Spotting expertise in the eyes: Billiards knowledge as revealed by gaze shifts in a dynamic visual prediction task

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In sports, as in other activities and knowledge domains, expertise is a highly valuable asset. We assessed whether expertise in billiards is associated with specific patterns of eye movements in a visual prediction task. Professional players and novices were presented a number of simplified billiard shots on a computer screen, previously filmed in a real set, with the last part of the ball trajectory occluded. They had to predict whether or not the ball would have hit the central skittle. Experts performed better than novices, in terms of both accuracy and response time. By analyzing eye movements, we found that during occlusion, experts rarely extrapolated with the gaze the occluded part of the ball trajectory—a behavior that was widely diffused in novices—even when the unseen path was long and with two bounces interposed. Rather, they looked selectively at specific diagnostic points on the cushions along the ball's visible trajectory, in accordance with a formal metrical system used by professional players to calculate the shot coordinates. Thus, the eye movements of expert observers contained a clear signature of billiard expertise and documented empirically a strategy upgrade in visual problem solving from dynamic, analog simulation in imagery to more efficient rule-based, conceptual knowledge.

Keywords: aiming sports, billiards, eye movements, expertise, knowledge, mental imagery, motion, simulation, trajectory extrapolation

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Introduction

The way we explore the world around us with eye movements can be a precious indicator of hidden cognitive processes (Buswell, 1935; de'Sperati, 2003a; Rayner, 1998; Viviani, 1990; Yarbus, 1967). Despite the gaze is in many cases attracted automatically and almost predictably by low-level elements of the visual scene in a bottom-up way (Itti & Koch, 2001), much of our oculomotor behavior is guided by cognitive top-down processes (Henderson, 2003).

Among the top-down factors, a prominent role in gaze guidance is played by expertise. Expertise can affect various aspects of the ocular exploratory behavior, such as the number, duration, and especially the spatial distribution of fixations. The scanpath (i.e., the hypothetically reproducible sequence of saccades and fixations; Noton & Stark, 1971) of expert and novice observers differs when they look at pictures or art pieces (Humphrey & Underwood, 2009; Nodine,

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Locher, & Krupinsky, 1993; Pihko et al., 2011; Vogt & Magnussen, 2007; Zangemeister, Sherman, & Stark, 1995), interpret medical images (Donovan & Manning, 2007; Nodine, Kundel, Lauver, & Toto, 1996), drive (Underwood, 1998), read music (Waters, Underwood, & Findlay, 1997), or play chess (Chase & Simon, 1973; Reingold, Charness, Pomplun, & Stampe, 2001).

In sports as well, visual cognition is of fundamental importance, and in fact expertise has been often associated with a particular gaze control. As compared with novices, athletes exhibit a different oculomotor pattern in a variety of disciplines and tasks, both when they perform actively and when they are simply external observers (for review, see Vickers, 2007). In ball sports such as table tennis, cricket, or squash, professional players have developed an exquisite ability to predict shots. This is achieved by building an implicit model of the ball dynamic behavior, which, together with contextual cues (Abernethy, 1990; Davids, Williams, & Williams, 1999; Shim, Les Carlton, & Kwon, 2006), allows them to anticipate with the gaze the course of the ball (Land, 2009; Land & Furneaux, 1997). Interestingly, implicit knowledge of the ball's physical behavior underlies the ordinary act of catching a bouncing ball (Hayhoe, Mennie, Sullivan, & Gorgos, 2005; Zago, Bosco, Maffei, Iosa, Ivanenko, & Lacquaniti, 2004), which suggests that mastering those ball sports is reached largely by strengthening visuo-motor functions that are already in place in beginners. Whereas studying eye movements of a performing athlete may have obvious outcomes in terms of potential skill improvement, for example, by learning to optimize the allocation of visuo-spatial attention for the best motor performance, studying an athlete during performance observation, that is, in a condition devoid of the physical aspects of the motor action, allows researchers to isolate cognitive aspects of the athlete's skill (Vickers, 2007).

In principle, therefore, from the typology of eye movements, it is possible to extract precious indications about expertise. However, it should be borne in mind that although gaze shifts reflect often the deployment of covert visuospatial attention (Findlay & Gilchrist, 2003), attention and eye movements are not always coincident, especially with dynamic stimuli (Cavanagh & Alvarez, 2005; Viviani, 1990), and caution must be exerted when interpreting eye movements patterns. Furthermore, it is difficult to infer a general "ocular rule" for expertise, as the pattern of exploratory eye movements depends heavily on the stimulus, context, and task (Land & Furneaux, 1997). Therefore, it is important to associate expertise to specific predictions concerning gaze allocation within any given experimental condition, an issue that could be especially important in the development of expertise tests, as a general test for expertise cannot exist. Studying the reflections of expertise on eye movements using specific tasks and/or under specific contexts can, however, also provide information of more general, theoretical interest, for example, by shedding light on the interplay between perceptual and cognitive factors in understanding dynamic events. Fast ball sports, however, are not particularly well suited to address this issue, because an explicit evaluation of the state of affairs may be excessively time-consuming.

Billiards is an interesting experimental model to investigate the signature of expertise potentially hidden in the scanpath. Besides being a chief example in the perceptual versus cognitive dispute on causality since the *Enquiry* of David Hume (1748), the simple geometrical and kinematical structure of billiard shots, and their relatively slow pace, favors the comparison between the intuitive knowledge of the ball trajectory of a novice and the skilled knowledge of a professional player. For novices, the simplest way to prepare a successful billiard shot seems to be predicting the ball trajectory as it unfolds in space and time. That is, mental imagery is the expected strategy in novices, either in the form of a simulation of the entire ball trajectory, as both classical experiments on mental rotation (Shepard & Cooper, 1986) and more recent evidence on eye movements in trajectory prediction tasks (Jonikaitis, Deubel, & de'Sperati, 2009) suggest, or in the form of piecewise mechanical reasoning about the ball-bouncing behavior at the cushions (Hegarty, 2004). Thus, it appears that in order to predict the outcome of a billiard shot, a novice simulates the ball behavior by running in imagery an explicit dynamic model of the ball motion (models of moving objects can be dynamical or kinematical, according to whether they include forces or only motion; Schwartz, 1999; however, for simplicity, we do not distinguish here between dynamical and kinematical models, and throughout the article we will use the term *dynamical*, although for the requirements of our task, a kinematical model is sufficient—in this sense, dynamic is to be intended as opposed to static). Notice that this aspect differentiates billiards from the above-mentioned ball sports, where, especially because of the faster pace and more difficult trajectories, novices do not usually rely on explicit visual imagery. Investigating how novices predict the trajectory of a billiard shot should allow us to extend to real-life conditions our knowledge of the mental representation of motion (de'Sperati, 1999, 2003a, 2003b; de'Sperati & Deubel, 2006; de'Sperati & Santandrea, 2005; Jonikaitis et al., 2009; Makin & Poliakoff, 2011).

Professional billiards players have instead learned to "see" the shot through the lens of expertise, which is made up of motor ability, visuo-spatial abilities, and professional "tricks." One such trick makes billiards a very special case, as compared with the above-mentioned ball sports. Professional players use a particular procedure to prepare, execute, and monitor the shot, the so-called "angolo 50" (Italian, literally "angle 50"; Fermi & Schiavi, 2009). This is based on a metrical system formed by visible reference points, the "diamonds," positioned at regular distance along the borders of the billiard table. Knowing the initial ball position and the target position, the player can precisely calculate the coordinate of the correct impact points of the ball on the cushions through numerical computation. Importantly, when professional players apply this procedure, they do not need to consider the full ball trajectory, as to predict the outcome of a shot, it is sufficient to evaluate the distance of a given bounce from the reference diamond, calculated through the angolo 50 rule. Thus, billiard experts embody an almost pure rule-based, nonimaginal representation of the shot, which is not to say that they do not see the ball trajectory or that they cannot imagine its evolution, just that they can quickly make a reading of a shot without representing the entire ball trajectory.

Thus, preparing a billiard shot may either entail the mental simulation, in space and time, of the ball trajectory in imagery, or reduce the shot to specific coordinates of certain bouncing points computed through the angolo 50 rule, eliminating space and time from the shot. This distinction is reminiscent of the long-standing analog/propositional dichotomy of mental representation (Kosslyn, 1994; Pylyshyn, 2003; see also Thomas, 2010).

To a first approximation, the *analog* side of the debate holds that the mental representations that we experience as imagery are, in some important sense, like pictures, with intrinsically spatial representational properties of the sort that pictures have. . . . The *propositional* side, by contrast, holds the relevant mental representations to be more like linguistic descriptions (of visual scenes), without inherently spatial properties of their own. (Thomas, 2010, paragraph 4.4)

Because of the large body of evidence in favor of the perceptual-like nature of visual mental imagery (Finke, 1985; Kosslyn, 1994), we will label these two forms of billiard knowledge *perceptually-based knowledge* and *conceptual knowledge* (although mental imagery is a cognitive activity that is not guided by immediate sensory information). The very possibility of showing that the same visual event affords such two qualitatively different mental representations in novices and experts would indicate that mental imagery is a primitive, heuristic form of knowledge for visual problem solving: Once a better form is found, imagery is replaced (Schwartz, 1996). Billiards seems to be an ideal test bed to observe the passage from novices' perceptually based knowledge to experts' conceptual knowledge, and eye movements may be specially suited to document empirically this passage.

In this study, we assessed whether the pattern of eye movements distinguishes these two different strategies in novices and experts while they are observing a billiard shot with the aim of predicting its outcome. To this end, controlled individual shots in which the final part of the ball trajectory was not displayed (occlusion, see the Methods section) were presented on a computer screen to novices and experts while recording their eye movements. We expected that novices explored extensively the ball trajectory with the eyes, also the occluded part where the trajectory could be only imagined, whereas the experts' gaze should instead reflect the behavioral salience of the reference points used to monitor the shot according the angolo 50 rule, thus clustering on a few specific points (Fermi & Schiavi, 2009; see the Discussion section). We also sought to verify whether a particular visuo-motor habit of elite athletes performing aiming sports, namely, the aptitude to make a long fixation on the target just before the aiming movement (which was termed *quiet eye*; Vickers, 2007), is retained when simply observing a billiard shot. The quiet eye is functional to prepare precision aiming actions, including billiard shots (Williams, Singer, & Frehlich, 2002), and helps the player to focus on the goal, perhaps filtering out unnecessary or even hampering information ("Keep your *eye* on the place aimed at, and your hand will fetch it; think of your hand, and you will very likely miss your aim," James, 1890/1983, p. 520; see also Janelle et al., 2000). We asked whether the quiet eye behavior becomes incorporated in the looking pattern of professional billiard players to the point of being triggered even in observational tasks for which it is seemingly useless. Thus, whereas finding the oculomotor signs of the angolo 50 strategy would reveal the use of conceptual knowledge, finding the quiet eye would suggest that professional players can deeply embody certain visuo-oculomotor routines.

Methods

Ethics statement

The study was conducted in accordance with the Declaration of Helsinki and the recommendations of the San Raffaele Ethical Committee. Before starting the experiments, written informed consent was obtained from all participants. All data from this study were analyzed anonymously.

Novices		Experts	
Expertise level	Number of subjects	Category ranking	Number of subjects
Every week	0	National Pro	1
Once a month	1	National	1
Sometimes in a year	3	Master	4
Sometimes in life	17	I cat.	6
Never	0	II cat.	7
		III cat.	2
		IV cat.	0

Table 1. Expertise level of novices and experts. *Note:* Higher ranking is on top.

Participants

Forty-two healthy participants volunteered for the experiment (all men but one, with normal or corrected-to-normal vision, aged between 27 and 70 years, naive as to the purpose of the experiment). Half were agonistic billiard players. The expertise level of the professional players was evaluated on the basis of the Italian national ranking, whereas in novices it was assessed with a questionnaire (Table 1).

An informal five-item questionnaire was administered to both novices and professional players to grossly assess visuo-spatial abilities (Supplementary Figure S1). Most novices responded correctly to all questions, whereas experts had more difficulties. In the debriefing, it emerged that they were not too familiar with those kinds of questions, but they could answer them correctly after a proper explanation. Because the questionnaire was administered only to verify informally that participants managed some basic geometrical visuo-spatial relations, the results were not further used in the study.

Stimuli and task

The stimuli were movies of real billiard shots. A professional player was engaged to execute a number of ad hoc shots on a professional billiard table without pockets (dimensions: 2.84 × 1.42 m). The shots were filmed from the top with a digital video camera (Hitachi DZ-GX5040E), which was mounted 3 m above the billiard table and centered. Lighting was provided through four fluorescent bulbs placed at the corners of the table.

The shots were intended to represent a simplified billiard game situation. Only one ball and a single central skittle were present on the table. The professional player had to launch the ball towards the skittle, without spin, in 24 different ways, with the following variations (Figure 1A through C):

- Two difficulties (short shot, with two cushions, or long shot, with five cushions)
- Three accuracies (centered, the ball strikes the skittle, or narrow or large, the ball passes immediately by the skittle on the right or the left, without pulling it down)
- Two horizontal directions (the stick launches the ball toward the left or the right hemifield)
- Two vertical directions (the stick hits the ball from upside or downside)

The shots were executed so that the ball stopped naturally beyond the skittle position and before touching the next cushion. The execution was repeated when necessary (usually because the shot was too large or too narrow). The recorded movie was then processed offline through a video-editing program (Vegas 7.0, Sony Creative Software, Inc.). First, we compensated the geometrical distortions due to the video camera lens (especially barrel distortion) and the slight misalignment due to video camera positioning. Then the single shots were separated into individual short movies.

To create movies of similar length, a shot was temporally defined as including the last three swing movements of the stick before the impact with the ball (the professional player did not always take the same time to prepare the different shots), up to six frames (200 ms) after the ball had bounced on the second (in the short shot) or the third (in the long shot) cushion, that is, well before the natural completion of the trajectory. Such early termination (occlusion) was dictated by the task (see below). Before the initial frame of each movie, we inserted a 5-s still image displaying the first video frame. This still image was introduced to allow the observers (especially the novices) to recognize which shot would be presented in the trial, thus avoiding possible confusion as to the trajectory of the impending shot. After the last frame, we inserted another 5-s still image displaying the last video frame, followed by a 2-s blank. This still image allowed the subject to respond (see below) without excessive time pressure. An example of a single shot after this packaging is shown in Movie 1 (Supplemental Material).

The short movies representing the individual shots were then pasted together in random sequence to make a single movie, with the blank serving as a separator between successive trials. Because each shot variation was (randomly) repeated twice, the movie consisted of a fixed sequence of 48 trials and lasted 15 min. This was the stimulus administered to each observer. Therefore, stimulus presentation was in fact pseudo-random and not self-paced. These steps have been adjusted several times before attaining the final version of the stimuli, both empirically and with the advice of a Manager of the Federazione Italiana Biliardo Sportivo (Italian Federation of Billiard Sports).

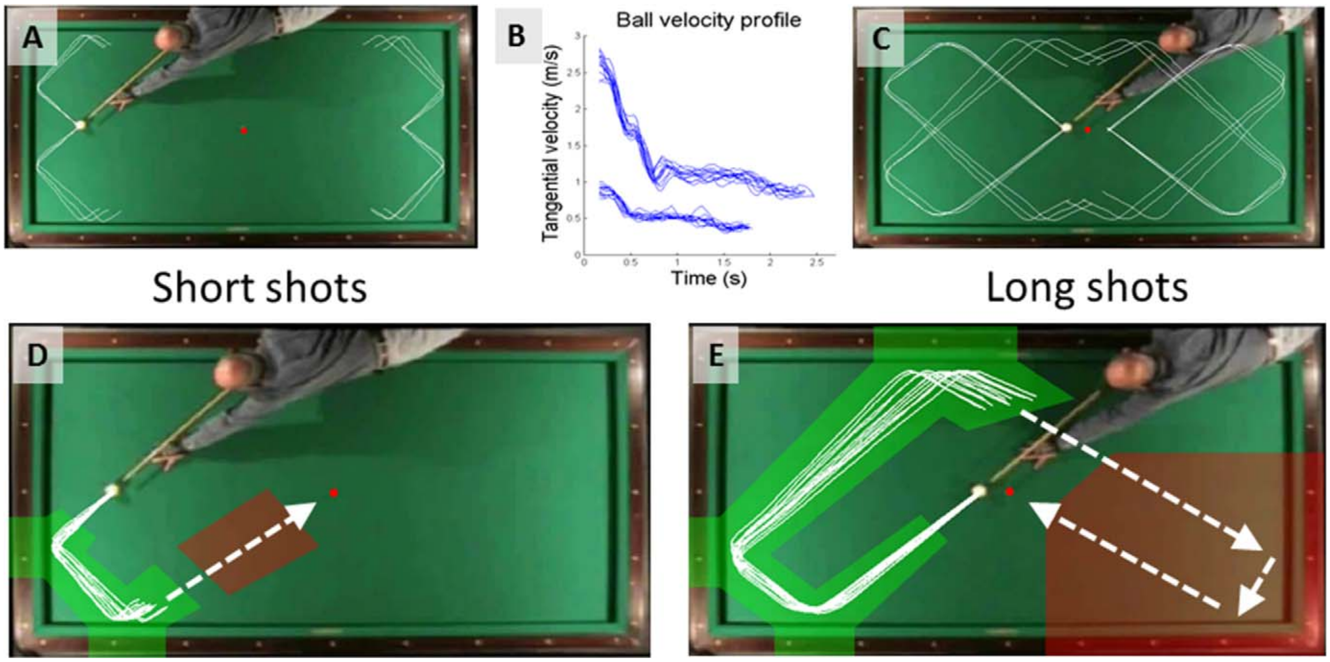

Figure 1. Details of the stimuli. (A, C) The visible portion of the trajectories of the ball for each of the 24 shot variations, as reconstructed offline frame by frame. Smoothing the trajectories rounded somewhat their shapes. (B) Instantaneous tangential velocity profile of the ball in the visible portion of the trajectory. The multiple traces represent the 24 individual shots (the 12 velocity profiles of the long shots and the 12 of the short shots are clearly separated, the former being higher and lasting longer than the latter). Time zero denotes the moment the ball is launched. The initial part of the traces is not shown to avoid smoothing artifacts. (D, E) Ball trajectories pooled after right-left and/or upside-down flipping. Also shown are the two couples of regions of interest used in the analyses (greenish for the visible trajectory, reddish for the unseen trajectory, symbolically represented by the arrows). The central red spot indicates the skittle position.

As can be seen in Figure 1, the final trajectories of the ball had a very consistent velocity, duration, and shape. The initial velocity was about 0.9 and 2.7 m/s (for the short and long shots, respectively), whereas at the time of occlusion, it was reduced to about 0.4 and 1.0 m/s. For each shot difficulty, the temporal variability of the period in which the ball was moving was less than 500 ms (duration of the ball motion: short shots, range = 1.6–1.9 s, mean and median = 1.8 s; long shots, range = 2.1–2.6 s, mean and median = 2.4 s). Within a given shot precision (narrow, centered, large), the geometry of the trajectories was very similar, as was their kinematics. On the screen, the billiard table subtended 30° × 15° of visual angle.

Observers were seated in a darkened room about 57 cm in front of a computer screen (Planar, 17″; frame rate: 60 Hz; resolution: 1280 × 1024 pixels), with the head resting on a forehead support. They took a pause in the middle of the session. Before the beginning of the experiment, observers got acquainted with the stimuli by watching a few examples of the original videos showing the entire shot without occlusion.

The task of the participants consisted of telling as soon as possible whether or not the ball would have pulled down the central skittle. They were informed that the ball had no spin. The responses were given verbally ("Yes"/"No") and recorded. Importantly, to avoid that observers simply waited for the ball to be very close to the skittle, which would require only a trivial visual exploration strategy, the task was built as a prediction task. Thus, as described above, the ball trajectory was occluded before reaching the skittle, so that the final portion of the trajectory remained always invisible. The two kinds of shot (two and five cushions) were markedly different in terms of both the visible and the invisible portion of the trajectory. As for the visible portion, the difference was mainly in terms of number of cushions, hence, of number of rectilinear segments of the trajectory, which were two and three, respectively, for the short and long shots. As for the unseen portion, whereas in the short shot the skittle was simply on the continuation of the ball trajectory and at short distance, in the long shot the ball had to reach the corner and return toward the central position, thus forming a long path that included also bouncing on two additional cushions. The presence of occlusion allowed us also to assess the possible motion imagery/extrapolation strategies.

Recording procedures

Two-dimensional eye movements were acquired through video-oculography (Eyegaze System, LC

Technologies; sampling frequency: 60 Hz; nominal precision: 0.18°). Monocular recordings were performed unobtrusively via a remote CCD video camera mounted below the computer screen. Gaze direction was determined by means of the pupil-center-corneal reflection method. Before the beginning of the experimental session, calibration was performed. To ensure a better stability of the eye position signals, calibration was repeated at the end of the pause in the middle of the session. The raw gaze position traces were low-pass filtered at 30 Hz.

Verbal responses were recorded with a microphone placed on the table in front of the observers and a digital audio recorder (Philips, Digital Voice Tracer LFH0622). For simplicity, eye movement recording and audio recording were started by the operator manually and simultaneously. This may have introduced a small asynchrony between the two recording streams but likely not exceeding a few tens of milliseconds. The responses of the observers ("Yes"/"No") and the response times (RT) were derived offline by the operator by careful back-and-forth replaying of the time-marked audio traces. We estimated that the final RT measurement error was less than 1%.

Data analyses

All data analyses except the statistical tests have been performed with programs written in Matlab 7.9 (The MathWorks, Inc.), equipped with PsychToolbox 3. As a preliminary step, we reconstructed the ball trajectories (Figure 1). This required a frame-by-frame analysis of each of the 24 shot variations, in which the center of the ball was marked manually through the mouse pointer. To reduce small imperfections in the reconstruction, the trajectory components were smoothed with a digital filter. The instantaneous tangential velocity of the ball was obtained from the first derivative of the smoothed trajectory components.

Fixations were identified by means of a simple dispersion criterion: We defined gaze samples as belonging to a fixation if they were located within an area of 25 pixels (corresponding to 0.67°) for a minimum duration of six video frames (corresponding to 100 ms). We obtained the same results by fixing a lower bound for fixations to 67 ms. Short fixations with a duration between 67 and 100 ms were very rare, amounting to 2.4% and 3.4% in novices and experts, respectively. We could not measure reliably smooth pursuit eye movements: The low sampling frequency, combined with the relatively short duration of the ball movement—and the three to four brisk motion direction changes due to the cushion bounces—made it difficult to clearly disentangle smooth pursuit eye movements from noisy fixations or small catch-up saccades. Thus, we performed only a gross analysis of slow eye movements, identifying those portions of the ocular traces in which the tangential velocity was between 0.5 and 40°/s, with a minimum duration of 100 ms.

For the gaze analysis, we pooled the data across repetitions, shot accuracy, and horizontal and vertical directions. The latter step required flipping the ball and gaze coordinates left-right and upside-down, thus obtaining a common prototypical path for each shot difficulty (Figure 1D and E).

We considered four regions of interest (ROIs), two for each shot difficulty: One ROI encompassed the ball visible trajectory, and the other ROI encompassed the unseen portion of the trajectory (Figure 1D and E). The ROIs of the visible portions were slightly prolonged beyond the occlusion point to account for automatic persistence in ocular tracking (Becker & Fuchs, 1985; Mitrani & Dimitrov, 1978). Also, the areas near the initial position of the ball and the central position were excluded to discount the clustering of fixations on those two positions (see the Results section), which may have masked between-group differences.

Statistical analyses have been performed with SPSS 16.0 (SPSS, Inc.). For hypothesis testing, we applied Student's t test and repeated-measures analysis of variance. The experimental design comprised five within-subjects factors (shot difficulty [two levels] × shot accuracy [three levels] × horizontal direction [two levels] × vertical direction [two levels] × repetition [two levels]) and one between-subjects factor (expertise [two levels]).

We also performed spatially extensive statistical comparisons to locate the regions fixated significantly longer by novices or experts, using a procedure adapted from Caldara and Miellet (2011), who applied to eye movements the statistical techniques widely used in brain imaging studies to build the activation maps (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007). In brief (for details, see Caldara & Miellet, 2011), a fixation heat map was first built through spatial smoothing of individual fixations (width of the Gaussian kernel = 50 pixels, equivalent to 1.34°, which corresponds roughly to the foveal region); then, isoprobability contours were obtained, which delimited the areas inside which novices and experts differed significantly ($\alpha = 0.05$) in terms of total fixation duration. This provided a very useful and immediate way to compare statistically the ocular behavior of the two groups of subjects over the entire spatial layout of the stimulus without selecting a priori any ROI over which performing standard hypothesis testing, although other data-driven methods exist (Grindinger et al., 2010). We also built dynamic fixation heat maps through temporal juxtaposition of time-defined static heat maps (epoch: 200 ms, no temporal convolution),

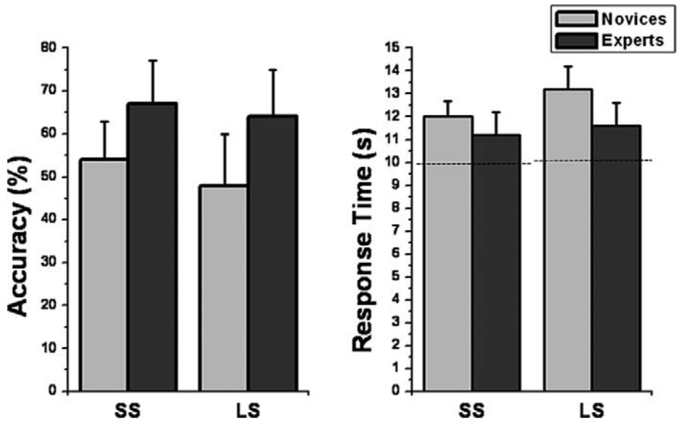

Figure 2. Task performance. Accuracy is calculated as percentage of correct responses. Response times are calculated from the beginning of the trial. SS, short shot; LS, long shot. The error bar represents the standard error of the mean. The horizontal dotted lines represent the onset of the occlusion. Experts were faster and more accurate than novices.

with the aim of rendering in the form of a movie the average gaze evolution over time.

Eleven trials (0.55% of total trials) were dropped because of response artifacts.

Results

The task performance of the experts was superior to that of novices (Figure 2). Accuracy (i.e., how well observers guessed correctly whether or not the ball would have hit the central skittle) was significantly higher in experts than in novices (main effect of expertise, $F[1, 40] = 23.322$, $p < 0.001$, on z-transformed values), with a nonsignificant interaction expertise × shot type ($F[1, 40] = 0.363$, $p = 0.550$). Novices' performance did not deviate significantly from chance level (50%) in both shot types (one-sample Student t, $t[20] = 1.927$, $p = 0.068$, and $t[20] = 0.668$, $p = 0.512$, on z-transformed values for the short and long shot type, respectively). Experts performed better than novices did also in terms of RT (main effect of expertise, $F[1, 40] = 18.772$, $p < 0.001$), especially in the long shot (interaction expertise × shot type, $F[1, 40] = 29.172$, $p < 0.001$): Consider that the RT gain of 1.6 s found in experts, relative to novices (13.2 s vs. 11.6 s), corresponded to 67% of the period during which the ball was in motion (2.4 s). In the long shot, the percentage of trials in which observers responded 1 s after the occlusion was 81% in novices but only 29% in experts. After 2 s, the percentage decreased to 13% (49% in novices) and dropped to 9% (26% in novices) after 3 s. That is, at any given time after occlusion, the number of trials in which novices were still pondering a decision was about 3 times that of experts.

This study was focused on eye movements. As for the basic oculomotor properties, the distributions of fixation duration were almost identical in the two groups of observers, with median values between 215 and 247 ms and the typical long tail (Figure 3A). There was a number of very long fixations (≥1 s), mostly directed on the initial position of the ball. The mean fixation frequency (on average 2.1 fixations/s) varied by about 2.5% between the two groups. Also, the distributions of gaze shifts between two successive fixations, which is approximately equivalent to saccade amplitude, were very similar, with median values between 2.3° and 2.7° and peaking at 1°, which

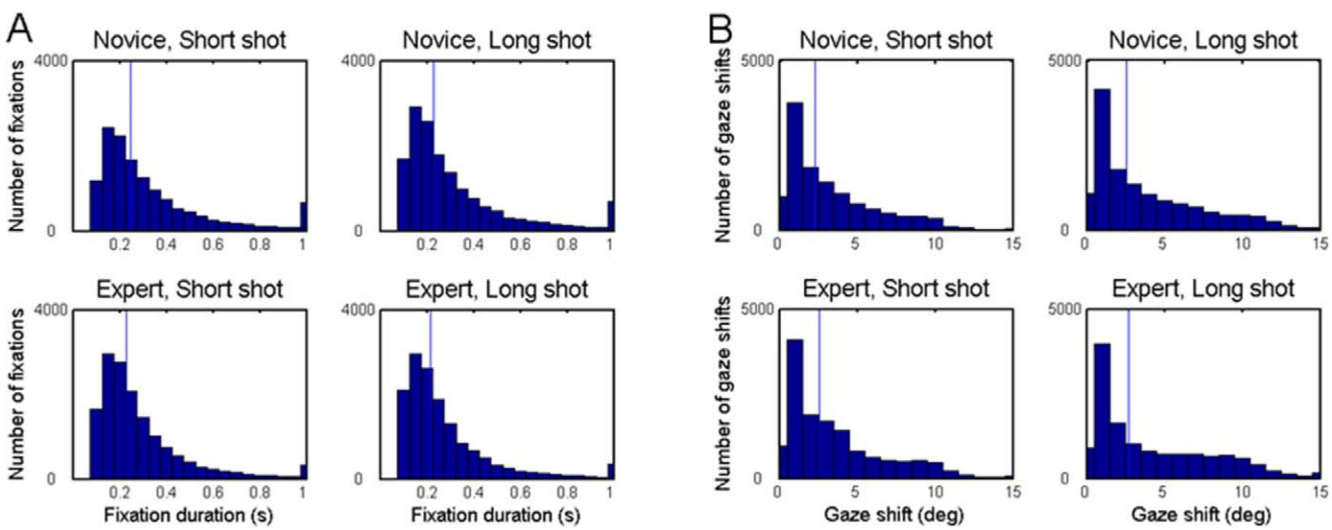

Figure 3. Basic visual/oculomotor properties. (A) Fixation distribution histograms, bin width: 50 ms. (B) Gaze shift distribution histograms, bin width: 1°. The vertical blue lines are the median values. The last bin contains also all larger values. No difference emerged between novices and experts.

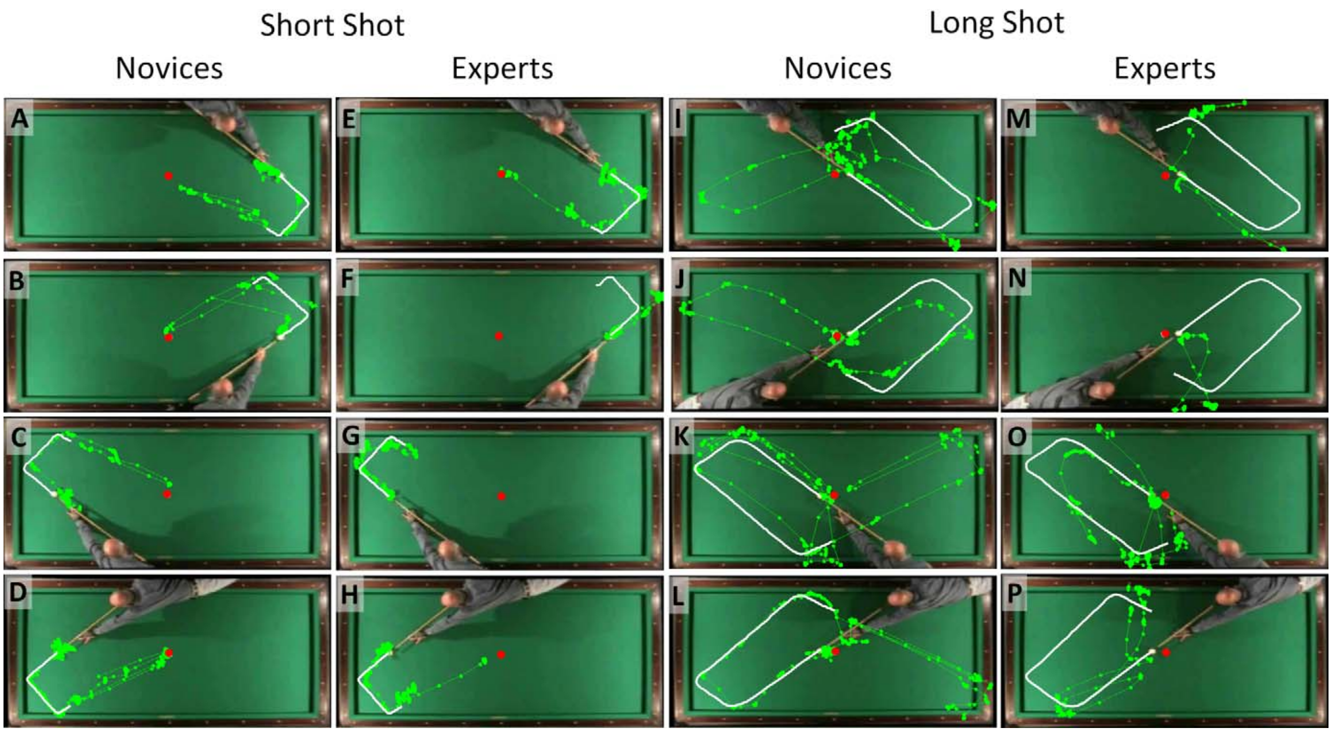

Figure 4. Examples of patterns of eye movements in individual trials. Green trace, raw gaze position, the markers are the data sample (temporally spaced ~17 ms from each other). White trace, ball visible trajectory. The ocular traces represent a time window that goes from the moment the ball was launched to the observer's response (RT). The central red spot indicates the skittle position. Novices followed rather closely the visible part of the trajectory, whereas experts tended to cluster the gaze on selected cushions. Also, especially in the long shot, ocular extrapolation could be extremely faithful in novices, but it was almost absent in experts.

indicated a somewhat narrow ocular scanning (Figure 3B). These data indicate that the basic visual/oculomotor properties were not substantially modulated by expertise.

As for the strategies of visual exploration, there were some similarities between experts and novices in the spatial distribution of eye movements, in that the shot trajectory attracted consistently the gaze of both groups of observers, to the extent that, especially in novices in the short shot, the trajectory could be reckoned just by visually inspecting the individual scanpaths or the fixation maps (Figures 4 and 5). However, two important differences emerged. First, novices tended to distribute the gaze over a wider area than experts, often covering large portions of the trajectory, whereas the experts' fixations appeared to be more clustered on a few bouncing points on the cushions. Second, novices—much more than experts—seemed to extrapolate the trajectory of the ball beyond the occlusion point.

As for trajectory extrapolation, in the ROI where the ball would have passed after the occlusion point, both the number of fixations (short shot: $t[40] = 3.469$, $p < 0.001$; long shot: $t[40] = 6.179$, $p < 0.001$) and the total fixation duration (short shot: $t[40] = 4.939$, $p < 0.001$; long shot: $t[40] = 6.996$, $p < 0.001$) were much higher in novices than in experts (Figure 6). Conversely, no significant differences between novices and experts were found in the ROI covering the actual ball trajectory before occlusion, either for the number of fixations (short shot: $t[40] = 1.726$, $p = 0.092$; long shot: $t[40] = 0.408$, $p = 0.686$) or for the total fixation duration (short shot: $t[40] = 0.782$, $p = 0.439$; long shot: $t[40] = 1.409$, $p = 0.167$).

The reduced exploratory behavior of experts, compared with novices, during the occlusion phase becomes evident by superimposing the raw eye position traces (Figure 7). Color codes time: Yellow represents the time window starting at the moment the ball is launched and lasting until the stimulus is frozen, whereas red represents the subsequent time window that goes from the beginning of occlusion to the individual RT. Note that, compared with the fixation maps of Figure 5 based on transparency effect, here the graphical impact of eye position is increased and saturated, because every sample of the eye movement traces is represented by a fully-colored pixel, with the effect of reducing the apparent contrast between experts and novices. Despite this, the figure illustrates nicely the postocclusion difference between the two groups of observers, where the ocular traces of experts do not produce saturation. The raw, sample-by-sample time spent by the gaze within the occlusion ROI after the scene was frozen confirmed quantitatively the drop

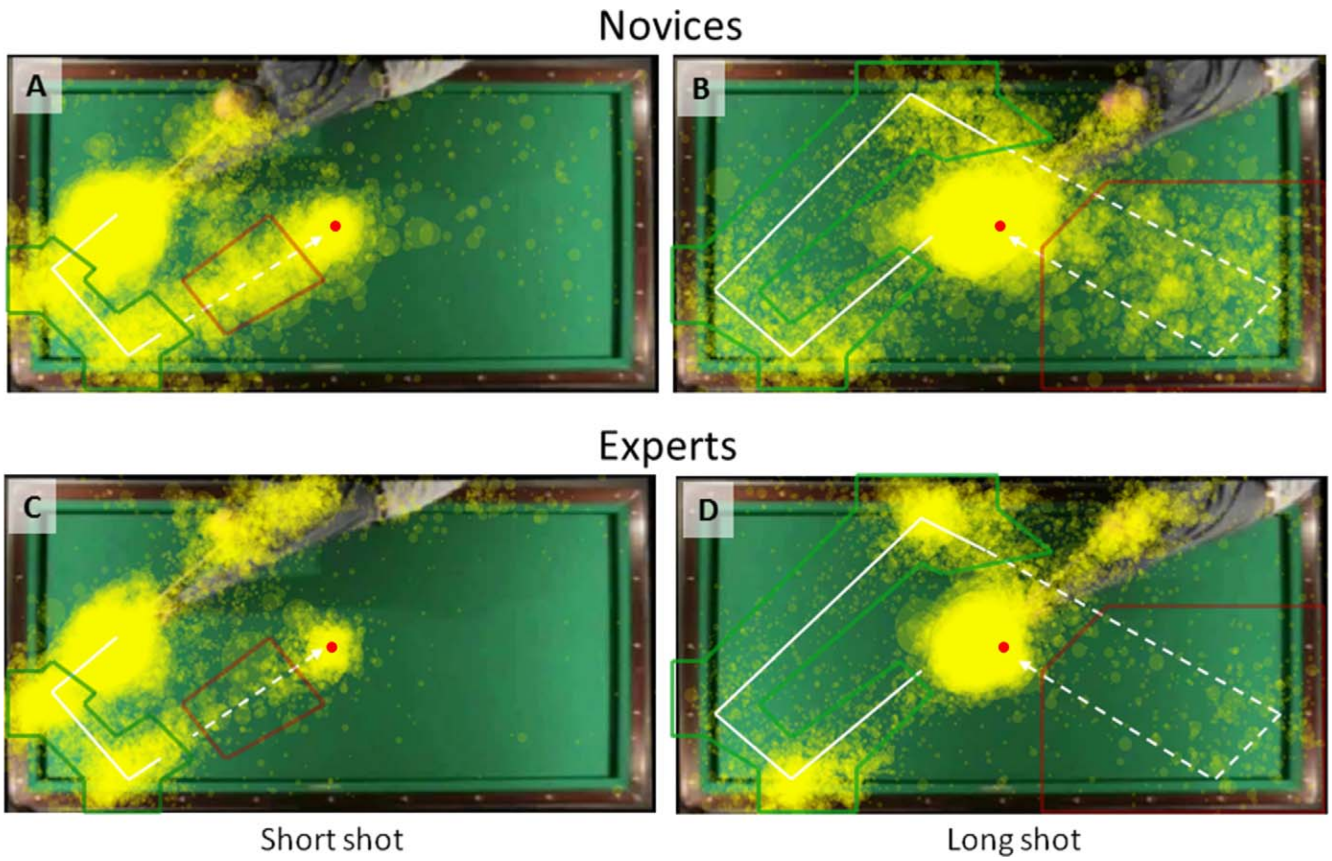

Figure 5. Fixation maps in novices and experts. (A, C) Short shot. (B, D) Long shot. All fixations from all subjects are superimposed (transparency, $\alpha = 0.15$), from the beginning of the trial to the observers' response (RT). Each yellow spot represents a fixation, whose diameter is proportional to the fixation duration. The central red spot indicates the skittle position, whereas the continuous and dashed white arrows indicate the average visible and unseen ball trajectory, respectively. The two couples of regions of interest are bordered (greenish for the visible trajectory, reddish for the unseen trajectory). Particularly visible is the clustering of experts' fixations on selected positions. For the long shot, the initial fixations on the ball's starting position cannot be distinguished from the fixations on the skittle. However, as evident in Movies 2 and 3, it is clear that the gaze is initially centered on the point of contact between the stick and the ball and not on the skittle.

of explorative oculomotor behavior of expert observers over this region of the table, as compared with novices, in both the short shot (from 255 ms to 71 ms, $t[40] = 2.435$, $p = 0.019$) and the long shot (from 985 ms to 182 ms, $t[40] = 4.217$, $p < 0.001$).

Because of the longer portion of occluded trajectory, the ocular extrapolation exhibited by novices was particularly clear in the long shot, where a variety of scanpaths could be observed, from trials in which the gaze traced faithfully the back-and-forth evolution of the unseen ball trajectory (see Figure 4I and J), to trials in which the gaze partially and/or repeatedly explored the unseen trajectory (see Figure 4K and L).

Ocular extrapolation was likely due to a stronger need for novices to mentally follow, or check, the ball trajectory until the point of potential impact with the central skittle. This strategy could be important for novices because they cannot exploit the predictive value of the bouncing points on the cushions as much as experts do. In fact, experts were faster to respond, with their responses occurring as soon as 0.3 and 0.5 s after occlusion, on average, for the short and long shot, respectively. Indeed, experts tended to anticipate the ball movement by focusing attention to the bounce points more consistently than novices, on both cushions in the short shots and on the first and third cushions in the long shots.

These bouncing points corresponded precisely to the regions that mostly differentiated novices and experts in the statistical fixations maps (Figure 8). In these maps (Figure 8A and B), the thick contours highlight the regions inside which the permanence of the gaze was significantly longer for novices than experts (red) or longer for experts than novices (blue). The underlying heat maps, depicted more explicitly in Figure 8C and D, code gradually the z-scored group difference on a pixel-by-pixel basis (where, to facilitate the visual comparison, greenish-bluish colors indicate a fixation prevalence of expert observers whereas reddish-brownish colors indicate a fixation prevalence of

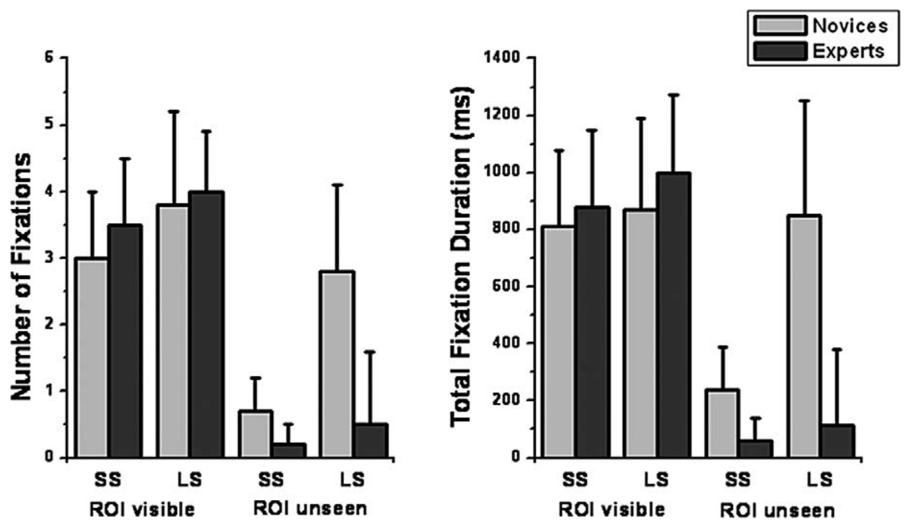

Figure 6. Region of interest (ROI) analysis. ROI visible and ROI unseen stand for the region of interest that covers the visible and invisible portions of the trajectory. SS, short shot; LS, long shot; SEM, standard error of the mean. In the unseen portion of the trajectory, the number and the total duration of fixations were much larger in novices than in experts.

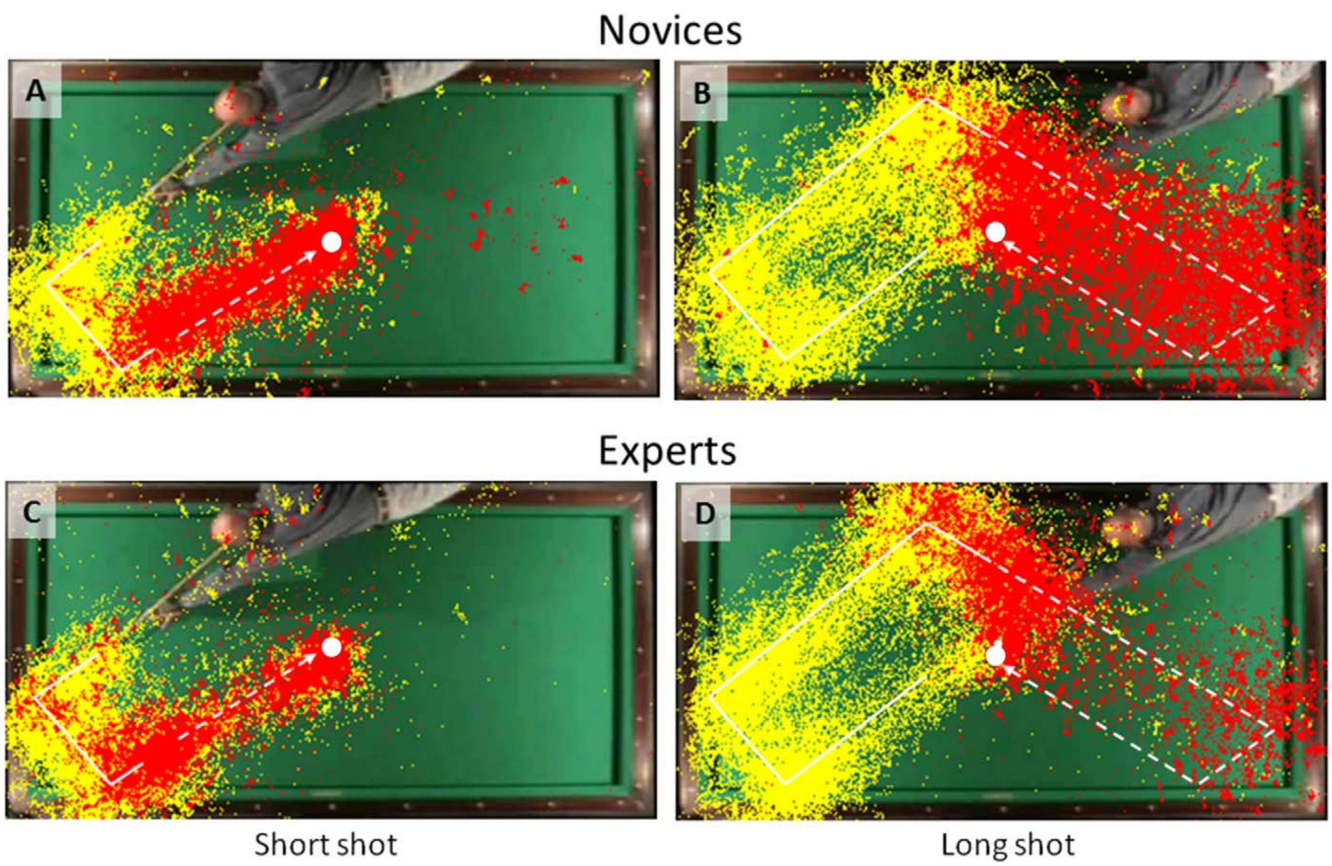

Figure 7. Raw eye position traces. (A, C) Short shot. (B, D) Long shot. Data from all trials and all subjects are superimposed. The yellow traces represent the time window from the moment the ball was launched to the occlusion (visible ball trajectory), whereas the red traces represent the time window from occlusion to the response time (unseen ball trajectory). The central white spot indicates the skittle position, whereas the continuous and dashed arrows indicate the average visible and unseen ball trajectory, respectively. Novices explored the unseen portion of the trajectory much more than the experts did.

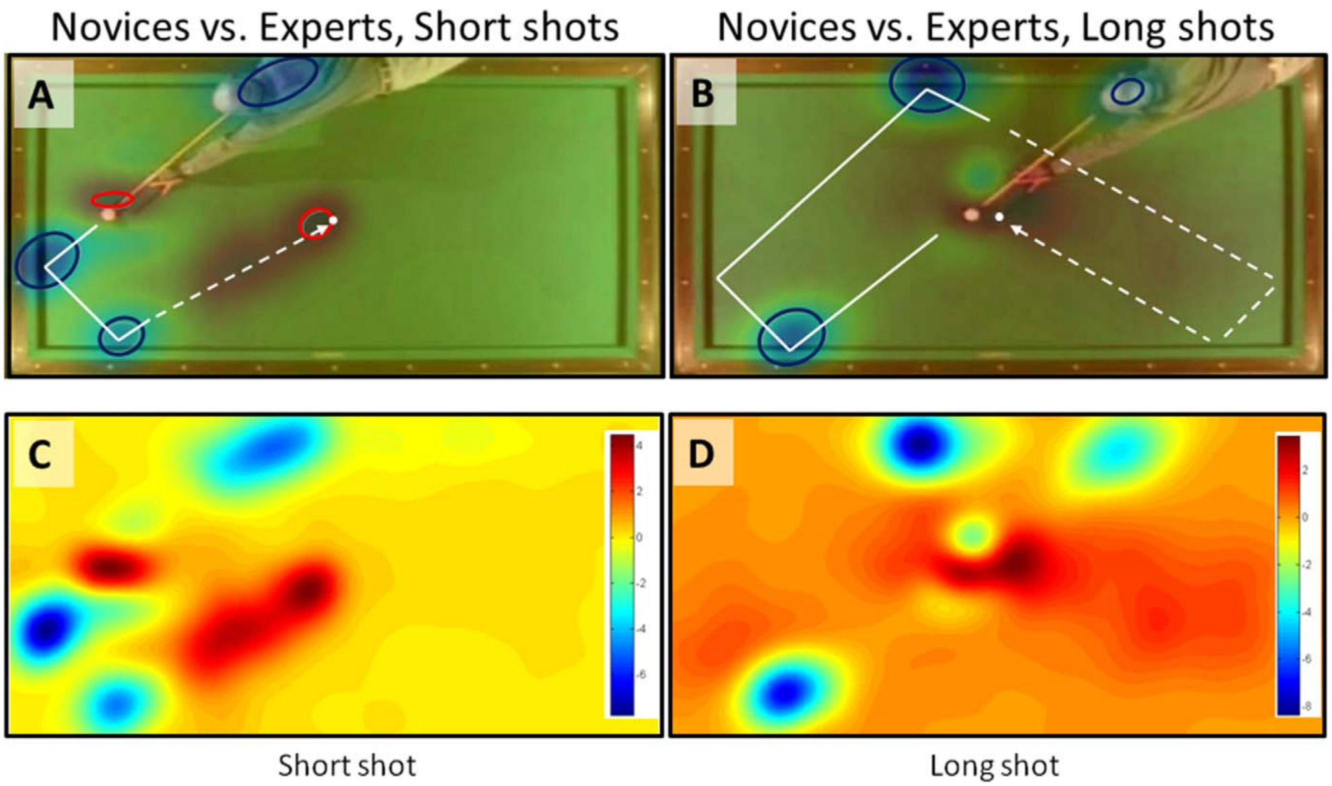

Figure 8. Statistical maps of fixation difference. (A, B) The ellipses highlight the regions inside which the permanence of the gaze was significantly longer for the novices than for the experts (red ellipses) or longer for the experts than for the novices (blue ellipses). The central white spot indicates the skittle position, whereas the continuous and dashed arrows indicate the average visible and occluded ball trajectory, respectively. The significant regions are superimposed to the respective maps of fixation duration, which for graphical clarity are also represented in panels C and D in their original colors and with the color calibration bars (z-score, color auto-scaling). Time window: from the beginning of the trial to individual response time. Experts' gaze clusters on specific bouncing points on the cushions.

novice observers). Especially illuminating is the case of the long shot, where, according to the metrical system used by professional billiard players, the bouncing points on the first and the third cushions, but not the second cushion, are important to monitor the trajectory of the shot (see the Discussion section). The bouncing points on the first and the third cushions were precisely the points that most attracted the gaze of the experts, as compared with novices. Figure 8 revealed also another aspect of the oculomotor behavior of the experts, namely, that they glanced consistently at the player, as if important information about the shot could be gained by observing the player's posture and/or movements.

Notice that, in apparent contrast with the ROI data reported above (Figure 6), the statistical maps of fixation difference did not show a significantly longer fixation time for the novices in the areas corresponding to the ball extrapolation regions (although a nonsignificant fixation advantage is visible in the z-scores, brownish shadowing in Figure 8). This lack of a significant effect depended on the difference between the two methods that we have used for the analysis (ROIs vs. statistical fixation map). In the statistical fixation map, the comparison covered the entire image and all fixations are considered, thus making this analysis useful to locate potentially interesting foci where there is predominance of fixations in one or the other group of observers. Conversely, by selecting a priori the ROIs, the comparison is limited to circumscribed regions, precisely where the effect is expected to be present and without the influence of the fixations directed to the other parts of the visual scene. Clearly, this advantage of the ROI analysis depends entirely on how well the ROIs are chosen.

In the attempt to verify whether a possible different dispersion of fixations in novices and experts could be at the basis of the effect of Figure 8, we computed the mean scalar distance of fixations from the bounce of the accurate (centered) shots on the three cushions, measured in the interval (−300 +100) ms from the ball bounce (this temporal window was chosen to avoid overlap between the first and the second cushion and to accommodate gaze anticipation; similar results were obtained with different time windows). In novices, the distances were 104 ± 75, 155 ± 127, and 105 ± 61 pixels ($M \pm SD$), respectively, for the first, second, and third cushion. The corresponding distances in experts

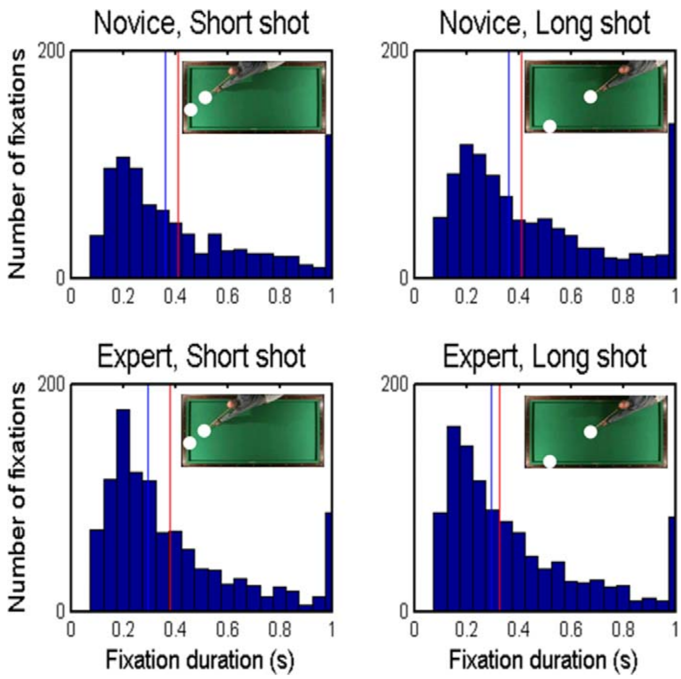

Figure 9. Fixation distribution histograms computed inside the regions of interest (ROIs) evidenced as white circles in the insets during the period from the moment the stick begins to swing until the contact with the ball. Data from the two ROIs in each panel are collapsed. Same conventions as Figure 3A. The vertical blue lines are the median values. The vertical red lines are the median duration of the very last fixation before the beginning of the swing phase. There was no evidence of the quiet eye phenomenon in expert observers.

were 82 ± 81, 173 ± 140, and 76 ± 45. However, although the effect of the cushion was significant, $F(2, 74) = 11.361$, $p < 0.001$, neither the main effect of expertise nor the interaction cushion × expertise reached statistical significance (always $p > 0.22$). Thus, it appears that the clustering effect illustrated in Figure 8 did not depend on a different spatial dispersion of fixation at the cushions between novices and experts but rather, as reported earlier for the statistical fixation maps, on fixation duration.

The kinematics of the average distribution of the gaze during the course of the trial, including the gross spatiotemporal relation between the gaze and the ball trajectory, can be appreciated in Movies 2 and 3 (Supplemental Material), in which the heat maps of fixations were computed every 200 ms, then merged temporally and superimposed to a prototypical shot (the shot that would strike the skittle, for the represented combination of directions and for each shot difficulty). Note that these dynamic heat maps have a different meaning than those depicted in Figure 8 (apart from the obvious exploitation of the temporal dimension): Here, the heat maps do not illustrate the difference between experts and novices but are ordinary heat maps showing how long observers, either novices or experts, look at certain parts of the image, as compared with the rest of the image. During the first part of the trial, before the ball launch, the ball was the big attractor of the eyes for both novices and experts, in both the short and the long shots. This is not to say that other spatial positions were not inspected by the gaze in this initial part of the trial, just that the clustering of fixations on the point of the upcoming impact between the stick and the ball was overwhelmingly predominant. Then, during the period of ball motion, the experts kept the gaze more systematically on the bouncing points over the cushions, anticipating the arrival of the ball, except for the second cushion in the long shot. Novices seem to follow the ball trajectory somewhat more passively. This is confirmed by the fact that the percentage of time spent in slow eye motion (0.5–40°/s) while the ball was moving was lower in experts than in novices (59% vs. 67%, $p < 0.001$). Another aspect evidenced by the dynamic plots is the postocclusion extrapolation in novices. These characteristics of experts' exploratory eye movements were more marked in the long shot.

Next, we sought to appraise whether a strategy analogous to the quiet eye phenomenon was present also in our visual prediction task and not only when an expert is actively engaged in playing billiards. To this end, we analyzed the number and duration of ocular fixations from the end of the initial still image to the moment the stick touched the ball, that is, during the swing phase of motor refinement of the shot. For this analysis, we selected two circular ROIs (radius = 50 pixels), one centered on the initial position of the ball and the other centered on the first bouncing point on the cushion. In analogy with the quiet eye phenomenon observed during the effective motor performance, an expert may wish to monitor carefully these regions just before the ball is launched, which therefore may attract fewer but longer fixations, as compared with novices. However, we found no evidence that the number of fixations directed inside these ROIs during the swing phase was lower, nor their duration longer, in experts than in novices (Figure 9). Rather, long fixations (≥1 s) tended to be more numerous in novices (13.1% vs. 7.4%) and short fixations (≤0.2 s) more numerous in experts (29.8% vs. 22.3%). Most of the fixations occurred in the ROI centered on the initial position of the ball (91%). Similar results were obtained also by limiting the time window of the analysis to the last second before the ball was launched, by limiting it to the last second before the beginning of the swing phase, or by extending it back to the beginning of the trial (data not shown). We also measured the duration of the very last fixation inside these ROIs before the beginning of the swing phase. However, the last

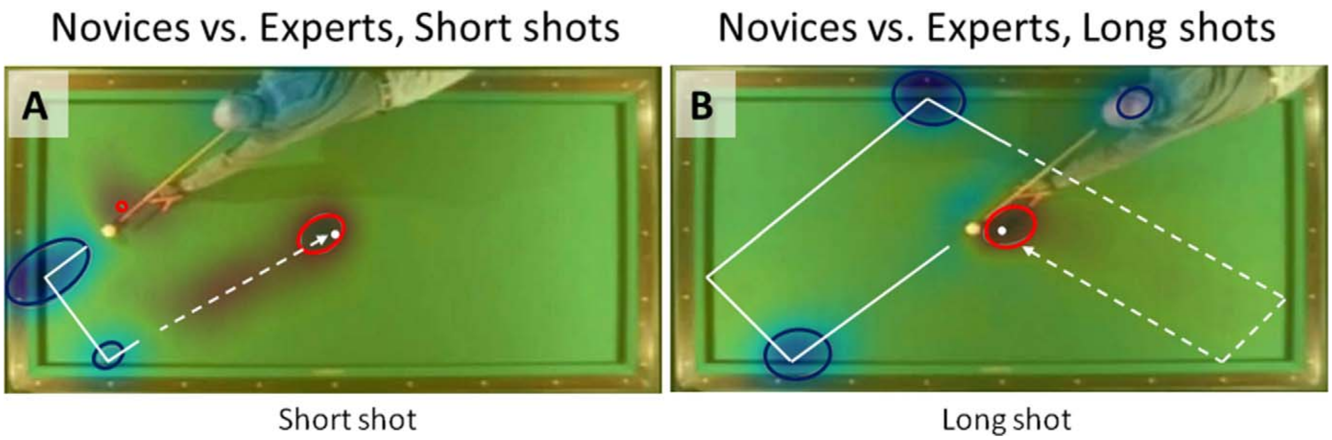

Figure 10. Statistical maps of difference of a subgroup of observers homogeneous for age, sex, and handedness. Same conventions, and results, as Figure 8A and B.

fixation did not last longer in experts than in novices (red lines in Figure 9).

The two groups of observers differed in age (mean age: 37 and 51 years, respectively, for novices and experts) and, to a lesser extent, handedness (17 novices and 20 experts were right-handed); moreover, the expert group included a woman. To exclude that these variables introduced differences in the ocular exploration behavior, we selected two subgroups that best matched jointly for these three factors (seven subjects per group; mean age: 42 vs. 48 years, respectively, for novices and experts; all observers were men and right-handed). We then performed the comparison of these two subgroups in terms of task performance and ocular fixations. As in the main comparison, experts were quicker than novices, $F(1, 12) = 23.795$, $p < 0.001$, and more accurate, $F(1, 12) = 13.134$, $p = 0.003$, on z-transformed values. Remarkably, the statistical fixation maps revealed a pattern that was almost identical to the pattern found in the main comparison (compare Figure 8 and Figure 10). Notice the same lack of visual attraction exerted by the second cushion in the long shots in expert observers. These data confirm that the differences between expert and novice observers depend specifically on expertise.

Discussion

In this study, we compared the ocular behavior of experts and novices while they were observing controlled billiard shots, partially occluded, with the task of predicting whether or not the ball would have struck the central skittle. The main finding was that the eye movements of experts and novices differed in terms of trajectory extrapolation during the occlusion period, which was widely present in the latter but not in the former, and for the clustering of longer fixations on selected points predicted by the angolo 50 rule in experts. Also, we did not find evidence for the phenomenon of the quiet eye in our visual prediction task.

Task performance

The percentage of correct responses of the expert observers was not as high as expected, given the ranking of the experts that we recruited. Especially surprising was the modest accuracy exhibited in the easier shot (i.e., the short one). One interpretation is that even though the stimuli displayed real shots, professional billiard players were not too familiar with the forced prediction task (Ericsson & Williams, 2007, p. 118–119) or with the relatively unusual view of the billiard table (although in some cases, TV programs use the top view to document a billiard match). Alternatively, experts may have felt pressure to respond quickly, sacrificing accuracy. A third possible explanation, related to causality perception, will be dealt with below (trajectory extrapolation section). Importantly, however, the performance of experts, both in terms of accuracy and RT, was definitely superior to that of novices.

Simulating the shot

Prolonging in mind the trajectory of a moving stimulus is common when objects suddenly disappear from sight (DeLucia & Liddell, 1998; Finke & Pinker, 1982; Hubbard, 2002; Jonikaitis et al., 2009; Shepard, 1984). Because in the present experiment the stimuli were frozen before the completion of the trajectory (occlusion), and the task required to make a prediction of the ball position well beyond the beginning of occlusion, mental extrapolation was the strategy that we expected in novices, as this seemed intuitively to be the simplest way for them to perform the task, especially with the long shots (we recall that the ball trajectories in the central, narrow, and large shots were just slightly different, therefore requiring a rather accurate estimate of the ball position at the time it would pass near/on the skittle). Indeed, novice observers adopted an ocular extrapolation strategy before responding, as can be clearly seen in Figure 4.

This finding is not new per se, as eye movements have been repeatedly shown to be a precise correlate of motion imagery and trajectory extrapolation of rectilinear and curvilinear motion in simple visuo-spatial tasks that do not require any special knowledge (de'Sperati, 1999, 2003a, 2003b; de'Sperati & Deubel, 2006; de'Sperati & Santandrea, 2005; Jonikaitis et al., 2009; Makin & Poliakoff, 2011). In this regard, the present study brings two notable advances: First, the stimuli represented real events, which included causal agency; second, in the long shots, the unseen portion of the trajectory did not consist of simple path continuation but contained two bouncing points. As for the first point, it is always desirable to confirm the results initially obtained with simplified stimuli and also with more complex real or realistic stimuli, as the one used in this study. Moreover, the presence of causal agency in our stimuli could be supposed to potentiate the observers' understanding of the scene. Yet, very recently, Levillain and Bonatti (2011) manipulated the perceived causality in a motion prediction task and found that it worsened the prediction accuracy of both naïf and expert observers, which was anyhow rather poor. The authors interpreted these findings as a sign that causality attribution and motion prediction were processed by independent systems, consistently with a propositional representation framework (Pylyshyn, 2003; see also Bonatti, 1994). We do not know whether the presence of causal agency in our task induced in the observers an analogous hampering effect, as we do not know what would be their performance without represented causal agency. If this were the case, it may be one reason for the relatively poor performance that we have found in experts.

As to the unseen trajectory, we first note that the term *extrapolation* is somewhat restrictive when applied to our task. Extrapolation is based only on previous history, which is not the case here, as there is nothing intrinsic to the ball motion that can predict its behavior at the cushions. To represent a bouncing ball, the law of bouncing should also be internalized (we recall that in preparing the stimuli, we asked the professional player to execute the shots with no spin), together with other implicit assumptions concerning the properties that concur to determine the real behavior of a moving object, such as gravity, friction, and elasticity (Gardin & Meltzer, 1989; Hubbard, 1995; Zago et al., 2005). We retain here the term *extrapolation* because it is widely used, implying, however, that mental imagery is far more complex: not only reproductive, or extrapolative, but constructive. That is, motion imagery can be more than a replica or an extension of a motion template. Our findings represent incremental evidence that eye tracking can reveal also constructive dynamic imagery, not just motion memory or motion extrapolation (de'Sperati, 1999, 2003a, 2003b; de'Sperati & Deubel, 2006; de'Sperati & Santandrea, 2005; Jonikaitis et al., 2009; Makin & Poliakoff, 2011).

Apparently, therefore, the way novices predicted the shot outcome was to simulate in imagery an analog model of the ball motion along the invisible portion of the trajectory, which can be regarded as a simple form of mechanical reasoning (Hegarty, 2004). With the notion of analog simulation, we do not imply that observers strictly and always reproduced in their mind the occluded ball trajectory, as if a movie of the shot would be reproduced in the mind—although in many cases, eye movements indeed depicted it with a remarkable degree of fidelity—but rather that they engaged in purposeful visual search within the region of the table corresponding to the invisible ball trajectory. That is, analog simulation may include trajectory extrapolation, total or partial, but also other spatial mental operations, such as evaluating the possible bouncing points and angles, ball direction, and potential impact with the skittle. For a novice, eye movements may be a precious tool to measure an imagined ball trajectory, globally or piecewise. Following Barsalou, Kyle Simmons, Barbey, and Wilson (2003), "Simulations are never complete re-enactments of the original modality-specific states, but are always partial and might contain distortions" (p. 89). This is in line with enactive theories of perception (Thomas, 2010), which hold that visual exploration is an inherent constituent not only of visual perception but also of visual imagery, and even—it is maintained—of conscious visual perception (O'Regan & Noe, 2001).

In sports, it is well known that mental imagery can be used to refine the motor preparation of an athlete. This kind of mental training, known as motor imagery, consists of mentally rehearsing the execution of an exercise, step by step or globally, and is thought to involve a substantial covert activation of the motor system (Jeannerod, 1995). However, given the third-person, top-view perspective of the displayed shots and the required visual prediction task that we have used in our experiment, the kind of mental imagery revealed in billiard novices through their eye movements is hardly motor imagery, being rather a form of dynamic visuo-spatial imagery aimed at simulating the ball trajectory.

The neglected cushion

In stark contrast with the novice observers, the paucity of fixations falling in the extrapolation area found in experts, together with their quick responses given shortly after occlusion onset (and sometimes even in advance), indicates that they did not need to reconstruct mentally the ball trajectory in imagery. But how could experts manage without mental imagery? It seems that for them, it sufficed a quick check on a few selected points on the cushions along the visible portion of the ball trajectory. In fact, experts almost did not look at the second cushion in the long shot, as compared with the first and third cushions. The reason is to be found in the metrical system that experts use to prepare, execute, and monitor a shot, the angolo 50 rule (Fermi & Schiavi, 2009; see also the Introduction). According to this system, the most informative diagnostic point to evaluate the outcome of the long shot is the third cushion, whereas how the ball impacts on the first cushion is the initial cue indicative of the overall shot accuracy (moreover, when actually preparing a shot, the first cushion is obviously the point to which the ball is first aimed). When professional billiard players prepare a five-cushion shot (we recall that the long shot was a five-cushion shot with the last two cushions occluded), they first evaluate the coordinates of the target and the ball, measured through the diamond system. The attack point (the first cushion) is then computed as the difference between these two values. The bounce position on the third cushion, which is used to monitor the precise shot execution, is in turn given by the difference between the position of the ball and the attack point, always measured through the diamond system (Fermi & Schiavi, 2009, p. 137). Therefore, for billiard professional players who know the angolo 50 procedure, the second cushion is less relevant to monitor the ball trajectory. Ocular fixations spotted perfectly this learned rule in experts.

This specific pattern of results in which the second cushion is not behaviorally salient is important, because it rules out a generic strategy based on checking the ball trajectory at the cushions and confirms that experts were indeed using explicit rule-based knowledge to accomplish the prediction task. This aspect differentiates our study from past studies that addressed an analogous issue in other ball sports, such as table tennis (Land & Furneaux, 1997; Ripoll, Fleurance, & Cazeneuve, 1987), squash (Hayhoe, McKinney, Chajka, & Pelz, 2012), cricket (Land & McLeod, 2000), or simply catching a bouncing ball (Hayhoe, Mennie, Sullivan, & Gorgos, 2005; Zago et al., 2004). In those cases, in fact, the anticipatory saccades were guided by an implicit model of the ball trajectory. In the present study, we also found proactive gaze in experts when the ball was still visible, which is probably a common feature of expertise in many dynamic conditions. However, billiard expertise it is not just a matter of anticipating an event: The expert observers predicted the outcome of the shot by explicitly applying conceptual knowledge, not evaluating the ball trajectory, for otherwise the second cushion would have had the same behavioral saliency as the others. This finding excludes a major role of direct perception (Gibson, 1979) in conferring to billiard experts a superior prediction capability, at least in our observation task. According to this theory, observers become attuned to certain relevant visual features, from which invariants are directly extracted. With experience, perceptual invariants would be extracted more reliably. This amounts to say that, by seeing portions of the ball trajectory, an expert would perceive directly the future shot outcome. Yet, our data indicate that for a billiard expert, the information contained in the ball motion is essentially functional to check the diagnostic points of the shot, not to derive the future ball trajectory. Again, obviously this does not imply that a billiard expert does not see the ball trajectory, just that the prediction is not based on kinematical parameters. Our findings excluded also that experts used perceptual heuristics, which can be regarded as mostly unconscious, "simple-minded ideas that people have about visual events when making dynamic judgments" (Gilden & Proffitt, 1994; Hecht, 1996). On the contrary, the experts' shot representation based on angolo 50 is definitely not unconscious and far from being "simple-minded."

Understanding dynamic visual events: From imagery to rules

Although the complexity of mental processes, even in a relatively simple visuo-spatial task such as predicting the outcome of a billiard shot, is not easily reducible to a pattern of eye movements, our findings are relevant for the debate on the format of mental representation (Kosslyn, 1994; Pylyshyn, 2003; see also Thomas, 2010), in that they bring empirical evidence that expertise may dampen a perceptually based, analog representation by superimposing rule-based, propositional knowledge. Notice that during visual inspection of static scenes—from the classic observations made by Yarbus to more recent experiments on artwork or specialized images viewing (Donovan & Manning, 2007; Nodine et al., 1993; Nodine et al., 1996; Pihko et al., 2011; Vogt & Magnussen, 2007; Zangemeister et al., 1995)—or in dynamic actions such as tea making, or driving, or ball sports (Land, 2009; Land & Furneaux, 1997), top-down knowledge integrates bottom-up visual information for eye guidance (Henderson, 2003), sometimes shutting down low-level visual saliency (Humphrey & Underwood, 2009) or using multiple type of information (Malcolm & Henderson, 2010). Our study addressed instead a strategy switch in visual problem solving that involved two qualitatively different top-down strategies, one based on mental imagery and the other based on conceptual knowledge, both acting at a higher level than bottom-up visual saliency. Interestingly, the pattern of results that we have found in billiard experts (higher performance, disappearance of imagery, and the passage to a rule-based indexing system) bears resemblance with a triplet of signs (quicker responses, disappearance of hand gesturing, and intrusion of numeric verbalization) that was observed after an initial period of familiarization in a simple reasoning task involving inferred motion in sketched gears (Schwartz, 1996), which led the authors to argue that a rule replaced a depictive model of the gears working. In the same vein, in our experiment, eye movements precisely mirrored a strategy upgrade from analog simulation in imagery in novices to conceptual knowledge in experts, thus pinpointing mental imagery as a basic, yet important, form of knowledge in visual problem solving (Arp, 2008): Once a better form is discovered or learned, imagery is taken over. That is, we highlighted the passage from understanding-by-simulation to understanding-by-knowledge.

The quiet eye

We did not find evidence that the phenomenon of the quiet eye (Vickers, 2007; Williams et al., 2002) is present in our billiards observation task. During the swing phase of the shot, both the number and duration of fixations directed to the ball or the first cushion were similar in novices and experts, as it was the duration of the very last fixation before the beginning of the swing phase. This result suggests that this visuo-motor habit functional to the preparation and execution of a skilled aiming action does not transfer automatically to a more abstract representation. Thus, the quiet eye seems to be associated with actual motor engagement, being a way for the athlete to concentrate on the impending goal, filtering out unnecessary of even hampering visual information (Janelle et al., 2000).

The absence of the quiet eye in our observation/prediction task may also depend on the peculiar point of view of the scene, which did not represent the first-person point of view of the player but an external point of view. Sharing the point of view, even only visually, may facilitate the triggering of certain visuo-motor habits, presumably because of the activation of resonance mechanisms. Indeed, changing the mental representation of the visual point of view may change even qualitatively the ensuing behavior (de'Sperati & Stucchi, 2000; Franklin, Tversky, & Coon, 1992; Nico & Daprati, 2009). Thus, in principle, it is entirely possible that a display portraying the subjective point of view of the billiard player could trigger the quiet eye behavior in the expert observer. This remains to be tested. More generally, there are clear differences in the way expertise is exploited in actually practicing a sport and in evaluating a sport action in a movie. The absence of the quiet eye in our task may reflect just such difference (Dicks, Button, & Davids, 2010).

Conclusions

We have shown that when a billiard expert is watching a shot with the goal of predicting its outcome, his eye movements bring the signature of expertise. The eye-tracking data were in perfect agreement with the initial hypotheses and documented the passage from the naïf knowledge of novices, gathered by running a simulation of the ball trajectory in imagery, to conceptual knowledge of experts, who replaced ocular trajectory extrapolation and exploration with selective fixations on the diagnostic points according to the angolo 50 formal rule. Thus, our study is a clear example of how eye movements can help to highlight the upgrade from imagining to knowing in dynamic visual problem solving. Considering that many studies aimed at investigating the nature of human knowledge rely on subjective, verbal reports, often in the form of think-aloud instructions (Ericsson, 1999), our data confirm that eye movements do represent a valuable tool to uncover visuo-spatial cognition. This is especially important when verbalization is not yet developed (Teglas et al., 2011) or when time is too short to permit reliably online verbalization of the flow of thought (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995).

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