A Bayesian approach to exploring expertise and putting success in adolescent and young adult golfers

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Abstract

Objectives: Putting behaviour was examined to explore if age influenced performance and the development of motor and perceptual-cognitive expertise during late adolescence and early adulthood. We also examined if motor control and perceptual-cognitive expertise was related to performance on a representative putting task.

Method: Twenty elite golfers (15 male; 17-24 years old; mean handicap of 0.5) completed eight straight and eight sloped putts at two distances (8ft/2.44m and 15ft/4.57m), on an indoor golf surface. Participants wore an eye tracker whilst putting and putting performance was assessed via putts holed and eye-movement behaviour, examining Quiet Eye (QE, the duration of the final fixation on the ball). A baseline profile for each participant was created using kinematic stroke data (collected using SAM PuttLab), average putts per round, greens in regulation and current practice hours (subjective self-report measures).

Results: Bayesian statistical analysis revealed 'moderate' evidence that age and baseline kinematic factors did not influence putting success rates. Eye movement data revealed 'moderate' evidence that i) successful performance was associated with less variability in QE duration and ii) extended periods of QE were associated with a decline in performance. Previous experience and current skill level were ruled out as potential confounds.

Conclusion: Our findings reveal performance and perceptual-cognitive expertise, did not improve with age. We suggest post 18 years, age should not be considered a factor in talent development programmes for golf putting. We discuss the benefits of adopting a Bayesian approach and suggest future studies employ longitudinal designs to examine changes in expertise over time.

Keywords: Perceptual-Cognitive; Golf; Adolescence; Expertise; Talent Development

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Sporting expertise develops over time and is generally thought to be “acquired as a result of successful interaction of biological, psychological and sociological constraints” (Baker et al., 2003, p. 1). More specifically, in golf, the period between late adolescence and young adulthood (from 17-24 years old) is considered a critical time-window during the development of expertise (Hayman et al., 2014). In this key period talent selection decisions are made, with the intention of giving the most successful individuals further opportunities to consolidate their expertise (Hayman et al., 2014). This approach to talent selection is informed by the Developmental Model of Sports Participation (DMSP) (Côté et al., 2003) which states that from the age of 16 to early adulthood (the investment years) each athlete either transitions to senior elite level or continues participating purely for enjoyment and/or personal development. In early adulthood, if the athlete successfully transitions to elite sport at the senior level, they are then considered to be in the maintenance years (Durand-Bush & Salmela, 2002). In the maintenance years the athlete is aiming to maintain the highest level of performance for an extended period of time (Durand-Bush & Salmela, 2002).

The transition from elite junior to senior level is considered to be the most challenging and complex of the within-career transitions (Stambulova et al., 2009). To assist with this transition, golfers commit more time to practice and competing (Hayman et al., 2014). To date, however, limited research has examined the late adolescence to young adulthood time period in terms of skill development (Hayman et al., 2014). The most salient evidence within golf comes from Hayman et al. (2014) in a qualitative analysis of golfers’ self-reported experience of transitioning from pre-elite to elite status. Using interpretative phenomenological analysis the authors reported three central themes underpinning success: 1) increasingly focused and coach-led practice, 2) family support, and 3) the development of psychological skills (e.g., the ability to maintain concentration and block out distractions) (Nicholls, 2007a; Nicholls, 2007b). Whilst this qualitative data provides useful insight into areas thought to contribute to successful development, the study did not directly examine performance *per se* - beyond revealing a steady decline in handicap up to 18 years and a plateau between the ages of 18 and 22. It is not known why handicap levels should plateau at this age, particularly as this is a key stage in the transition from junior to senior, when golfers typically experienced more coaching and increased opportunities to practice and compete in environments consistent with the Senior Tour (Hayman et al., 2014). Understanding why this plateau occurs, or what factors could prevent any potential plateau, could aid future coaching practice. Furthermore, examining actual putting performance may assist in understanding whether the development of expertise is related to age or to other factors such as motor control and perceptual-cognitive skill.

Progression to the senior level in golf demands high levels of perceptual-cognitive expertise because, following the transition from junior to senior, a golfer is required to play more challenging courses and must adapt to playing a wider variety of courses around the World (on their associated Tour). Consequently, to perform successfully at senior elite level, golfers must be highly skilled, with sufficient expertise to be able to respond, adapt and use affordances in the environment during practice and competition (Bruineberg & Rietveld, 2014). Gibson (1979) introduced the concept of affordances as possibilities for action provided by interactions of an individual with the environment. In the context of golf, the environment includes a wide range of changeable properties including course layout, inclement weather, crowd conditions, and opponents' performances. Critically, experts can use environmental and task-related constraint information to achieve consistent performance outcomes within an ever-changing environment (Seifert et al., 2014). Task constraints are boundaries that shape and guide movement behaviour (cf. Newell, 1986; golf examples include hole location, putt type and putt length). From a psychological perspective, therefore, golf involves a series of perception and action problems, each of which requires perception-based prospective control solutions. For example, in golf putting, the environment can influence the pace of the ball; golfers must take into consideration the environment and initial conditions when making a decision about what pace to hit a ball at, and not just complete a series of pre-programmed motor actions based on memory and repetition from an internal model.

Golf putting expertise reflects visuo-spatial processing associated with an individual performer's capacity for motor and attentional control (Park et al., 2015). Currently, research has largely focused on the well-documented visual strategy of 'Quiet Eye' (QE; the final fixation on the back of the ball; see Vickers, 2007) as a specific factor influencing motor and attentional control, and as a marker of expertise in golf putting (Mann, et al., 2007). Quiet Eye has been shown to be a robust marker of perceptual-cognitive expertise, based at least in part on the claim that it can differentiate between highly-skilled and less-skilled performances, even within experts (Lebeau et al., 2016; Wilson et al., 2016). Existing research has not, however, shown whether age is a factor in developing Quiet Eye during the key transition period between adolescence and young adulthood. Furthermore, kinematics has also been found to be a marker of expertise (Hurrion, 2009; Marquardt, 2007), with an appropriate stable putting technique the basis for a successful putt (Hurrion, 2008). Again, however, it is not clear how kinematics change (if at all) during the period from adolescence to young adulthood.

Consequently, the present study examines elite adolescent and young adult golfers who are enrolled on long term elite performance programs (aligned with the investment phase of the DMSP model, Côté et al., 2003) with the goal of achieving elite performance outcomes at senior level, via dedicated intense practice in one sport. We characterise expertise in relation to age across this critical developmental transition from junior to senior status by examining *in situ* putting performance (assessed directly using a representative putting task), perceptual-cognitive expertise (i.e., Quiet Eye) and kinematic putting profiles in relation to age. As the DMSP proposes, the investment phase focuses on an intense period of training with the sole purpose of developing elite performance in the selected sport (Côté & Vierimma, 2014). The increase in intense practice acquired during this phase of development suggests that performance should improve as individuals spend longer in the investment phase. However, as Hayman et al. (2014) highlights, between the age period of 18-22 there is a plateau in handicap in elite golfers. Therefore, despite increased investment in practice in one sport, we predict that there should be no direct relationship between age and performance (regardless of whether it is assessed indirectly via average putts per round, or directly via percentage putts holed).

We also hypothesized that there will be no relationship between age and QE duration (a marker of perceptual cognitive expertise, Mann et al., 2007). Similarly, we predict there will be no relationship between age and motor control (assessing motor control through increased consistency on kinematic measures). Although these predictions follow previous findings (Hayman et al., 2014) they are at odds with the central aims of performance development programs, where age is factored into decisions about which athletes should progress on funded programs. Finally, with the predication that age is not related to performance, our study design allowed us to examine whether motor control and perceptual-cognitive expertise influences putting success. Irrespective of age, we expect that longer QE duration and increased consistency in stroke would both predict higher levels of performance. We anticipate that our findings will help inform future practice and further understanding of expertise at this key time period in development.

Methods

Participant

Participants were twenty experienced golfers (fifteen males and five females with an age range of 17-24 years; M = 20.5, SD = 1.9; and average handicap of +1.7, SD = 2.1) selected on the basis of age from a larger (N = 35) cohort of volunteer golfers. All participants were right-handed, right eye dominant, and had normal or corrected-to-normal vision. Ethical approval was granted by the relevant University ethics review board authorities. The lead researcher contacted the performance director from a National Governing Body for permission to speak to players matching the eligibility criteria (a handicap below 3, with no current injuries or visual impairment). Following initial discussions interested players sent the lead researcher a signed copy of the informed consent sheet, along with their demographic information. All participants were enrolled on an elite performance pathway, but the golfers were made aware that participation was not a requirement, that it was voluntary without obligation, and that participation had no influence on training and selection.

Procedures

Participants attended one two-hour testing session (Figure 1) completing a representative putting task, on an indoor artificial surface, whilst behavioural data (performance, gaze behaviour and kinematics) was collected. The putting surface had a stimp value of 10.2 stimp (stimp rating is a measure of green speed, whereby the higher the stimp rating the faster the green) which is comparable with competitive green speeds during competition with elite golfers.

Figure 1 about here

At the start of the testing session, participants were invited to ask any questions and then an ASL mobile eye tracker (XG Mobile Eye Tracker, Applied Science Laboratories, Waltham, MA) was fitted to the participant by the lead researcher, consistent with previous research carried out on visual gaze in putting (Vine & Wilson, 2010; Wilson & Pearcy, 2009). The eye tracker was calibrated using five coloured markers positioned near the participant's feet when standing in putting posture and addressing a golf ball. During calibration participants were asked to adopt a normal putting stance and to hold their vision steady on the centre of each marker, in a pre-designated order, for a duration of 100-200ms. During the calibration process and when putting, participants used their own putter (that had been fitted by a golf professional prior to the study, to ensure consistency for all participants) and Srixon AD333 Tour golf balls (consistent with the protocol for the rest of the testing session).

Participants then completed a warm-up (involving 12 practice putts; 6 straight and 6 sloped with different putt locations than those used in the experimental task). Following the warm-up participants completed 16 straight putts captured by SAM PuttLab (Version 5, Science & Motion Sports) to gain a profile of their putting kinematics. To use SAM PuttLab a triplet was fitted to the participant's putter and calibrated as per SAM PuttLab instructions.

Following the SAM PuttLab profile, the participants completed a representative task with a total of 32 putts (evenly split across the distances of 8ft and 15ft and across straight and sloped putts). Participants completed four trials (to form a block) from one putt type (e.g., 8ft straight) and the blocks of putt types were randomised (Figure 1). The participants were instructed to follow their normal competition routines, with the aim to hole-out in one putt. When participants missed the hole, the ball was removed prior to the next putt. Testing time ranged from 1.5 to 2 hours. After all putting was completed, participants were given a chance to ask any questions and reminded about their ability to withdraw. Eight participants went on to complete a further 30 minutes of putting in an unrelated activity after the debrief; these data are not reported here. Participants were also given the researcher's contact details to give the participant a chance to ask any questions in the future.

Measures

Expertise: Average putts per round, greens in regulation and current practice hours are metrics recommended by Carey et al. (2017) to characterise putting expertise because the standard measure of handicap alone is not a sensitive measure of putting ability *per se*. Participants were asked to self-report current average putts per round, greens in regulation, number of years playing golf and total hours per week practice. Importantly, to answer these questions participants accessed previously recorded performance data stored in a cloud-based database that they were required to keep regularly updated after every round (and weekly) based on their enrolment on a performance programme.

Performance: Putting performance was assessed through the number of successful putts, defined as the putt being "holed" in one stroke and expressed as a percentage of total putts.

Visual Search Behaviours: Visual search behaviours were captured using ASL XG Mobile

Eye Tracker, consisting of mobile eye tracker lenses and EyeVision software (ASL Results Pro Analysis, Argus formally, ASL) installed on a laptop (Dell Inspiron6400). Consistent with previous research (Vine, Moore, & Wilson, 2011) gaze location is depicted by a crosshair (+) cursor (representing 1° of visual angle) in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision, 30 Hz frame rate). The lead researcher checked the accuracy of the calibration periodically throughout the testing session, re-calibrating whenever necessary (e.g., after a pupil recognition loss >100ms or if the calibration had been lost). The eye tracker was also calibrated at the start of each putt block. All analysis was completed post testing, using event by event analysis specific to the area of interest (i.e., the ball). The change in visual degree of angle was monitored and evaluated via ASL Results Pro. Blink frequency and blink duration (ms) were also monitored via the use of a blink detection algorithm. If pupil recognition was lost during a recognised fixation (for example, due to a blink) for less than the time specified as "Maximum Pupil Loss" (100ms), then the fixation does not end, and fixation duration continues. If pupil recognition is lost for a longer period (>100ms), the fixation is considered to have ended at the beginning of the recognition loss period. The QE onset had to begin before movement initiation of the backswing but could continue through the putting movement (e.g., as in Causer et al., 2017). QE offset occurred when gaze deviated from the target (ball or fixation marker) by more than 3° of visual angle, for longer than 100 ms (Moore et al., 2012; Vickers, 2007). The absence of a QE fixation was scored as a zero.

Kinematics: Two kinematic variables of impact spot and face angle consistency were used to act as indirect measures of motor control and a marker of expertise. These kinematic indexes were chosen because they are considered fundamental to putting performance (Marquardt, 2007).

Impact Spot is defined as the exact location the ball hits the putter face. Impact Spot consistency highlights the variability in point of impact, with 100% being no variability and 0% being high variability. Face Angle at Impact consistency reflects how consistent the participant is at keeping the face relative to the target aim. A poor Face Angle at Impact consistency has been linked to visual perception problems. For both measures, a score of >75% consistency is indicative of an expert skill level (Marquardt, 2007).

Power and Statistical Analysis

Power

We carried out *a priori* power calculations using G * Power (version 3.0.1; Faul, et al., 2007) to explore the impact of changes in age on putting performance. We choose to use two tails and the default settings of a small effect size 0.3, an *α* error probability of 0.05, and Power (1-β err prob) of 0.95. The power analysis outcomes suggested that we would need a sample of 138 elite golfers to be confident of finding a reliable effect of age on performance. We also conducted a power calculation in relation to the impact of changes in QE duration on performance. In this case we used the G * Power default setting for a within-participants repeated measures F test. Calculations were therefore completed based on the parameters of an effect size 0.25, α error probability of 0.05, Power (1-β err prob) of 0.95, with analysis tailored to fit our design (an ANOVA with one group and four repetitions). The output confirmed a total sample size of n = 36. Previous studies of putting in elite golfers have achieved cohort sizes ranging from 5 to 22 (cf. Redondo et al., 2020; Tanaka, & Iwami, 2018; Hayman et al., 2014; Álvarez et al., 2012; Vine et al., 2011; Nicholls et al., 2010; Nicholls, 2007; Nicholls et al., 2005), and taking into account our knowledge about the availability of golfers, it was immediately clear that obtaining these sample sizes was not practicable.

Given our concern about sample size, and wider awareness of the problems associated with the null hypothesis testing approach (Wagenmakers et al., 2018), here we decided to employ Bayesian methods. Three features of the Bayesian approach are particularly attractive in the current context. First, unlike with traditional frequentist statistics, Bayesian statistics can be used to assess both the null and alternate hypotheses. This feature of Bayes is particularly important in the current context because it allows the null hypothesis to serve as a testable prediction – assessing the assumptions that there would be no change in expertise with age. Second, rather than relying on an arbitrary significance threshold, Bayesian statistics provide information about the strength of evidence in support of a conclusion (from anecdotal to extreme). Third, Bayes allows researchers to monitor findings using sequential analysis to explore the evidence as a function of increasing sample size (van Doorn et al., 2020). Using this approach offers a significant advantage in allowing studies to be carried out using a ‘stopping rule’ to determine when there is sufficient data to support a conclusion. For example, Schönbrodt and Wagenmakers (2018) recommend that data collection can safely be stopped once ‘strong’ evidence is found. In practice, due to the short time period these high performing athletes were available for participation in the study, monitoring findings using sequential analysis was not possible during our data collection (as recommended by van Doorn et al., 2020). Consequently, we conducted *a posteriori* sequential analysis to explore if there was sufficient evidence to support a clear conclusion. As outlined below in detail, analysis revealed a clear plateau in the strength of evidence. Given that logistical challenges made obtaining additional data increasingly difficult, and more importantly that the analysis of the data suggested recruiting more participants would add very little additional evidence, we chose not to extend recruitment/data collection beyond the current sample.

Statistical Analysis

Characterizing the effect of age

Initial analyses were designed to establish if age influenced the baseline skill level profile of the golfers. Two Bayesian paired correlations were used to explore the relationship between age and the kinematic variables of impact spot and face angle consistency. In addition, and again using Bayesian correlations, we assessed the relationship between age and three separate self-reported indexes of experience (average putts per round, greens in regulation and number of hours spent practicing). Following the examination of baseline skills an additional set of analyses using Bayesian correlations was performed to explore if there was a relationship between age and putting performance (% total successful putts) on the representative putting task. Furthermore, a Bayesian correlation was also conducted to assess whether there was a relationship between age and mean QE duration during the putting task.

Analysis of performance and motor control

Putting success relative to kinematic factor was explored using separate Bayesian Paired correlations for both performance (% total performance) on the representative task and average putts per round (global performance measure) for the two kinematic variables of impact spot consistency and face angle rotation consistency.

Analysis of performance and perceptual-cognitive expertise

Total putting success rates on the representative task were assessed in relation to the mean QE duration using Bayesian paired correlations to explore if QE duration influenced performance independently of age. Additional analysis was conducted to examine mean QE duration for successful and unsuccessful putts using Bayes Paired *t*-test. Further analysis was completed analyzing the variability in QE duration between successful and unsuccessful putts using a Bayes Independent Samples Paired *t*-test. To measure variability Standard Deviation (*SD*) was used and this has been reported to be an appropriate way to measure variability (Altman & Bland, 2005). Further analysis using a Bayesian repeated measures ANOVA was conducted to explore the impact of QE duration and performance. QE duration data was binned according to the length of the QE period (based on individual quartiles), and performance was measured through percentage success rates in each quartile (eight trials per quartile).

Results

Characterizing the effect of age

Age and expertise at baseline

A series of Bayesian paired correlations were completed to explore if expertise, as measured by average putts per round, greens in regulations, hours practice per week and stroke kinematic factors (impact spot and face angle consistency) was related to age. Analysis revealed no relationship (r = -0.018) between age and average putts per round (see Figure 2), providing 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.603). Analysis also revealed no relationship between age and greens in regulation (r = 0.331), providing 'anecdotal' evidence in favour of the null hypothesis (BF_{01} = 1.394). Similarly, analysis revealed practice (hours per week) did not vary with age (r = 0.002), providing 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.613, Figure 2). Analysis also revealed no relationship between age and face angle rotation consistency (r = 0.158), again providing 'anecdotal' evidence in favour of the null hypothesis (BF_{01} = 2.937). Lastly, analysis revealed that there was no relationship between age and impact spot consistency (r = -0.047), providing 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.549, Figure 2). Taken together the results provide 'moderate' support for the claim that expertise at baseline is not related to age.

Figure 2 about here

Age and putting performance

One participant was removed from the analysis due to the performance (% total performance) on the representative task being an outlier (i.e., greater than 3 standard deviations from the mean). As can be seen in Figure 3, analysis revealed that there was no relationship between age and putting performance (r = 0.018), providing 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.515) and suggesting that performance on the putting task was not related to age.

Figure 3 about here

Age on QE duration

As shown in Figure 4, analysis revealed no evidence of a relationship between age and mean QE duration (r = 0.135), providing 'moderate' evidence in favour of the null hypothesis (BF_{01} = 0.322) and suggesting that QE duration does not increase with age.

Figure 4 about here

Analysis of performance and motor control

A series of Bayesian paired correlations were completed to explore the relationship between kinematic factors and performance (average putts per round and % performance on the representative task). As noted above, for all analysis on the representative task, one outlier was removed. Analysis revealed that there was no relationship between face angle rotation consistency and average putts per round (r = -0.106), with 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.296). Analysis also revealed that there was no relationship between face angle rotation consistency and performance on the representative task (r = 0.174), with 'anecdotal' evidence in favour of the null hypothesis (BF_{01} = 2.78).

Analysis revealed that there was no relationship between impact spot consistency and average putts per round (r = 0.006), with 'moderate' evidence in favour of the null hypothesis (BF_{01} = 3.612). Analysis also revealed that there was no relationship between impact spot consistency and performance on the representative task (r = 0.281), with 'anecdotal' evidence in favour of the null hypothesis (BF_{01} = 1.869). Taken together, kinematic variables did not impact on performance. We note, however, 90% of the sample demonstrated kinematic variables in line with experts (Marquardt, 2007), exhibiting over 75% consistency in their impact spot location and face angle rotation.

Analysis of performance and perceptual-cognitive expertise

Analysis was also completed to explore the relationship between perceptual-cognitive expertise and performance (% putts holed). Bayesian correlation analysis revealed that there was no relationship between mean QE duration (ms) and putting performance (r = -0.222), but provided only 'anecdotal' evidence in favour of the null hypothesis (BF_{01} = 2.38). Mean QE duration of successful putts (M = 1621.157 ± 385.917ms) were similar to that of mean QE duration for unsuccessful putts (M = 1627.040 ± 345.871ms). A Bayes paired sample t-test revealed 'moderate' evidence in favour of the null hypothesis (BF_{10} = 0.240, error % = 0.022). There was, however, a high level of variation with the mean QE duration measured via *SD* ranging from 92.106 - 630.604 (*M* = 364.257, *SD* = 180.587). As a result, it was of interest to explore if variation differed as a function of putt success. Mean variation in QE duration of successful putts was lower (*M* = 318.392 ± 176.110ms) than mean variation for unsuccessful putts (*M* = 382.378 ± 190.393ms). A Bayes paired sample independent *t*-test revealed 'moderate' evidence in favour of the alternative hypothesis (BF_{10} = 9.997, error % = 7.115e-4).

Lastly, due to the high level of individual variation between participants (mean QE ranged from 1087ms to 2111ms), we assessed the impact of QE duration (for this analysis QE duration was binned according to the length of the QE period, based on individual quartiles) on performance. A Bayes one-way repeated measures ANOVA found that the model with the main effect predicts the observed data just slightly better than the null model (BF_{10} = 1.23, Error % = 0.468) and the BF_{incl} is 1.23 (P(incl) = 0.500, P(excl) = 0.500, P(incl/data) = 0.552, P(excl/data 0.448)), showing that model with the main effect is marginally more likely than those without that main effect, but the evidence is too weak to be conclusive. As shown in Figure 5, mean performance steadily rose from quartile 1 (*M* = 41 ± 19%) to quartile 2 (*M* = 48 ± 17%) and was similar in quartile 2 and 3 (*M* = 48 ± 11%) but decreased in quartile 4 (*M* = 38 ± 15%). Post hoc comparisons (detailed in Table 1) revealed 'anecdotal' evidence in favour of the alternative hypothesis between quartile 2 and quartile 4 and 'moderate' evidence in favour of the alternative hypothesis between quartile 3 and quartile 4, consistent with decline in performance for the longest QE duration visible in Figure 5.

Table 1 near here

Discussion

The aim of the current study was to characterise expertise (and the factors that influence putting success) in relation to age across the critical developmental period from late adolescence to young adulthood. From an applied perspective, this period is critical for golfers because talent selection decisions made at this time determine who progresses to elite senior levels within the sport. From a theoretical perspective, the Developmental Model of Sports Performance (DMSP; Cote et al., 2003) states the investment phase focuses on an intense period of training with the sole purpose of developing elite performance in the selected sport (Côté & Vierimma, 2014) but previous research has shown a plateau in handicap in elite golfers between 18-22 years (Hayman et al., 2014). To investigate this issue, we explored whether motor control, perceptual-cognitive expertise and specific expertise markers relevant to golf (such as average putts per round) were correlated with age (17-24 years old).

The data here provides provisional evidence that age is not correlated with measures of putting expertise. Despite performance differing across participants in the *in-situ* putting task (ranging from 12% to 59% success), analysis using Bayesian statistics provided highly consistent 'moderate' evidence that age does not correlate with adolescent and young adult golfers putting success. This finding is, to our knowledge, the first empirical investigation to examine age-related ability during the late adolescence to young adulthood period using actual putting performance as a measure of expertise. Additionally, there was limited evidence to suggest that age influences other performance markers such as average putts per round, stroke kinematics, or the ability to develop perceptual-cognitive expertise. More importantly, perhaps, the present experimental findings are supported by data from the PGA Tour, where age does not appear to be a determining factor for performance: the youngest first time Tour winner this century was aged 19 years, and the oldest first-time winner was 47 years old (PGA Tour, 2020).

Our findings are also in accord with data from Hayman et al. (2014) who demonstrated that changes in handicap plateau between the ages of 18-22 years, suggesting limited age-related expertise differences during this time period. Critically, the current findings add experimental evidence for the claim that age is not a valid basis on which to judge putting success. From a theory perspective, the current findings highlight that future research needs to explore what factors underpin an athlete's transition from the investment years to maintenance years as it seems that talent is consolidated from the age of 18. These findings are consistent with the predictions of DMSP model (Côté & Vierimma, 2014) that by late adolescence athletes have developed the physical, cognitive, social, emotional, and motor skills needed to invest their efforts into highly specialized training in one sport (Postulate 7, p. *S*67). Critically, however, our findings suggest that more time spent undertaking the highly specialized training does not necessarily lead to improvement in skill level beyond those achieved in late adolescence. Although the present findings demonstrate that actual golf putting performance does not vary with age, it is important to acknowledge that the data do not provide an assessment of the quality of golf practice that each athlete experienced during their normal routines. As we outline below, on this basis it would be of particular interest for future studies to examine what kinds of practice are most effective at enhancing junior talent.

Given that adolescence and young adulthood is the key period during which career decisions are made, the present findings raise important questions about how talent can best be identified to ensure a successful transition from junior to senior elite. In this respect, and based on the current findings, it is worth considering the large individual variation when interpreting the results and any implications for practice. The findings provided 'moderate' evidence suggesting less variability in QE duration was associated with successful performance, consistent with findings that expertise is associated with less variability (Mann et al., 2011). The data also suggests the potential of an individual threshold whereby performance declined once QE duration was extended over a prolonged period. In support of our findings, a recent study by Harris et al. (2020) assessing the functional parameters of the Quiet Eye using novice golfers completing a golf putting task in immersive virtual reality found that "*the spatial and temporal parameters of the fixation may be less important than previously thought*" (p. 37). In their discussions the authors highlight the potential of individual-specific thresholds and the notion of 'long enough' and 'close enough' to the target. The findings reported here suggest that perceptual-cognitive expertise is important for performance, but that putting success may not be related to increases in QE duration *per se*, depending instead on each individual's threshold for performance improvement. Moving forwards, we recommend that future researchers and practitioners should focus on understanding how golfers develop perceptual-cognitive expertise throughout the developmental pathway.

More broadly, the current findings highlight how limited current knowledge is regarding visual strategies underpinning successful performance, such as where golfers look when scanning a green in preparation for hitting the putt (Craig et al., 2000) and how visual information is used to direct action. The development of light-weight mobile physiological measures (including eye-tracking, EEG and EMG) has inspired renewed interest in real world data collection (e.g., see Park et al., 2015, in relation to the use of mobile EEG in sport; and for broader discussion see Ladouce et al., 2017). In the context of golf performance, future research is required to establish whether golfers exhibit individualized visual strategies, during planning (viewing of the hole and ball prior to putting during the green reading phase) and feedback (information gained from viewing the outcome of the putt) phases and to explore any associated performance impact related to these visual strategies.

When developing through the pathway, a golfer is given more opportunities to practice and compete both Nationally and Internationally. Davids (2000; see also Seifert et al., 2013) highlighted the cyclical nature of skill learning and the development of expertise through the athlete being involved in continual interactions with the environment, utilizing a range of task and environmental constraints during both simulated practice and competition (Davids et al., 2008). To expand on our findings, future studies should aim to understand the type of practice and the associated task and environmental constraints which link to the development of expertise. Furthermore, from an applied point of view, it would be valuable to understand whether selection decisions differ when they take place in environments that are familiar (i.e., practiced) versus unfamiliar (i.e., novel) to the golfer, because previous experience of a green/course will impact on the golfer’s ability to adapt and use affordances in the environment.

In the present study the use of a representative task (a quantitative assessment of the impact on age on performance *in situ)* enabled the specific performance contexts to be more closely matched to setting that the findings are intended to be applied in. For example, the putting performances reported in this study are highly consistent with those seen on Tour in comparison to those typically reported in laboratory studies using repetitive putts (where performance reaches 70%). Dicks et al. (2009) highlight how the use of representative task design is critical when studying the development of perceptual skill. Therefore, it is proposed any future study in this area continues to adopt a representative task design.

One distinct strength of the current study is our use of Bayesian statistics, which allowed us a) to test the potential for both alternative and null hypotheses, and b) to characterise the strength of evidence. As noted in the method we originally carried out traditional power analysis, which suggested a very large cohort should be examined. Given the inherent limited availability of elite athletes our response was to adopt a Bayesian approach, including the use of sequential analysis to help us assess the strength of evidence. Whilst acknowledging the Bayesian analysis provided only ‘moderate’ support for the null hypothesis, our view is that the consistency of the results and the clear plateau across all measures adds some confidence to the outcome. We also note that recruiting more than twenty expert adolescent and young adult golfers is a known challenge due to the nature of the cohort (Starkes & Ericsson, 2003). We do, however, recommend where possible in future data collections that sequential analysis is completed during data collection to allow researchers to explore the evidence as a function of increasing sample size (van Doorn et al., 2020). Using this analysis, researchers will be able to make informed judgements about when sufficient evidence has been reached and when to cease data collection. More significantly, we note that any conclusions based on the average behaviour of large cohorts tested on one occasion are not necessarily informative about any one individual. Given that the ultimate aim in sport, in particular golf, is for individual athletes to succeed, there is clearly a pressing need for approaches that focus on developing expertise within individuals (Seifert et al., 2018). Thus, rather than moving towards ever larger cohorts of cross-sectional designs, our view is that there is far greater need for longitudinal single case studies, examining changes in expertise over time.

Conclusion

We investigated factors influencing performance in highly skilled adolescent and young adult golfers using a representative task design, and measures of putting behaviour. Using a Bayesian approach, we found during late adolescence and early adulthood golfing ability does not increase with age *per se.* Our findings question current practice involving age-based talent selection and suggest instead that changes in individual's performance should be tracked across the developmental pathway. Whilst we found no evidence that baseline kinematic variables influenced performance, independent of age, we observed a reduction in putting performance for longer QE durations. Taken together our findings suggest that perceptual-cognitive expertise is linked to putting success, highlighting the need for a far broader conceptualisation of perceptual-cognitive expertise, including wider use of representative task designs, greater use of longitudinal studies, and the adoption of new mobile physiological measures. To enable evidence-based talent selection future research must employ longitudinal designs, using representative tasks, to provide better understanding of how perceptual-cognitive expertise is developed.

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Tables

Table 1

Pairwise comparisons between putting success rates for each quartile of QE duration. Bayes Factors and associated model error are reported ('U' denotes uncorrected), along with an indication of how strong the evidence is, and which hypothesis the evidence supports. Putting success rate data for each quartile are shown in Figure 5.

Pairwise Comparisons		**Prior Odds**	**Posterior Odds**	**$BF_{10, U}$**	**Error %**	**Strength of Evidence**	**Hypothesis**
Q1	Q2	0.414	0.222	0.536	0.009	Anecdotal	Null
	Q3	0.414	0.253	0.611	0.006	Anecdotal	Null
	Q4	0.414	0.127	0.308	0.02	Moderate	Null
Q2	Q3	0.414	0.097	0.234	0.022	Moderate	Null
	Q4	0.414	0.753	1.818	0.003	Anecdotal	Alternative
Q3	Q4	0.414	2.692	6.499	0.001	Moderate	Alternative

Figures

Figure 1: Schematic of the different phases of testing (top), the testing environment demonstrating a participant in action using the eye tracker and kinematic equipment (middle) and a breakdown of the putts required in the representative task design (bottom).

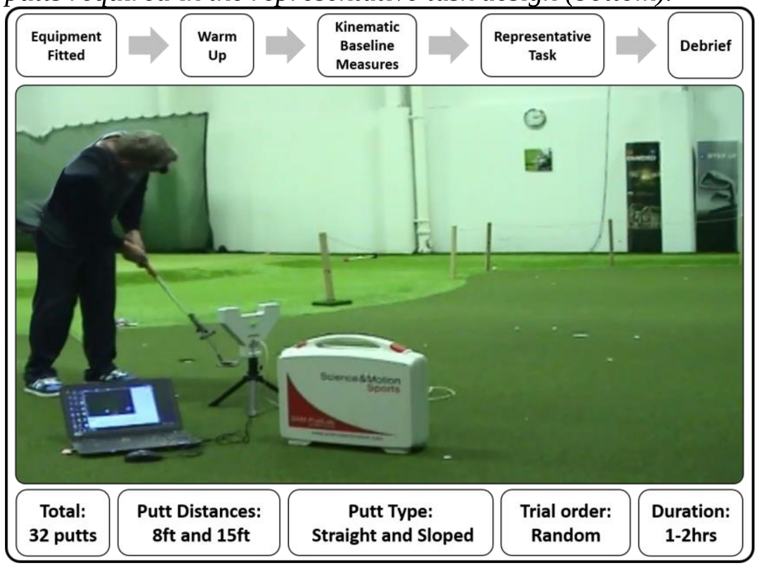

Figure 2: Moderate evidence in favour of the null hypothesis showing that age is not related to expertise (average putts per round: top row plots in Panel A), hours practiced per week (middle row plots in Panel B) and impact spot consistency (bottom row plots in Panel C). The plots on in the middle of each panel row show the sequential analysis, highlighting that the strength of evidence plateaus and becomes stable by around participants 15.

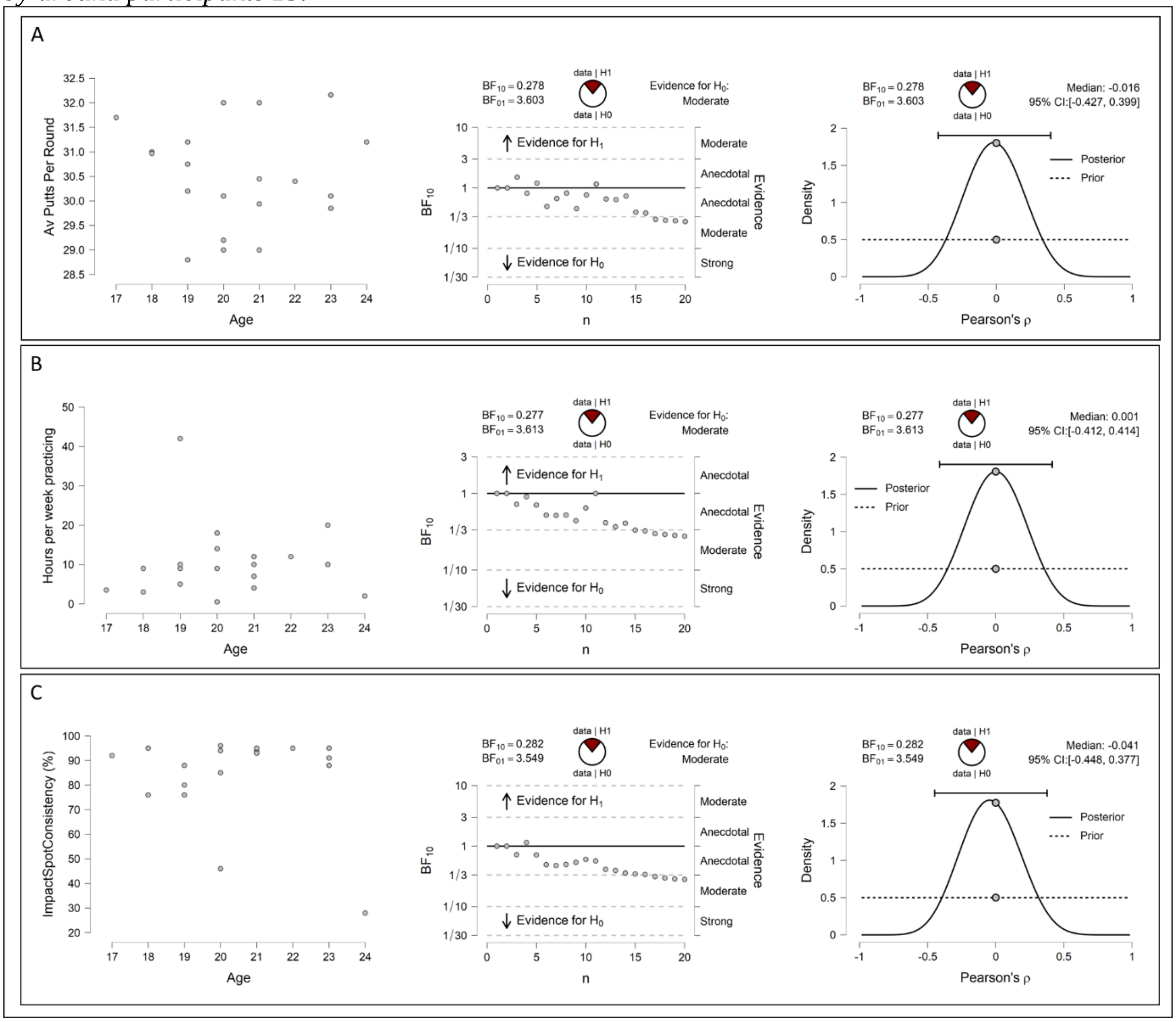

Figure 3: Moderate evidence in favour of the null hypothesis, suggesting that age does not impact on performance on the representative task (Panel A). Sequential Analysis shown in Panel B highlights that the strength of evidence plateaus and becomes stable from participant 12 onwards.

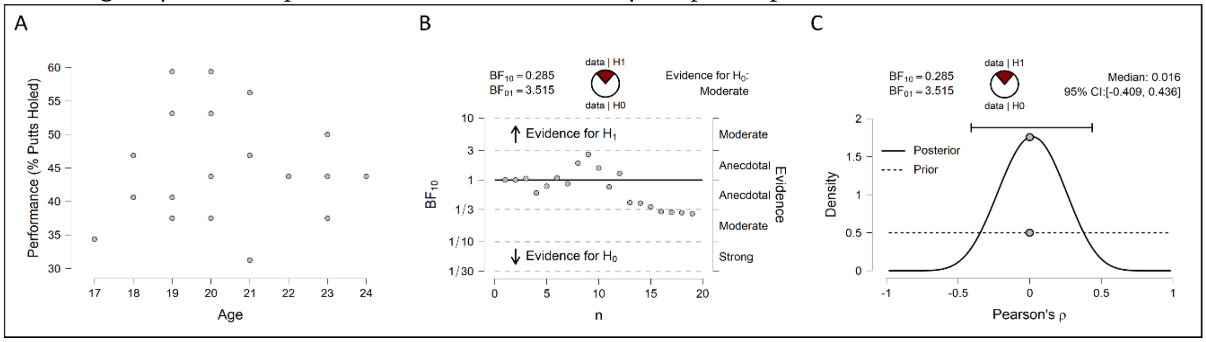

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Figure 4: Moderate evidence in favour of the null hypothesis, suggesting that age does not impact on QE duration on the representative task (Panel A). Sequential Analysis shown in Panel B highlights that the strength of evidence plateaus and becomes stable from participant 11 onwards.

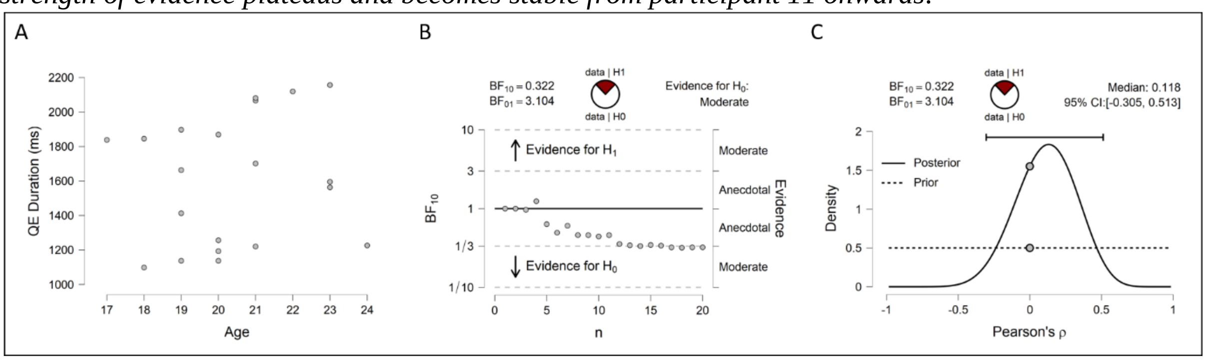

Figure 5: Percentage putting success (Mean and 95% CI) as a function of Quiet Eye duration. Quiet Eye duration was split into quartiles for each participant. On average performance steadily increases in line with increasing Quiet Eye duration from quartile 1 to quartile 3 and then declines in the last quartile. Confidence intervals indicate a large degree of variability in performance across participants.