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Gaze in Golf Putting: Effects of Slope

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We introduced a sideward slope to the putting surface (i.e., 0 %, 1% and 2% slopes) to examine the effects of task complexity on visual search behaviour during golf putting. Seventeen high-skilled golf players were divided into two groups on the basis of their overall putting performance. Slope did not affect the number of holed putts, but it did significantly influence the type of miss. A significantly higher proportion of balls were missed at the low side than at the high side of the hole, the effect being more pronounced for the group of less successful participants. With respect to gaze, it was found that increasing the steepness of the slope resulted in more fixations to the high side of the hole. Furthermore, the participants also spent less time viewing the ball for the steeper slopes. The final fixation durations were not affected by steepness of slope. It is argued that in dealing with a sloped green, the prime adjustment in gaze is in the spatial domain rather than in the temporal domain.

KEY WORDS: Action, Gaze, Golf putting, Task complexity, slope, Visual search.

Introduction

A major focus of sport sciences is the impact of visual search behaviour on performance. The main assumption in this field of research is that success or skill in performance is associated with more efficient strategies of visual search. The research has therefore predominantly been focused on comparisons of visual search between athletes of diverse skill levels and between successful and unsuccessful performances. The present study, following an earlier lead of Williams et al. (2002), adds an extra dimension to this field of research by assessing the relation between visual search behaviour and performance in tasks that have different degrees of complexity.

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We investigated the visual search behaviour of skilled golf players as they performed putts from a distance of 1.8 m on a green with different sideward slope. Golf putting is a far aiming task that entails a player pacing and aligning the direction of the swing through the ball with the distant target hole. Complexity of golf putting is dependent on many factors, such as, distance to the hole and the resistance and slope of the putting surface. In our experiment, task complexity is manipulated by varying the sideward slope angle of the green. The larger the sideward slope angle of the green the more the ball will be deflected from its straight line by gravity, which makes it necessary for the player to adjust both the direction and the velocity of the swing. Consequently, to successfully perform this task, the player not only needs information about the distance to the target hole, but also about the steepness of the slope. Hence, golf players must move their gaze over the putting surface to assess its slope, but also over the target, the club, the ball and perhaps the feet, which serves to prepare the direction and velocity of the swing and the orientation of the club head at the moment of impact. In this regard, an impressive body of work by Proffitt and colleagues (e.g., Proffitt, 2006; Proffitt et al., 1995; Witt & Proffitt, 2007; see also Feresin & Agostini, 2007) shows that perceived slant of sloping surfaces are usually overestimated, albeit that the magnitude of the overestimation is dependent on the type of judgment. A translation of such perceptual overestimations into putting, especially during the preparation phase, would result in a high proportion of errors to the high side of the hole.

In a recent meta-analysis, Mann et al. (2007) found systematic and consistent differences in visual search behaviour between sports players of different skill levels, the nature of these differences being highly task-dependent. They discerned interceptive, strategic and far aiming tasks. These tasks have different characteristics and were shown to constrain visual search in a different manner. For instance, the visual search strategy of high-skilled sports players can be characterized by fewer fixations of longer duration as compared to low-skilled players. However, these skill-related differences are much more pronounced in strategic tasks (e.g., passing a ball in soccer) than in interceptive tasks (e.g., returning a tennis serve), a difference that is attributed to distinct temporal constraints of the two types of tasks. With this task-dependency of visual search in mind, we restrict further discussion to far aiming tasks such as basketball free throwing (Vickers 1996a, 1996b), pistol and riffle shooting (Ripoll et al. 1985; Janelle et al. 2000), dart throwing (Vickers 2000), playing billiards (Williams et al. 2002) and golf putting (Vickers 1992, 1993; Naito et al. 2004).

Based on a detailed analysis of gaze during putting, Vickers (1992) argued that as skill improves golf players develop a more efficient visual search strategy. She reports that high skilled golfers (i.e., handicap 0-8) exhibit fewer gazes combined with faster gaze shifts than less skilled players (i.e., handicap 10-16). These gazes are directed to more critical locations (i.e., ball and hole, but not club head, feet and putting surface) and are of longer duration. In particular, the final gaze fixation before contact with the ball was found to be an important predictor of skill level and putting accuracy. That is, the final gaze to the ball was almost twice as long among the high-skilled players as compared to the less-skilled players. As an explanation for these skill-related differences in visual search behaviour, Vickers (1992) hinted that longer periods of steady gaze enhances the precision of the control of the arms (club). In her subsequent work using other far aiming tasks (e.g., basketball, Vickers 1996b; darts, Vickers 2000), Vickers provided additional evidence for the existence of a relation between the duration of the final gaze before movement onset (which she denoted 'quiet eye') and aiming skill. In billiards, Williams et al. (2002) found final gaze duration to vary as functions of both skill level and successfulness compared to unsuccessful shots in billiards: longer final gaze duration was associated with more accurate performance. It is argued that these longer final gazes allow players to better set and attune the parameters of the ensuing movement, which in turn results in an increased aiming accuracy. In other words, the final gaze duration is considered an important constituent of a successful visual search strategy in far aiming tasks.

In sum, the inter-individual differences in visual search behaviour are thought to be reliably related to skill level and/or success during performance (Mann et al. 2007). Indeed, previous explanations of the link between visual search behaviour and performance are almost solely based upon comparisons of players of different skill levels or comparisons between successful and unsuccessful performances. The generalisability of these explanations would be further enhanced if it could be demonstrated that similar differences in visual search behaviour occur across different levels of task complexity. Williams et al. (2002) manipulated the complexity of a billiards task by having participants sink balls under different spatial constraints. They found longer final gaze durations with increasing task complexity among both the less skilled and the skilled players. They argued that the prolonged final fixation duration reflects that more complex aiming tasks require longer times to set and attune the parameters of the movement. The effects of complexity on the other visual search characteristics (e.g., mean fixation durations, number of fixation, fixation location) were not directly compared, however.

The present study aims to further examine the effects of task complexity on visual search behaviour by increasing the number of variables (or sources of information) that need to be taken into account. To this end, we introduced a sideward slope to the putting surface. We assumed that with a sloping surface golfers need to gather more information in the preparation phase, and hence, it was expected that they need more and longer fixations to extract the relevant information from the environment (e.g., areas surrounding the aim-line and break, Pelz 2000; for further explanation see also Figure 2). More successful golfers were expected to execute fewer visual fixations of longer duration on relevant locations than less successful golfers, which would demonstrate that more time is taken to get informed on relevant cues. We further expected longer duration of final gaze due to the introduction of slope angle of the green, because the time needed to set the parameters is thought to vary as a function of task complexity.

We also examined how visual search behaviour relates to expertise and success during performance. We reasoned that as high-skilled golf players (i.e. with low-handicap) are not necessarily proficient putters (e.g., Pelz 1999 p.37), it would be appropriate to employ a within task criterion (i.e., the percentage of putts holed) to demarcate successful and less successful putters (Whiting 1986; Savelsbergh et al 2005). As slope effects on breaking of the ball are usually underestimated (Pelz, 2000 p. 151; cf. Proffitt, 2006), we expected the more successful golfers to fixate more at the high side of the hole on sloped greens (i.e., with the ball breaking from right to left more to the right side of the hole). In addition, we expected the successful golfers to make less fixations of longer duration. In particular, it was hypothesized that duration of the final gaze fixation would be longer for this group. We also expected temporal differences in gaze behaviour: as is the case in putting on a flat green (Vickers 1992), the more successful putters were expected to use less gaze shifts of longer duration from ball to hole and vice versa, thereby using a visual search strategy characterized by more economy and efficiency. Similar differences were expected when comparing holed putts to missed putts.

Method

Participants

Twenty right-handed teaching golf professionals volunteered to participate (2 female and 18 male; age: mean = 36.9; sd = 6.5 years; handicap: mean = 3.4; sd = 2.0). Three participants were excluded because of technical failure. Six participants were assigned to the successful group (age: mean = 40.7; sd = 8.3 years; handicap: mean = 3.8; sd = 2.3) and six others to the less successful group (age: mean = 36.0; sd = 6.7 years; handicap mean = 2.5; sd = 1.5). Classification was based on the proportion of holed putts across the three conditions (i.e., > 0.62 and < 0.40 for the successful and less successful group respectively). We only considered visual search behaviours for these twelve participants; the visual search behaviour of the five remaining participants was not analyzed. Participants were treated in accordance with the local institution's ethical guidelines.

MATERIAL AND APPARATUS

The experiment was carried out in a large laboratory using a triangular platform, 4 m long and 4 m wide, covered with synthetic turf and artificial grass (Greenfields, Genemuiden, The Netherlands). The speed of the artificial green was fast (i.e., 14 stimp). The platform could be tilted to create slopes of 1 and 2% (i.e., sideward slope perpendicular to the putting direction). For practical reasons the green was only tilted from right to left (i.e., the high side of the slope was to the right of the hole). Every effort was made to keep the green clean in order to avoid any artificial reference points that could be used for targeting. All participants used the same standard putter and high quality golf balls.

Gaze behaviour was registered using an eye tracking system (Applied Science Laboratories 501, Bedford, MA) that consisted of a head-mounted scene camera and a monocular corneal reflection system (see Savelsbergh et al. 2002). The eye-tracker system works by collecting three pieces of information: displacement between the left pupil and cornea reflex, position of eye in the head, and position and orientation of head in space. The relative position of these features is used to compute visual point-of-gaze with respect to a pre-calibrated 9-point grid built up near the hole on the green. A video image of the scene including the point-of-gaze cursor, captured with a miniature scene camera, was then stored using a JVC BR-DV3000U digital video recorder for further analysis (25 Hz). The accuracy of the system was ± 1-degree visual angle, which from the point of observation of the participant amounts to an accuracy of approximately 2.6 cm at the ball and 4.4 cm at the hole. The system's calibration was checked before each trial. If necessary (i.e., approximately once or twice every 10 trials) the system was recalibrated using the quick and manual recalibration procedure. The eye-tracker was connected to the main computer with a 6-m long cable. The cable was attached to the waist of the participant using a waistband in such a way that it did not interfere with putting. A LED, which was located on the green at 1 m behind the ball (i.e., seen from the perspective of the participant), served as a visual signal indicating the start of each trial and the triggering of the ASL and video registration.

Procedure and task

First, the participants were informed about the procedures of the experiment, and the ASL helmet was fixed and calibrated. The participants then received the task instructions. They were instructed to start their habitual preparations to execute the putt (e.g., address the ball by setting up behind the ball) when a visual signal was given. They were instructed to try to hole the ball, or at least try to let the ball terminate as close as possible to the hole. The later instruction was given to prevent participants from making a fast straight shot, which would reduce the effect of slant on the ball's trajectory. Yet, to prevent them from playing consistently short, participants were also told that an overshot was to be preferred over an undershot. To encourage the participants to putt at their best according to these instructions, a competition was organized among participants, in which they could earn a maximum of 225 points. For each of the 45 putts, they were awarded 5 points for each putt that was holed, 2 points for missed putts that ended not further than 30 cm past the hole, and 1 point for missed putts that ended within 30 cm short of the hole. After each trial, the participant had to step aside, turn away from the hole and wait for the experimenter to announce the next trial. The participants then waited for the visual signal to perform the next trial.

Design

All participants performed 45 golf putts from 1.8 m (i.e., 6 foot) in three different slope conditions: 0 % (i.e., a flat green), 1%, and 2% slope with the ball breaking from right to left (i.e., from the participants perspective, the right side of the hole was higher than the left side). Slope conditions were presented in blocks, the order of which was randomized across participants. Participants were allowed to take a short rest period between trials.

Data reduction

During the experiment, we scored whether the putt was holed or missed. A miss was further categorized as a miss to the left or as a miss to the right (i.e., the ball passed the hole to the left or the right). Next, the proportion of balls holed (i.e., the number of balls holed divided by the total number of trials), and the proportion of misses to the left or the right (i.e., number of misses to the left or the right divided by the total number of trials) was calculated for each slope condition separately.

The recordings of ASL-scene camera were used to determine the moments of initiation of the backswing and downswing, and the moment of impact. From these measures, we calculated the total preparation (i.e., the time between the visual signal and the onset of the backswing), backswing and downswing times. To address visual search behaviour, point-of-gaze was analyzed frame-by-frame from the moment the visual signal was turned on until putter-ball contact. We coded gaze fixations and gaze shifts. A fixation was coded when point-of-gaze was directed at the same location for at least 3 consecutive frames (i.e., 120 ms). Four locations were distinguished: the hole including the surrounding areas 18 cm to the left and right of the hole (hole fixations); the area between the hole and the ball; the ball and putter head; and a rest category, which comprised fixations to locations deemed irrelevant for task execution (e.g., the visual signal, areas outside the artificial green) and missing out of range samples (e.g., blinking). This rest category (i.e.. 1.6% of all coded frames) was excluded from further analysis.

The number of gaze fixations, the mean fixation duration, and the percentage of viewing time to the hole, to the area between the hole and the ball, and to the ball and putter were determined (i.e., time spent viewing at the particular area divided by total fixation time). We also determined the duration for the final fixation on the ball until the onset of the backswing, the duration between the end of the last hole fixation until the onset of the backswing, and the duration of the final fixation on the hole. Finally, the precise location of the fixations to the hole area was established. To this end, we subdivided the hole and its surrounding area in ten areas categorized between 0 and 9. Each location was 5.4 cm (i.e., a half hole width) in width. Areas 0 to 3 were located left to the hole, 4 and 5 were located in the hole, and areas 6 to 9 were located to the right of the hole. With these categories we determined the location of the final hole fixation per trial and the location of the highest hole fixation (i.e., farthest to the right of the hole). We also calculated the average location of all hole fixations per trial by dividing the sum of the product of each hole fixation duration and hole fixation location by the total hole fixation duration.

Statistical analysis

For the performance measures two separate repeated measures ANOVAs were conducted. The proportion of ball successfully putted was submitted to a 2(group: successful, less successful) x 3(slope: 0%, 1%, 2%) analysis of variance with repeated measures on the last factor, whereas the proportions of misses to the left and right were submitted to 2(group: successful, less successful) x 2(type of miss: left, right) x 3(slope: 0%, 1%, 2%) analysis of variance with repeated measures on the last two factors. For the dependent variables that are indicative for the temporal characteristics of putting (i.e., preparation, back- and downswing times) and visual search behaviour (i.e., number and mean duration of gaze fixation and gaze shifts, percentages of viewing time, final fixation durations and locations) 2(group: successful, less successful) x 2(success: holed, missed) x 3(slope: 0%, 1%, 2%) analyses of variance with repeated measures on the last two factors were conducted. We applied Greenhouse-Geisser corrections to the degrees of freedom in the case of any violations of sphericity and computed partial eta-squared (η_p^2) values to determine the proportion of total variability attributable to each factor or combination of factors. Finally, Tukey HSD post hoc test procedures were used as follow up.

Results

Putting performance

Table I presents the results for putting performance. Obviously, the analysis of variance confirmed a significant effect for group on the proportion of balls successfully putted ($F(1, 10) = 19.5$, $p < 0.001$, $\eta^2 = 0.66$). By contrast, there was no effect of slope on the proportion of balls that was successfully putted ($F(2, 20) = 0.014$)[1], nor was there a significant interaction between group and slope ($F(2, 20) = 0.69$). The analysis of variance for the type of miss revealed that a significantly higher proportion of balls were missed to the left

[1] We also analyzed the effect of slope for all participants (N = 17), but again, the analysis of variance did not reveal a significant effect of slope on the proportion of balls successfully putted ($F(2, 32) = .095$).

Table I

Proportions of Holed Balls (SD), Misses to the Left, and Misses to the Right as Function of Slope and Putting Skill

	Slope		
	0%	1%	2%
Holed putts			
Successful	0.59 (0.16)	0.65 (0.19)	0.61 (0.17)
Less successful	0.45 (0.05)	0.37 (0.12)	0.40 (0.16)
Misses to the left			
Successful	0.32 (0.13)	0.20 (0.17)	0.18 (0.18)
Less successful	0.45 (0.09)	0.45 (0.21)	0.41 (0.14)
Misses to the right			
Successful	0.09 (0.05)	0.14 (0.11)	0.21 (0.19)
Less successful	0.11 (0.08)	0.19 (0.10)	0.19 (0.11)

of the hole (i.e., under the hole) than to its right ($F(1, 10) = 18.7$, $p < 0.01$, $\eta^2 = 0.65$). This effect was mediated by group ($F(1, 10) = 4.99$, $p < 0.05$, $\eta^2 = 0.33$), but not by slope. Post hoc analysis indicated that only the less successful golfers putted more balls to the left than to the right of the hole.

Temporal aspects of putting

The results for the preparation, backswing, and downswing times as a function of group, slope and performance are shown in Table II. The analyses of variance did not reveal any significant differences for these dependent variables.

Table II

Temporal Organization of the Putting Action as a Function of Slope and Putting Success and Putting Skill

	Slope					
	0%		1%		2%	
	Holed	Missed	Holed	Missed	Holed	Missed
Preparation time (s)						
Successful	11.2 (4.9)	11.5 (4.5)	11.7 (4.5)	11.9 (4.2)	10.9 (5.3)	10.9 (4.7)
Less Successful	10.0 (3.4)	9.3 (2.8)	9.3 (2.3)	9.3 (2.8)	8.5 (2.8)	8.8 (3.2)
Backswing time (s)						
Successful	0.68 (0.13)	0.62 (0.10)	0.58 (0.15)	0.67 (0.14)	0.67 (0.14)	0.65 (0.14)
Less Successful	0.69 (0.13)	0.68 (0.13)	0.58 (0.21)	0.67 (0.13)	0.65 (0.10)	0.66 (0.07)
Downswing time (s)						
Successful	0.27 (0.04)	0.32 (0.11)	0.34 (0.14)	0.28 (0.03)	0.29 (0.05)	0.29 (0.06)
Less Successful	0.30 (0.05)	0.31 (0.02)	0.35 (0.09)	0.31 (0.03)	0.31 (0.03)	0.32 (0.03)

NB. For both groups, values are based on n=6, except the successful group preparation time, where n=5.

Table III presents the temporal characteristics of visual search behaviours during the preparation of the putt as a function of group, slope and success. Analyses of variance for the number of fixations and the mean fixation duration did not reveal significant effects for group ($F (1, 10) = 0.27$ and $F (1, 10) = 0.40$ for number and duration respectively), slope ($F (2, 20) = 0.12$ and $F (2, 20) = 1.50$, respectively), nor for the group by slope interactions ($F (2, 20) = 0.20$ and $F (2, 20) = 0.52$, respectively). For the percentage of viewing time at the three fixation locations three separate a 2(group: successful, less successful) x 2(success: holed, missed) x 3(slope: 0%, 1%, 2%) analyses of variance with repeated measures on the last two factors were performed. These analyses showed a significant effect of slope on the viewing time at the ball and putter ($F (2, 20) = 6.30$, $p < 0.01$, $\eta^2 = 0.39$). Post hoc tests indicated that the time spent viewing to the ball and putter was less in the 2% slope than in the 0% and 1% conditions (see Table III). The effects of slope on the percentage viewing time at the hole ($F (2, 20) = 0.99$) and at the green between ball and hole ($F (2, 20) = 2.52$, $p = 0.12$, $\eta^2 = .20$) were not significant. Finally, neither the effects for group, nor for success, nor any interaction was found significant ($F (1, 10) = 2.00$; $F (1, 10) = 1.63$; $F (1, 10) = 0.02$) for the effect of success on the viewing time at the ball and putter, the hole, and the green between ball and hole, respectively).

TABLE III
Temporal Characteristics of Gaze Behaviour (SD)

	Slope					
	0%		1%		2%	
	Holed	Missed	Holed	Missed	Holed	Missed
Number of fixations						
Successful	7.9 (2.1)	8.3 (1.8)	8.4 (1.6)	8.8 (2.3)	8.6 (2.6)	8.6 (2.6)
Less Successful	9.5 (3.7)	9.3 (4.2)	9.4 (4.9)	9.0 (3.8)	9.7 (3.7)	9.0 (3.7)
Fixation duration (s)						
Successful	1.10 (0.35)	1.06 (0.33)	1.17 (0.45)	1.12 (0.45)	1.06 (0.44)	1.06 (0.44)
Less Successful	1.11 (0.32)	1.11 (0.25)	1.07 (0.40)	1.10 (0.42)	0.96 (0.35)	0.97 (0.25)
Viewing hole (%)						
Successful	36 (20)	36 (14)	36 (14)	35 (18)	41 (18)	37 (17)
Less Successful	29 (17)	28 (17)	29 (17)	27 (15)	29 (17)	29 (20)
Viewing ball & putter (%)						
Successful	60 (15)	60 (12)	58 (9)	58 (11)	54 (12)	57 (13)
Less Successful	63 (15)	65 (15)	67 (16)	68 (12)	58 (15)	60 (15)
Viewing green (%)						
Successful	4 (6)	4 (4)	6 (8)	7 (8)	5 (8)	7 (9)
Less Successful	8 (8)	7 (8)	4 (8)	5 (9)	13 (14)	11 (11)

In nearly all trials (i.e., 98.1 % in both groups) the final gaze fixation before onset of the backswing was directed toward the ball and putter head. Table IV reports the duration of the final gaze fixations for these trials. No significant effects on the duration of the final fixation on the ball and putter were found for the factors group ($F(1, 10) = 0.65$), slope ($F(2, 20) = 0.84$) and success ($F(1, 10) = 1.96$), nor were there any significant interactions. The factor success did significantly affect the duration between the end of the last hole fixation until the onset of the backswing ($F(1, 10) = 8.00$, $p < 0.05$, $\eta^2 = 0.45$), the duration being longer for the holed (1.74 s) than the missed putts (1.58 s). The analysis of variance did not reveal significant effects for group ($F(1, 10) = 1.28$) and slope ($F(1, 20) = 0.38$), nor was there any interaction between these factors. Finally, the duration of the final hole fixation was not affected by group ($F(1, 10) = 1.88$), slope ($F(2, 20) = 1.66$), success ($F(2, 20) = 1.41$) nor were any interactions found.

TABLE IV
Final Fixation Durations (SD)

	Slope					
	0%		1%		2%	
	Holed	Missed	Holed	Missed	Holed	Missed
Duration final ball fixation (s)						
Successful*	1.3 (0.8)	1.3 (1.1)	1.3 (0.8)	1.1 (0.8)	1.3 (0.9)	1.1 (0.8)
Less Successful	1.7 (1.7)	1.9 (1.6)	2.1 (1.9)	1.9 (1.5)	2.0 (2.3)	1.5 (1.4)
Duration between final hole fixation and onset backswing (s)						
Successful*	1.3 (1.0)	1.4 (1.3)	1.4 (0.9)	1.2 (0.9)	1.4 (1.0)	1.3 (1.0)
Less Successful	2.2 (1.7)	2.2 (1.7)	2.2 (1.1)	1.8 (1.1)	2.0 (0.9)	1.7 (0.8)
Duration of final hole fixation (s)						
Successful*	0.5 (0.3)	0.6 (0.4)	0.7 (0.2)	0.6 (0.2)	0.9 (0.1)	0.7 (0.4)
Less Successful	1.4 (1.4)	1.0 (0.7)	1.0 (0.6)	1.0 (0.5)	1.6 (1.9)	1.3 (1.1)

NB.* n=5.

Table V reports the location of the fixations surrounding to the hole. Analysis of variance on the average hole fixation revealed a significant main effect of slope ($F(2, 18)$[2] $= 4.91$ $p < 0.05$, $\eta^2 = 0.35$), while the effect of success just failed to reach significance $F(1, 9) = 2.77$, $p = 0.13$, $\eta^2 = 0.24$). The ANOVA on the location of the highest hole fixation also revealed significant

[2] We were unable to categorize the hole fixation location in approximately half of the trials for one participant in the successful group and therefore decided to exclude this participant from the present analysis. Additional analysis suggested, however, that inclusion of the data of this participants would not lead to a different pattern in the outcomes for the hole location fixations.

Table V
Hole Fixation Locations (SD)

	Slope					
	0%		1%		2%	
	Holed	Missed	Holed	Missed	Holed	Missed
Location of average hole fixation						
Successful*	4.0 (0.4)	3.8 (0.4)	4.5 (0.3)	4.3 (0.4)	4.6 (0.5)	4.6 (0.5)
Less Successful	4.5 (0.3)	4.6 (0.4)	4.7 (0.3)	4.8 (0.4)	5.1 (0.5)	4.8 (0.4)
Location of highest hole fixation						
Successful*	4.5 (0.3)	4.2 (0.4)	5.0 (0.4)	4.9 (0.4)	5.3 (0.5)	5.2 (0.4)
Less Successful	5 (0.3)	5 (0.3)	5.3 (0.3)	5.2 (0.4)	5.8 (0.4)	5.5 (0.4)
Location of final hole fixation						
Successful*	4.0 (0.4)	3.8 (0.4)	4.7 (0.4)	4.6 (0.4)	5.0 (0.5)	4.7 (0.5)
Less Successful	4.7 (0.4)	4.7 (0.4)	4.8 (0.4)	4.7 (0.4)	5.6 (0.4)	5.1 (0.4)

NB.* n=5.

effects of slope; (F (1, 18) = 8.28, $p < 0.01$, $\eta^2 = 0.48$) and success (F (1, 9) = 5.59, $p < 0.05$, $\eta^2 = 0.38$). The location of the final hole fixation was also significantly affected by slope (F (2, 20) = 5.16, $p < 0.05$, $\eta^2 = 0.34$), whereas the effects of success (F (1, 10) = 3.82, $p = 0.08$, $\eta^2 = 0.28$) and the slope by success interaction (F (2, 20) = 3.41, $p = 0.06$, $\eta^2 = 0.25$) both just failed to reach significance (however, both effects showed a large effect size). No effect of group was present (F (1, 10) = 1.94). Post hoc analyses showed that the steeper the slope, the further to the right of the hole the participants directed their gaze (Figure 1). These effects were more pronounced for the holed putts.

Discussion

We explored the relationship between task complexity in a golf putting task and visual search behaviour for two groups of different levels of putting skill. Task complexity was varied by having participants putt on a flat (i.e., 0%) and sloped (i.e., 1% and 2%) greens, varying the amount of break (see Figure 2) from right to left on the putted ball. Participants of both groups were quite capable of dealing with the increase in task complexity as the number of successfully putted balls was not significantly affected by the steepness of the slope. This is perhaps surprising, because people tend to perceptually overestimate the slant of a slope (e.g., Proffitt et al., 1995). These perceptual overestimations, provided they were present in the current situation, did not influence the participants' putting actions, as this would have resulted in balls to be aimed at the high (i.e., right) side of the hole. By

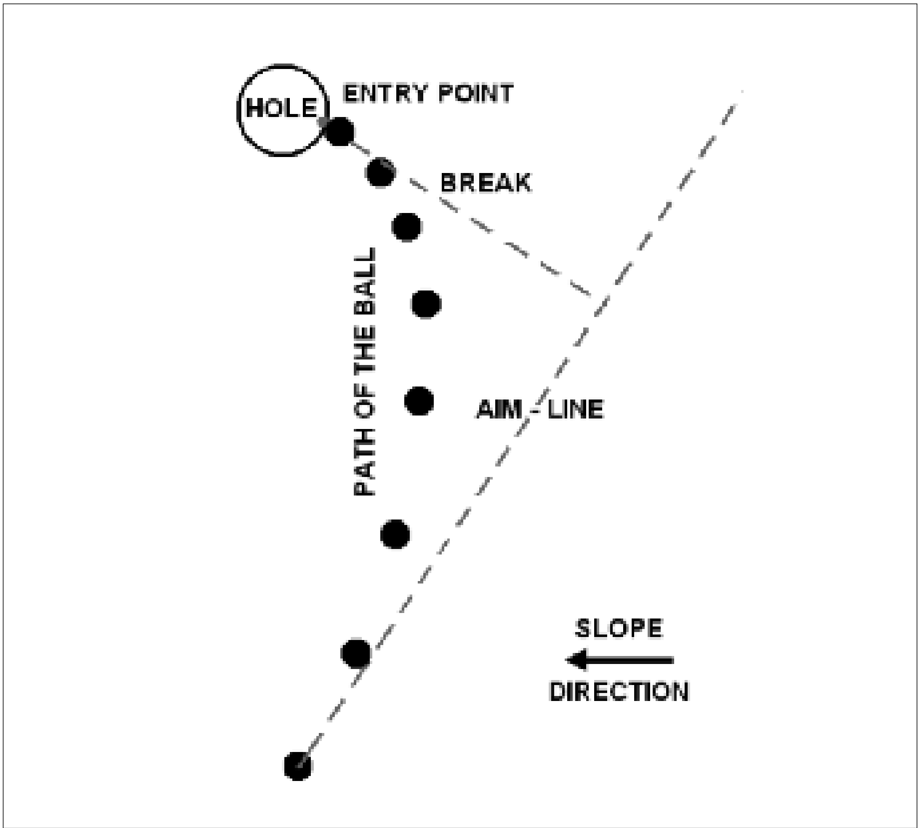

Fig. 1. A schematic representation of the putting surface, including path of the ball, aim-line, break and entry point. The ‘aim-line’ is the desired initial direction of the putt; the break is the perpendicular distance of the aim-line to the hole, and the entry point is the point where the ball ideally enters the hole.

contrast, the missed balls more frequently passed the hole at its low side (i.e., to the left), in particular among the less successful participants. Milner and Goodale (2008; see also van der Kamp, Rivas, van Doorn & Savelsbergh, 2008) argued that the use of visual information for making perceptual judgments (i.e., gathering knowledge about objects, events and places) and the use of visual information to guide action (i.e., movement control) are neuroanatomically and functionally dissociated. Consequently, inaccuracies in perception do not necessarily crop up in action and vice versa. Accordingly, perceptual overestimations of the slant of a slope do not necessarily have to translate into the truly visuomotor task of putting (see also Witt & Proffitt,

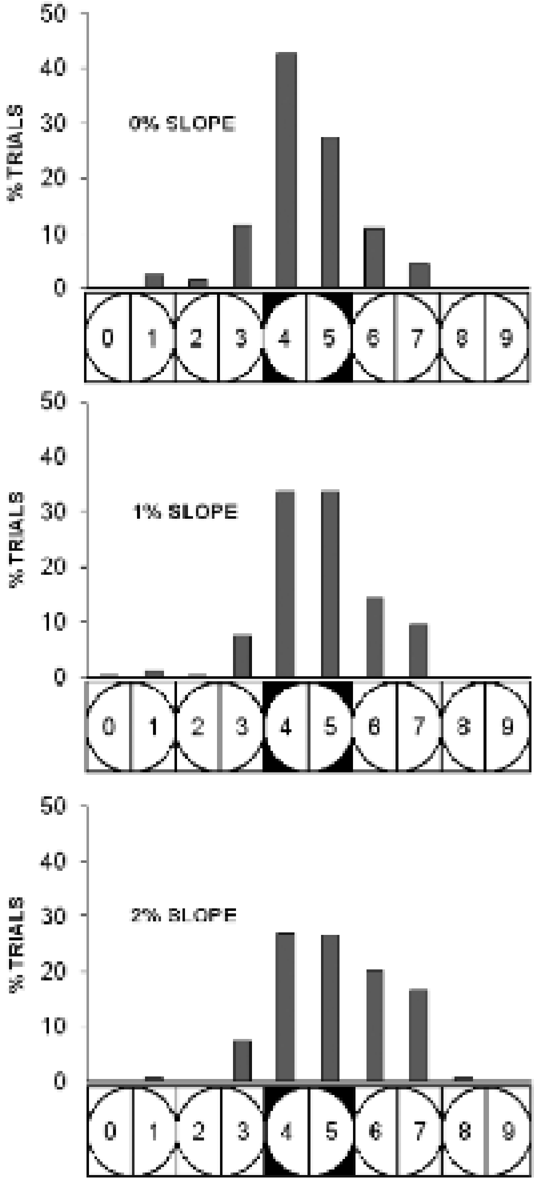

Fig. 2. Percentage of viewing time to the locations surrounding the hole. Each location is 5.4 cm (i.e. a half hole width) in width. Location 0 is 21.6 – 16.2 cm to the left of the hole, 4.5 is the centre of the hole, and location 9 is 21.6 – 16.2 cm to right of the hole.

2007). It further appears that the successful adaptation to a more complex environment was primarily brought about by an alteration in visual search behaviour, as we found no changes in the organization of the putting action itself. Participants did not take more time to prepare the putting movement and also the (relative) durations of the back- and downswing were not affected by slope.

The most obvious adaptation to the introduction of a slope was a shift of the location within the hole area at which the participants were looking. As slope increased, participants were looking more to the high side of the hole (i.e., the right side), albeit that the lateral shift was rather small. This was true for the final hole fixation location as well as for the average and highest hole fixation locations. On the flat green, participants looked slightly to the left of the center of the hole, whereas for the 1% and 2% slopes, they fixated the right half of the hole and slightly to the right of the hole, respectively (Figure 1). In addition, participants spent less time focusing at the ball and putter for the steepest slope. Although this effect failed to reach significance, participants tended to look marginally longer (i.e., ≈ 3-5%) at the green between the ball and hole for the steepest slope, which comprises[3] areas surrounding the future ball track and the point to which participants direct their putt, i.e., the 'aim-line'[4] (Pelz, 2000).

Pelz (2000) stressed the importance of gazing along the aim-line for accurate putting on a sloped green. We therefore anticipated a comparatively high proportion of viewing time to a point on the aim-line at considerable distance to the side of, and aligned with, the hole. Yet, the participants were found to spend much more time viewing at or in the near proximity of the hole, the exact location of which was dependent on the amount of break. This suggests that accurate putting on a sloped green critically depends on fixating the point at which the ball will enter the hole (i.e., entry point, Figure 2). With increasing steepness of the green, the entry point shifts to the high side of the slope, and participants were found to adjust gaze accordingly. This is not say that a quick glance along the aim-line would be entirely irrelevant; nonetheless, perusal of the gaze recordings showed that participants performed a considerable amount of putts without fixation of the green between the hole and the ball.

[3] Without artificial reference points on the green, we were unable to determine the exact location of the fixation locations between the ball and the hole. Hence, it remains unclear at what exact point (e.g., on the aim-line or future ball track) on the green between the ball and the hole the participants' gaze resided.

[4] The 'aim-line' is the initial direction of the ball and depends on the amount of break, which in turn depends on the slope of the green. (Pelz, 2000)(Figure 2).

Williams et al. (2002) reported longer final gaze durations with increasing task complexity among billiard players. They argued that the prolonged final fixation duration reflects that more complex aiming tasks require longer times to set the parameters of the movement (see also Vickers, 1996b). In the present study, however, temporal adjustments associated with the introduction of a sloping surface, such as an increase in final fixation durations, were not found. Nor were there any differences in the number of fixations or fixation durations, which are assumed to reflect the efficiency of visual search. Instead, task complexity in the current study primarily resulted in spatial adjustments of visual search.

Obviously, the absence of a relation between the amount of slope and the temporal parameters of visual search, such as final fixation duration, does not necessarily imply that these parameters should be deemed irrelevant for accurate performance. After all, the importance of these parameters has been established by comparing visual search behaviours as a function of skill and performance (Mann et al. 2007). Hence, we also compared visual search behavior between the most successful and least successful golf players that participated in our study. A distinction on basis of putting performance was the more justified, because it is plausible that players with similar levels of golf skill (i.e., indicated by their playing handicap) have rather disparate success rates in putting (Pelz 1999; see also Whiting 1986; Savelsbergh et al. 2005). The scoring percentage for a 1.8 m putt among golf professionals is approximately 50% (Pelz 1999, p. 28). Hence, out of our sample of low-handicap golf players, we defined two subgroups that putted significantly above and below 50% (i.e., 62% and 40 % respectively). The successful participants not only holed a higher proportion of balls, they also made a lower proportion of misses to the left side of the hole (i.e., the low side) than the unsuccessful participants. For a slope with a break from right to left, this side of the hole is considered to be the 'amateur side' (i.e., in contrast to high-skilled players, low-skilled golfers tend to putt short or on the low side on sloped greens).

A relationship between putting skill and visual search behaviour was not immediately apparent, however. Neither the temporal, nor the spatial parameters of visual search could account for the difference in putting skill between the groups. Nevertheless, we did discern differences in visual search that were related to putting success on individual trials (i.e., independent of putting skill). These differences were partly analogous to the effects of slope: participants looked slightly further to the left of the centre of the hole (i.e., the balls entry point) on holed as compared to missed putts. This was particularly true for the final fixation on the hole. Once more, this underlines the importance of adjusting the spatial properties of visual search. Intriguingly, the time between picking up pertinent information about the entry point (i.e., the end of the final hole fixation) and the onset of the swing was significantly longer for the holed as compared to the missed putts. In contrast, the other temporal parameters of visual search (i.e., number and duration fixation, final fixation duration toward the hole, and the final fixation duration to the ball and putter) did not vary as a function of performance on individual trials. Vickers (1996b) argued that increased performance is associated with a prolonged time of picking up the final relevant information and setting the movement parameters. In golf putting, she found that a longer final fixation on the ball resulted in higher accuracy of putting (Vickers 1992). We were not able to replicate this finding and thus failed to find strong support for a relation between final gaze duration and performance accuracy (see also de Oliveira, Oudejans, & Beek, 2008).

In sum, we examined the effects of task complexity on visual search behaviour in golf putting. It is concluded that the prime adjustments to different amounts of task complexity are spatial (i.e., fixation locations) rather than temporal (i.e., fixation durations) in nature.

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