common mode rejection ratio of the signal. The signal was amplified and digitized at 2048 Hz with 24-bit resolution, with no online filter, using the ActiveTwo recording system (Biosemi, Netherlands).

Digital triggers were sent to the BioSemi system to identify the onset of the audiovisual cue onset and backswing initiation, identified by the putter head moved away and thereby breaking from an infrared beam controlled by a digital switch (E18-D80NK). In addition, vibrations from putter-ball impact were recorded using a piezo sensor (MiniSense 100) attached to the back of the putter head and interfaced with the BioSemi system as an external analog channel. Offline, a bespoke MATLAB script identified the timing of cue, backswing, and impact events for each putt.

All physiological channels were referenced to the mastoids, down-sampled to 512 Hz, and band-pass filtered 0.1-40 Hz (Finite Impulse Response, filter order = 2^15. Epochs were cut from -3.5 to +1.5 s relative to backswing initiation and cue and then voltages were centered within each epoch (i.e., the epoch mean was subtracted to each data point in that epoch). Epochs were visually inspected and those showing movement artefacts were discarded (these trials were also discarded from other non-EEG analyses). The number of backswing-centered epochs that were retained was 19.84 (*SD* = 0.37, *minimum* = 19) for the baseline condition, 79.25 (*SD* =

2.66, *minimum* = 65) for the test condition, and 19.91 (*SD* = 0.30, *minimum* = 19) for retention. The number of cue-centered epochs that were retained was 19.88 (*SD* = 0.34, *minimum* = 19) for the baseline condition, 79.21 (*SD* = 2.66, *minimum* = 65) for the test condition, and 19.91 (*SD* = 0.30, *minimum* = 19) for retention. No bad channels were identified. Independent Component Analysis (ICA) weights were obtained through the Runica Infomax algorithm (Makeig et al., 1996) running on EEG, EOG, and ECG signals (i.e., 38 channels yielding same number of independent components) that, prior to ICA, were down-sampled to 256 Hz, 2-40 Hz band-pass filtered (Finite Impulse Response, filter order = 1000), and concatenated across all conditions within each participant. Then, ICA weights were applied to the 0.1-40 Hz filtered signals and the components that presented obvious non-neural activity upon visual inspection (e.g., eye blinks, horizontal eye movements, cardiac artefact, muscle / movement artefacts) were manually rejected. On average 4.94 components (*SD* = 1.39) were rejected per participant. Finally, ECG and EOG channels were discarded and the remaining thirty-two EEG channels were average-referenced. These pre-processing steps were performed using EEGLAB functions (Delorme & Makeig, 2004) for MATLAB.

Measures

Performance. Performance on each putt was scored as radial error (cm), length absolute error (cm; hereafter “length error”), and angle absolute error (degrees; hereafter “angle error”). A trial was discarded from any further analysis when the ball rolled off of the putting surface (this occurred only once). A camera system with bespoke MATLAB scripts, inspired by Neumann and Thomas (2008), was used to score performance (see Supplemental Material of Chapter Three, Appendix 1).

Self-report. Task difficulty was measured by asking each participant to rate ‘*How difficult* *was it to get the ball to finish within 5 cm of the target(s)?*' on a Likert scale ranging from 1 (*not difficult at all*) to 7 (*extremely difficult*). Mental effort was measured by asking each participant to rate '*How much mental effort did you exert while putting?*' on a Likert scale ranging from 1 (*no effort at all*) to 7 (*extreme effort*). Both items were rated after each block of 20 putts in relation to the block of putts just completed.

Alpha power. Time-frequency decomposition was performed through short-time Fast Fourier Transform (FFT) conducted on 65 overlapping windows, each of 1 s, with central points ranging from -3 to 1, relative to backswing onset and cue onset (Figure 3.1). Prior to FFT, data points in each window were Hanning tapered and 0-padded to reach 4 s. This procedure generated complex-valued coefficients in the time-frequency plane with a precision of 0.06 s and 0.25 Hz, separately for each channel and trial. Signal amplitude was doubled for all positive frequencies and alpha power was computed as the squared amplitude in the 8-12 Hz frequency range.

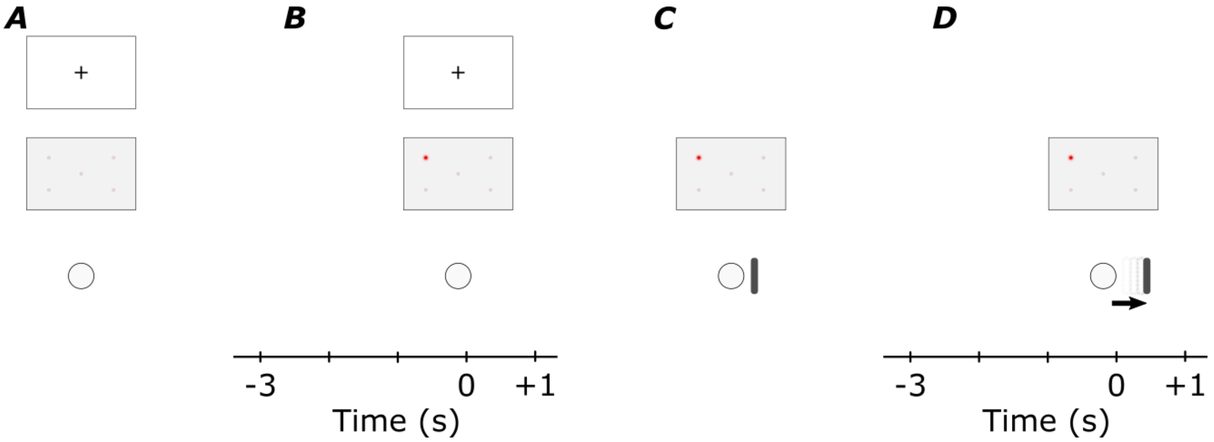

Figure 3.1. EEG epoching relative to the movements involved in the putting task. (A) The participant stood upright in front of the ball and maintained his gaze on the fixation cross located at eye-sight on the opposite wall. (B) Cue onset: one of the LEDs turned on concomitantly to the acoustic tone, informing the participant of the location of the target. (C) At his own time, the participant positioned the putter head next to the ball and prepared for the putt. (D) Backswing initiation: The participant initiated the backswing. EEG alpha was examined from -3 to +1 s relative to this instant.

We computed two metrics of alpha power per trial. *Absolute* alpha power was computed with no baseline correction; instead, skewness and between-subject differences in the power density distribution were minimized through a median-scaled log transformation, whereby power values of each participant were scaled by the median of all values within that participant, and then subjected to a 10·log10 transformation (cf. Gallicchio et al., 2016b). Absolute alpha power was computed for both types of epoch—time-locked to backswing initiation and cue onset. *Relative* alpha power was computed only for the epoch that was time-locked to backswing initiation as percentage change from a baseline, identified as the two seconds preceding cue onset (averaged across trials, separately per each condition) using the formula described in Pfurtscheller and Lopes da Silva (1999): $r_{t,p,c} = 100\left(b_{t,p,c} - \overline{c_c}\right)/\overline{c_c}$, where $r_{t,p,c}$ indicates relative alpha power at time *t*, putt *p*, and condition *c* (i.e., baseline, test, retention), $b_{t,p,c}$ indicates alpha power time-locked to backswing initiation at time *t*, putt *p*, and condition *c*, and $\overline{c_c}$ indicates alpha power averaged across the data points within the 2 s preceding cue onset and across putts in condition *c*. Six regions of interest (ROI) were identified based on inspection of topographic maps (Figures 3.2A and 3.2B): frontal (F3, Fz, F4), left temporal (T7, F7, CP5), left central (C3, CP1), right central (C4, CP2), right temporal (T8, F8, CP6), and occipital (O1, Oz, O2). Values within each ROI were averaged. Signal processing was performed in MATLAB.

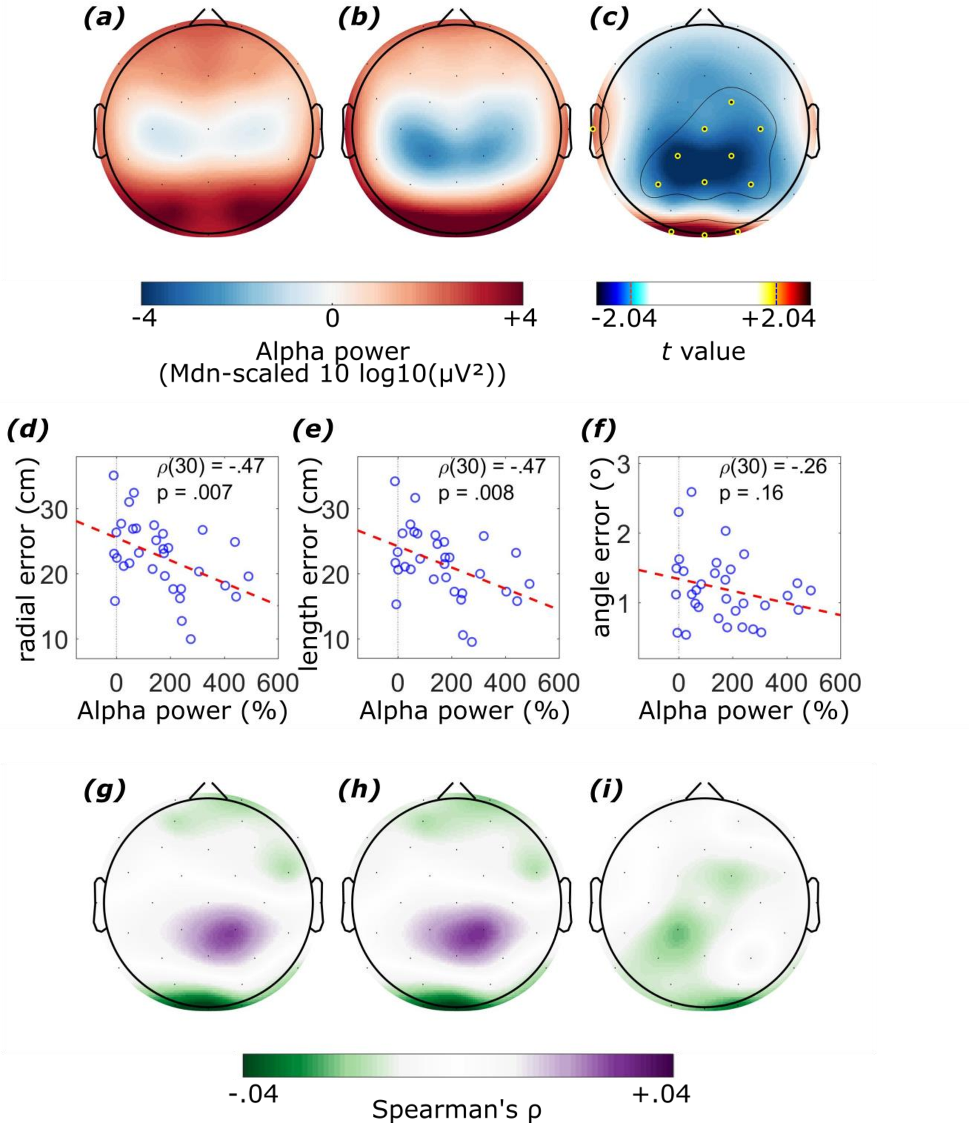

Figure 3.2 (A, B) Scalp maps of absolute alpha power in the 2 s prior to (A) cue onset and (B) backswing initiation. (C) Scalp map of paired-sample *t* values (df = 31) comparing pre-cue and pre-backswing alpha power. Values of -2.04 and 2.04 correspond to *p* = .05 on a *t* distribution with 31. Statistical thresholding was applied using the maximum-statistic permutation testing (Cohen, 2014; Nichols & Holmes, 2001) controlling for multiple comparisons in the channel dimension with alpha set at .01. Statistically significant channels are indicated by a yellow-black markers and are surrounded by a solid contour line. (D, E, F) Scatter plots showing (D) radial, (E) length, and (F) angle errors as a function of relative alpha power at Oz in the 2 s prior to backswing initiation along with Spearman's ρ and *p* values. (G, H, I) Scalp maps of Spearman's ρ computed between relative alpha power in the 2 s prior to backswing initiation and (G) radial error, (H) length error, and (I) angle error. Statistical thresholding was applied using the maximum-statistic permutation testing controlling for multiple comparisons in the channel dimension with alpha set at .01: no significant effects was revealed. All participants (*n* = 32) and only trials from the baseline condition were included in these graphs.

Statistical Analyses

Alpha gating. A 6 ROI × 2 epoch type (cue, backswing) analysis of variance (ANOVA) on absolute alpha power was conducted to evaluate the presence of regional effects of alpha power consistent with the gating phenomenon and, by comparing the 2 s preceding cue onset against the 2 s preceding backswing initiation, to determine whether this regional phenomenon was specific to preparation for putting. Additionally, we explored regional effects through nonparametric permutation testing. The multiple comparison problem (i.e., one test for each channel) was solved through the "maximum statistic" method (Cohen, 2014; Nichols & Holmes, 2001) applied to the channel dimension. Namely, we compared paired-sample t values of each channel with an empirical distribution of t values constructed in the following way. First, we permuted the data by randomly swapping the 'cue' and 'backswing' labels within each participant. Second, we ran a paired-sample t test separately for each channel. Third, we pooled the t values across channels and stored the two most extreme values (i.e., minimum and maximum). Fourth, we repeated this procedure 1000 times to create a distribution of 2000 minimum and maximum t values. Finally, we compared the non-permuted t value of each channel with the empirical distribution of t values described above: we computed p values as the proportion of the permutation t values that were more extreme than the t value of each channel.

Spearman's rank correlations (ρ) explored the association between performance and relative alpha power in the 2 s preceding backswing initiation. These analyses were conducted on the putts from the baseline condition, pooling participants from both groups ($n = 32$). In addition, we explored the topography of the alpha-performance correlation through permutation testing corrected for multiple comparisons across the channel dimension. Namely, the ρ coefficient obtained for each channel was compared with a distribution of the 2000 most extreme ρ

coefficients across channels (i.e., 1000 minimum and 1000 maximum) whereby at each repetition participants were permuted for one of the two variables involved in the correlation.

Manipulation of target variability. These analyses evaluated the impact of the manipulation of target variability on performance, self-report, and alpha power measures. Independent-sample t-tests examined group differences in performance and self-report measures of difficulty and mental effort (as change scores relative to baseline) on trials of the test condition. Performance absolute scores are reported in the Supplemental Material of Chapter Three (Appendix 2).

A 2 group × 6 ROI × 4 time × 4 subset ANOVA was conducted on relative alpha power (i.e., as percentage change from the 2 s preceding cue onset). The time factor identified four 1-s intervals from -3 to +1 relative to backswing initiation. The subset factor identified four 20-putt sets, so that subset 1 included the first 5 putts struck to each target – these were consecutive putts for the blocked but not the random group – subset 2 included the next 5 putts to each target, and so on. Only trials from the test condition were included in these analyses. Additionally, we explored the topography of group differences through permutation testing controlling for multiple comparisons in the channel × time dimensions, separately for each subset. Namely, independent-sample *t* values computed for each channel and each time were compared with a distribution of the 2000 most extreme *t* values across channels and time (i.e., 1000 minimum and 1000 maximum) whereby group allocation was permuted across participants at each repetition.

Retention effects. These analyses examined the short-term persistence of effects following the manipulation of target variability. Group differences in performance and self-report measures of difficulty and mental effort (expressed as change scores relative to baseline) were assessed through independent-sample t-tests. A 2 group × 6 ROI × 4 time ANOVA was conducted on relative alpha power. Only trials from the retention condition were considered in these analyses. Additionally, we explored the topography of group differences through permutation testing controlling for multiple comparisons in the channel × time dimensions with the same procedure described for the analyses of target variability.

2.6.4 Additional frequency bands. In order to evaluate the involvement of frequency bands other than alpha we conducted the analyses described above in the theta (4-6 Hz) and beta (15-25 Hz) frequency bands. In addition, to explore patterns within the broad alpha band, we analyzed separately the lower (8-10 Hz) and upper (10-12 Hz) alpha sub-bands. These supplementing analyses are reported in the Supplemental Material of Chapter Three (Appendix 4).

The multivariate solution was adopted where appropriate (Vasey & Thayer, 1987) and Wilks' lambda (λ) reported. Significant interactions were interrogated using post hoc t-tests and polynomial trend analyses. Univariate partial eta-squared (η_p^2) and r^2 were reported as measures of effect size, with values of .02, .13, and .26 reflecting small, medium, and large effects, respectively (Cohen, 1992).

Results

Alpha gating

To address our first study aim we conducted analyses to ascertain the existence of the movement-related alpha gating phenomenon and its behavioral relevance. The regional distribution of absolute alpha power is shown as a function of epoch type in Figures 3.2A and 3.2B. The ROI × epoch type ANOVA yielded a main effect of ROI, $F(5,27) = 157.95$, $p < .001$,

$\lambda = .033$, $\eta_p^2 = .889$, indicating that alpha power was highest for the occipital region, lower for the left and right temporal and frontal regions, and lowest for the left and right central regions. This effect was superseded by a ROI × epoch interaction, $F(5,27) = 47.17$, $p < .001$, $\lambda = .103$, $\eta_p^2 = .767$: post hoc paired-sample t-tests revealed that alpha power decreased from pre-cue to pre-backswing for the left central, right central, and frontal regions, $ts(31) > 2.90$, $ps < .007$, and increased for the occipital region, $t(31) = 7.50$, $p < .001$. No differences emerged for left, $t(31) = 0.70$, $p = .49$, and right, $t(31) = -0.84$, $p = .41$, temporal regions. No main effect emerged for epoch type, $F(1,31) = 0.46$, $p = .50$, $\eta_p^2 = .015$. Channel-wise exploratory analyses conducted through permutation testing revealed that, compared to the pre-cue period, pre-backswing alpha power decreased for central channels (FC2, Cz, C4, CP1, CP2, P3, Pz, P4) and increased for occipital (O1, Oz, O2) and left temporal (T7) channels (Figure 3.2C).

To rule out the existence of group differences at baseline, we conducted a 2 group × 6 ROI × 4 time ANOVA on relative alpha power (i.e., alpha power around backswing initiation as percentage change from the 2 s preceding cue onset). The results of this analysis are reported fully in the Supplemental Material of Chapter Three (Appendix 3), along with exploratory channel-wise analyses of group differences through permutation testing. No group effects were revealed at baseline.

Channel-wise Spearman's correlations between relative alpha power and radial error revealed that the participants who obtained lower radial error were those that showed the largest increase in alpha power at Oz, $\rho(30) = -.47$, $p = .007$, and O1, $\rho(30) = -.38$, $p = .04$, compared to the pre-cue onset period. Similar effects were revealed for length error (Oz: $\rho(30) = -.47$, $p = .008$; O1: $\rho(30) = -.36$, $p = .04$). No effects were revealed for angle error. Figure 3.2 illustrates the scatter plots of the relation between relative alpha power at Oz and radial error (panel D), length error (panel E), and angle error (panel F). Figures 3.2G, 3.2H, and 3.2I show the topography of these correlations together with the outcome of permutation testing corrected for multiple comparisons. These analyses indicated that the findings reported above did not survive a rigorous control of multiple testing. However, the exploration of multiple frequency bands (i.e., theta, lower alpha, upper alpha, and beta) indicated that these correlations emerged only for the alpha band and particularly for the upper alpha sub-band (see Appendix 4 in the Supplemental Material of Chapter Three).

Manipulation of target variability

To address our second study aim we conducted analyses to examine the impact of the manipulation of target variability on performance, self-reported difficulty and mental effort, and alpha gating.

Performance. Compared to baseline putts, radial error decreased for the blocked group (M = -2.59, SD = 4.33 cm) and increased for the random group (M = 0.66, SD = 4.40 cm), which produced a significant group difference in terminal distance from the target, $t(30) = -2.11$, $p = .04$, $r^2 = .359$. Length error decreased in both the blocked (M = -3.02, SD = 4.41 cm) and random (M = -0.23, SD = 4.46 cm) groups, $t(30) = -1.78$, $p = .09$, $r^2 = .309$. Angle error increased for both the blocked (M = 0.22, SD = 0.43 degrees) and random (M = 0.52, SD = 0.48 degrees) groups, $t(30) = -1.90$, $p = .07$, $r^2 = .328$. Potential group differences in putting performance were further explored through independent-sample t-tests conducted separately for each subset of putts; where subset refers to the first, second, third, and fourth set of five putts struck to each target (i.e., 20 putts per each subset). These analyses revealed that clear group differences in extent-based errors emerged during the second subset of putts and that these differences faded during the third and fourth subset of putts (Table 3.1).

Table 3.1. Mean (*SD*) of performance measures of each group as change scores from the baseline condition in each subset along with the results of independent-sample t-tests. A negative change score indicates that performance improved during the test compared to baseline.

Performance measure	**blocked**	**random**	***t*(30)**	***p***	**r^2**
subset 1					
Δ radial error (cm)	0.37 (6.78)	2.87 (5.51)	-1.15	.26	.215
Δ length error (cm)	0.06 (7.37)	1.83 (5.74)	-0.76	.46	.137
Δ angle error (degrees)	0.27 (0.62)	0.63 (0.61)	-1.67	.11	.292
subset 2					
Δ radial error (cm)	-2.65 (3.59)	1.69 (3.47)	-3.47	.002	.535
Δ length error (cm)	-3.05 (3.89)	0.91 (3.47)	-3.03	.01	.484
Δ angle error (degrees)	0.18 (0.43)	0.54 (0.46)	-2.32	.03	.390
subset 3					
Δ radial error (cm)	-4.04 (5.24)	-0.68 (5.37)	-1.79	.08	.311
Δ length error (cm)	-4.55 (5.3)	-1.25 (5.23)	-1.77	.09	.307
Δ angle error (degrees)	0.23 (0.48)	0.36 (0.49)	-0.76	.46	.137
subset 4					
Δ radial error (cm)	-4.01 (4.99)	-1.21 (6.04)	-1.43	.16	.253
Δ length error (cm)	-4.48 (5.07)	-2.38 (6.25)	-1.04	.31	.187
Δ angle error (degrees)	0.20 (0.56)	0.56 (0.61)	-1.74	.09	.303

Self-report. Compared to the baseline condition, self-reported difficulty increased more for the random group (M = 0.97, SD = 1.15) than the blocked group (M = 0.11, SD = 1.06), $t(30)$ = -2.20, p = .04, r^2 = .373. No difference emerged for self-reported mental effort (blocked: M = -0.39, SD = 0.71; random: M = -0.20, SD = 0.96), $t(30)$ = -0.63, p = .54, r^2 = .114.

Alpha power. The group × ROI × time × subset ANOVA on relative alpha power revealed main effects for ROI, $F(5,26)$ = 17.51, $p < .001$, λ = .229, η_p^2 = .564, and time, $F(3,28)$ = 6.38, p = .002, λ = .594, η_p^2 = .172. These effects were superseded by a ROI × time interaction, $F(15,16)$ = 3.34, p = .01, λ = .242, η_p^2 = .285, revealing cubic temporal trends (i.e., increase, decrease, increase) for the frontal, $F(1,31)$ = 13.79, p = .001, η_p^2 = .308, left central, $F(1,31)$ = 13.75, p = .001, η_p^2 = .307, right central, $F(1,31)$ = 10.38, p = .003, η_p^2 = .251, and left temporal, $F(1,31)$ = 17.06, $p < .001$, η_p^2 = .355, regions. Changes in the occipital region were best described by a linear trend (i.e., decrease), F(1,31) = 17.56, p < .001, eta = .362. No temporal trend emerged for the right temporal region. No main group effect was revealed, $F(1,30)$ = 1.59, p = .22, η_p^2 = .050. However, the ANOVA analysis also revealed interactions for ROI × time × subset, $F(45,1350)$ = 2.03, $p < .001$, η_p^2 = .063, and group × ROI × time × subset, $F(45,1350)$ = 1.49, p = .02, η_p^2 = .047.

Post hoc independent sample *t*-tests revealed greater alpha power for the random compared to the blocked group for selected channels and only for subsets 2 to 4 (Figure 3.3). For subset 2, effects emerged from -3 to -2 s at FC5, $t(30)$ = 2.07, p = .05, r^2 = .353, from -2 to -1 s at F7, $t(30)$ = 2.08, p = .05, r^2 = .355, and FC5, $t(30)$ = 2.04, p = .05, r^2 = .350, from -1 to 0 s at F7, $t(30)$ = 2.29, p = .03, r^2 = .385, FC5, $t(30)$ = 2.52, p = .02, r^2 = .418, and T7, $t(30)$ = 2.09, p = .05, r^2 = .356. For subset 3, effects emerged from -3 to -2 s at F7, $t(30)$ = 2.62, p = .01, r^2 = .432, and FC5, $t(30)$ = 2.27, p = .03, r^2 = .383. For subset 4, effects emerged from -3 to -2 s at F7, *t*(30) = 2.31, *p* = .03, r^2 = .388, F3, *t*(30) = 2.27, *p* = .03, r^2 = .383, and FC5, *t*(30) = 2.48, *p* = .02, r^2 = .412, from -2 to -1 s at F7, *t*(30) = 2.14, *p* = .04, r^2 = .365, FC5, *t*(30) = 2.16, *p* = .04, r^2 = .367, T7, *t*(30) = 2.05, *p* = .05, r^2 = .350, and C4, *t*(30) = 2.06, *p* = .05, r^2 = .352. Permutation testing conducted to control for multiple comparisons in the channel × time dimensions indicated that the findings reported above did not survive a rigorous statistical control (Figure 3.3). The exploration of multiple frequency bands (theta, lower alpha, upper alpha, and beta) revealed that the effects described above were not specific to the alpha frequency band although they appeared especially distinctly for the upper alpha sub-band (see Appendix 4 in the Supplemental Material of Chapter Three).

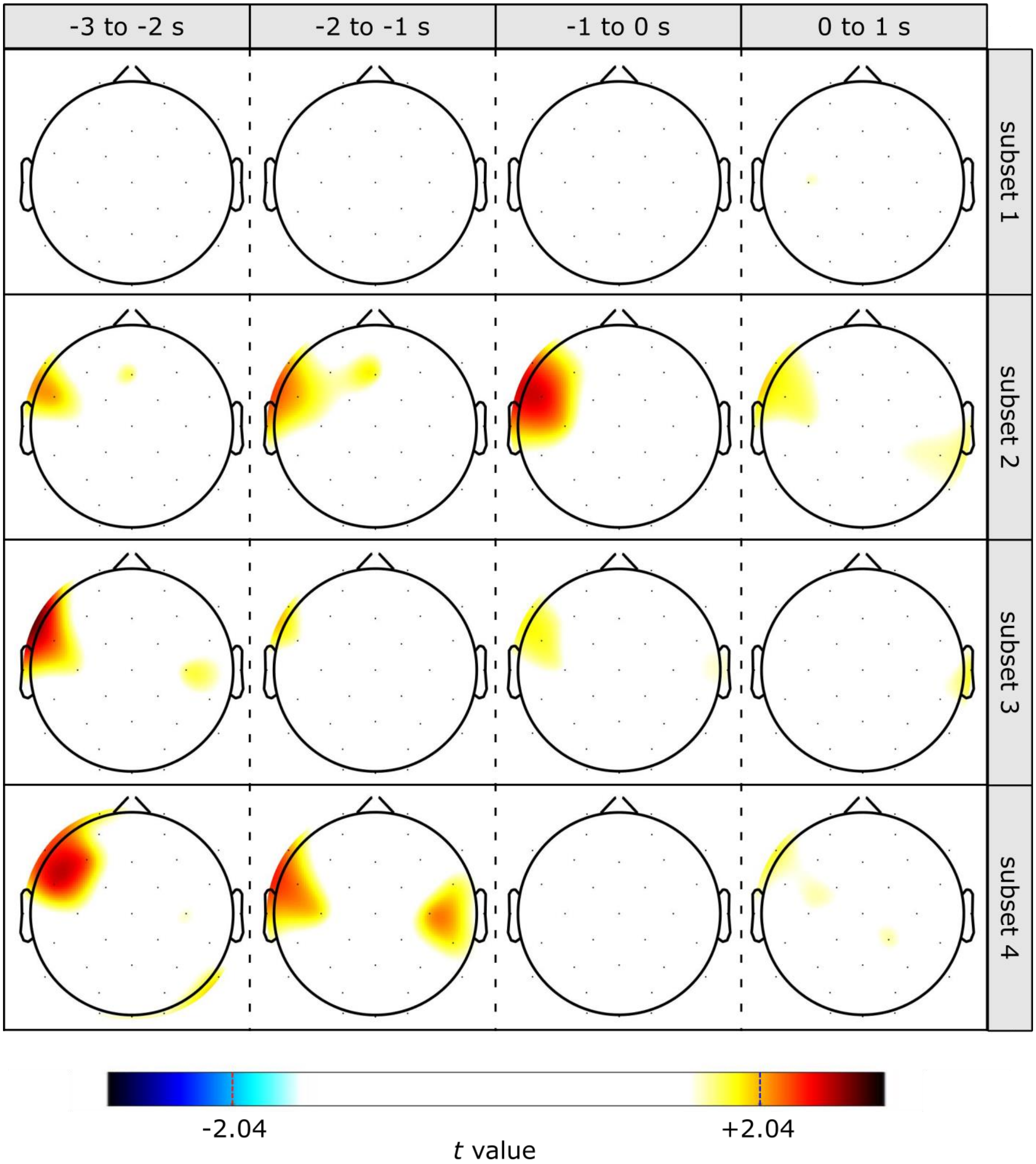

Figure 3.3. Scalp maps of independent-sample *t* values comparing blocked versus random groups, as a function of time and subset. Values of -2.04 and 2.04 correspond to $p = .05$ on a *t* distribution with 30 *df*. Positive values indicate greater whereas negative values indicate smaller relative alpha power for the blocked than the random group. Statistical thresholding was computed using the maximum-statistic permutation testing (Cohen, 2014; Nichols & Holmes, 2001) controlling for multiple comparisons in the channel × time dimensions with alpha set at .01: no significant effect was revealed.

Retention effects

To address our third study aim we conducted analyses to explore the persistence of the effects due to the manipulation of target variability in an immediate retention test with no target variability

Performance. Performance at retention was better than baseline. However, no group differences emerged for radial error (blocked: *M* = -3.97, *SD* = 5.62 cm; random: *M* = -2.14, *SD* = 5.53 cm; *t*(30) = -0.93, *p* = .36, r^2 = .167), length error (blocked: *M* = -3.82, *SD* = 5.37 cm; random: *M* = -1.99, *SD* = 5.54 cm, *t*(30) = -0.95, *p* = .35, r^2 = .171), or angle error (blocked: *M* = -0.21, *SD* = 0.62 degrees; random: *M* = -0.11, *SD* = 0.40 degrees, *t*(30) = -0.57, *p* = .58, r^2 = .104).

Self-report. Compared to baseline, during the retention test self-reported difficulty decreased similarly for the blocked (*M* = -0.88, *SD* = 1.20) and random (*M* = -0.56, *SD* = 1.41), groups, *t*(30) = -0.67, *p* = .51, r^2 = .121. Mental effort also decreased similarly from baseline to retention for the blocked (*M* = -0.75, *SD* = 0.68) and random (*M* = -0.88, *SD* = 0.96) groups, *t*(30) = 0.43, *p* = .67, r^2 = .078.

Alpha power. The group × ROI × time ANOVA conducted on relative alpha power revealed main effects for ROI, *F*(5,26) = 22.92, *p* < .001, λ = .185, η_p^2 = .530, and time, *F*(3,28) = 5.39, *p* = .01, λ = .634, η_p^2 = .174. These main effects were superseded by a ROI × time interaction, *F*(15,16) = 3.93, *p* = .01, λ = .213, η_p^2 = .204, indicating that the time effect was best described by a cubic trend (i.e., increase, decrease, increase) for the frontal, *F*(1,30) = 15.02, *p* = .001, η_p^2 = .334, right central, *F*(1,30) = 4.25, *p* = .05, η_p^2 = .124, left temporal, *F*(1,30) = 16.96, *p* < .001, η_p^2 = 361, and right temporal, *F*(1,30) = 5.74, *p* = .02, η_p^2 = .161, regions. Changes in the occipital region were best described by a linear trend (i.e., decrease), *F*(1,30) = 16.76, *p* <

.001, $\eta_p^2 = .358$. No trend was evident for the left central region. No main effect for group emerged, $F(1,30) = 2.62$, $p = .12$, $\eta_p^2 = .080$, or group interactions. Appendix 3 in the Supplemental Material of Chapter Three illustrates scalp maps along with the outcome of permutation testing conducted for group differences at retention. Appendix 4 in the Supplemental Material of Chapter Three reports the analyses conducted on multiple frequency bands (theta, lower alpha, upper alpha, and beta).

Discussion

This study investigated movement-related alpha gating in a golf putting task. Our first goal was to establish the existence and behavioral relevance of a topographic pattern of alpha power compatible with the gating phenomenon in preparation for movement execution. Our second goal was to alter this gating phenomenon via an experimental manipulation of target variability by comparing blocked versus random schedules of movement repetitions. Our final goal was to evaluate the short-term persistence of functional adaptations induced by the manipulation of target variability. The findings of this study are discussed below, separately with regard to each goal.

Alpha gating

Regional analyses of alpha power in the 2 s preceding movement execution revealed a focal pattern whereby alpha power was highest for the occipital region, intermediate for the bilateral temporal and frontal regions, and lowest for the bilateral central regions (Figure 3.2). Based on the proposed inhibitory function of cortical alpha (Klimesch et al., 2007; Klimesch, 2012) and the gating-by-inhibition model (Jensen & Mazaheri, 2010), our findings imply that cognitive activity was clearly diverted away from processes performed in the occipital region, and, to a lesser extent, the temporal and frontal regions, and instead routed towards processes performed in the central regions. This finding provides further evidence of the existence of the aiming movement-related alpha gating phenomenon (Gallicchio et al., 2016b; 2017).

That the focal pattern of alpha power was specific to movement preparation is supported by analyses comparing the 2 s preceding movement initiation with the 2 s preceding cue onset (i.e., the stimulus prompting participants to start their putting preparation). These analyses revealed that, relative to the pre-cue period, alpha power increased in the occipital and left temporal regions and decreased for the central and frontal regions (Figure 3.2C). No significant change occurred in the right temporal region. In other words, the gating pattern became more intense just before the start of movement execution. Our finding replicates that of Gallicchio et al. (2016) who observed a focal topography of alpha power prior to rifle shooting but not at rest. These findings help consolidate the argument that the alpha gating phenomenon observed in motor tasks is specific to preparation for movement. The fact that a weaker alpha gating effect was evident in the pre-cue periods (Figure 3.2A) may reflect a state of nascent preparation for movement in the time between one repetition and the next (cf. Cooke et al., 2015). The suppression of central alpha just before movement initiation is a well-known phenomenon in the psychophysiological literature concerned with the study of movement and it is interpreted as reflecting the activation of sensorimotor processes necessary for the execution of the movement (Neuper & Pfurtscheller, 2001; Pfurtscheller, 1992).

Finally, we observed that the intensity of the alpha gate was associated with the accuracy of the movement. Namely, participants with larger increases for occipital alpha performed better in terms of smaller radial and length errors (Figures 3.2D and 3.2G). Moreover, the association between performance and EEG power was evident only for the alpha frequency bands (see Appendix 4 in the Supplemental Material of Chapter Three). This finding suggests that the inhibition of the occipital region is functionally implicated in the performance of target-based motor tasks. It is worth noting that, optimal programming of force and direction may rely on two distinct neural patterns because the topographies showing the correlation of alpha power with either length or angle errors appeared qualitatively different (Figures 3.2H and 3.2I).

Target variability

The most important purpose of the present study was to attempt to experimentally alter the alpha gating phenomenon by manipulating trial-by-trial target variability. At the behavioral level, individuals who putted to randomly varying targets within blocks reported greater task difficulty than those who putted to the same target within blocks. Accordingly, compared to baseline, performance during the scheduling manipulation declined for the random group (the ball finished 2.6 cm farther from the target) and improved for the blocked group (the ball finished 0.7 cm closer to the target). However, it should be noted that the self-reported measure of mental effort was not different between the random group and blocked group.

Group differences in performance became particularly evident after participants had some time to adapt to the constant or random repetition schedule. Specifically, the random and blocked groups started to differ in the second subset of repetition, that is after they had putted the first 20 putts in their respective condition: 20 putts to a random sequence of the four peripheral targets, for the random group, and five consecutive putts to the same target for each of the four peripheral targets, for the blocked group. All indices of performance (i.e., radial, length, and angle errors) indicated that the random group performed significantly worse than the blocked group, with large effect sizes. It is interesting to note that for the blocked group, performance improved steadily (i.e., radial error kept decreasing) across all repetition subsets, whereas, for the random group, performance decreased during the first 2 subsets and started to improve during the 2 final subsets (Table 3.1). The decline in movement accuracy when performing under the randomly varying conditions has been previously observed in golf putting tasks (e.g., Porter & Magill, 2010) and has been attributed to its greater cognitive load (Lee & Magill, 1985; Shea & Morgan, 1979). Below we consider how the neurophysiological data recorded in the present study can shed light on how the additional cognitive load might have interfered with the selective allocation of resources to relevant processes and inhibiting irrelevant processes.

Alpha power followed a temporal trend that can be best described as an initial increase, followed by a decrease (peaking at movement initiation), and a final increase (during movement execution). This pattern has been previously interpreted as the timely allocation of resources to motor preparation processes (Cooke et al., 2015). Importantly, the peak-to-trough pattern has been found to be greater for experts than novices (Cooke et al., 2014) and associated with larger performance improvements after training (Gallicchio et al., 2017).

Spatial analyses revealed that group differences were mostly localized to the left temporal region. More specifically, compared to the blocked group, the random group showed a reduced left temporal alpha activity across the 3 s preceding movement onset. Mirroring the results for performance, group differences emerged after the participants had time to adapt to the requirements of putting to either the same target or a randomly varying target (Figure 3.3). Because alpha reflects regional inhibition (Klimesch et al., 2007; Klimesch, 2012), this finding indicates that prior to movement initiation the left temporal regions was inhibited less for the random group than the blocked group. Within the framework of the alpha gating-by-inhibition model (Jensen & Mazaheri, 2010) this result can be interpreted as deficient gating of cognitive resources across the cortex. In line with previous interpretations of the movement-related alpha gating phenomenon (Gallicchio et al., 2016b, 2017), the weaker alpha gate observed for the random group reflects less psychomotor efficiency (Hatfield & Hillman, 2001; Hatfield, 2018) compared to the blocked group. These novel findings provide evidence that increased inhibition of cortical regions that are not involved with movement seems to be more important than increased activation of regions that are responsible for movement control. Indeed, Gallicchio et al. (2017) found that larger improvements in putting performance were associated with stronger inhibition of non-motor regions rather than greater activation of motor regions.

It is worth pointing out that the left temporal region appears to play a special role in the control and learning of motor skills. Previous investigations have observed greater alpha power (i.e., stronger inhibition) in the left temporal region as a function of expertise (Haufler, Spalding, Santa Maria, & Hatfield, 2000), performance (Gallicchio et al., 2016b), and training (Gallicchio et al., 2017; Kerick, Douglass, & Hatfield, 2004; Landers, Han, Salazar, Petruzzello, Kubitz, & Gannon., 1994). Past studies have also found increased functional disconnection between the left temporal region and other regions involved with movement as a function of expertise (Deeny, Hillman, Janelle, & Hatfield, 2003), performance (Gallicchio, Cooke, & Ring, 2016), and training (Gallicchio et al., 2017; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Left temporal activity in a movement tasks has been interpreted as cognitive/verbal interference during motor preparation (Deeny et al., 2003) and reinvestment of declarative knowledge to consciously monitor and control movements (Zhu et al., 2011). It is tempting to speculate that verbal processes concerned with use of declarative knowledge may impair motor performance and hold back progress in learning of a motor skill. However, due to the unfeasibility of mapping one region to one cognitive function, we urge researchers to study the function of left temporal alpha in motor tasks.

Retention effects

The evaluation of group differences at retention enabled us to test predictions derived from motor learning theories that have argued for a learning advantage following variable practice (Schmidt, 1975). Contrary to our expectations, no behavioral or neurophysiological differences emerged at retention, when both groups putted repeatedly to the same central target. The lack of effects could be attributed to the short duration of the putting practice: participants may have not accumulated sufficient practice during one session of only 80 repetitions. The lack of effects may also be attributed to the fact that the post-test assessment was a retention rather than a transfer test (i.e., participants putted to the same target as baseline rather than to a different target). It is also likely that the participants had a certain degree of neural efficiency at baseline (Figure 3.2): the random variability practice posed a temporary challenge to this efficiency but then functional activity reverted to its initial pattern once the challenge had been removed. These issues can be addressed in future studies.

Limitations and directions for future research

The findings of the present study shed light on the neurophysiological mechanisms underlying variable practice. However, in order to appreciate the applicability of our findings and identify directions for future research, we need to acknowledge some study limitations. First, the fact that, compared to the blocked group, the random group performed worse (i.e., made larger errors) may have contributed to group differences in alpha gating. Namely, the production of larger errors may have resulted in enhanced cognitive activity aimed at improving performance on the next trial (Cooke et al., 2015).

Second, this study failed to find any retention effects after practicing under variable conditions. Future research could adopt a longitudinal design to explore the impact of longer trainings that could result in a more stable functional adaptation. It would be interesting to examine whether repetition under a variable schedule leads eventually to performance improvements and to identify the neurophysiological mechanisms explaining such an improvement.

Third, most findings of this study regard activity detected by sensors located at the edge of the spatial configuration examined. Due to our efforts in attenuating movement artefacts we have interpreted these effects in terms of cortical activity. However, we cannot rule out that non-neural activity, such as neck movements, has influenced our results. We recommend that future research pays particular attention to this issue. As instance, researchers could record head movements through accelerometers and identify the independent components that are statistically related to this signal (cf. Daly, Billinger, Scherer, & Müller-Putz, 2013).

Finally, due to the compelling body of literature implicating the left temporal region in motor control and learning (Deeny et al., 2003; Gallicchio et al., 2016a, 2016b, 2017; Haufler et al., 2000; Kerick et al., 2004; Landers et al., 1994; Zhu et al., 2011), we recommend researchers to address the pressing issue of explaining the functional role being played by this region in movement tasks. For example, if inhibition of the left temporal region is linked to decreased verbal activity (e.g., Zhu et al., 2011), then future studies could manipulate self-talk and look for associated changes in neurophysiology.

Conclusions

The present study demonstrated the explanatory utility of the alpha gating model in motor control research. We provided evidence of the existence of movement-related alpha gating and its relevance for motor performance. We also demonstrated that this phenomenon can be changed in an experimental setting by manipulating variability across repetitions of the movement. The utility of a theoretical model, such as the alpha gating model, accounting for improvement in motor performance opens interesting avenues for future applications to enhance motor acquisition and evaluate the quality of training programs.

Our findings indicate that inhibition of occipital and temporal regions enhances performance in a target-based motor task. Because these regions are involved with cognitive processes, including visual perception and retrieval of declarative knowledge, we could speculate that, once the spatial features of the target and movement parameters, such as force and direction, have been internalized as a mental representation of an action plan, further rumination in terms of visual processing and declarative thoughts may hinder rather than support performance. Accordingly, our evidence-based recommendation to athletes at this stage would be: "*don't look, don't think, just do it!*"

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CHAPTER FOUR

Assessing ocular activity during performance of motor skills using electrooculography

Abstract

Eye-tracking research has revealed that, compared to novices, experts make longer ocular fixations on the target of an action when performing motor skills, that is they have a longer *quiet eye*. Remarkably, the reason why a longer quiet eye aids movement has yet to be established. There is a need for interdisciplinary research and new measures to accelerate progress on the mechanistic understanding of the phenomenon. With the aim to provide researchers with new tools, we assessed the utility of electrooculography (EOG) to examine ocular activity while 10 experts and 10 novices putted golf balls. We measured quiet eye durations, distinguishing its pre- and post-movement initiation components, and developed a novel time-varying index of ocular activity, eye quietness, computed as the variability of the EOG in short time intervals: lower values correspond with greater quietness. Finally, we measured movement durations using a combination of infrared and sound sensors. Experts had longer post-movement initiation quiet eye compared to novices; however, total and premovement quiet eye durations did not differ between groups. Eye quietness was inversely correlated with quiet eye duration, and was greatest immediately after movement initiation. Importantly, movement duration correlated positively with post-movement initiation quiet eye and negatively with eye quietness shortly after movement initiation. This study demonstrates the utility of assessing ocular activity during performance of motor skills using EOG. Additionally, these findings provide evidence that

expert-novice differences in ocular activity may reflect differences in the kinematics (e.g., movement duration) of how experts and novices execute motor skills.

Introduction

The study of eye movements during performance of motor skills can yield important information to understand how individuals control their actions. In a seminal study, Vickers (1992) used camera-based eye-tracking to examine the gaze of 12 experienced golfers – comprising five skilled golfers (mean handicap 6.2) and seven less skilled golfers (mean handicap 14.1)[1] – as they putted balls to a 3 m distant hole. Vickers found that, compared to the less skilled golfers, skilled golfers made fewer and longer fixations on the ball prior to movement initiation, during movement execution, and even after movement completion. In the intervening 25 years since this influential initial report of visual gaze control in putting, researchers have used camera-based eye-tracking to examine individuals' ocular activity, and especially their *quiet eye*, during performance of motor skills.

The quiet eye is defined as the final ocular fixation on the target location (e.g., the ball in golf putting), with onset occurring prior to initiation of a critical phase of the movement and offset occurring when the gaze deviates from the target location (Vickers, 1996, 2007). A compelling body of literature has reported that experts show longer quiet eye durations than

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[1] Golf handicap represents the number of strokes taken in relation to the number of strokes expected to be taken to complete a round of golf. It indexes golfers' ability: the lower the value, the better the player.

novices for a variety of motor skills, ranging from precision sports to surgery (for reviews see Gonzalez, Causer, Miall, Grey, Humphreys, & Williams, 2017; Rienhoff, Tirp, Strauß, Baker, & Schorer, 2016; Vickers, 2007; Wilson, Causer, & Vickers, 2015; for meta-analyses see Lebeau, Liu, Sáenz-Moncaleano, Sanduvete-Chaves, Chacón-Moscoso, Becker, & Tenenbaum, 2016; Mann, Williams, Ward, & Janelle, 2007). For instance, Walters-Symons, Wilson, and Vine (2017) tested 18 experienced golfers (mean handicap 5.7) and 21 novices (no formal handicap), as they putted balls to a 10 foot (i.e., 3 m) distant hole. They found that the experienced golfers had longer quiet eye durations (M = 1.9 s) than the novices (M = 1.2 s). Due to the extensive research, long quiet eye is currently considered a feature of expertise and is often cited along classic models of skill acquisition (e.g., Fitts & Posner, 1967) whereby experts have greater movement accuracy, consistency, automaticity, and efficiency than novices.

Despite the robustness of the quiet eye phenomenon in revealing differences between expertise levels, there is no consensus on whether and how the quiet eye influences motor performance (e.g., Causer, 2016; Williams, 2016; Wilson, Wood, & Vine, 2016). A number of possible cognitive mechanisms have been proposed. The dominant hypothesis (Vickers, 1996) contends that movement-related visual processing is enhanced and movement parameters, such as force and direction, are programmed during the quiet eye period. Therefore, an extended quiet eye period could lead to improved motor programming and, consequently, to enhanced motor performance. Other hypotheses argue that a longer quiet eye duration allows inhibition of task-irrelevant processing (Klostermann, Kredel, & Hossner, 2014) or promotes an external focus of attention (Vine, Moore & Wilson, 2014), which has been associated with improved motor performance (Wulf, 2013). An alternative hypothesis is that the quiet eye reflects psychomotor quiescence. Accordingly, rather than eliciting cognitive benefits, the longer quiet eye of experts could be associated with (or be a consequence of) the cleaner and more consistent movement kinematics of expert compared to novice performers, such as a slower and more stable swing in golf putting (Cooke et al., 2014; Delay et al., 1997; Sim & Kim, 2010).

None of the studies to date have provided unequivocal empirical evidence that a longer quiet eye is directly associated with enhanced visual perception or cognitive processing, while our newly suggested kinematic hypothesis has yet to be tested at all. To shed light on these fundamental questions of why experts have a longer quiet eye than novices and why a longer quiet eye aids performance, researchers have been encouraged to employ objective psychophysiological measures to simultaneously assess cognitive, physiological and kinematic variables (for review of research in sport psychophysiology, see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004). Unfortunately, the simultaneous assessment of eye-movements with such psychophysiological and kinematic variables is a challenge for camera-based eye trackers; the primary and often only technique used to assess ocular activity by previous quiet eye and human performance research. Fortunately, an alternate psychophysiological tool used to record eye movements exists. Electrooculography (EOG) measures time-varying changes in the electric dipoles of the eyes, by recording voltage differences from electrodes placed close to the eyes (Young & Sheena, 1975; Shackel, 1967). A goal of this study is to apply novel EOG methods to quiet eye research and shed new light on the relationship between ocular activity and performance. Some advantages of EOG for quiet eye researchers are as follows.

First, the eyes move at speeds up to 100 Hz (Krauzlis, Goffart, & Hafed, 2017). Therefore, based on Nyquist-Shannon sampling theorem (Shannon, 1948), ocular activity should be sampled at least at 200 Hz (corresponding to 1 data point every 5 ms) to prevent aliasing and avoid temporal distortions (i.e., key features of the signal are missed or altered). Because typical camera-based mobile eye-tracking systems sample data at 30 Hz, (i.e., 1 frame every 33 ms) researchers have expressed the need for tools with greater temporal sensitivity than the ones used to date (e.g., Causer, 2016; Gonzalez et al., 2017; Williams, 2016). Typical systems for psychophysiological recording have a sampling frequency of 512 Hz (i.e., 1 voltage value every 2 ms) or higher. Accordingly, the EOG offers sufficient temporal precision to fully capture time-varying ocular activity.[2]

Second, by definition, the quiet eye period can extend beyond movement initiation and even beyond movement completion as long as the eyes are on the target (Vickers, 1996, 2007). Because the preprogramming of movement parameters such as direction and force ends with movement initiation, mechanistic studies of the quiet eye should benefit from distinguishing the pre- and post-movement initiation components of the quiet eye period. Surprisingly, only a few recent camera-based studies have reported these components in a golf putting task (Causer, Hayes, Hooper, & Bennett, 2017; Vine, Lee, Moore, & Wilson, 2013; Walters-Symons, Wilson, Klostermann, & Vine, 2017). Causer et al. (2017) found that for novice golfers (no formal handicap), longer quiet eye durations were associated with better performance (lower radial error) in both the pre- and post-movement initiation phases of the putt. Vine et al. (2013) found that for experts (mean handicap 3.6) only the post-movement initiation component of the quiet eye distinguished holed from missed putts (longer duration for holed putts). Finally, Walters-

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[2] The influence of sampling rate on ocular activity has been investigated by Helsen, Starkes, Elliot, and Ricker (1998). They sampled ocular activity at 60 and 120 Hz using camera-based eye-tracking while participants performed a finger movement task. They found that the two sampling rates produced different results for saccade durations but not for fixation durations.

Symons et al. (2017) tested experienced golfers (mean handicap 6.4) and found that, compared to shorter putts (4 feet, 1.2 m), longer putts (8 feet, 2.4 m) were associated with less accuracy and longer post-movement initiation quiet eye durations. They also found no differences in pre-movement initiation quiet eye durations between long and short putts. These findings cast doubt on any quiet eye mechanism that concerns what happens before movement initiation, such as improved preprogramming of movement parameters. By exploiting the multi-measure approach favored in psychophysiology, EOG recordings can be supplemented with external transducers (e.g., an infrared sensor) to detect movement initiation, such as the beginning of the backswing in golf putting (e.g., Cooke, Kavussanu, McIntyre, & Ring, 2010), thereby ensuring that both pre- and post-movement initiation components of the quiet eye can be easily explored.

Third, the eyes are not completely still during a fixation (e.g., Krauzlis et al., 2017). Therefore, identifying a quiet eye period requires a threshold criterion to be applied. Because the fovea corresponds to less than 2° of the visual field (Guyton & Hall, 2006), most quiet eye studies have defined fixations in terms of when gaze remains within 3° or 1° of visual angle on the target location (Gonzalez et al., 2017; Lebeau et al., 2016; Vickers, 2007). Because the threshold influences the duration of the fixation, whereby stringent thresholds identify shorter fixations, the impact of threshold choice on quiet eye durations has been recommended as a research question to better understand the quiet eye phenomenon (Gonzalez et al., 2017). One of the strengths of data processing in psychophysiology is that the signal can be scored repeatedly and automatically using different settings, such as voltage thresholds in the EOG.

Fourth, the EOG allows researchers to examine the quiet eye phenomenon from a novel perspective that is commonplace in psychophysiology, where signals are measured as a function of time relative to a critical event. Accordingly, instead of defining quietness using a threshold and measuring quiet eye duration (see previous point), researchers could quantify the amount of eye quietness as a function of time relative to movement initiation (e.g., Webb & Obrist, 1970).

To date, only one study has used the EOG to examine the quiet eye in a golf putting task. Mann, Coombes, Mousseau, and Janelle (2011) tested 10 skilled (mean handicap 1.2) and 10 less skilled golfers (mean handicap 11.3) as they putted balls to a 12 foot (i.e., 3.7 m) distant hole. They computed the quiet eye by applying a voltage threshold to the EOG signal and found that the more skilled golfers had longer quiet eye durations (around 2.3 s) compared to the less skilled golfers (around 2.1 s). However, they only scored the pre-movement initiation component of the quiet eye, and not the potentially more important post-movement initiation component (Vine et al., 2013; Walters-Symons, Wilson, Klostermann, & Vine, 2017). Furthermore, they applied an atypical threshold criterion of 100 µV (corresponding to 5° of visual angle) to the EOG signal; all other golf putting studies have employed a threshold of either 1° or 3° of visual angle (for reviews see Gonzalez et al., 2017; Lebeau et al., 2016).

With the overarching goal of introducing psychophysiological methods to quiet eye research, this study evaluated the utility of EOG in assessing ocular activity during performance of motor skills. We conducted new analyses on a golf putting dataset with known expert-novice and holed-missed differences for several psychophysiological indices (Cooke, Kavussanu, Gallicchio, Willoughby, McIntyre, & Ring, 2014). Our primary aims were threefold. First, to quantify both pre- and post-movement initiation components of the quiet eye using EOG. Second, to develop a novel, time-varying measure of ocular activity in the form of eye quietness. In line with the existing literature, we expected that quiet eye durations would be longer and eye quietness greater in experts compared to novices and on holed putts compared to missed putts. Third, we aimed to evaluate the validity of the eye quietness index by assessing its correlation with quiet eye durations. We expected that the two measures would be highly negatively correlated.

Our secondary aims were threefold. First to examine the impact of threshold level (e.g., 1° or 3° of visual angle) on quiet eye duration. We expected that more stringent thresholds would generate shorter quiet eye periods. Second, to determine the influence of expertise on the consistency of indices of ocular activity and kinematics across putts. We expected greater consistency in experts based on theoretical models arguing for decreased performance variability as a function increased expertise and learning (e.g., Fitts & Posner, 1967). Finally, we examined the relation between ocular activity (i.e., quiet eye durations, eye quietness) and swing duration. This analysis provided the first test of our kinematic hypothesis of the relationship between quiet eye and performance; namely that a longer quiet eye is associated with a cleaner and more consistent technique. We expected that longer swing durations would be associated with longer post-movement initiation quiet eye durations and greater eye quietness during swing execution.

Method

Participants

Twenty right-handed male golfers took part in this study. Ten were experts (age: *M* = 20.90, *SD* = 0.74 years; experience: *M* = 11.25, *SD* = 3.78 years; handicap: *M* = 1.50, *SD* = 2.32) and ten were novices (age: *M* = 19.00, *SD* = 0.66 years; experience: *M* = 1.85, *SD* = 2.49 years; no formal handicap). All provided informed consent.

Putting task

Participants putted golf balls (diameter 4.7 cm) on an artificial flat putting surface

(Turftiles) to 2.4 m distant hole, using a blade-style putter (length 90 cm). The hole was of regular size for novices (diameter: 10.8 cm) and half-size for experts (diameter: 5.4 cm). This difference in hole size was chosen so that the two groups holed a similar number of putts and thereby putting outcome (holed, missed) could be used as a factor in our analyses (cf. Babiloni et al., 2008). Indeed, the performance of the two groups did not differ, $t(18) = 1.18$, $p = .25$, $r^2 = .072$, with experts holing 41% (*SD* = 17%) and novices holing 31% (*SD* = 19%) of putts. Participants were instructed to get each ball "ideally in the hole, but if unsuccessful, to make them finish as close to the hole as possible." Addressing of the ball, movement initiation (i.e., beginning of backswing), and putter-ball impact were detected through the combination of infra-red (S51-PA 2-C10PK, Datasensor, Monte San Pietro, Italy) and sound (NT1, Rode, Silverwater, Australia) sensors.

EOG signal

Three pairs of Ag-AgCl electrodes, each with an integrated preamplifier, were applied to the participant's skin. These were placed at the bottom and outer canthi of both eyes as well as on the forehead (Fp1 and Fp2 location in the 10–20 system, Jasper, 1958). Common mode sense and driven right leg electrodes were used instead of ground and reference electrodes to enhance the common mode rejection ratio of the signal. Voltages were recorded and digitized at 512 Hz (24-bit resolution) using the ActiveTwo system (BioSemi, Netherlands). Offline, the electrodes were bipolar-referenced to obtain one horizontal EOG and two vertical EOGs channels: for the horizontal channel, positive and negative voltages indicated eye movements respectively to the left and to the right; for the vertical channels, positive and negative voltages indicated respectively upward and downward eye movements. The signals were band-pass filtered 0.1 to 30 Hz (FIR, Order 512) according to guidelines (Marmor et al., 2011). Epochs were extracted from –9 to +3 s relative to movement initiation (i.e., beginning of backswing), unless two contiguous trial epochs overlapped (in this case, the prebackswing portion was cut shorter). All participants’ vertical and horizontal EOG signals are presented in the Supplemental Material of Chapter Four (Supplement S1) and examples are shown in Figure 4.1A. As golf putting is performed in the frontal plane, we focused our analyses on the horizontal signals. Signal processing was performed using MATLAB (MathWorks, Natick, MA).

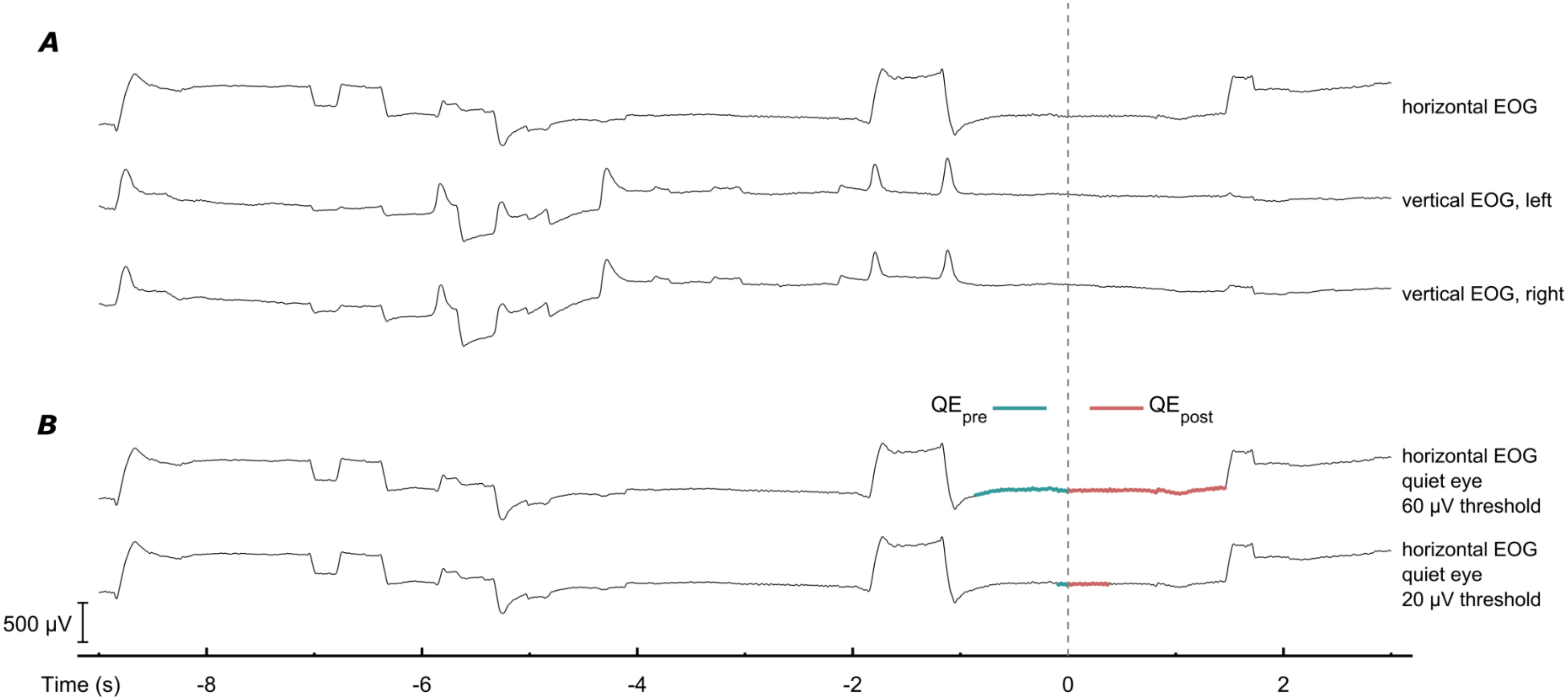

Figure 4.1. (A) Horizontal and vertical (left and right eye) EOG signals. Voltages (µV) are represented as function of time (s). Voltage increases indicate eye movements to the left or upward; voltage decreases indicate movements to the right or downward. Eye blinks are evident in the vertical EOG signals. (B) Output of the QE algorithm with 60 and 20 µV thresholds. Thick colored lines indicate the quiet eye period in its pre-movement initiation (QE_{pre}) and post-movement initiation (QE_{post}) components.

Procedure

Following instrumentation and task familiarization (20 putts), participants putted 60 balls in each of two counter-balanced pressure conditions. Due to the methodological nature of this study, only the no-pressure condition was analyzed. It is worth noting that the null effects of pressure on performance and other psychophysiological signals have been reported by Cooke et al. (2014). The mean inter-putt interval for the no-pressure condition was 15.44 s (*SD* = 1.90). Light conditions were kept constant throughout testing.

Measures

Quiet eye. The duration of the total quiet eye (QE_{total}) was measured as the time (in seconds) between quiet eye onset and quiet eye offset. QE_{total} comprised the sum of the pre-movement initiation (QE_{pre}) and post-movement initiation (QE_{post}) components. The onset and offset of the quiet eye were detected using a voltage-threshold algorithm, which is described in detail in the Supplemental Material of Chapter Four (Supplement S2). This algorithm was employed twice: once using a 60 µV threshold and once using a 20 µV threshold, corresponding with eye movements of 3° and 1° of visual angle, respectively (Shackel, 1967; cf. Mann et al, 2011). The outputs of both algorithms for all participants are presented in the Supplemental Material of Chapter Four (Supplement S3); examples are shown in Figure 4.1B.

Eye quietness. Eye quietness was operationalized as the standard deviation of the horizontal EOG signal (HEOG-SD), measured in µV, within each of 12 0.5 s bins, ranging from –4 to +2 s relative to movement initiation. Lower HEOG-SD values correspond with less movement of the eyes, i.e., greater quietness. The bin width was chosen following exploratory analyses using a range of widths (0.125, 0.25, 0.5 and 1 s): 0.5 s was sufficiently brief to capture variation in eye quietness in the context of golf putting whereas 1 s was too coarse.

Putting times. Address time was measured as the time, in seconds, between the positioning of the putter head next to the ball and movement initiation (i.e., beginning of backswing). Swing time was measured as the time, in seconds, between movement initiation and putter-ball impact.

Performance. Performance was measured as the percentage of holed putts.

Data reduction and statistical analyses

Putting times, quiet eye and eye quietness measures were computed for each putt. These were used to compute each participant's (a) arithmetic mean, as an index of the average value, and (b) standard deviation, as an index of variability across putts. Analyses involving quiet eye durations were conducted twice, separately for the two thresholds (60 and 20 µV) .

Group, outcome, and time differences. Differences in quiet eye durations and putting times were examined using 2 Group (expert, novice) × 2 Outcome (holed, missed) ANOVAs, with group as a between-subjects factor and outcome as a within-subjects factor. Differences in eye quietness were examined using 2 Group (expert, novice) × 2 Outcome (holed, missed) × 12 Time (0.5 s bins from –4 to +2 s) ANOVA, with group as a between-subjects factor and outcome and time as within-subjects factors. The multivariate solution was adopted where appropriate (Vasey & Thayer, 1987) and Wilks' lambda (λ) reported. Univariate partial eta-squared (η^2_p) was reported as a measure of effect size, with values of .02, .13, and .26 reflecting small, medium, and large effects, respectively (Cohen, 1992). Significant interactions were interrogated using posthoc t-tests (reported for $p < .05$).

Relations between quiet eye and eye quietness. Pearson's correlations were conducted between quiet eye durations and eye quietness (HEOG-SD) to examine the relationship between the two indices of ocular activity. Only relevant comparisons were considered: QE_{pre} with pre-movement initiation eye quietness and QE_{post} with post-movement initiation eye quietness.

Impact of threshold on quiet eye durations. We employed 300 different thresholds, ranging from 2 to 600 µV (in 2 µV increments), corresponding to a range of 0.1 to 30° (in 0.1° increments) of visual angle. For each threshold we evaluated group differences through independent-sample t-tests.

Correlates of performance. Pearson's correlations were conducted between the percentage of holed putts and (a) quiet eye durations, (b) eye quietness, and (c) putting times. These correlations were performed separately for each group due to the different hole sizes (i.e., task difficulties) used for these two groups.

Relations between putting times and ocular activity. Pearson's correlations were conducted to explore the relations between ocular activity (quiet eye and eye quietness) and putting times (address and swing times).

Results

Group, outcome, and time differences

Quiet eye. The mean (*SD*) quiet eye durations for each group's holed and missed putts are presented in Table 4.1. More and greater expert-novice differences were detected using the more restrictive 20 µV threshold than the 60 µV threshold. It is noteworthy that QE_{total} and QE_{pre} durations did not differ between experts and novices. However, experts had longer QE_{post} (for 60 µV and 20 µV thresholds) than novices. In terms of variability across putts, experts had less variable QE_{total} and QE_{pre} durations (for 60 µV threshold) but more variable QE_{post} duration (for 20 µV threshold) compared to novices.

Table 4.1. Mean (*SD*) of quiet eye durations (QE_{total}, QE_{pre}, and QE_{post}), computed with 60 and 20 µV threshold levels, and putting times (address and swing times), with the results of the 2 Group (expert, novice) × 2 Outcome (holed, missed) mixed ANOVAs. Values were examined as average (e.g., QE_{total}) and standard deviation (e.g., SD QE_{total}) across putts.

	Experts (n = 10)		Novices (n = 10)		Group		Outcome		Group × Outcome	
Measures	Holed	Missed	Holed	Missed	*F*(1,18)	η^2_p	*F*(1,18)	η^2_p	*F*(1,18)	η^2_p
Quiet eye durations (s), 60 µV										
QE_{total}	1.983 (0.60)	2.002 (0.52)	2.400 (1.65)	2.557 (1.72)	0.78	.041	0.66	.035	0.40	.022
QE_{pre}	1.032 (0.49)	1.061 (0.50)	1.848 (1.59)	2.014 (1.63)	2.88	.138	0.81	.043	0.40	.022
QE_{post}	0.952 (0.21)	0.942 (0.23)	0.552 (0.25)	0.543 (0.21)	16.49**	.478	0.26	.014	0.00	0.00
SD QE_{total}	0.57 (0.43)	0.55 (0.35)	1.15 (0.83)	1.19 (0.62)	6.61*	.268	0.01	.000	0.07	.003
SD QE_{pre}	0.46 (0.49)	0.44 (0.38)	1.06 (0.86)	1.11 (0.68)	6.28*	.259	0.03	.002	0.07	.004
SD QE_{post}	0.21 (0.12)	0.22 (0.08)	0.25 (0.06)	0.25 (0.08)	0.73	.039	0.05	.003	0.22	.012
Quiet eye durations (s), 20 µV										
QE_{total}	0.705 (0.25)	0.655 (0.21)	0.664 (0.54)	0.627 (0.44)	0.04	.002	4.03	.183	0.08	.004
QE_{pre}	0.417 (0.19)	0.381 (0.13)	0.497 (0.51)	0.454 (0.41)	0.25	.014	2.91	.139	0.02	.001
QE_{post}	0.288 (0.11)	0.275 (0.11)	0.167 (0.06)	0.173 (0.07)	8.29*	.884	0.13	.007	0.89	.047
SD QE_{total}	0.33 (0.13)	0.32 (0.09)	0.38 (0.29)	0.38 (0.25)	0.38	.020	0.35	.019	0.02	.001
SD QE_{pre}	0.27 (0.11)	0.25 (0.08)	0.35 (0.30)	0.34 (0.28)	0.82	.044	0.89	.047	0.04	.002
SD QE_{post}	0.16 (0.07)	0.16 (0.08)	0.08 (0.04)	0.10 (0.05)	8.73**	.327	1.02	.054	0.51	.027
Putting times (s)										
Address	2.92 (0.81)	2.99 (0.90)	4.79 (3.3)	4.43 (2.78)	2.79	.134	1.16	.061	2.47	.121
Swing	0.89 (0.15)	0.90 (0.16)	0.71 (0.14)	0.71 (0.15)	8.53**	.321	0.44	.024	0.15	.008
SD Address	0.78 (0.60)	0.79 (0.48)	1.96 (1.47)	2.15 (1.60)	6.19*	.256	1.54	.079	1.13	.059
SD Swing	0.04 (0.02)	0.06 (0.09)	0.07 (0.03)	0.20 (0.44)	1.35	.070	1.18	.062	0.66	.036

* $p \leq .05$; ** $p < .01$

Eye quietness. The mean (*SE*) HEOG-SD measures of eye quietness as a function of group, outcome, and time are illustrated in Figure 4.2. A consistent time-varying cubic pattern can be seen: ocular activity increased during the movement preparation phase (–4 to –1 s), peaking just before movement initiation (c. –1 s), before dropping, with a trough around movement execution (0 s), and then increasing again after the ball was struck (c. 1 s).

The 2 Group × 2 Outcome × 12 Time ANOVA conducted on the mean HEOG-SD revealed a main effect for time, $F(11,8) = 7.87$, $p = .004$, $\lambda = .085$, $\eta^2_p = .247$, and a Group × Time interaction, $F(11,8) = 9.95$, $p = .002$, $\lambda = .068$, $\eta^2_p = .141$. Independent-sample t-tests revealed that, compared to novices, experts had greater HEOG-SD from –2.5 to –1.5 s and smaller HEOG-SD from 0 to 1 s. No effects emerged for group, $F(1,18) = 0.96$, $p = .34$, $\eta^2_p = .051$, outcome, $F(1,18) = 0.51$, $p = .49$, $\eta^2_p = .027$, Group × Outcome, $F(1,18) = 1.11$, $p = .31$, $\eta^2_p = .058$, Outcome × Time, $F(11,8) = 0.65$, $p = .75$, $\lambda = .528$, $\eta^2_p = .070$, nor Group × Outcome × Time, $F(11,8) = 0.78$, $p = .65$, $\lambda = .481$, $\eta^2_p = .044$.

The 2 Group × 2 Outcome × 12 Time ANOVA conducted on the variability of HEOG-SD revealed a main effect for time, $F(11,8) = 5.24$, $p = .01$, $\lambda = .122$, $\eta^2_p = .414$, namely, a cubic (increase, decrease, increase) pattern. No effects emerged for group, $F(1,18) = 0.27$, $p = .61$, $\eta^2_p = .015$, outcome, $F(1,18) = 1.11$, $p = .31$, $\eta^2_p = .058$, Group × Outcome, $F(1,18) = 0.72$, $p = .41$, $\eta^2_p = .038$, Outcome × Time, $F(11,8) = 3.13$, $p = .06$, $\lambda = .189$, $\eta^2_p = .115$, Group × Time, $F(11,8) = 2.84$, $p = .07$, $\lambda = .204$, $\eta^2_p =.139$, or Outcome × Group × Time, $F(11,8) = 0.85$, $p = .61$, $\lambda = .462$, $\eta^2_p = .023$.

Putting times. The mean (*SD*) putting times for each group’s holed and missed putts are presented in Table 4.1. Experts had longer swing times and less address time variability (indicative of greater consistency across putts) than novices.

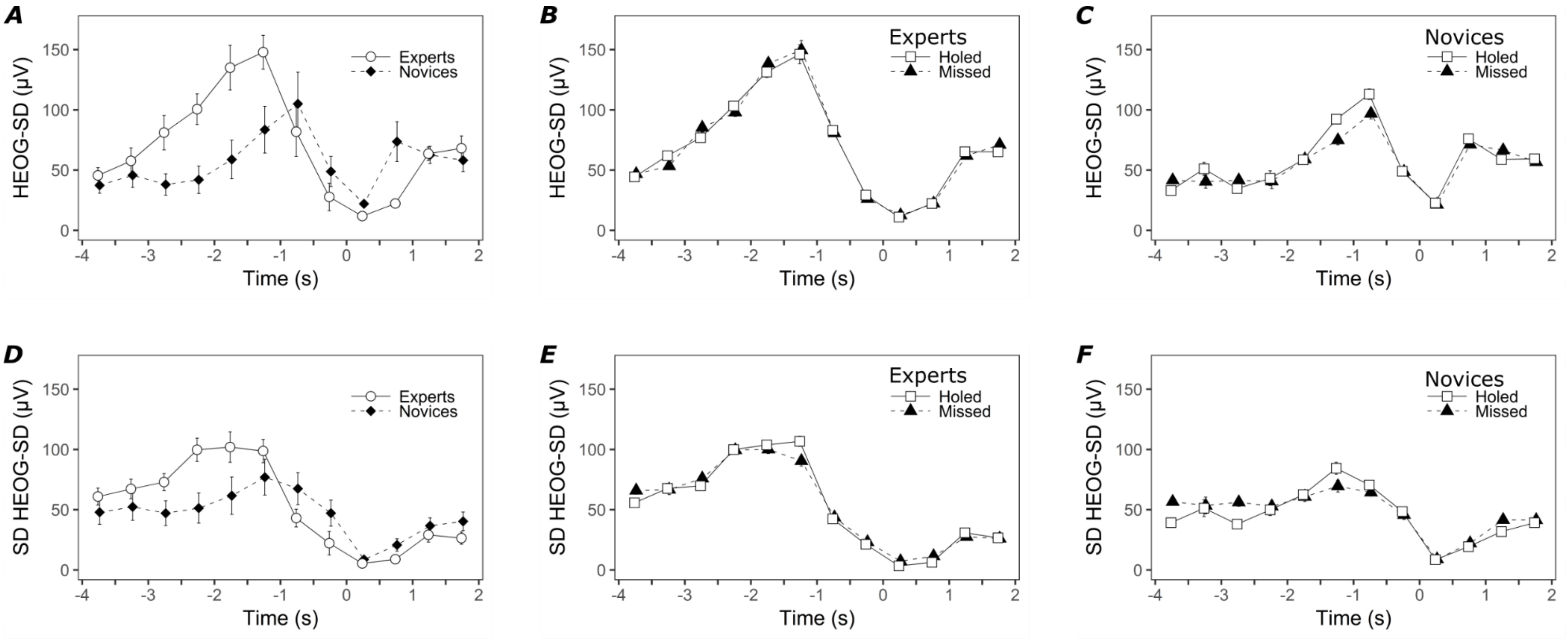

Figure 4.2. Eye quietness, i.e., HEOG-SD (µV), (panels A, B, and C) and its variability across putts, i.e., SD HEOG-SD (µV), (panels D, E, and F) as a function of time (s) from −4 to 2 s and either group (experts, novices) or outcome (holed, missed). HEOG-SD is inversely related to eye quietness: lower values indicate greater quietness. Panels A and D show Group × Time effects. Error bars indicate between-subject *SE*. Panels B and E show Outcome × Time effects for the experts. Panels C and F show Outcome × Time effects for the novices. Error bars indicate within-subject *SE* computed through normalization of the outcome factor (Cousineau, 2005).

Relation between quiet eye and eye quietness

Quiet eye durations were negatively correlated with HEOG-SD in both the pre- and post-movement initiation phases, most notably and prominently in the second before and the second after the onset of the backswing (see Table 4.2). As expected, these analyses confirm an inverse association between the quiet eye and eye quietness measures.

Table 4.2. Pearson's correlations between quiet eye durations (QE_{pre} and QE_{post}), computed with 60 and 20 µV threshold levels, and eye quietness (HEOG-SD), computed in different time intervals relative to backswing initiation. The table shows only relevant comparisons (e.g., pre-movement initiation quiet eye with pre-movement initiation eye quietness).

	QE_{pre} (s)		QE_{post} (s)	
HEOG-SD (µV)	60 µV	20 µV	60 µV	20 µV
–4 to –3.5 s	–.50*	–.34	-	-
–3.5 to –3 s	–.41	–.21	-	-
–3 to –2.5 s	–.38	–.07	-	-
–2.5 to –2 s	–.34	–.02	-	-
–2 to –1.5 s	–.33	–.11	-	-
–1.5 to –1 s	–.64**	–.35	-	-
–1 to –0.5 s	–.62**	–.50*	-	-
–0.5 to 0 s	–.48*	–.49*	-	-
0 to 0.5 s	-	-	–.91***	–.80***
0.5 to 1 s	-	-	–.53*	–.33
1 to 1.5 s	-	-	.11	–.18
1.5 to 2 s	-	-	.19	.29

* $p \leq .05$; ** $p < .01$; *** $p < .001$

Impact of threshold level on quiet eye duration

To further explore the impact of threshold level on expert-novice differences in the quiet eye, we computed their quiet eye durations corresponding to visual angles of 0.1 to 30° (2 to 600 µV). Importantly, experts never exhibited longer durations of QE_{total} (Figure 4.3A) or QE_{pre} (Figure 4.3B) than novices. Unexpectedly, compared to experts, novices showed longer QE_{total} durations at extremely high thresholds spanning approximately 400-500 µV (i.e. 20-25° of visual angle) as well as longer QE_{pre} durations at high to extremely high thresholds spanning 100-500 µV (5°-25° of visual angle). Finally, experts displayed longer QE_{post} durations than novices at thresholds of 20-150 µV, corresponding to 1°-7° of visual angle, which overlap with those used in camera-based research.

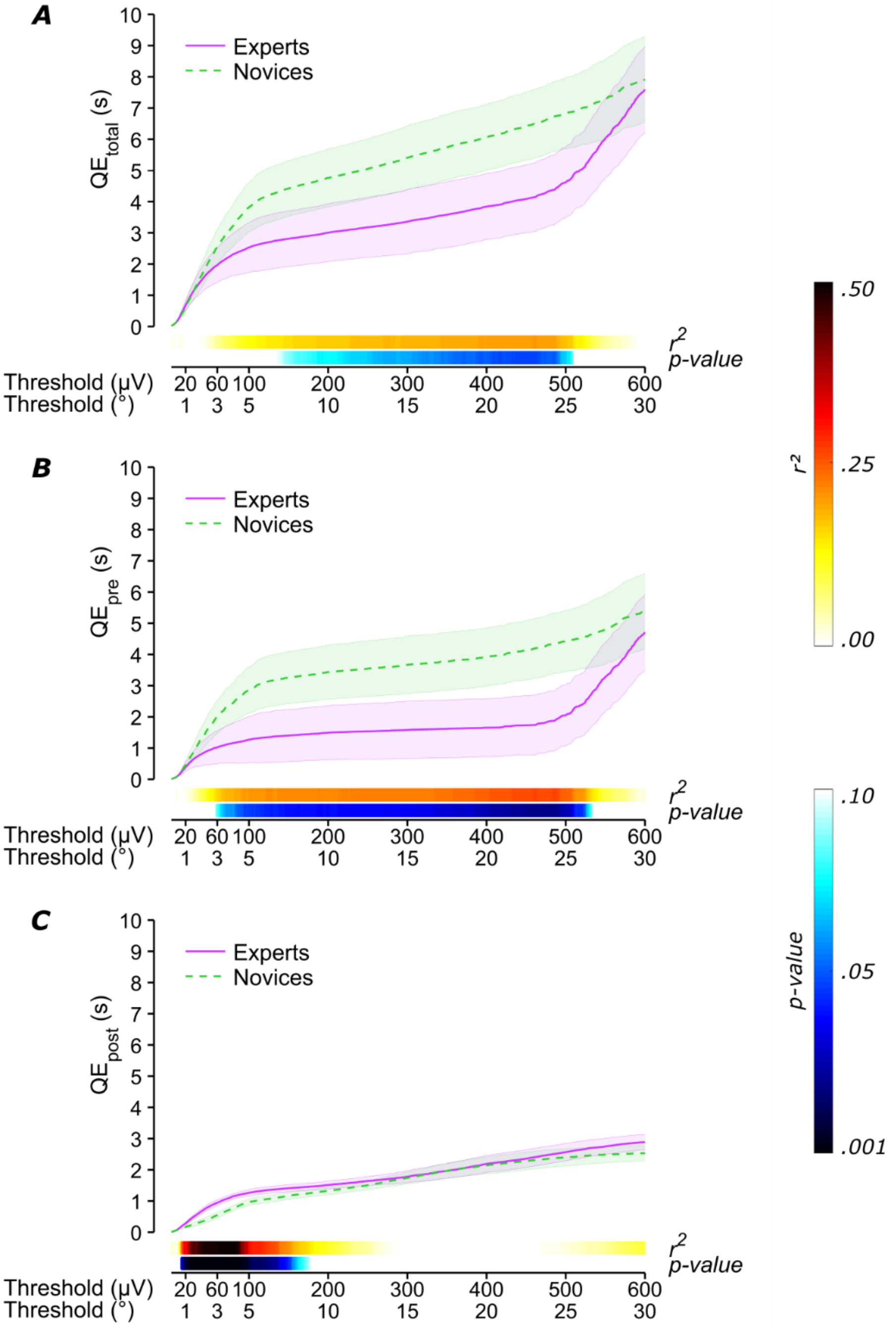

Figure 4.3. Durations (s) of total (QE$_{total}$, panel A), pre-movement initiation (QE$_{pre}$, panel B), and post-movement initiation (QE$_{post}$, panel C) quiet eye, as a function of threshold (µV and corresponding degrees of visual angle). The solid and dashed lines represent mean durations, respectively for experts and novices. The two colored bars above the x-axis indicate r^2 and *p* values associated with the independent-sample t-tests conducted on group differences (*df* = 18). The shaded areas represent the *SE* of each group's means and were computed using pooled estimates, hence corresponding with the independent-sample t-tests (Pfister & Janczyk, 2013).

Correlates of performance

For experts, the percentage of holed putts was unrelated to putting times, quiet eye durations, and eye quietness, with two exceptions (see Supplement S4 in the Supplemental Material of Chapter Four). Expert performance was negatively correlated with mean HEOG-SD in only the –2 to –1.5 s ($r = –.76$, $p = .01$) and 1.5 to 2 s ($r = –.71$, $p = .02$) bins, indicating that more putts were holed by players whose eyes were quieter within these intervals. For novices, the percentage of holed putts was unrelated to putting times, quiet eye durations, and eye quietness, with three exceptions (see Supplement S4 in the Supplemental Material of Chapter Four). Novice performance was negatively correlated with the QE_{total} ($r = –.63$, $p = .05$) and QE_{pre} ($r = –.63$, $p = .05$) with the 60 μV threshold, showing that more putts were holed by players with shorter total and pre-movement initiation quiet eye durations. Lastly, novices' performance was positively correlated with mean HEOG-SD in just the –0.5 to 0 s bin ($r = .73$, $p = .02$), indicating that more putts were holed by participants whose eyes were less quiet within this interval.

Relations between putting times and ocular activity

Pearson's correlations were computed between pre-movement initiation ocular activity and address times as well as between post-movement initiation ocular activity and swing times (Supplement S5 in the Supplemental Material of Chapter Four). These analyses showed that address times were unrelated to quiet eye and eye quietness. Crucially, ocular activity after backswing initiation was associated with the duration of the swing time. Namely, swing times correlated positively ($r = .52$, $p = .02$) with QE_{post} (60 μV threshold) and negatively ($r = –.63$, $p = .003$) with HEOG-SD measured 0.5 to 1 s after swing initiation. Thus, participants with longer putting strokes were characterized by longer post-movement initiation quiet eye durations and greater quietness around impact with the ball.

Discussion

This report explored the utility of EOG in the study of ocular activity during performance of a motor skill. Specifically, we conducted the first analysis of the effects of expertise on both pre- and post-movement initiation quiet eye components in golf putting. We also developed a new measure of movement-related ocular activity in the form of eye quietness, inversely related with quiet eye duration. The analyses generated a number of novel findings shedding light on the mechanisms underpinning the relationship between ocular activity and motor behavior. These effects are discussed below.

Quiet eye

A primary aim was to quantify both pre- and post-movement initiation components of the quiet eye using EOG and a secondary aim was to examine the impact of threshold level on quiet eye duration. We examined quiet eye durations at threshold levels corresponding with 3° and 1° of visual angle (i.e., respectively, 60 µV and 20 µV; Shackel, 1967), typically used in the quiet eye literature. As expected, quiet eye durations were longer with 3° (around 2 s for experts and 2.5 s for novices) than with 1° (around 0.7 s for experts and 0.6 s for novices). However, contrary to expectations, total quiet eye duration (i.e., QE_{total}) did not distinguish experts from novices. Interestingly, group differences emerged when the quiet eye period was broken down relative to the moment of movement initiation. Compared to novices, experts showed a shorter, albeit not significant, pre-movement initiation quiet eye (i.e., QE_{pre}), and longer post-movement initiation quiet eye (i.e., QE_{post}) (Table 4.1). Further analyses revealed that there was no threshold setting at which experts had a longer total quiet eye (QE_{total}) or pre-movement initiation quiet eye (QE_{pre}) than novices. Instead, experts only had shorter durations than novices, although this difference was significant only for threshold levels that were larger than typically used in literature (Figure 4.3A and 4.3B). These analyses also confirmed that experts showed a longer post-movement initiation quiet eye (QE_{post}) than novices (Figure 4.3C).

That the post-movement initiation component of the quiet eye was more sensitive than the pre-movement initiation component of the quiet eye in revealing differences in putting performance in experienced golfers is consistent with two previous studies (Vine et al., 2013, 2015). First, Vine et al. (2013) tested 50 expert golfers (mean handicap 3.6) as they putted balls to a 5 foot (i.e., 1.5 m) distant hole. They examined the quiet eye in different phases of the putt and found that, compared to missed putts, holed putts were characterized by a longer post-movement initiation quiet eye, whereas the pre-movement initiation quiet eye was not different. Second, Vine et al. (2015) tested 27 experienced golfers (mean handicap 5.8) as they putted balls to a 10 foot (i.e., 3 m) distant hole. Participants' view of the ball was occluded either before or after movement initiation, through a liquid crystal glass panel – positioned above the ball –turning opaque. The authors found that, compared to a no-occlusion condition, performance was impaired by post-movement initiation occlusion but not by pre-movement initiation occlusion. Taken together, these findings were interpreted as evidence that visual information was actively processed only after movement initiation (i.e., during the execution of the movement), suggesting that post-movement initiation quiet eye was involved in the online control of movement (Vine et al. 2015). However, it has to be noted that this interpretation may not apply to novices (Causer et al., 2017).

To our knowledge, this is the first golf putting study to separately examine quiet eye durations before and after movement initiation in an expert-novice design. The fact that effects of expertise, as well as of performance, emerged only after movement initiation, i.e., when movement preprogramming is completed, raises doubts on the interpretation of the quiet eye as correlate of motor programming (Vickers, 1996). Further mechanistic psychophysiological research is needed to clarify this issue. The EOG methodology developed here offers a promising tool to permit such research.

Eye quietness

Our primary purposes here were to develop a novel time-based EOG measure of eye-quietness, and to evaluate its validity by assessing correlations with our measure of quiet eye. We examined ocular activity as a function of time by computing the variability (standard deviation) of the EOG signal in short intervals (500 ms). This index allowed us to evaluate not only how long the eyes remained "quiet" but also how "quiet" the eyes were for intervals overlapping the quiet eye period. Time-varying statistical analyses revealed that eye quietness fluctuated over time, decreasing prior to movement initiation, increasing around movement execution, and then finally decreasing after movement completion (Figure 4.2). It is interesting to note that the eyes were quietest immediately after movement initiation. Group differences emerged in the second after the ball was struck, which were times that roughly overlapped movement execution, when experts kept their eyes quieter compared to novices. Experts also showed more ocular activity than novices around 2 s prior to movement initiation, perhaps indicative of them taking a final look at the hole consistently at that time (see Supplement S1 in the Supplemental Material of Chapter Four) .

As expected, these results for eye quietness broadly match those for quiet eye durations, i.e., greater post-movement initiation eye quietness corresponded with longer quiet eye duration, whereas less pre-movement initiation eye quietness corresponded with shorter quiet eye duration. Indeed, further analyses confirmed our hypothesis that eye quietness would correlate negatively with quiet eye durations, particularly at times immediately preceding and following movement initiation (Table 4.2), concurrently validating eye quietness as a measure of ocular activity. This new measure of movement-related ocular activity promises to be especially useful for future multi-method psychophysiological investigations, where it will allow time-synchronized analyses of ocular activity with other signals of interest such as EEG. This research is needed to shed further light on the mechanisms that underpin motor performance.

Consistency

We hypothesized that consistency of ocular activity across putts would be greater in experts than novices. The analyses of the variability (standard deviation) across putts for quiet eye durations and address times revealed that experts generally showed greater consistency than novices (Table 4.1), in line with classic models of motor skill acquisition (e.g., Fitts & Posner, 1967). Such group differences are also noticeable from inspection of the individual EOG waveforms (see Supplement S1 in the Supplemental Material of Chapter Four). This consistency effect may reflect the fact that experts have a more consolidated and permanent putting routine than novices, involving address time as well as ocular behavior.

Performance effects

We predicted, based on extant literature, that quiet eye durations would be longer, and eye quietness greater, for holed compared to missed putts. No differences emerged comparing holed and missed putts for all measures of ocular activity and movement times (Table 4.1). However, performance effects were detected when we considered the variability of participants separately within each group (see Supplement S4 in the Supplemental Material of Chapter Four). Correlation analyses revealed that among the novices, those with shorter quiet eye durations (total and pre-movement initiation quiet eye) and less eye quietness immediately before movement initiation holed more putts. This finding is in contrast with the view that longer quiet eye leads to better performance (Vine et al., 2014) but is consistent with the finding of this study that, on average, experts showed shorter total and pre-movement initiation quiet eye durations than novices. In other words, the novices that showed ocular activity more similar to that of the experts performed better. For the experts, those with greater eye quietness two seconds before and after movement initiation holed more putts. These findings may indicate that better performance was achieved by experts who moved their eyes less before putting (perhaps because they did not need to look at the hole as often, due to superior green-reading abilities) and after movement completion (perhaps because the ball ended in the hole more often or was rolling directly to the target and, therefore, there was less need to track it in some other spatial locations).

Kinematic hypothesis

Our final prediction was that longer swing durations would be associated with longer post-movement initiation quiet-eye durations and greater eye quietness during swing execution. Experts took around 200 ms longer than novices to swing the putter and hit the ball (Table 4.1). This finding is consistent with studies that have examined expert-novice differences for movement kinematics in golf putting (e.g., Delay et al., 1997). The fact that experts showed less ocular activity (i.e., greater eye quietness) than novices at times overlapping the execution of the swing suggests a connection between ocular activity and movement duration. Further analyses confirmed that swing duration correlated positively with the duration of the post-movement initiation quiet eye (i.e., QE_{post}) and negatively with eye quietness 0.5 to 1 s after movement initiation (see Supplement S5 in the Supplemental Material of Chapter Four). These results suggests that group differences for post-movement initiation ocular activity, discussed above, may be explained, at least in part, by the fact that experts took longer to perform the movement compared to novices. This provides promising evidence for the kinematic hypothesis as a mechanism to explain individual differences in gaze behavior. Specifically, keeping a quiet eye during the swing may enhance postural stability and permit a smoother movement execution. Alternatively, a longer and smoother technique may prompt a longer quiet eye and greater eye quietness during the swing. Indeed, compared to novices, experts swing the putter with lower variability in the axis perpendicular to the putting line (Cooke et al., 2014; Sim & Kim, 2010). The hypothesis that quiet eye represents a correlate of stability during the movement execution is worthy of more direct examination by future research. For example, studies could manipulate features of the movement (e.g., by varying putting distance; Delay et al., 1997) and examine their impact on putting kinematics (e.g., swing duration, smoothness, stability) as well as ocular activity to provide more direct tests of the kinematic hypothesis.

Limitations and Directions

The findings of this study need to be considered in light of some limitations. First, the EOG measures eye movements relative to the head and, therefore, head movements are confounded with eye movements (Young & Sheena, 1975). For example, a shift in gaze to the left with a still head generates an EOG signal that looks similar to a head movement to the right with a still gaze: in both cases the eyes move to the left but indicate a saccade and a fixation, respectively. In the present study we were able to observe that all participants rested their head above the ball during the final seconds before and during movement. Nonetheless, it would be better for future studies to directly measure head movements to control for this source of bias. Second, we computed quiet eye durations using the EOG signal from only the horizontal channel. However, to increase reliability and generalizability of this method to a variety of movement tasks, future studies could develop better algorithms that combine information from both the vertical and horizontal EOG channels. Third, we acknowledge that the equivalence of 20 µV on the horizontal EOG signal with 1° of visual angle is an oversimplification (Shackel, 1967). In fact, the corneo-retinal potential that generates the electrical activity that is detected by the EOG changes according to ambient luminance (Young & Sheena, 1975). This effect does not bias our findings because light conditions were kept constant throughout testing and adaptations to luminance changes occur over the course of several minutes (Marmor et al., 2011). Nonetheless, we recommend that researchers calibrate the EOG signal to visual stimuli placed at a known distance in visual angles, for each participant, to account for inter-individual variability. Fourth, differently from eye-tracking, the EOG does not provide spatial information on gaze location. For example, we could not distinguish whether, during the quiet eye period, the gaze was on the target (i.e., the ball) or on a location near the target (e.g., putting surface, putter head). In light of the fact that less skilled golfers make more fixations than more skilled golfers prior to backswing initiation (e.g., Vickers, 1992), this limitation may explain why our finding that novices had longer pre-movement initiation quiet eye durations than experts departs from what is reported in most other quiet eye studies. Fifth, experts putted to a smaller hole than novices. This ensured that the two groups achieved a similar number of holed and missed putts. However, the novelty of putting to a smaller hole may have affected experts' preparatory processes and their ocular behaviour. Finally, EOG can provide complementary information to eye-tracking. Therefore, future studies would do well to concurrently record eye-tracking and EOG to combine the greater spatial resolution of the former with the greater temporal resolution of the latter.

Conclusion

This study demonstrated the utility of new EOG-based methods as complementary techniques to camera-based eye-tracking to assess ocular activity during execution of motor skills. By incorporating EOG methods, quiet eye research should benefit from the body of knowledge produced by psychophysiological research about expertise and performance in motor control (for review of studies see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004). This interdisciplinarity should provide novel viewpoints on pressing issues, such as the *efficiency paradox* (Mann, Wright, & Janelle, 2016), questioning the function of a longer quiet eye when most psychomotor indices, including those of brain activity, indicate that expertise is associated with quietening of task-irrelevant activity and enhancement of task-relevant activity (e.g., Gallicchio, Cooke, & Ring, 2017). The evidence garnered here favors a more parsimonious explanation for previously identified expert-novice differences in quiet eye duration; they could simply reflect experts' better and smoother technique.

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CHAPTER FIVE

The quiet eye effect: A test of the visual and postural-kinematic hypotheses

Abstract

The quiet eye effect describes the performance advantage associated with a long ocular fixation on a critical target of an action, prior to and during movement execution. Researchers have advocated a multi-measure approach to shed light on the mechanism(s) behind the association between ocular activity and motor performance. In this study we used psychophysiological methods to test whether the quiet eye period is associated with enhanced visual processing (*visual hypothesis*) or longer movement durations (*postural-kinematic hypothesis*). Thirty-two recreational golfers putted 20 balls to a 2-m distant target on a flat surface. We examined quiet eye duration and time-varying eye quietness using electrooculography, occipital alpha power as inverse neural marker of visual processing using electroencephalography, and swing duration using kinematic sensors. Occipital alpha power increased prior to and during swing execution, suggesting decreased visual processing compared to baseline. Correlations revealed that, despite the overall decrease, visual processing decreased less with a longer quiet eye and greater eye quietness. Importantly, swing duration was strongly and positively correlated with both indices of ocular activity: longer quiet eye and greater eye quietness were associated with longer swing duration. Our findings support the postural-kinematic hypothesis, confirming that the duration of the quiet eye is associated with a slow movement execution and question the role of visual processing in the final moments of closed-loop aiming tasks. We anticipate major advancements in the mechanistic understanding of the quiet eye effect as researchers adopt psychophysiological

methods to examine eye movements in combination with measures of other biological systems.

Introduction

The way we move our eyes has been linked with the precision of movements requiring fine motor control, such as those used in target sports. Research using eye-tracking technology has revealed that, compared to novices, experts make fewer ocular fixations of longer duration on action-related locations prior to and during the execution of a motor skill (Mann, Williams, Ward, & Janelle 2007). The duration of the final ocular fixation on a critical target of the action, labelled the *quiet eye* (Vickers, 1996), has attracted much interest from researchers due to its ability to distinguish skilled from less skilled performers and successful from unsuccessful performance (for reviews of studies see Lebeau et al., 2016; Mann, Williams, Ward, & Janelle, 2007; Rienhoff, Tirp, Strauß, Baker, & Schorer, 2016; Vickers, 2007; Wilson, Causer, & Vickers, 2015). In the case of golf putting, the quiet eye period has been defined as the duration of the final ocular fixation on the ball, with onset prior to the initiation of the swing movement and offset when the gaze deviates from the ball, potentially even after putter-ball impact (Vickers, 2007). Longer quiet eye durations have been reported for experienced versus novice golfers (e.g., Walters-Symons, Wilson, & Vine, 2017) and for holed versus missed putts in experienced golfers (e.g., Wilson & Pearcy, 2009).

Despite the compelling evidence endorsing the existence of the quiet eye effect, researchers still debate how it might influence performance. In order to advance our understanding and inform the design of training programs aimed at improving performance, researchers have advocated the use of mechanistic and cross-disciplinary investigations to test the validity of the various competing hypotheses (Causer, 2016; Williams, 2016; Wilson, Wood, & Vine, 2016). A comprehensive review of the putative mechanisms goes beyond the scope of the present work, and for a detailed account we refer the reader to a recent review by Gonzalez et al. (2017a). In the present study, we evaluated two mechanistic hypotheses: the visual hypothesis and the postural-kinematic hypothesis.

Visual hypothesis

Vision-action coupling constitutes a key element in the debate on quiet eye mechanisms. Researchers have described the quiet eye as a perceptual-cognitive phenomenon reflecting the selective processing of movement-related visual information through overt attention (see Posner, 1980). For example, in their study of the quiet eye in billiards, Williams et al. (2002) concluded that 'To execute the shot, players must successfully integrate visual information from the cue, cue ball, target ball, and pocket.' The thesis that visual processing plays a major role in the quiet eye was emphasized by Vickers (2012), who referred to the dorsal cortical stream – which is a network of visual attention (Corbetta & Shulman, 2002; Goodale & Milner, 1992) – to explain the putative mechanism underlying the quiet eye effect. In short, processing of visual information has been the dominant mechanism in this context, even for closed-loop aiming tasks with stationary targets, such as golf putting. Indeed, in their study of the quiet eye in golf putting, Vine et al. (2015) concluded that 'it seems that visual information is being actively extracted and processed, likely to aid the control of the putter head and to ensure good putter-ball contact.' In the current study we refer to this visual attention mechanism as the *visual hypothesis*.

Cognitive processes, including attention and perception, can be studied in an objective and unobtrusive manner by recording individuals' electroencephalogram (EEG) as they perform goal-oriented actions. More specifically, the selective allocation of attentional resources to processing of visual information can be assessed using the magnitude of cortical oscillations (i.e., power) within the alpha frequency band (8-12 Hz) in the occipital regions of the brain. Studies have established that increased occipital alpha power reflects decreased visual processing (Romei, Gross, & Thut, 2010; Romei, Rihs, Brodbeck, & Thut, 2008; Vanni, Revonsuo, & Hari, 1997). EEG methods have been successfully implemented in sport research (for review of studies see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004). For example, EEG research has revealed that superior motor performance is associated neural efficiency by alpha gating, which describes the allocation of attentional resources towards movement-related and away from movement-unrelated information processing (e.g., Gallicchio, Finkenzeller, Sattlecker, Lindinger, & Hoedlmoser, 2016; Gallicchio, Cooke, & Ring, 2017).

Given the extensive use of EEG in sport research it is surprising that, with one exception, the association between quiet eye and visual processing, assessed using EEG, has been largely neglected. The exception is the study by Janelle et al. (2000) that reported a positive correlation between quiet eye duration and EEG occipital alpha power in experienced marksmen. Contrary to the visual hypothesis, this finding suggests diminished visual processing during the quiet eye period in a shooting task. Given that this critical piece of evidence appears to have been overlooked within the quiet eye literature and, moreover, that this finding has never been replicated, the association between occipital alpha power and quiet eye duration warrants further investigation.

Postural-kinematic hypothesis

An alternative *postural-kinematic hypothesis* contends that the link between quiet eye and performance is accounted for by a kinematic mechanism, whereby postural stability (involving trunk, limbs, head, and eyes) before and during movement is associated with better performance and longer quiet eye. In the case of golf putting, a slower and more stable swing may be linked with (a) a cleaner putter-ball impact to optimize impact velocity and angle and thereby ensuring greater putting accuracy, and (b) greater likelihood to keep the head and eyes still and thereby resulting in delayed quiet eye offset and longer quiet eye. Each of these two elements is considered next.

First, the association between swing kinematics/biomechanics (i.e., a slow and stable movement) and superior putting performance is substantiated by research indicating that, compared to less skilled counterparts, expert golfers sway less (i.e., exhibit less centre of pressure variability) (e.g., Hurrion, 2009; McLaughlin, Best, & Carlson, 2008; Richardson, Hughes, & Mitchell, 2012), generate less lateral putter head acceleration (i.e., they are less likely to swing out of line) (e.g., Cooke et al., 2014; Sim & Kim, 2010), and putt more slowly (e.g., Delay et al., 1997; Gallicchio, Cooke, & Ring, 2018).

Second, the association between putting kinematics/biomechanics and longer quiet eye is relatively unexplored. For sake of clarity, this association can be examined separately for stability and duration. The argument that greater movement stability is associated with longer quiet eye is supported by the finding that novice golfers trained to increase their quiet eye duration in a putting task also generated decreased lateral and vertical putter head acceleration, compared to a control group (Moore, Vine, Cooke, Ring, & Wilson, 2012). The argument that longer movement duration (i.e., slower swing) is associated with longer quiet eye is supported by the findings that experts swung for longer than novices and that movement duration was positively correlated with post-movement initiation quiet eye duration (Gallicchio et al., 2018). In other words, because novices swung the putter quicker than experts they had less reason to keep their head still and dwell on the impact location. Conversely, novices had more reason to start to track the moving ball sooner (see online supplementary material, Gallicchio et al., 2018), and, therefore, exhibited an earlier quiet eye offset compared to experts. The current study aims to extend and replicate the study by Gallicchio and colleagues by testing the movement duration element of the postural-kinematic hypothesis both within and between participants.

The Present Study

In the present study we had two aims. Our first aim was to assess whether ocular activity was associated with EEG occipital alpha power and thereby test a core tenet of the visual hypothesis. Our second aim was to assess whether ocular activity was associated with movement duration in order to test a core tenet of the postural-kinematic hypothesis. We used EEG to examine brain activity implicated with visual processing (e.g., Janelle et al., 2000), and movement sensors to examine the duration of the movement (e.g., Gallicchio et al., 2018). We used electrooculography (EOG) to score the quiet eye period in different phases of the movement (e.g., Gallicchio et al., 2018; Gonzalez et al., 2017b; Mann, Coombes, Mousseau, & Janelle, 2011). We supplemented quiet eye information with the novel ‘eye quietness’ index (Gallicchio et al., 2018), which, unlike quiet eye duration, measures the extent to which the eyes are quiet (rather than dichotomizing eye movements into a state of ‘quiet’ or ‘non quiet’) with high temporal resolution.

Method

Participants

We tested 32 right-handed male relatively-inexperienced recreational golfers (age: *M* = 20.09, *SD* = 2.04 years) with no formal golf handicap and occasional golf experience: they reported to have played 12.06 times (*SD* = 12.96) in the 12 months preceding testing. Participants were asked to refrain from alcohol, caffeine, and nicotine 3 hours prior to testing. All provided signed consent to take part in the study and were compensated with £10 and research credits. This study was approved by the local ethics committee.

Putting task

Participants putted golf balls (diameter 4.7 cm) to a 2-m distant target with a 91-cm blade-style putter on a 5 × 1.5 m flat surface (Turftiles; Stimpmeter value: 2.27 m). The target was a 6 mm diameter adhesive paper marker placed on the putting surface. Participants were instructed to execute the putt at their own pace (i.e., no time pressure) with their goal to "*get the final position of the ball as close as possible to the target*". Prior to each putt participants were required to stand in a relaxed position and maintain their gaze on a fixation cross placed at eye level on the facing wall (c. 1.5 m away) for 4-5 s, until a 200-ms acoustic tone prompted them to prepare for the putt. This acoustic tone was generated by a piezo buzzer controlled by an Arduino Micro board (Arduino, Italy) interfaced with a computer running MATLAB (MathWorks, USA).

Procedure

Upon arrival in the laboratory, participants were briefed and instrumented for physiological recording. Then, participants performed 10 putts to a series of targets varying in distance and extent to familiarize them with the putting surface. Finally, participants putted 20 balls to a straight 2-m distant target. The average time between consecutive putts was 22.82 s (*SD* = 2.45). After each putt the researcher took a photo of the putting area using a ceiling-mounted camera and repositioned the ball for the next putt.

Physiological signals

Electrophysiological signals were recorded using an ActiveTwo system (BioSemi, Netherlands). The EOG was recorded using four electrodes applied on the participant's skin near the eyes: two were placed at the outer canthi of each eye and the other two at the bottom of each eye. The EEG was recorded through 32 electrodes applied on scalp sites Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2 (10-20 system, Jasper, 1958). Additional electrodes were applied to the mastoids and to the chest (proximal lead-II ECG montage) for offline denoising purposes (described below). The signal was amplified and digitized at 2048 Hz with 24-bit resolution and no filter was set during recording. All channels were recorded in monopolar. Common mode sense and driven right leg electrodes were used to enhance the common mode rejection ratio of the signal.

Digital triggers (transistor-transistor logic inputs) were sent via parallel communication to the recording system in order to detect (a) the onset of the acoustic tone (prompting the participant to prepare for the putt), (b) the initiation of the backswing, and (c) the impact of the putter head with the ball. Participants were instructed to align the putter head with an infrared digital switch (E18-D80NK) when ready to putt: this sensor sent a digital trigger as the putter head moved away from the ball at the initiation of the backswing. In addition, a piezo sensor (MiniSense 100) attached to the back of the putter head was used to record putter-ball impact vibrations. This sensor was interfaced with the recording system to synchronize information about the impact with the electrophysiological signals.

After recording, we performed the following pre-processing steps. Signals were down-sampled to 512 Hz. For the analysis of the quiet eye, the electrodes positioned at the canthi of each eye were re-referenced to each other to create a bipolar horizontal EOG channel. Then we applied a 30 Hz low-pass filter (Finite Impulse Response, filter order = 2^8) according to EOG guidelines (Marmor et al., 2011). No high-pass filter was applied in order to preserve flat sections of the signal, typical of ocular fixations (Acuña et al., 2014). Epochs were segmented from -9 to +3 s (0 s = backswing initiation) and the voltages were linearly detrended (i.e., the best straight-line fit was subtracted to each epoch signal). Finally, a 125-ms median filter was applied to attenuate ocular overshoots while preserving sharp vertical edges typical of ocular saccades (Bulling et al., 2011; Juhola, 1991). Figure 5.1

shows the horizontal EOG channel from selected trials for illustration. All single-trial waveforms can be accessed from the Supplemental Material of Chapter Five (Appendix S1).

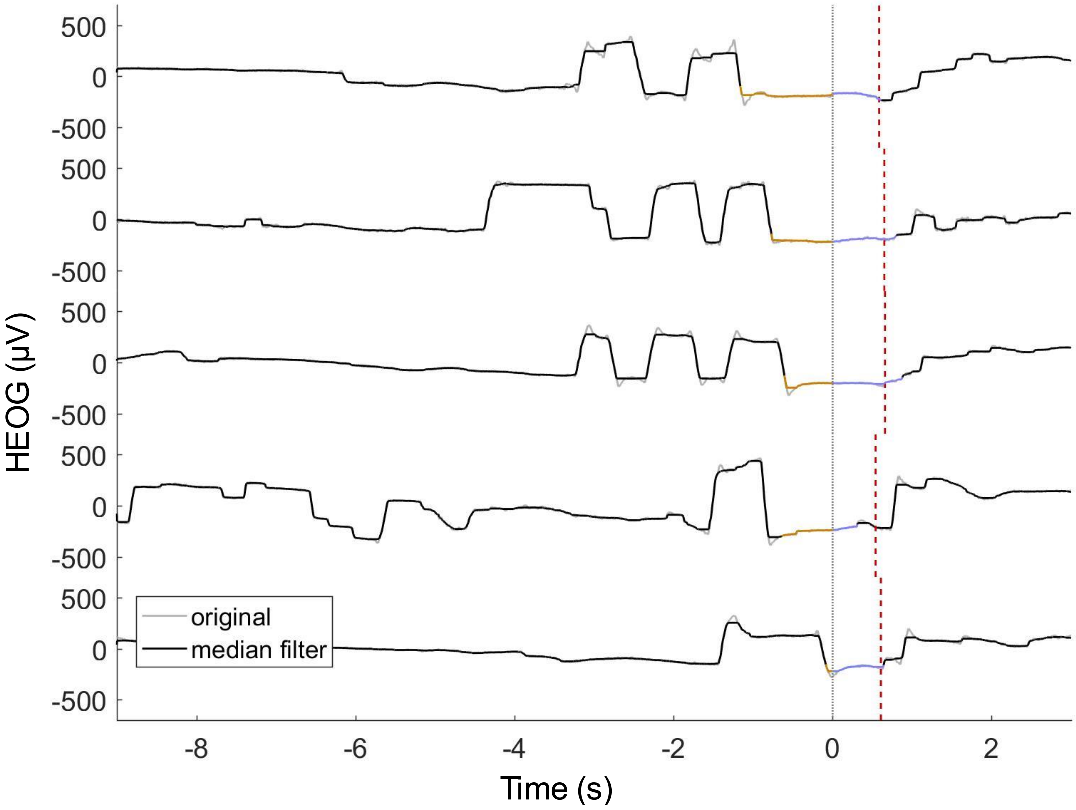

Figure 5.1. Voltage of the horizontal EOG channel as a function of time (0 s = backswing initiation) for selected putts. Increases and decreases in signal amplitude indicate saccades to the left and right, respectively, whereas a flat signal indicates absence of eye saccades (i.e., fixations). For each waveform, the grey line represents the original signal (low-pass filtered at 30 Hz); the black line represents the same signal after median filtering; orange and blue portions represent respectively QE_{pre} and QE_{post} durations identified with the 60 µV threshold; the red vertical line indicates putter-ball impact.

For the analyses of EEG activity and eye quietness we applied a 0.1-40 Hz band-pass filter (Finite Impulse Response, filter order = 2^15). Two types of epochs were segmented from -3.5 to +1.5 s relative to (a) the acoustic tone and (b) the initiation of the backswing. Voltages were mean-centered within each epoch. Epochs were visually inspected and were discarded from all subsequent analyses if they showed movement or electrical artefacts. The mean number of backswing-centered epochs that were retained was 19.84 (*SD* = 0.37, *minimum* = 19). The mean number of tone-centered epochs that were retained was 19.75 (*SD* = 0.51, *minimum* = 18). Independent Component Analysis (Makeig et al., 1996) was performed to attenuate any electrical artefacts due to ocular, cardiac, and muscular activity in the EEG signal using the EOG and ECG channels. Finally, the EEG channels were average-referenced.

Measures

Quiet eye. Quiet eye durations (ms) were calculated for two periods and were obtained by further processing the horizontal EOG signal: QE_{pre} defined as quiet eye onset to backswing initiation, and QE_{post} defined as backswing initiation to quiet eye offset. Onset and offset of the quiet eye were identified through a threshold algorithm. Specifically, voltages at successive time points were compared with the voltage at the instant of the initiation of backswing (i.e., time = 0 s). Quiet eye onset and offset were respectively defined as the farthest time points preceding and following backswing initiation that did not exceed a certain threshold (Gallicchio et al., 2018). We evaluated the quiet eye durations for 30 threshold options (ranging from 5 to 150 µV in 5 µV steps). We conducted exploratory analyses using all these threshold settings (Figure 5.2); however, for our main analyses, we chose a threshold of 60 µV, corresponding with eye movements of 3° of visual angle (Shackel, 1967). This choice was informed by visual inspection revealing that, compared to other thresholds (including 20 µV corresponding with 1° of visual angle), the 60 µV threshold detected most accurately the duration of the final fixation, commencing with the foot of the final square wave prior to backswing initiation (Figure 5.1). Moreover, 60 μV is the same threshold deemed optimal in a previous study (Gallicchio et al., 2018). The interested reader can inspect the single-trial quiet eye durations identified by the different threshold options in the Supplemental Material of Chapter Five (Appendix S1).

Eye quietness. Eye quietness (%) was computed as the standard deviation of the horizontal EOG channel (HEOG-SD) in eight non-overlapping 0.5 s intervals ranging from -3 to +1 s (0 s = backswing initiation) (Gallicchio et al., 2018). Each HEOG-SD value reflected how much the eyes moved or were active in the horizontal plane: larger values indicated more and larger eye movements (hence less eye quietness); conversely, smaller values indicated fewer and smaller eye movements (hence greater eye quietness). Finally, HEOG-SD was baseline-corrected to reflect the percentage change relative to average HEOG-SD in the 2 s prior to the onset of the acoustic tone. This transformation was performed to minimize variability between participants and, moreover, this procedure is implemented as standard in the analysis of EEG signals (Pfurtscheller & Lopes da Silva, 1999).

Occipital alpha power. Time-frequency decomposition was performed through short-time Fast Fourier Transform (FFT), conducted on eight non-overlapping 0.5 s windows ranging from -3 to +1 s (0 s = backswing initiation), to match the windows used for the analysis of eye quietness. Prior to FFT, each window was mean-averaged, multiplied by a Hanning function to taper both ends, and then zero-padded to reach a length of 4 s, yielding a frequency resolution of 0.25 Hz. The amplitude of the signal resulting from the FFT was doubled for all positive frequencies and alpha power was computed as the squared amplitude in the 8-12 Hz frequency range. Then, alpha power was baseline-corrected to reflect the percentage change (Pfurtscheller & Lopes da Silva, 1999) relative to the average baseline activity in the 2 s prior to the onset of the acoustic tone. Finally, occipital alpha power was obtained by averaging values for the O1, Oz, and O2 channels to create an occipital region of interest, consistent with previous research (e.g., Gallicchio et al. 2017).

Movement duration. The duration of the swing (ms) was measured as the time between backswing initiation and putter-ball impact. These two events were detected through a bespoke MATLAB script that combined data from the infrared switch and the piezo sensor.

Putting performance. Radial error (cm) was computed as the distance between the target and the terminal position of the ball after each putt. Scoring was performed through a bespoke MATLAB script that used the photos of the target area taken after each putt (Gallicchio & Ring, 2018).

Statistical Analyses

We used two statistical strategies to examine the associations between ocular activity (i.e., quiet eye and eye quietness) and (a) brain activity (i.e., occipital alpha power), (b) movement duration, and (c) putting performance (i.e., radial error). Correlations were computed using the Spearman's rank test to examine non-linear associations. Spearman's ρ was used as the effect size, with values of .10, .30, and .50 reflecting small, medium, and large effects, respectively (Cohen, 1992).

Our first strategy sought to capture the effects for each participant at the individual trial level. We refer to this as trial-level analysis. This strategy involved two steps. First, we correlated the two variables across all trials separately for each participant. Second, we performed a one-sample *t* test on the Fisher-Z transformed correlation coefficients across all participants (cf. Klostermann et al., 2014). For this analysis we report the group mean of the back-transformed Spearman's rho correlation coefficient (ρ_M) along with the *t* value and the associated *p* value. Our second strategy sought to compare participants using the average scores over all of their trials; this is the typical correlation analysis. We refer to this as participant-level analysis. For this analysis we report the Spearman's rho coefficient (ρ) and the associated *p* value. The purpose of each analysis and our selection of the pairs of measures is described next.

Quiet eye and eye quietness. We correlated quiet eye and eye quietness to cross-validate these two indices of ocular activity. More specifically, we correlated QE_{pre} with pre backswing initiation HEOG-SD (i.e., in the six time intervals from -3 to 0 s) and QE_{post} with post backswing initiation HEOG-SD (i.e., in the two time intervals from 0 to 1 s).

Correlates of occipital alpha power. We correlated ocular activity (i.e., quiet eye and eye quietness) with brain activity (i.e., occipital alpha power) to test the visual hypothesis. For the analyses involving the quiet eye, we correlated QE_{pre} with pre backswing initiation occipital alpha power (i.e., in the six time intervals from -3 to 0 s), and QE_{post} with post backswing initiation occipital alpha power (i.e., in the two time intervals from 0 to 1 s). For the analyses involving eye quietness, we correlated HEOG-SD and occipital alpha power in each of the eight time intervals from -3 to +1 s. In addition, we evaluated the specificity of any effect to the alpha band by conducting further analyses on activity in other EEG frequencies. We examined non-alpha frequencies to evaluate the extent to which any effect for the alpha band was unequivocally attributable to visual processing rather than indicating a general electrophysiological phenomenon (e.g., elevated somatic activity).

Correlates of movement duration. We correlated ocular activity (i.e., quiet eye and eye quietness) with movement duration to test the postural-kinematic hypothesis. Because it was necessary to measure movement duration from the initiation of the backswing, we correlated only the post-backswing initiation indices of ocular activity (i.e., QE_{post} and HEOG-SD in the 2 intervals from 0 to +1 s).

Correlates of performance. We correlated ocular activity (i.e., QE_{pre}, QE_{post}, and HEOG-SD in each of the eight time intervals from -3 to 1 s) with radial error to explore performance effects linked with gaze behaviour.

Results

Quiet eye and eye quietness

We computed the quiet eye for two intervals: before backswing initiation (QE_{pre}) and after backswing initiation (QE_{post}). The threshold algorithm at 60 µV identified the following mean durations: QE_{pre} 928 ms (*SD* = 501, *range* = 227 to 2623) and QE_{post} 819 ms (*SD* = 219, *range* = 367 to 1213). The main analyses reported below were conducted using the 60 µV threshold (see Measures section above for the rationale underlying this choice). Nonetheless, there is a healthy debate among quiet eye researchers about the appropriate choice of this threshold (i.e., visual angle), and therefore, we have displayed the influence of threshold choice on quiet eye duration in Figure 5.2A, which shows that the higher the threshold the longer the duration.

We analysed eye quietness (i.e., HEOG-SD) as a function of time (**Figure 3**). Smaller values reflected less variability, hence greater quietness. Eye quietness was best described by a cubic trend, $F(1,31) = 16.84$, $p < .001$, $\eta_p^2 = .352$, whereby quietness decreased until -1 s, increased until +0.5 s, and finally decreased after +0.5 s. It is worth mentioning that the greatest quietness was evident between 0 and +0.5 s, that is, during the execution of the swing.

To evaluate the utility of eye quietness as index of ocular activity we examined its correlation with quiet eye durations. The outcomes of trial- and participant-level correlations are reported in Table 5.1. Both types of analyses confirmed that greater eye quietness (i.e., smaller HEOG-SD) was associated with longer quiet eye durations before (i.e., in the time intervals from -1.5 to 0 s) and after (i.e., in the time intervals from 0 to 1 s) backswing initiation, with small to large effect sizes. It is noteworthy that this association held across multiple thresholds (Figure 5.2B and 2C).

Table 5.1. Trial-level analyses (i.e., average Spearman's ρ and t values) and participant-level analyses (i.e., Spearman's ρ) of the relation between quiet eye durations (QE$_{\text{pre}}$ and QE$_{\text{post}}$) and eye quietness (HEOG-SD) in 8 0.5 time intervals from -3 to +1 s (0 s = backswing initiation).

		QE$_{\text{pre}}$			**QE$_{\text{post}}$**	
Time	**$\rho_M(18)$**	**$t(31)$**	**$\rho(30)$**	**$\rho_M(18)$**	**$t(31)$**	**$\rho(30)$**
-3 to -2.5 s	-.08	-1.86†	-.00			
-2.5 to -2 s	.01	0.16	-.06			
-2 to -1.5 s	-.02	-0.29	-.26			
-1.5 to -1 s	-.12	-2.48*	-.25			
-1 to -0.5 s	-.30	-5.85***	-.42*			
-0.5 to 0 s	-.31	-4.34***	-.42*			
0 to +0.5 s				-.09	-2.15*	-.29
+0.5 to +1 s				-.03	-0.71	-.40*

Note. Only relevant comparisons are reported: QE$_{\text{pre}}$ with pre during initiation HEOG-SD (i.e., 6 intervals from -3 to 0 s) and QE$_{\text{post}}$ with post during initiation HEOG-SD (i.e., 2 intervals from 0 to +1 s).

† < .10, * $p < .05$, ** $p < .01$, *** $p < .001$

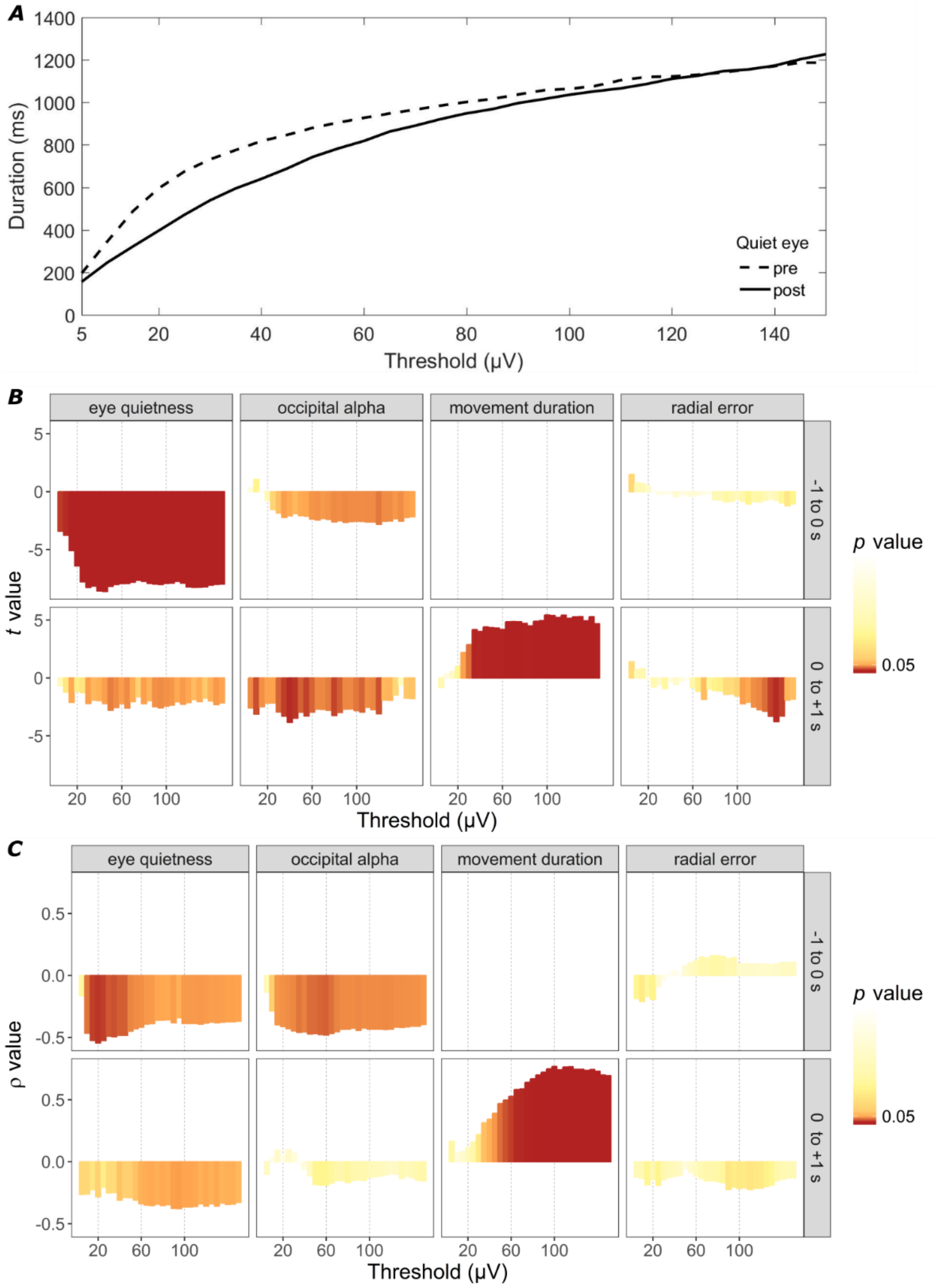

Figure 5.2. Effect of threshold (5-150 µV) on quiet eye durations (s) in the 'pre' and 'post' phases (panel A). Trial-level (panel B) and participant-level (panel C) analyses exploring the relation between quiet eye (s) and eye quietness (%), occipital alpha power (%), movement duration (s), and radial error (cm), as a function of thresholds (µV).

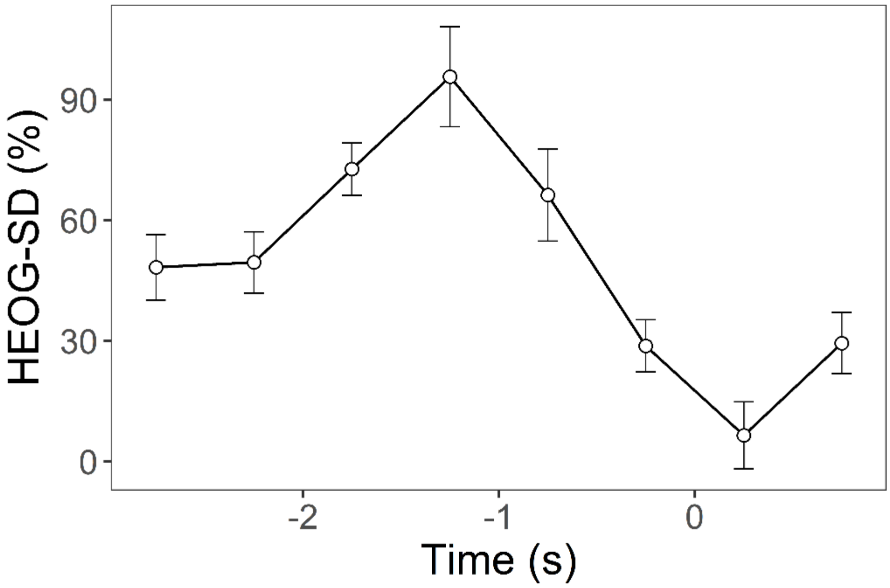

Figure 5.3. Eye quietness (HEOG-SD) as percentage change from the baseline (i.e., cross-trial average activity in the 2 s prior to the onset of the acoustic tone) as a function of time (i.e., 0.5-s non-overlapping intervals from -3 to +1 s; 0 s = movement initiation). Smaller values indicate less variability on the horizontal plane hence greater eye quietness. Error bars indicate within-participant *SE* computed through normalization of the outcome factor (Cousineau, 2005)

Correlates of occipital alpha power

Occipital alpha power averaged 157 μV^2 (*SD* = 187, *range* = -59 to 693) in the 1 s prior to backswing initiation and 125 μV^2 (*SD* = 158, *range* = -55 to 535) in the 1 s following backswing initiation, indicating an overall increase from the pre-cue period. The topography of alpha power for the 32 EEG channels is presented in the Supplemental Material of Chapter Five (Appendix S2).

Quiet eye. Quiet eye durations correlated negatively with occipital alpha power, with small to large effect sizes (Table 5.2). More specifically, trial-level analyses revealed that longer QE_{pre} was associated with decreased occipital alpha power from -2 to -1.5 s prior to backswing initiation. Longer QE_{post} was associated with decreased occipital alpha power in the 1 s following backswing initiation (i.e., approximately during swing execution). Participant-level correlations revealed that participants who showed larger decreases in occipital alpha power from -3 to -2.5 s and in the 1 s prior to backswing initiation were those with longer QE_{pre}.

Eye quietness. HEOG-SD was positively correlated with occipital alpha power, with small to large effect sizes (Table 5.2). More specifically, trial-level correlations revealed that greater eye quietness (i.e., smaller HEOG-SD) was associated with a decrease in occipital alpha power in the 2.5 s prior to backswing initiation. Participant-level correlations confirmed the same pattern for the 1 s following backswing initiation: participants with greater eye quietness were those with the largest decrease in occipital alpha power.

Alpha specificity. The exploration of other (i.e., non-alpha band) frequencies revealed that the association between occipital activity and ocular activity (i.e., quiet eye and eye quietness) was part of a more general phenomenon that was not specific to alpha band activity (Figure 5.4).

Table 5.2. Correlations between ocular activity (QE$_{pre}$, QE$_{post}$, and HEOG-SD) and occipital alpha power in 8 0.5 time intervals from -3 to +1 s (0 s = backswing initiation). Spearman's ρ is reported for the participant-level correlations. Average ρ and *t* values are reported for the within-participant correlations.

	QE$_{pre}$			**QE$_{post}$**			**HEOG-SD**		
Time	**ρ$_M$(18)**	***t*(31)**	**ρ(30)**	**ρ$_M$(18)**	***t*(31)**	**ρ(30)**	**ρ$_M$(18)**	***t*(31)**	**ρ(30)**
-3 to -2.5 s	.00	0.02	-.37*				0.04	0.76	.04
-2.5 to -2 s	.04	0.84	-.27				0.11	2.61*	.09
-2 to -1.5 s	-.09	-2.24*	-.28				0.13	3.04**	.21
-1.5 to -1 s	-.03	-0.82	-.29				0.12	2.47*	.07
-1 to -0.5 s	-.08	-1.58	-.44*				0.12	2.37*	.32†
-0.5 to 0 s	-.09	-1.54	-.51**				0.09	1.67	.47**
0 to +0.5 s				-.14	-3.38**	-.10	0.05	1.04	.36*
+0.5 to +1 s				-.08	-2.21*	-.28	0.08	1.84	.42*

Note. Only relevant comparisons are reported: QE$_{pre}$ with pre during initiation occipital alpha power (i.e., 6 intervals from -3 to 0 s) and QE$_{post}$ with post during initiation occipital alpha power (i.e., 2 intervals from 0 to +1 s).
† < .10, * *p* < .05, ** *p* < .01, *** *p* < .001

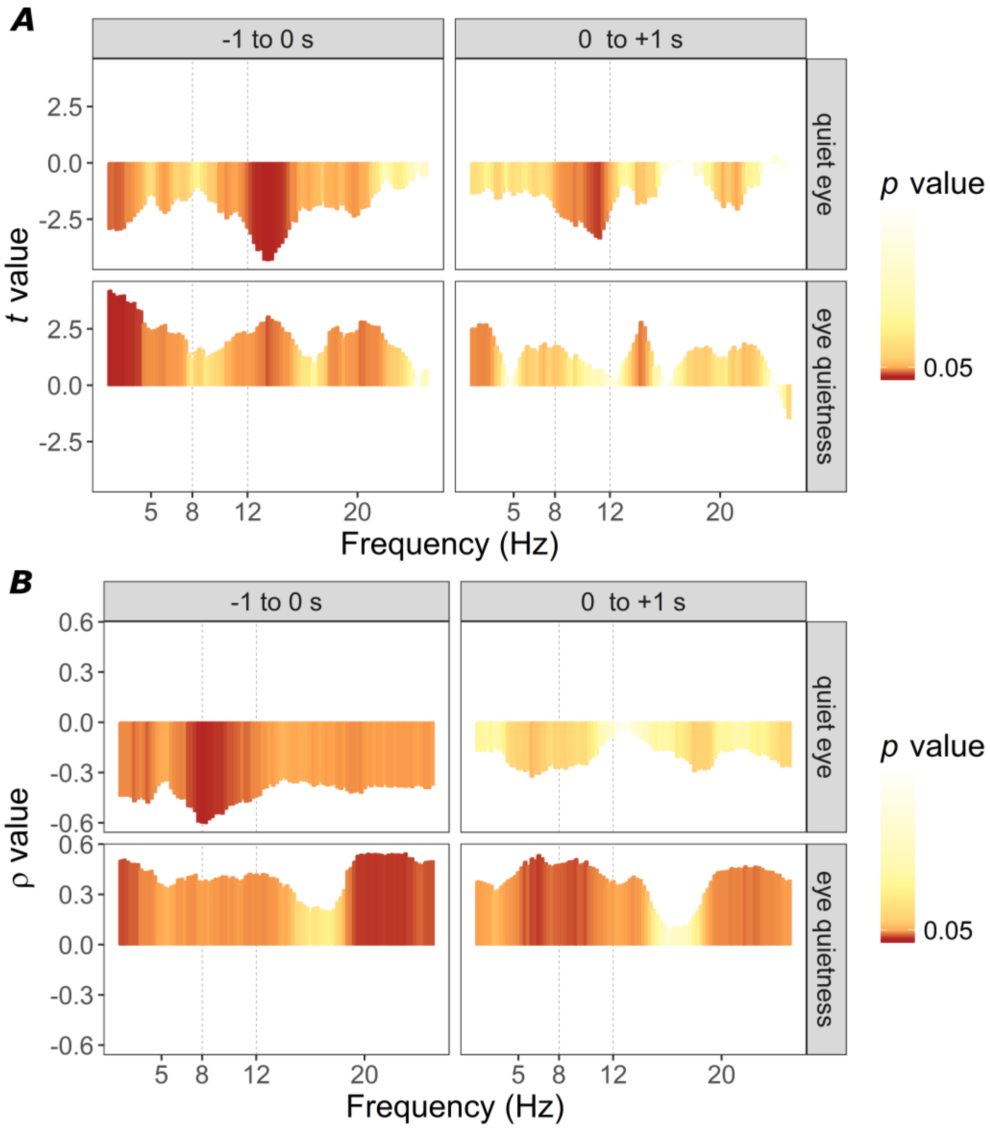

Figure 5.4. Trial-level (panel A) and participant-level (panel B) analyses exploring the relation between EEG power (%) in the 1 s preceding (-1 to 0 s) and following (0 to +1 s) backswing initiation and either quiet eye (s) or eye quietness (%), as a function of frequency (Hz).

Correlates of movement duration

Movement duration averaged 719 ms (*SD* = 174, *range* = 427 to 1057). Correlations examined the relation between movement duration and ocular activity (i.e., quiet eye and eye quietness) to test the postural-kinematic hypothesis. Only the indices measured after backswing initiation were used in these analyses (i.e., QE_{post} and HEOG-SD in the two intervals from 0 to 1 s).

Quiet eye. Quiet eye duration was positively associated with movement duration, with medium to large effect sizes. The trial-level analysis revealed that movement duration was positively correlated with QE_{post}, $\rho_M(18) = .32$, $t(31) = 4.19$, $p < .001$. Participant-level analysis confirmed this association, revealing that participants who executed the swing more slowly were those with longer QE_{post}, $\rho(30) = .53$, $p = .002$.

Eye quietness. Eye quietness was inversely associated with movement duration, with small to medium effect sizes, and only for certain time intervals. More specifically, trial-level analyses yielded a negative correlation between movement duration and HEOG-SD in the interval from 0.5 to 1 s, $\rho_M(18) = -.18$, $t(31) = -3.40$, $p = .002$, but not from 0 to 0.5 s, $\rho_M(18) = -.01$, $t(31) = -0.18$, $p = .86$. Participant-level analyses confirmed the same general pattern, albeit these were not statistically significant: participants with longer movement durations tended to show greater eye quietness (i.e., smaller HEOG-SD) from 0.5 to 1 s, $\rho(30) = -.27$, $p = .15$, but not from 0 to 0.5 s, $\rho(30) = .01$, $p = .92$.

Correlates of performance

Putting performance was assessed as radial error (*M* = 22.64 cm, *SD* = 5.47, *range* = 9.93 - 35.05). Trial- and participant-level correlations examined the relation between radial error and ocular activity (i.e., quiet eye and eye quietness). These results are described below.

Quiet eye. Trial-level analyses revealed that radial error was not significantly correlated with QE_{pre}, $\rho_M(18) = -.02$, $t(31) = -0.40$, $p = .69$, and QE_{post}, $\rho_M(18) = -.03$, $t(31) =$

-0.84, $p = .41$. Participant-level analyses also revealed non-significant correlations between radial error and QE_{pre}, $\rho(30) = .12$, $p = .51$, and between radial error and QE_{post}, $\rho(30) = -.12$, $p = .53$. Additional exploratory analyses conducted with less stringent thresholds for scoring the quiet eye duration revealed a negative and statistically significant relation between radial error and QE_{post} duration (see Figure 5.2B), providing some evidence that longer QE_{post} was associated with superior putting performance.

Eye quietness. No relation emerged between radial error and eye quietness (i.e., HEOG-SD) from -3 to + 1 s at the trial level, ρMs(18) = .00 to .06, *t*s(31) = -0.12 to 1.37, *p*s = .18 to 97, or at the participant level, ρs(30) = -.07 to .09, *p*s = .62 to .89.

Discussion

The goal of this study was to shed light on two of the putative mechanisms behind the quiet eye phenomenon. We tested the links between ocular activity and visual processing (visual hypothesis) and between ocular activity and movement kinematics (postural-kinematic hypothesis). Our findings provided support for the postural-kinematic hypothesis and only limited support for the visual hypothesis. Although we did not make explicit predictions regarding path (i.e., mediation) analyses we noted that, in our sample of recreational golfers, gaze measures were not reliably associated with putting performance. The implications of our findings are discussed below.

Quiet eye and eye quietness

Quiet eye was scored for separate movement phases: QE_{pre} before movement initiation and QE_{post} after movement initiation. A threshold of 60 µV – corresponding to approximately 3° of visual angle (Shackel, 1967) – yielded a total quiet eye duration of 1747 ms. Quiet eye durations associated with multiple thresholds and different phases of movement are illustrated in Figure 5.2A. As expected, larger thresholds yielded longer quiet eye durations, in line with that reported in a previous multiple-threshold EOG study (Gallicchio et al., 2018). Moreover, these values for the quiet eye components are consistent with those obtained using camera-based eye tracking in a similar population (e.g., Walters-Symons, Wilson, & Vine, 2017).

Eye quietness was scored as the standard deviation of the horizontal EOG signal (HEOG-SD) as a function of time relative to the initiation of movement. A trend analysis revealed a cubic pattern consisting of three phases: first, increased ocular activity 1 to 2 s prior to movement initiation; second, decreased ocular activity (i.e., increased eye quietness) during movement execution; and third, increased ocular activity. It is possible that the increased ocular activity in the first and third phases is attributable to saccades directed towards the target prior to swing initiation and to the ball and target following swing execution, to confirm the target location and monitor the rolling ball towards the target location, respectively. Importantly, the increased eye quietness around movement execution should reflect the quiet eye period. This interpretation is supported by the finding that eye quietness was strongly associated with quiet eye durations around movement initiation. The link between quiet eye and eye quietness was robust because (a) both trial- and participant-level analyses yielded medium to large effect sizes (Table 5.1), (b) the effect emerged for multiple quiet eye thresholds (Figure 5.2), and (c) it replicated previous findings (Gallicchio et al., 2018).

Visual hypothesis

EEG occipital alpha power was measured as percentage change from a pre-putt baseline during which participants fixated their gaze on a cross at eye level. The finding that this change score was positive indicates an increase from baseline, which can be interpreted as a withdrawal of processing resources away from visual processing (Romei et al., 2008, 2010; Vanni et al., 1997). In other words, the participants performed less visual processing in the moments just before, during, and just after putting the ball. In line with Janelle et al. (2000), this key finding undermines the visual hypothesis.

The co-examination of EEG and EOG revealed that occipital alpha power correlated negatively with quiet eye durations (QE_{pre} and QE_{post}) and positively with eye quietness (HEOG-SD). The size of these effects ranged from small to large (Table 5.2) and emerged for different quiet eye thresholds (Figure 5.2). These results could be interpreted as suggesting that, despite the overall decrease in visual processing, it decreased less for longer quiet eye durations and greater eye quietness, providing some limited support for the visual hypothesis. Importantly, however, the fact that these effects were not restricted to time intervals overlapping the quiet eye period (Table 5.2) and were not specific to the alpha frequency band (Figure 5.4) raises doubts on the plausibility of this interpretation. Accordingly, any interpretation of the relationship between EEG occipital alpha power and ocular activity in terms of visual processing should be treated with caution: at the moment we cannot rule out a more parsimonious electrophysiological interpretation whereby postural-kinematic quiescence influenced EEG recordings across a broad spectrum of brain waves that includes alpha. Furthermore, exploratory correlation analyses of the alpha-eye movement relationship across multiple EEG channels suggests that non-occipital areas are also implicated with longer quiet eye and greater eye quietness (see Appendix S2 in the Supplemental Material of Chapter Five). Indeed, additional analyses conducted on this dataset, reported in Gallicchio and Ring (2018), revealed that processing resources were gated towards the sensorimotor regions, presumably reflecting increased attention to and processing of proprioceptive afference to aid postural stability.

Postural-kinematic hypothesis

Both measures of ocular activity (quiet eye and eye quietness) were robustly associated with movement duration. First, post-movement initiation quiet eye (i.e., QE_{post}) correlated positively with movement duration. This association emerged for both trial- and participant-level analyses with large effect sizes and for multiple quiet eye thresholds (Figure 5.2). Second, eye quietness correlated negatively with movement duration. Interestingly, this association emerged only for the time interval that included the conclusion of movement execution (i.e., from +0.5 to +1 s after movement initiation) and, therefore, it indicates that a slower swing was associated with greater and longer-lasting eye quietness. These results replicate previous findings (Gallicchio et al., 2018) and provide additional support for the postural-kinematic hypothesis, which maintains that longer and greater ocular quietness after movement initiation is associated with a longer movement in closed-loop aiming tasks.

In line with the predictions of the postural-kinematic hypothesis, these analyses focused exclusively on the post-movement initiation component of gaze behaviour. It is noteworthy that the relatively few studies that have examined the separate contribution of pre- and post-movement initiation quiet eye in golf putting have all attributed a greater importance to the latter (Causer et al., 2017; Gallicchio et al., 2018; Klostermann et al., 2014; Vine, Lee, Moore, & Wilson, 2013; Vine, Lee, Walters-Symons, & Wilson, 2015). These findings imply that many other previously reported quiet eye effect findings may be at least partly attributable to differences in the kinematics of the movement: a longer post-movement initiation quiet eye could be due to a longer and smoother movement execution.

Correlates of performance

Our primary analyses were designed to test the visual and postural-kinematic hypotheses by focusing exclusively on the neurophysiological and kinematic correlates of the quiet eye and eye quietness (i.e., irrespective of performance). Nonetheless, incorporating performance data into the picture is a useful exercise for our mechanistic understanding of the quiet eye.

Gaze behaviour (quiet eye and eye quietness) was not reliably associated with putting performance. A recent meta-analysis of studies reporting within-participant associations between quiet eye duration and performance did not uncover any studies involving relatively inexperienced participants (Lebeau et al., 2016). The conspicuous absence of findings – positive, negative, and null – suggests a “file drawer” reporting bias, where null findings among non-experts have not been reported by authors. Accordingly, our null finding appears to be compatible with this hidden literature. It is also worth noting that the exploratory analyses involving less stringent quiet eye thresholds (c. 6 degrees of visual angle) revealed a positive association between quiet eye duration and performance: putts with longer post-movement initiation quiet eye duration were associated with lower radial error (Figure 5.2). Importantly, the null finding for gaze behaviour and performance does not undermine our findings concerning the visual and postural-kinematic hypotheses. Separate analyses conducted on the current dataset (see Gallicchio & Ring, 2018) revealed that putting performance was better for participants who exhibited elevated EEG occipital alpha power, suggesting that diminished visual processing is conducive to superior performance. This finding is consistent with Loze, Collins, and Homes (2001) who reported that best pistol-shooting accuracy was accompanied by elevated EEG occipital alpha power compared to worst performance, indicating withdrawal of resources from visual processing. Finally, additional analyses conducted on the current dataset revealed that changes in swing duration did not correspond with changes in performance[3]. However, it is worth mentioning that a previous investigation (Gallicchio et al., 2018) reported longer swing times for experts than novices. In sum, it is clear that future studies are needed to examine the extent to which the

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[3] Movement duration was not significantly associated with radial error as revealed by trial-level analyses, ρM(18) = -.03, *t*(31) = -0.86, *p* = .40 and participant-level analyses, ρ(30) = -.05, *p* = .80.

effect of gaze behaviour on performance is mediated by visual processing and swing duration.

Limitations

The present findings need to be considered in light of some potential study limitations. First, our results on quiet eye duration might be biased by the fact that, differently from camera-based eye tracking, EOG does not provide spatial information on the gaze location. Despite observing that participants kept their head above the ball during the swing we cannot confirm whether their gaze was on the expected focus point (i.e., the ball) or on locations near this point (e.g., the putter head) during the quiet eye period. The uncertainty of gaze location is aggravated by the fact that the equivalence of 20 µV on the horizontal EOG signal with 1° of visual angle is more a guideline rather than an exact mathematical law (Shackel, 1967). With this in mind, we recommend that researchers co-record EOG with camera-based eye tracking to determine which processing parameters (e.g., EOG threshold) provide the most accurate measures of quiet eye.

Second, we could not co-examine horizontal and vertical eye movements because EOG recordings were not calibrated to visual stimuli placed at known distances. While we concede that the horizontal signal is more meaningful than the vertical signal in a putting task (which is performed in the frontal plane) we recommend that future studies pay greater attention to this technical point. To address this limitation, future studies should consider calibrating the EOG signal (e.g., Gonzalez et al., 2017b) to achieve a better voltage-to-visual angle mapping.

Third, our analyses could not determine whether the association between quiet eye and activity in the visual regions of the brain was due to fixation on the critical focus location (i.e., the ball) or just a general ocular quiescence. To answer this question, future research should examine EEG occipital alpha power while individuals are instructed to fixate the critical focus location or an irrelevant spot nearby this location (cf. Williams, 2016). Connected to this point, future research should consider recording the EEG from a larger set of electrodes to discern activity from primary and secondary visual regions of the brain. This point arises from the acknowledgement of an alternative interpretation of our findings: the increase in EEG occipital alpha power may reflect diminished processing of task-irrelevant visual information, hence a sharpened visual focus on task-relevant visual information (i.e., the ball in golf putting).

Fourth, this study does not provide a comprehensive test of the postural-kinematic hypothesis. Future studies interested in this mechanism should assess movement smoothness and postural stability by recording, respectively, multi-axis movement acceleration (e.g., Cooke et al., 2014; Moore et al., 2012) and body sway (e.g., Hurrion, 2009) in relation with quiet eye duration.

Finally, by focusing on the association between ocular activity and visual processing / movement kinematics, this study tested only one path of the mediation model described by the visual and postural-kinematic hypotheses: we did not examine the mediatory role of visual processing or movement kinematics on the relation between quiet eye and performance. With the basic understanding accrued so far, future research is now well-equipped to address causality in the proposed mechanisms by employing experimental manipulations and mediation analyses.

Conclusion

Our study demonstrates the utility of adopting psychophysiological methods in quiet eye research. We anticipate valuable developments in the mechanistic understanding of this phenomenon as quiet eye researchers incorporate this methodology to study eye movements together with the activity of multiple other biological systems. Furthermore, the use of EOG opens new avenues for novel training programmes based on real-time eye quietness biofeedback. Our findings imply that the quiet eye may be indicative of a quiet body (cf. Obrist, Webb, & Sutterer, 1969) and question the role played by visual attention before and during movement execution in golf putting. It is entirely plausible that attention to visual information plays an important role at an earlier stage of movement planning – the so-called “green reading” in golf – where individuals make perceptual judgments on spatial features of the target scene (e.g., distance, slope) to calibrate movement parameters, such as force and direction (Carey, Jackson, Fairweather, Causer, & Williams, 2017). It is likely that individuals internalize these parameters into an action plan and maintain it in working memory before and during movement execution. Obviously, these ideas need to be addressed by future research. Finally, we foresee that a multi-method approach, such as the one that we advocate, will allow research teams to confirm the mechanism(s) underlying the quiet eye phenomenon as we approach the end of the third decade since its discovery.

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CHAPTER SIX

General Discussion

The aim of my thesis was to increase our understanding of the biological correlates of superior motor performance by providing an integrated account of the models of neural efficiency (Hatfield & Hillman, 2001) and quiet eye (Vickers, 2007). For this purpose, I conducted a series of four empirical studies adopting a multi-measure, psychophysiological approach to analyse brain activity – through electroencephalography (EEG) – and eye movements – through electrooculography (EOG) – in golf putting. In this final chapter I provide an integrated summary of the findings of these studies. Then, I propose a model of superior motor performance that reconciles the thus-far divergent predictions of the neural efficiency and quiet eye models. In the next section I highlight some limitations of this model and suggest directions for future research within this framework. Finally, I describe some practical implications for athletes.

Summary of Findings

The overarching aim of study one (described in Chapter Two and in Gallicchio, Cooke, & Ring, 2017) and study two (described in Chapter Three and in Gallicchio & Ring, 2018a) was to evaluate the utility of an extension of the model of neural efficiency (Hatfield & Hillman, 2001) incorporating the gating-by-inhibition framework of alpha oscillations (Jensen & Mazaheri, 2010). This framework was deemed useful to reconcile the apparently conflicting findings associating superior motor performance to elevated alpha power (i.e., decreased activity) in some regions and diminished alpha power (i.e., increased activity) in other regions (for a review of studies see Cooke, 2013; Hatfield, Haufler, Hung, & Spalding, 2004).

Topographical EEG analyses revealed a focal pattern whereby alpha power was lowest in the central regions, intermediate in the temporal regions, and greatest in the occipital regions. This pattern emerged in both study one and study two. Study two also indicated that this pattern varied as a function of time relative to movement onset and that, therefore, it reflected a phasic process specific to the movement preparation and execution rather than a general tonic process. In line with the gating model (Jensen & Mazaheri, 2010), the focal distribution of alpha indicated that, in preparation for and during movement execution, cortical resources were diverted away from the occipital and temporal regions and directed towards the central regions. Because the central regions are involved with sensorimotor processing whereas the occipital and temporal regions are involved with non-motor cognitive processing (Bears, Connors, & Paradiso, 2007), the movement-related alpha gating pattern most likely reflects the temporary shift of cognitive resources, including attentional focus, towards movement-related processing.

Importantly, the movement-related alpha gating pattern appeared to be functionally related to performance. Specifically, study one revealed that larger performance improvements following practice of the golf putting task over the course of several days were partly attributable to increased inhibition and functional isolation of the left and, to a lesser extent, right temporal regions. Study two revealed that better performance accuracy was preceded by greater inhibition of the occipital region. Taken together, these findings suggest that, provided that cognitive resources are gated towards sensorimotor processes, additional inhibition of movement-unrelated activity (i.e., in the temporal and occipital regions) is more beneficial than additional enhancement of movement-related activity (i.e., in the central regions).

The behavioural relevance of the movement-related alpha gating was further highlined by the finding that an experimentally induced disturbance to the gating resulted in the impairment of performance. Namely, the findings of study two indicated that when performing under conditions of high variability (e.g., by having the position of the target of the action vary randomly at each repetition) the task was perceived as more difficult, performance deteriorated, and alpha gating was disrupted. This disruption was marked by weakened inhibition of the left and, to a lesser extent, right temporal regions. In other words, non-motor processes based in the temporal regions are likely to have interfered with the optimal execution of the movement.

It is noteworthy to point out that the findings of study one and study two attributed greater importance to the inhibition of the temporal regions rather than the occipital regions. As suggested in study one, the fact that these effects were not evident in the occipital region is most likely because inhibition was already the strongest in the occipital region out of the brain regions examined. Notably, the finding that the activity in the occipital region – which is directly involved with visual processing – was detrimental for performance in an aiming task, even though replicating previous findings (e.g., Loze, Collins, & Holmes, 2001) was puzzling and warranted further investigation. Accordingly, study three (described in Chapter Four and in Gallicchio, Cooke, & Ring, 2018) was designed to pioneer the co-analysis of alpha gating and vision. More specifically, the aim of this study was to validate EOG tools to examine ocular activity during the execution of a motor skill. The methodological innovations of this study consisted in the development of a measure to examine time-varying eye quietness and a procedure to score the quiet eye period by employing multiple thresholds. The main theoretical contribution of this study was the specification of the kinematic hypothesis, contending that expert-novice differences in post-movement initiation quiet eye duration are associated with differences in movement kinematics, such as movement duration and smoothness.

Finally, by integrating the methodological tools and the theoretical framework developed in the preceding empirical studies, study four (described in Chapter Five and in Gallicchio & Ring, 2018b) assessed the mechanistic roles of both visual processing and movement kinematics in the quiet eye phenomenon. The findings of this study provided additional support for the kinematic hypothesis by revealing that intra-individual differences as well as inter-individual differences in post-movement initiation quiet eye were related to the duration of movement execution. Importantly, this study revealed that visual processing does not play an important role during the final stages of movement preparation. This evidence underpinned my interpretation of the quiet eye as manifestation of psychomotor quiescence whereby a quieter eye reflects greater efficiency. In the next section, I discuss these ideas in more detail and introduce a revised integrated model of neural efficiency and quiet eye.

Neural Efficiency and Quiet Eye Revisited

The overarching aim of this thesis was to extend our understanding of the biological correlates of superior motor performance by overcoming some theoretical drawbacks in the neural efficiency (Hatfield & Hillman, 2001) and quiet eye (Vickers, 2007) models with regards to their external validity and generalizability. In this section I propose an integrated neural efficiency-quiet eye model of performance. This model consists of two core ideas: neural efficiency as gating and quiet eye as efficiency.

Neural Efficiency as Gating

Since its first introduction in the human movement science literature, the model of psychomotor efficiency became very influential as it was able to explain a broad range of effects involving various biological systems (Hatfield & Hillman, 2001). A subcomponent of this model that regarded brain activity – the neural efficiency model – contended that superior motor performance was accompanied by diminished overall neural effort due to the attenuation of task-unrelated processes (Hatfield & Hillman, 2001). Despite the initial success of the neural efficiency model (for reviews of study findings interpreted within the neural efficiency model see Hatfield et al., 2004 and Hatfield & Kerick, 2007), it soon struggled with contradictory and incompatible findings that associated motor expertise and improved performance with elevated – rather than decreased – neural effort (e.g., Babiloni et al., 2008; Cooke et al., 2014).

In order to accommodate these seemingly contradictory pieces of evidence, a revised neural efficiency model would need to incorporate the concept that superior performance requires optimal activity in some task-related cortical regions while insulating this activity from other task-unrelated processes. In this context, the gating-by-inhibition model of alpha oscillations (Jensen & Mazaheri, 2010) provides a suitable framework for the analysis of diverging patterns of alpha power across multiple regions of the cerebral cortex. According to this gating model, cortical resources are channelled away from regions exhibiting elevated alpha activity and conveyed towards regions exhibiting diminished alpha activity. The research described in this thesis demonstrated the utility of the concept of *neural efficiency as gating*. Within this framework, efficiency is no longer defined as overall decreased activity but as a differential pattern of cortical activity whereby some activity is inhibited while other activity is enhanced.

The model of neural efficiency as gating is defined by two concepts: regional distribution and intensity. First, the regional distribution of the alpha gating indicates which regions are active and which regions are inhibited. By comparing the actual regional distribution with the theoretical regional distribution – based on a priori knowledge of neuroanatomy and neuropsychological networks – this regional distribution can reveal the extent to which cortical activity is routed towards task-related processes. For example, performing a motor task should elicit activity in the sensorimotor cortex, involved with cognitive processes associated with motor control and kinaesthetic sensation (Bears et al, 2007). Moreover, depending on the nature of the motor task (e.g., closed-loop or open-loop motor task), activation of non-sensorimotor regions may reflect task-irrelevant processing which may interfere with the optimal execution of the movement. Accordingly, a gate that is localized exclusively in the sensorimotor regions should reflect the efficient distribution of resources towards task-related sensorimotor processes while resourced towards other task-unrelated cognitive processes are minimized.

Second, the intensity of the alpha gating should reflect the strength by which task-related processes are insulated from the cognitive interference of other task-unrelated processes that are detrimental to task performance. In other words, a more intense gate should reflect the stronger inhibition of task-irrelevant processes, whereas a weaker gate may indicate allocation of mental resources towards task-irrelevant processes. In the case of a closed-loop motor task, it is plausible that a strong inhibition of non-sensorimotor processes can lay the neurophysiological foundations for optimal movement execution. In summary, a strong and spatially-localized alpha gating may reflect neural efficiency as a mental state characterized by a sharp and exclusive attentional focus on mental processes that matter for the successful execution of the task at hand.

Quiet Eye as Efficiency

Because the main function of the eyes is to extract visual information from the environment, it seems logical to conceive that the association between quiet eye and superior motor performance reflects some form of enhanced visual processing (Vickers, 2012). As a matter of fact, there is an almost unanimous consensus among quiet eye researchers (e.g., Vine et al., 2015; Williams et al., 2002) on the importance of vision. However, the finding that superior performance is associated with longer – rather than shorter – quiet eye durations seems to defy the widely-accepted principle of efficiency whereby superior motor performance is characterized by faster and more specific mental processes (Mann, Wright, & Janelle, 2016). Moreover, the association of expertise with long quiet eye duration contradicts the findings of the broader, non-motor literature (e.g., reading) that expertise corresponds with shorter ocular fixations (Foulsham, 2016).

A working solution to the efficiency paradox has been proposed by Klostermann, Kredel, and Hossner (2014) who suggested that the quiet eye period reflects the time spent on inhibiting non-optimal task solutions. This inhibition mechanism is based on the notion that experts have a larger movement repertoire than novices and, therefore, they require more time in order to inhibit competing movement variants and select one of the many possible options. While this inhibition hypothesis is certainly a solution to the efficiency paradox, it is not clear how this mechanism would differ if the gaze was on an irrelevant spot or not steady: would the inhibition of competing movement options be altered by a steady gaze away from the visual target of the action or by movement of the eyes? This point clearly warrants further investigation. Moreover, the inhibition mechanism does not take into account the different phases of the movement. This distinction appears important in light of recent evidence that most quiet eye effects are localized to the post-movement initiation component of the quiet eye period (e.g., Vine, Lee, Walters-Symons, & Wilson, 2015), that is when presumably motor preparation processes are completed and a movement option has already been selected.

The discussion on psychomotor efficiency as pruning of task-unrelated processes (Hatfield & Hillman, 2001) together with the realization (study four, described in Chapter Five) that visual processing may play little-to-no role during the final stages of movement preparation and execution of a closed-loop motor skill encouraged a re-examination and radical reinterpretation of the quiet eye phenomenon. The findings of the empirical research described in this thesis allowed me to reconsider the role played by visual processing in the performance of a closed-loop motor task and conceive a model of *quiet eye as efficiency*.

This model stems out of the following hypothetical scenario: how would the eyes move if vision did not play a key role for performance in a closed-loop motor task? This possibility cannot be ruled out until there is solid empirical evidence supporting the role of vision during the quiet eye period. Crucially, based on the concept of psychomotor efficiency, the answer to this question is that, if vision was irrelevant, the brain would allocate fewer resources to visual processing and the eyes would remain still, for as long as vision was not needed. Thereby, the inhibition of vision would produce a longer quiet eye. According to the model of quiet eye as efficiency, during the quiet eye period, the eyes go quiet not to process more but to process less: eye movements decrease because there is no need to acquire visual information (Loze et al., 2001). This concept implies that it does not matter where the gaze is directed, as long as the eyes are still and provide a stable visual reference for the smooth execution of the movement (Konttinen, Landers, & Lyytinen, 2000).

According to this idea, the quiet eye can be interpreted as a manifestation of a general postural-kinematic stability and somatic quiescence (cf. Obrist, Webb, & Sutterer, 1969). Namely, a prolonged period of eye quietness – especially during the execution of the movement – confers performance advantages through its association with a smooth and steady execution of a movement, which have been linked to better motor performance (e.g., Cooke et al., 2014; Hurrion, 2009; McLaughlin et al., Best, & Carlson, 2008; Richardson, Hughes, & Mitchell, 2012) as contended by the kinematic hypothesis (Gallicchio et al., 2018; Gallicchio & Ring, 2018b). In contrast, unnecessary eye movements may interfere with the fine control of movement execution as well as with the optimal allocation of cortical resources towards sensorimotor processes. Accordingly, the suppression of eye movements should reduce any such interference.

An Integrated Account of Neural Efficiency and Quiet Eye

I propose that conceiving ocular activity as being integrated – and not isolated – within a biological system where multiple processes are orchestrated towards one goal, allows us to resolve the apparent discrepancy between the neural efficiency and quiet eye models of superior motor performance. The neural efficiency-quiet eye model argues that, in order to move optimally, the sensorimotor processes necessary to execute a movement need to be shielded from activity that is unnecessary for (or even detrimental to) performance. In light of the evidence accrued in this thesis, it makes sense to conceive that, during the final stages of movement preparation, the integrated mind-body system – comprising brain, ocular, as well as other biological activity – operates as one to actualise a pre-planned motor programme.

Limitations and Future Directions

Conceiving neural efficiency as gating and quiet eye as efficiency opens exciting new possibilities for researchers and athletes alike. However, for the sake of scientific progress, it is important to acknowledge some potential limitations of the current work. First, the ‘neural efficiency as gating’ model contends that superior performance arises from the optimal activation of task-related processes that are insulated from unnecessary processes. This concept may appear rather simplistic because it does not answer the question of how to identify which processes are necessary and which are detrimental to performance for each motor skill. One way to discern task-relevant and task-irrelevant processes is by using a theoretical model informed on the psychological, physiological, and behavioural evidence described within the human movement science literature. Another way entails empirically testing the link between successful performance and psychobiological activity. Such empirical tests are especially important to study the generalizability of the neural efficiency-quiet eye model to motor skills that were not examined in this thesis. For example, it is likely that open-loop motor skills (e.g., interceptive actions) elicit a less-focused alpha gating during movement execution that enables the system to process visual information and adapt to a changing and unpredictable environment. Future research should address this question by applying research methods similar to those used in this thesis to other types of motor skills.

Second, the link between psychophysiological states and cognitive activity during performance of motor tasks is still underdeveloped. Admittedly, this thesis adds little to this knowledge because the empirical studies described in the previous chapters did not manipulate selectively a specific cognitive function. For example, there is a large body of literature assuming a link between activity of the left temporal region of the cortex and verbal interference during motor execution. However, this link has yet to be empirically proven. Future research could manipulate self-talk during action preparation and execution to shed light on the neurophysiological correlates of verbal processing.

Third, the methods developed and applied in this thesis to extract information from the EEG and EOG on psychophysiological processes related to motor performance are far from being definitive and may represent a departure from conventions in the literature. Accordingly, it is desirable that researchers improve these methods. For example, an exciting research goal for future research would be to combine psychophysiological techniques with camera-based eye-tracking methods to measure brain and ocular activity with greater accuracy than currently possible.

Fourth, considering the quiet eye as a manifestation of psychomotor quiescence implies that ocular stillness is functional to performance, at least in part, via a process of postural-kinematic stabilization. From this concept it can be deduced that, because vision is not important, the precise spatial location where the eyes rest does not matter. Future research should test this idea for example by instructing individuals to rest their eyes on irrelevant locations or to close their eyes during movement execution (Williams, 2016).

Fifth, this thesis demonstrated the utility of mediation analysis for mechanistic understanding of the neural efficiency phenomenon. The quiet eye literature is rich in descriptive reports but still lacking of mechanistic work. Scientists interested in the causal mechanisms behind the quiet eye-performance effect could employ mediation analyses in combination with experimental manipulations (e.g., of postural-kinematic parameters) to provide a more compelling test of the many competing hypotheses proposed to date.

Finally, the most interesting challenge for future research is to attempt to integrate not just brain and ocular activity but other biological systems, including autonomic and somatic activity. The evidence gathered so far allows us to appreciate that brain, eyes, heart, and muscles operate as one to prepare the body for action (Wilson, Cooke, Vine, Moore, & Ring, 2012). However, the terms of this interaction across biological systems are still unknown and future research addressing this issue promises to be highly valuable to expand our conceptual understanding of fine motor control and learning.

Practical Implications for Athletes

The model of neural efficiency-quiet eye proposes that motor execution is assisted by a psychophysiological state consisting in the activation of movement-related processes (i.e., motor control and kinaesthetic sensation) along with the attenuation of task-irrelevant processes (e.g., visual and verbal processing). There is a number of practical ways to implement this framework to train athletes to be more efficient and perform better. One such way is through biofeedback. Namely, athletes could be trained to self-regulate their biological activity (e.g., brain and ocular activity) in a way that is beneficial to motor performance (cf. Cooke, Bellomo, Gallicchio, & Ring, 2018). A fascinating idea would be to train athletes to maintain an optimal level of psychomotor efficiency during conditions that challenge postural-kinematic stability, psychomotor quiescence, and the integrity of the alpha gating, such as during elevated psychological pressure or physical load.

Another way to apply the knowledge accrued in this thesis is to borrow some elements of inoculation training from cognitive-behavioural therapy, commonly used for the management of stress and anxiety (Meichenbaum & Deffenbacher, 1988). More specifically, athletes could be encouraged to practice under conditions of elevated cognitive load, for example, through increased practice variability (as shown in Chapter Three). By practicing under conditions of gradually increasing cognitive challenge, athletes may develop and strengthen their coping strategies to focus on the relevant information for performance (e.g., postural-kinematic stability) while concomitantly ignoring information that is potentially detrimental for performance (e.g., vision). As a result of continued practice, athletes should become more resilient to cognitive interference.

Finally, the nascent association of psychophysiology with computational methods such as machine learning (Yarkoni & Westfall, 2017) will allow researchers to build individual models of performance allowing athletes to receive personalised training protocols to help optimize their learning and performance.

General Conclusion

The main contribution of my thesis was to introduce a novel perspective into a field of science that, following initial enthusiasm and progress, became dormant on issues of theoretical relevance for the mechanistic understanding of how we control, learn, master, and disrupt the control of actions. The knowledge described in my thesis is far from being definitive, however, it can help lay the foundations for future interdisciplinary work. By permitting the objective, unobtrusive, and simultaneous measurements of multiple biological systems along with their association with different mental states, it is likely that psychophysiology will play a leading role in forging the next scientific breakthroughs in this context.

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The Supplemental Material of each chapter is available at the following links:

Chapter Two

http://supp.apa.org/psycarticles/supplemental/spy0000077/spy0000077_supp.html

Chapter Three

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Chapter Five

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