Regular and Random Components in Aiming-Point Trajectory During Rifle Aiming and Shooting

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ABSTRACT. The authors examined the kinematic qualities of the aiming trajectory as related to expertise. In all, 2 phases of the trajectory were discriminated. The first phase was regular approximation to the target accompanied by substantial fluctuations obeying the Weber–Fechner law. During the first phase, shooters did not initiate the triggering despite any random closeness of the aiming point (AP) to the target. In the second phase, beginning at 0.6–0.8 s before the trigger pull, shooters applied a different control strategy: They waited until the following random fluctuation brought the AP closer to the target and then initiated triggering. This strategy is tenable when sensitivity of perception is greater than precision of the motor action, and could be considered a case of stochastic resonance. The strategies that novices and experts used distinguished only in the values of parameters. The authors present an analytical model explaining the main properties of shooting.

Keywords: Brownian motion, control strategy, experts, novices, shooting phases

A number of issues have challenged studies of target shooting kinematics. One of these issues is that shooting is an action in which the motor and perceptual systems are tightly interconnected. An individual achieves control over aiming and shooting with a fine level of visuomotor interaction, which demands a high degree of spatial resolution with low tolerance for deviation from an intended target. Because of the low tolerance, the noise acting in the visuomotor system can be problematic when it results in a small signal-to-noise ratio. During precision target shooting, participants' control of the motor system is challenged by the system's sensitivity (Zatsiorsky & Aktov, 1990) so that experimentally measured parameters of the visuomotor system are at the level of noise. In such conditions, the noise plays a substantial role in the formation of kinematic trajectories of aiming and shooting actions. This problem creates additional difficulties for researchers in data analysis and understanding shooting mechanisms.

In this regard, a number of psychophysiological investigations of target shooting have revealed that experts typically show adaptive levels of arousal relative to novices during the aiming period, when assessed with peripheral measures such as electrodermal and cardiovascular activity (Konttinen, Lyytinen, & Viitasalo, 1998; Tremayne & Barry, 2001) and refined cerebral cortical activation as indicated by central measures such as electroencephalography (EEG; Hatfield, Haufler, Hung, & Spalding, 2004). That is, the levels of arousal manifest in the various physiological systems of an expert motor performer and enable the individual to effectively respond to a given challenge

(i.e., execute a motor skill in an efficient manner within the task constraints). In essence, the expert achieves a level of arousal in the relevant neural and physiological systems of the body that may be relatively high or low compared with a nonexpert but is essentially consistent with the various demands of the task (Guillot, Collet, Molinaro, & Dittmar, 2004). Such managed levels of arousal that are associated with heightened levels of motor skill, particularly with regard to the cerebral cortex, would likely lead to reduced noise in the perceptual motor system, making the expert–novice contrast an ideal framework with which to relate the kinematics of aiming and the role of noise in a detailed manner. More specifically, Hatfield and Kerick (2007) recently described the psychomotor efficiency hypothesis so that expert motor performance is characterized by lower cortico–cortical communication between nonmotor association and motor regions of the brain, resulting in reduced neuromotor noise in the visuomotor system. Such an attenuation of nonessential cerebral cortical activity would then be reflected by less noise in the kinematic qualities of expert performance (i.e., low variability in the aiming trajectory) relative to those of people with lesser skill.

Another challenge related to the studies of target aiming and shooting is the analysis of the ways in which the CNS deals with motor system redundancy (Bernstein, 1967). The problem appears when researchers consider shooting a multi-joint movement. In this case, the dimensions of the aiming point position are two, whereas the number of joints participating in the movement is greater than two, so the motor control system must choose an appropriate joint configuration strategy to achieve the goal of aiming. In this regard, Pellegrini and Schena (2005) assessed the kinematics of multiple body segment contributions (neck, shoulder, elbow, wrist) to air-pistol-shooting performance, but they did not contrast the observed patterns between groups differing in ability (i.e., experts vs. novices). In contrast, Mononen, Konttinen, Viitasalo, and Era (2007) contrasted aiming trajectories as related to differing levels of skill and found the following four common factors: (a) holding area, (b) accuracy of aiming, (c) cleanliness of triggering, and (d) time on target. Most important, Mononen et al.'s results revealed that the aiming point (AP) trajectory was the principal kinematic variable for the discrimination of ability level. It accounted

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for 43% of the variability between skill groupings. Thus, the kinematic quality of the AP trajectory is highly sensitive to ability level and likely related to central perceptual motor processes. However, the shooting task Mononen et al. used was a dynamic challenge involving a running target or moving target for which the relation between neuromotor noise and kinematic noise may be specific to the task.

Mononen et al. (2007) then extended this work to kinematic assessment of stationary target shooting in terms of balance and rifle stability (i.e., horizontal and vertical deviation of the aiming point from target center) in novice shooters and observed significant negative relations between sway and performance accuracy (i.e., less sway with superior performance or accuracy). However, Mononen et al. failed to make comparisons across ability levels. Most interesting, Kontinen et al. (1998) conducted a study in which brain processes and rifle shooting performance were contrasted in marksmen of varying ability levels (elite vs. preelite) and found differing control strategies. On the basis of examination of cortical movement-related slow potentials, Kontinen et al. deduced multiple components of aiming strategy and stated that “in the last seconds prior to the motor action an elite athlete presumably reaches an automatic mode of processing during which he or she makes the critical adjustments in the preparatory set” (p. 275). Automaticity of motor planning, as achieved by the expert, should then lead to significant reduction of noise in the final AP trajectory relative to those of lesser ability. This assertion is based on the strong possibility of heightened levels of central noise as indicated by remarkably heightened cortical activation levels (Haufler, Spalding, Santa Maria, & Hatfield, 2000) and cortico-cortical communication in novices (Deeny, Haufler, Saffer, & Hatfield, 2009) relative to expert target shooters.

Beyond the role of central arousal and noise on the quality of performance (i.e., AP kinematics), Scholz, Schöner, and Latash (2000) also studied shooting performance through the framework of uncontrolled manifold theory (UCM; Latash, Scholz, & Schöner, 2002; Scholz & Schöner, 1999). The further analysis of shooting control could be based on the existing models of feedback (Todorov & Jordan, 2002) or feedforward (Goodman & Latash, 2006) control in conditions of redundancy, but researchers can also expect the emergence of new or nonstandard mechanisms of motor control. Thus, the identification of additional strategic approaches to precision visuomotor aiming performance was a primary goal of the present study. The detailed contrast of the AP trajectory between expert and novice target shooters offers a novel way to examine the possibility of a waiting strategy in support of this visuomotor task.

In summary, *shooting* is characterized by movements of relatively small amplitude and rate, which makes it compatible with various electrophysiological methods that are sensitive to mechanical interference. Together with the dependence of shooting results on the emotional state of marksmen, this makes shooting a convenient experimental model used extensively in studies of various physiological

reactions: in particular, EEG (Haufler et al., 2000; Holmes, Collins, & Calmels, 2006), video-oculometric technique (Ripoll, Papin, Guezennec, Verdy, & Philip, 1985), heart rate estimation (Kontinen et al., 1998), and skin conductance measurements (Tremayne & Barry, 2001). In this regard, the results obtained from kinematic and brain-imaging studies of target shooting can yield insights into the function of the human nervous system during motor behavior. Such a position is warranted because of the unique opportunity afforded by such a task to simultaneously assess cerebral cortical activity and behavioral indexes of performance (i.e., kinematic analysis of aiming behavior). However, much of the previous research on target shooting performance has focused heavily on the psychophysiological processes (i.e., brain electrical activity), whereas relatively little attention has been given to the examination of the behavioral or kinematic aspects of the aiming performance. As we stated previously, the studies of brain activity during aiming and shooting have revealed that the aiming period during expert target shooting performance is characterized by refinement of cortical activity and efficiency of neuro-cognitive processes (Hatfield et al., 2004). More important, examination of the kinematics of aiming, particularly in the manner of an expert–novice contrast, can provide additional insight into the nature of expert motor performance.

Researchers may surmise that the qualities of the AP trajectory should be highly related to the differential qualities of the brain processes in relation to expertise, as described previously. That is, the brain processes that reside in motor performance and the observed reduction of noise in brain activity during expert performance, relative to that observed in novices, should also be reflected in the quality of the aiming behavior. In addition, a detailed examination of the aiming paths can provide insight into whether the strategies that experts and novices use are fundamentally the same or different.

Thus, investigation of aiming and shooting would help researchers understand general mechanisms of fine motor control. The purpose of the present study was to understand the aiming process through detailed kinematic analyses of aiming trajectory. We examined the trajectory of the aiming point on the target plane, as assessed in two-dimensional space, resulting from the precision target shooting behavior. The quantitative approach we took allowed us to capture the essential nature of the aiming behavior and was designed to assess and compare strategies that the novice and expert rifle shooters adopted. Haufler et al. (2000) described a contrast of the EEG activity between the expert and novice groups examined in the present study, in which a remarkable difference in cerebral cortical activity was reported. That is, experts exhibited significantly lower activation in all of the major regions of both of the cerebral hemispheres. However, Haufler et al. did not conduct a detailed assessment of the AP trajectories, which was the purpose of the present study.

In accordance, we expected less noise in the aiming trajectories of the experts as a consequence of the relative

quiescence of cerebral cortical activity, which we previously reported. Thus, the data presented in the present article provide further grounds for the explanation of the role of event-related EEG activity in precision target shooting. In addition, we attempted to analytically model the behavior observed by way of the aiming trajectories to capture the essential strategic control processes of aiming and shooting. We conducted this specific aspect of the present study to determine whether the strategic approach to the aiming behavior differed or was similar in relation to skill level in an attempt to provide general clues on control strategies in movement control systems in which the accuracy of perception is greater than the precision of motor action.

Method

Participants

In all, 28 people participated in the present study. Participants were 14 marksmen (12 men, 2 women; M age = 26.5 years, $SD = 11.1$ years), who had an average of 13.4 years ($SD = 10.6$ years) of experience in national and international competitions of position shooting (i.e., shooting under regulated conditions while in a standardized posture), and 14 novice volunteers (14 men; M age = 23.1 years, $SD = 5.5$ years). None of the novices had any experience with position shooting. We screened all participants with a health history questionnaire and determined that all satisfied the following inclusion criteria: (a) no history of neurological, cardiovascular, or other major disorders; (b) no history of psychiatric disorders; (c) no current use of medications; and (d) no hospitalizations or experience of general anesthesia in the prior 12 months. All participants were right-hand dominant—as determined by way of procedures that Chapman and Chapman (1987) developed—and were ipsilateral

eye dominant. Prior to testing, all participants provided written consent on a form that the Institutional Review Board for the Protection of Human Participants approved.

Shooting Tasks

Each participant completed a shooting task in a sound-attenuated testing chamber (Industrial Acoustic Company, Inc., New York). The shooting task consisted of 40 self-paced trials in which the participant aimed a .22-caliber competition rifle at a modified small-bore rifle target (A-17) positioned 4 m from the firing line at eye level. We recorded aiming performance data with a Noptel Shooter Training System (model ST-2000, Version 2.33, Oulu, Finland). The Noptel system used optical devices, which included a barrel-mounted light emitting and sensing unit and a reflective target border that enabled the position of the instantaneous aiming point to be recorded in two-dimensional space as a function of time throughout each trial. The location of each shot was also recorded as the position of the AP on the target plane at the time of the trigger pull, which was detected on dry firing (i.e., no bullet was used) by way of a small microphone attached to the rifle. As the shooting lane was shorter than 50 ft, which is a standard distance for competition, the standard target was reduced in diameter to 0.787 cm to keep the visual size of the target equivalent to that of a standard-sized target placed at 50 ft. Reliability of the Noptel ST-2000 system has been demonstrated using various shooting distances. We required participants to complete the shooting trials in an 80-min period, which is the time allotted to complete 40 shots during competition under International Shooting Union rules. Figure 1 shows the target plane with one trial time trajectory (see Figure 1A) from a representative participant (an expert). The positions of the shots for all

trials from the same participant are also shown on the target plane (see Figure 1B). In the figure, the center of the target is located at the origin of the target plane coordinate system so that the position of the AP on the plane is given by its horizontal and vertical coordinates. The vector of the AP position in the same coordinate system was defined as $z(t) = (x(t), y(t))$. We synchronized the time trajectories of the AP positions offline with respect to the moment of shooting for follow-up analysis. Record time t was in the limits of $-4 \dots 0$ s prior to trigger pull (reverse time counting) and continued for 0.2 s after shooting for all trials. The sampling frequency was 63.3 Hz so that the data from a trial was represented in discrete time as $x = \{x_n\}$ and $y = \{y_n\}$, $n = 1 \dots N$, $N = 285$, with shooting at the score, $n = 271$.

Calculations of Distance, Speed, and Cosine Angle of the Aiming Point

The AP velocity is $\dot{z}(t) = (\dot{x}(t), \dot{y}(t))$, where $\dot{x}(t)$ and $\dot{y}(t)$ are derivatives. The distance $d(t)$ between AP position and target position and the AP speed $v(t)$ are given by the following equations:

$$d(t) = |z(t)| = \sqrt{x^2(t) + y^2(t)}, \quad (1)$$

$$v(t) = |\dot{z}(t)| = \sqrt{\dot{x}^2(t) + \dot{y}^2(t)}. \quad (2)$$

Derivative of distance with respect to time is the rate of reaching of AP to target

$$\dot{d}(t) = -\cos(a(t))|\dot{z}(t)| \quad (3)$$

where a is the angle between direction of AP motion and direction to target at time t , (e.g., for a constant velocity v , $d(t)$, and $\cos(a)$ are proportional). $\cos(a)$ can be calculated from the following equation:

$$\cos(a) = z^T \dot{z} / |z||\dot{z}|. \quad (4)$$

Further, we used $\cos(a)$ to describe the direction of the AP movement (see Figure 1C). To check the hypothesis of the uniform distribution of the velocity direction, we calculated uniform cumulative distribution function $f_u(a)$, for $2p \geq a \geq 0$, and empirical cumulative distribution function $f_e(a)$ for $a = \arccos(z^T \dot{z} / |z||\dot{z}|)$. Then, we estimated the closeness of the empirical function to the uniform function by statistical significance of linear regression relation between functions $f_u(a)$ and $f_e(a)$.

Estimation of Random and Regular Components of AP Position

For follow-up analysis, we used the index g to designate groups of novices and experts ($g = \text{nov}, \text{exp}$), the index s to denote the numbers of participants ($s = 1 \dots S_g$), and the index l to denote the numbers of trials ($l = 1 \dots L_{sg}$). For example, $d_{lsg}(n)$ is the distance in the moment n and trial l of a participant s from the group g . We omitted some indexes when it did not lead to confusion. We calculated the mean distances and variances for participants across trials, $d_s(n) =$

$M_{(\text{across } l)}\{d_{ls}(n)\}$ and $SD_s^2 = \text{var}_{(\text{across } l)}\{d_{ls}(n)\}$ and for groups across participants, $d_g(n) = M_{(\text{across } l)}\{d_{lsg}(n)\}$ and $SD_g^2 = \text{var}_{(\text{across } l)}\{d_{lsg}(n)\}$.

The relative contribution of the random component to AP trajectory was estimated by mean coefficients of variation (CVs). In particular, to estimate the average scatter of distance across trials, we calculated distance means and standard deviation time profiles for each participant s across trials (i.e., $M_{(\text{across } l)}\{d_{lsg}(n)\}$ and $SD_{(\text{across } l)}\{d_{lsg}(n)\}$) and then the mean value of $CV_{\text{tr}_g}(n)$ across participants in the group:

$$CV_{\text{tr}_g}(n) = M_{(\text{across } s)}\{SD_{(\text{across } l)}\{d_{lsg}(n)\} / M_{(\text{across } l)}\{d_{lsg}(n)\}\}. \quad (5)$$

To estimate the average scatter of distance across participants, we first calculated mean and standard deviation of the distance-time profile for the group g across participants $M_{(\text{across } s)}\{M_{(\text{across } l)}\{d_{lsg}(n)\}\}$ and $SD_{(\text{across } s)}\{M_{(\text{across } l)}\{d_{lsg}(n)\}\}$, and then the value of $CV_{\text{sbj}_g}(n)$ time profile for the group:

$$CV_{\text{sbj}_g}(n) = SD_{(\text{across } s)}\{M_{(\text{across } l)}\{d_{lsg}(n)\} / M_{(\text{across } s)}\{M_{(\text{across } l)}\{d_{lsg}(n)\}\}. \quad (6)$$

We performed similar calculations for coordinates x and y , and for cosines. The participant's grand mean distance was calculated as

$$gm_s = M_{(\text{across } l)}\{M_{(\text{across } n)}\{d_{ls}(n)\}\}. \quad (7)$$

Thus, the regular component was represented by the time profile of the mean distance, and the random component was represented by the time profile of the standard deviation.

Two Phases of the Aiming Process

We identified two phases that showed visibly different aiming processes (see Figure 2).

In the first phase, the mean distance of the AP to the target approximately linearly decreased, whereas the second phase showed a distance with a stronger drop and subsequent increase.

Regression Models for Phase 1

The distance dependence of time was approximated by linear regression of mean distance for each individual and for the marksmanship ability groups:

$$d(t) = d_0 + rt \quad (8)$$

where intercept d_0 was interpreted as typical distance at the beginning of the record, and slope r was the rate of the linear estimation of AP approximation to target.

The relation of the distance standard deviation and mean distance was represented by the following linear regression model for each participant and for all participants in the groups:

$$SD(d) = a_0 + bd \quad (9)$$

FIGURE 2. Determination of the regular and random components of the distance-time profiles as distance mean and standard deviation. Abscissa: time ($-4 \dots 0$ s of reverse time before shooting, $0 \dots 0.2$ s after shooting). $d(t)$ is distance of the aiming point from the target, in millimeters. Thick lines are the distance means across participants; dotted lines are the distance standard deviations; thin lines are examples of distance-time profiles in an individual trial; and dashed lines are regression lines of distance as function of time. $\cos(a(t))$ is cosine of the angle between tangential velocity and direction to target (thick lines; for direct movement to target, $\cos(a) = 1$). Empty circles denote the moment of shooting ($t = 0$). Phase 1 is the phase of regular approximation to target lasting to approximately 0.7 s prior to shooting. Phase 2 is the phase of change of the tracking strategy.

where b played a role of a typical coefficient variation of distance between AP and target and where intercept a_0 characterized the nonlinearity of the dependence for small values of distance. We estimated the quality of regression models by coefficients of determination R^2 .

Duration of Phase 2 Defined by Distance Averaged Across Participants

Phase 1 began at the beginning of the trial, and Phase 2 began when the mean distance began to collapse (see Figure 2). If the moment of shooting ($t = 0$) was the end of Phase 2, researchers could say that the time boundary t_b between the phases is also the duration of Phase 2. We estimated the time boundary t_b (given by vertical dashed-dotted line in Figure 2) by comparing the mean distance time profile across trials and participants $d(t)$ and regression line $d_0 + vt$. For the criterion of the comparison, the following relative regression error is

$$\xi^2(t) = \xi^2_{\text{abs}}(t) / \max(\xi^2_{\text{abs}}(t)), \% \quad (10)$$

where $\xi^2_{\text{abs}}(t) = M_{(\text{across } t)}\{(d_0 + vt - d(t))^2\}$. During Phase 1, the relative regression error value was small, but for Phase 2, $d(t)$ deviated from the regression line, and $\xi^2(t)$ increased. Because of the significant value of the random component of the trajectory, we chose the following procedure to determine the boundary between the phases. We found and averaged the times in which $\xi^2(t) = 20\%$, 10% , and 5% of the maximum. The result of this procedure is the value t_b used as the time boundary between Phases 1 and 2 (and as the estimation of mean duration of Phase 2).

Distance-Time Profiles of Participants During the Last Second Prior to Shooting

In the previous section, we used the procedure of estimation of the boundary t_b between Phases 1 and 2 for the distance averaged across participants. When applied to individual trials of a single participant, this procedure led to large scatter of t_b values. This occurred because of the high level of noise the random component of distance provided.

Because of this, we used a simplified procedure measuring only the duration of the ascending part of Phase 2, from the moment of distance minimum to the moment of shot, or from $T_{\min}(s, g) = \arg(M_{(\text{across } I)}\{d_{ls}(n)\})$ to $t = 0$. Mean values of $T_{\min}$ allowed for estimating of this part of Phase 2 durations within groups, whereas the standard deviations of $T_{\min}$ reflect its scatter among participants; we used the sets of $T_{\min}(s, g)$ to compare Phase 2 timing between groups (analysis of variance [ANOVA], 1 group, two levels).

Comparison of Aiming Parameters in Different Time Intervals in Phase 2

To compare mean values of distances and cosines in different time intervals of Phase 2, we used averaging in time in these intervals and further comparison of the obtained mean values with 2×5 (Group $\times$ Time interval) ANOVAs, with repeated measures on the second factor (see Results section).

Analytical Model of Aiming Control Strategy

The presumable control strategy of aiming that marksmen used was modeled with the help of the following stochastic differential equation:

$$\dot{z} = (\mu A + \sigma V)(z - z_{\text{tar}}), \quad (11)$$

where $\dot{z}$ is the velocity of the AP, z is an AP vector, z_{tar} is the target coordinates, V is a random matrix, A is a constant matrix, μ is drift term, and σ is volatility (these terms are borrowed from description of geometric Brownian motion; Borodin & Salminen, 2002; Karatzas & Shreve, 1991). For modeling shooting, we considered the matrix A a description of properties of the deterministic part of motor tracking system, and we interpreted matrix V as a description of the combination of random properties of the motor and perception systems. Further, we complemented Equation 11 by the logic equation of the trigger-pulling strategy that marksmen of different ability levels used (see Discussion section).

Results

The mean distance–time profiles and distance standard deviations across participants, and cosines of the angle between direction to target and direction of the AP velocity are represented in Figure 2. Analysis of the time profiles showed that the aiming process can be divided into two phases, with presumably different control strategies. The boundary between these phases is approximately 0.6 s . . . 0.8 s prior to shooting, for each group.

The general observations on aiming kinematics from Figure 2 include the following:

1. In Phase 1, the time profile of target or aim–point distance contained a component that systematically approximated the aim point to target and was accompanied by a significant random component in the aim–point position.
2. Scatter of the aim point position decreased with approximation to the target.

3. During Phase 2, the mean distance–time profile demonstrated a valley, as the aim point abruptly approached the target. Some peculiarities were seen at the end of the cosines–time profiles, in which they showed an oscillation with positive and negative semiwaves.

4. Despite the differences between novices and experts in accuracy of shooting, their aiming processes were qualitatively similar.

We describe these observed peculiarities in detail with corresponding statistical analysis.

Regular Component of the Shooting Process in Phase 1

During Phase 1, the mean distance between AP and target systematically decreased. To establish this assertion, we tested it with the linear regression model $d(t) = d_0 + vt$. We calculated the parameters d_0 and v for each participant and then averaged across participants. The results are shown in Table 1. Intercept of the regression line $d(0)$ can be interpreted as the average distance in the moment of 4 s prior to shooting and slope v as the average velocity in direction to target. Linear regression explains the dependence $d(t)$ with $R^2_{\text{nov}} = .61$ and $R^2_{\text{exp}} = .72$ ($p < .001$).

Relative Contribution of Random Component to Aiming Trajectory (Phase 1)

Phase 1 lasted until 0.7 s . . . 0.8 s prior to shooting. In this phase, researchers saw a component regularly approximating AP to target, accompanied by a random component. We assumed that a random component has zero mean. Thus, we characterized the random components with distance standard deviation and the regular tracking component with mean distance. The contribution of the random component into AP trajectory is characterized by CV of AP variables $x(n)$, $y(n)$, and $d(n)$. We characterized groups by CVs in two different ways. First, we calculated $CV(n)$ across trials for each participant (see Method section) and averaged them across participants. Variable $CV_{tr, g}(n)$, $g = \text{nov, exp}$ characterized the scatter of the variables from trial to trial. Second, we calculated $CV(n)$ as standard deviation across participants, divided by mean across participants; this CV, $CV_{sbj, g}(n)$, characterized the homogeneity of participants in the groups. The mean CVs across time for AP coordinates (x , y) and distance (d), $\pm CV$ standard deviations, are given in Table 2. The CV standard deviations characterize the stability of CVs in time. To avoid the possible influence of the correlation between samples of CVs, we calculated the values of CV standard deviations from 20 randomly chosen samples. As seen from Table 2, these values are approximately 10–20% of the mean values (i.e., the CVs did not change in time significantly). A Bonferroni–Holm t test allowed us to reject the hypotheses of mean distances' equality across participants and trials in novices and experts on the .01 significance level. However, the comparison of means provided ground for the following conclusion: The relative scatter measured by $CV_{sbj, g}$ (see Method section) across experts was higher than across novices, but experts

were more consistent in their trials (which is measured by CV_{tr-q}). The more important conclusion is that scatter among trials in novices and experts is even greater than between participants. This underscores the significant contribution of the random component into the trajectory in each trial.

Direction of AP Movement During Phase 1

From the perspective of reaching, the best direction of the AP motion from any position was direction to the target or with $\cos(a) = 1$. However, the means and standard deviations for $\cos(a)$ are the following: for novices, $M = 0.068$, $SD = 0.034$; for experts, $M = 0.067$, $SD = 0.024$ (see Figure 2). This could have happened because the direction of AP velocity (i.e., the angle a) was distributed uniformly. Formulating this hypothesis statistically (see Method section), we found that for the single trial distance–time profiles, we could not reject it on the .001 significance level. Nevertheless, the distribution of the angle slightly distinguished from the uniform one because mean $\cos(a)$ was greater than zero (t test, $p < .001$), indicating that the regular component systematically decreases distance between AP and target.

The values of cosine in novices and experts are not distinguishable—95% $CI_{nov} = (0.053; 0.08)$, 95% $CI_{exp} = (0.048; 0.088)$ —because their confidential intervals overlap.

Connection Between Regular Tracking and Random Components of Shooting

As seen from Figure 2, the distance between AP and target decreases with time, as does the standard deviation. The connection between the regular and random components during reaching is illustrated by the dependence $SD(d)$ (see Figure 3). To estimate this dependence statistically, we tested a linear regression model of distance standard deviation on distance, $SD(d) = a_0 + bd$. The parameters of this model, calculated as in the previous regression model, are given in Table 1. The value of a_0 is the standard deviation for the closest distance between AP and target: $a_0 > 0$ in novices and $a_0 < 0$ in experts—which is evidence of nonlinear dependence, $SD(d)$ —for small values of d . When absolute value of intercept is significantly less than maximal standard deviation, the parameter b can be interpreted as CV for distance. As seen in Table 1, the coefficient of determination (R^2) is high, and the dependence $SD(d)$, as in other biological processes, obeys the Weber–Fechner’s law. Note that for experts, the slope was greater than for novices (t test for difference in slopes, without regard to intercepts, gives $p < .001$).

Boundaries Between Phases 1 and 2

We measured the boundary between Phases 1 and 2 on the mean distance over participants, in both groups of participants, using the regression error (according to the procedure described in the Method section).

TABLE 1. Means and Standard Errors for Parameters of Linear Regression Models Across Participants

Participant type	Distance upon time: $d = d_0 + vt$						Distance standard deviation upon distance: $SD = a_0 + bd$					
	d_0 (mm)		v (mm/s)		R^2		a_0 (mm)		b (unitless)		R^2	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Novice	104.0	13.0	−14.0	2.9	0.61	0.07	18.0	5.0	0.48	0.03	0.63	0.04
Expert	16.2	1.6	−5.9	1.4	0.72	0.07	−4.4	1.7	0.71	0.06	0.82	0.03

Note. Intercept d_0 in $d(t)$ is the average distance for $t = -4$ s; the slope is the rate of approximation to target. In $SD(d)$, $a_0 = 18$ in novices can be interpreted as evidence of insufficient relaxation before shooting, whereas $a_0 = -4.4$ in experts results from nonlinearity of the $SD(d)$ for small values of d . b is CV of distance, if $a_0 < bd_{max}$.

TABLE 2. Means and Standard Errors for Coefficients of Variation (CVs) of Aiming Point Coordinates X and Y and its Distance to Target d Across Participants and Trials

Participant type	X				Y				d			
	Participants		Trials		Participants		Trials		Participants		Trials	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Novice	0.45	0.10	0.82	0.05	0.35	0.04	0.83	0.04	0.38	0.05	0.62	0.04
Expert	0.53	0.07	0.75	0.03	0.49	0.10	0.76	0.07	0.47	0.07	0.56	0.05

Note. CVs characterize contribution of random processes into aiming. CVs calculated across trials are substantially greater than CVs calculated across participants.

We found the grand means of the time boundaries t_b corresponding to errors of 5%, 10%, and 20% for novices and experts, rounded them to -0.7 s, and then further considered Phase 2 as lasting from -0.7 s to the end of the record.

Difference of Phase 2 Duration in Mean Distance of Different Participants

Figure 4 shows the visible presence of Phase 2 on the mean distance profiles of individual participants (thin lines). We estimated the Phase 2 durations in different participants by the time position of the mean distance minimum; these minimums reside in the duration of Phase 2 as defined previously (i.e., $t_b < T_{\min} < 0$), and the mean values of their moments mean ($T_{\min}$) and $SD(T_{\min})$ are the following: for novices, -0.198 s ($SD = 0.074$ s); and for experts, -0.242 s ($SD = 0.096$ s). The ANOVA did not allow us to distinguish between the sets of $T_{\min}$ corresponding to novices and experts. In Figures 2 and 5, the thick lines represent mean distances that we obtained by averaging the individual participants' distances aligned with respect to time of mini-

mums (compare with the means of nonaligned individual participants' distances in Figures 2 and 5). It should be noted that in individual trials, Phase 2 was more difficult to see (the phase could even include many minimums, as can be seen in Figure 2).

Intervals in Phase 2

The time profile of $d(t)$ during Phase 2 had an abrupt value decrease, then had a minimum, and then began to increase, whereas $\cos(a(t))$ showed two semiwaves, positive and negative. We divided Phase 2 into five intervals (see Figure 5B and Table 3).

We calculated means of the variables d and $\cos(a)$ for the intervals and tested the difference between them using two-way ANOVAs. The factors were qualification (levels: novices and experts) and intervals (levels: onset, pre.min, glob.min, post.min, relaxation; see Figure 5). For distances, the main effects were shown because of both factors: for qualification, $F(1, 130) = 2.9$, $p = .025$; for intervals, $F(4, 130) = 203$, $p < .001$. Multiple comparison

FIGURE 3. Regression of distance standard deviation on mean distance during the first phase of the aiming (data from all participants; means and standard deviations of distances for each participant have been calculated across trials). Arrows with the t show the time direction; Empty Circles A correspond to the moment of hitting ($t = 0$), and Empty Circles B correspond to the beginning of the record ($t = -4$ s). Regression lines (dashed) explain linear relations between mean distance and standard deviation with high significance (coefficient of determination $R^2 = .625$ for A and $R^2 = .80$ for B). Distance between aim point and target and its standard deviation obeys the Weber–Fechner law, which suggests crucial participation of sensory processes in aiming.

FIGURE 4. The last second of the mean distance time profiles (individual participants). t_b is the boundary between Phases 1 and 2, calculated on grand distances (averaged across trials and participants); $T_{\min}$ is the mean values of the moments of distance minimums; $t = 0$ is the moment of shooting. For novices, $M(T_{\min}) = -0.198$ s, $SD(T_{\min}) = 0.074$ s; and for experts, $M(T_{\min}) = -0.242$ s, $SD(T_{\min}) = 0.096$ s, which is statistically undistinguishable. The thick lines are means of distances obtained by averaging the individual participants' distances aligned with respect to time of minimums. Although these means look more even than without aligning, we did not find qualitative or quantitative differences from means of nonaligned graphics.

tests of means for intervals showed the difference between mean distances in the interval glob.min and the rest of the intervals ($p < .05$). For cosines, the main effect appeared only because of the intervals, $F(4, 130) = 97$, $p < .001$. Multiple comparison tests showed the difference between mean distances of interval groups onset or pre.min and glob.min or post.min or relaxation ($p < .05$). Therefore, we found significant evidence of peculiar behavior for distance and cosine during Phase 2. There were no interac-

tions among factors and no differences between results of multiple comparisons in novices and experts. The means and standard deviations for cosines and distances in the intervals of Phase 2 are shown in Figure 6; the values of the means are given in Table 3.

Comparison of Global Minimums of Distances in Phases 1 and 2

The goal of this analysis was to find when and how close AP approximates the target during Phases 1 and 2. To do this, we found distance global minimums (DGM) and the time of their appearance (T(DGM)) in both phases. We found the minimum values and their instances for each participant (from the corresponding mean distance–time profile) and then averaged them across participants (see Table 4). As seen, time interval between global minimums in Phases 1 and 2 was approximately 1 s, and the values of minimums in Phase 1 were less than in Phase 2 (10.6 mm vs. 34.6 mm in novices, and 3.04 vs. 7.98 mm in experts). We applied a two-way ANOVA to DGMs, with factors qualification (levels: novice and expert) and phases (levels: Phase 1 and Phase 2), and to moments of T(DGM), with the same factors. The DGM showed main effects for both factors: for group, $F(1, 52) = 41$, $p < .001$; for phase, $F(1, 52) = 29$, $p < .001$. Alternatively, the T(DGM) showed a main effect for factor phases, $F(1, 52) = 340$, $p < .001$, but not for the factor qualification, $F(1, 52) = 1.33$, $p < .25$ (i.e., within the phases), and thereby T(DGM)s in novices and experts were not distinguishable.

The distance grand means (Gr.m.) and final shooting accuracy of the groups (Hit) across Phase 1 are presented in Table 4. The calculated correlations (R) between them are $R_{\text{nov}} = .88$ and $R_{\text{exp}} = .91$ ($pR > 0 < .000$), indicating that the average rate of target reaching also correlates with hitting accuracy.

Discussion

The kinematic data of AP revealed the following findings on novices' and experts' rifle shooting in the present study:

1. The time profile of the distance between the AP and the target has two statistically distinguished phases, before and after the instance of approximately 0.7 s prior to trigger pulling.

2. As seen explicitly in the first phase, the distance–time profile can be represented as a sum of two components: The first is the actual target search (we represent it by the mean distance), and the second is a random process (we represent it by distance standard deviation). We calculated the distance mean and standard deviation across trial and participants.

3. During the first phase, the distance from the target obeys the Weber–Fechner law.

4. In the second phase, the expert marksman and the novice wait for approximately 0.7 s for the approximation to the target, and then pull the trigger.

5. In general and more important is that the distance–

FIGURE 5. Determination of the time boundary between Phases 1 and 2. Error time profiles $\xi^2(t)$ for the linear regression model of dependence $d(t)$ for novices (firm line) and experts (dashed line), and means across participants. The bars represent the standard errors for the calculated means. The circles show the time boundaries in which the errors are 20%, 10%, and 5% of the maximal error (100%). The grand mean of these boundaries (rounded to -0.7 s) as time in which the Phase 1 passes to Phase 2. The dependence $d(t)$ loses its linear character to -0.7 s and becomes a valley. Peculiarities of aiming point trajectory in Phase 2. Ordinates are $\cos(a)$ and distance $d_u(t)$. They are unitless and scaled. Thick lines are mean distances (unitless, scaled to make visualization more convenient), and thin lines are cosines. Firm lines are novices, and dotted lines are experts. The mean value of cosines in experts during Phase 1 was 0.068 (for novices, 0.067). The empty circles show time boundaries between intervals of Phase 2; the leftmost circle divides Phases 1 and 2. The following intervals in Phase 2 were defined as the following: 1, onset to Phase 2; 2 and 4, preminimum and postminimum, the previous and following intervals with respect to global min; 3, interval of global minimums of the mean trajectories of participants; 5, $t = 0$ is the moment of shooting after which there is an interval of relaxation.

TABLE 3. Mean Values for Distance and $\cos(a)$, Across Different Intervals of Phase 2

Variable	Onset	Pre.min	Glob.min	Post.min	Relax
Interval number	1	2	3	4	5
<i>M</i> distance (mm)					
Novices	102.0	83	63.9	70.9	99.1
Experts	19.8	16	14.0	17.3	20.9
<i>M</i> $\cos(a)$					
Novices	0.22	0.103	-0.093	-0.104	-0.033
Experts	0.13	-0.011	-0.09	-0.070	-0.028
Number of average samples	13	14	10	10	14

Note. Pre.min = preminimum; glob.min = global minimum; post.min = postminimum; relax = relaxation. The intervals' boundaries in seconds were the following: for onset, $-0.7 \dots -0.5$ s; for pre.min, $-0.5 \dots -0.3$ s; for glob.min, $-0.3 \dots -0.15$ s; for post.min, $-0.15 \dots 0$ s; for relax, $0 \dots 0.2$ s. During the interval of glob.min, the aiming point is the closest to target position, and the value of $\cos(a)$ is the closest to 0. The intervals' boundaries in scores were the following: for onset, 224–237; for pre.min, 237–251; for glob.min, 251–261; for post.min, 261–271; and for relax, 271–285.

FIGURE 6. Distance to the target and cosine of direction of the aiming point movement (means in intervals in the second phase of aiming). Bins of abscissa are intervals of Phase 2 in which the mean values of distances and cosines were measured. The time intervals have conventional boundaries of $-0.7 \dots -0.5$ s (1 = onset of Phase 2); $-0.5 \dots -0.3$ s (2 = preminimum interval); $-0.3 \dots -0.15$ s (3 = distance global minimum of Phase 2); $-0.15 \dots 0$ s (4 = postminimum interval; up to $t = 0$, the inverse time to hitting was used); and $0 \dots 0.2$ s (5 = relaxation).

TABLE 4. Comparison Between Distance Parameters During Phases 1 and 2

Participant type	Phase 1						Phase 2					
	Gr. m. (mm)		DGM (mm/s)		T(DGM) (s)		DGM (mm)		T(DGM) (s)		Hit (mm)	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Novice	126.5	46.2	10.60	4.78	-1.444	0.374	34.60	18.9	-0.179	0.032	85.9	35.5
Expert	27.7	12.8	3.04	1.90	-1.262	0.300	7.98	3.89	-0.212	0.026	19.2	8.70

Note. Gr.m = distance grand mean (across time and participants); Hit = the final accuracy of hitting; DGM = distance global minimum in the corresponding phase; T(DGM) = moment of time of the distance global minimum. The conventional boundary between phases is $t_b = -0.7$ s. The aiming point happened to be closer to target during Phase 1 than during Phase 2 ($10.6 < 34.6$ and $3.04 < 7.98$, respectively), but the permission to shoot was given only in Phase 2.

time profiles do not show differences in aiming strategies of experts and novices: They are distinguished by scale but not by shape.

6. As predicted, and on the basis of the attenuation of cerebral cortical arousal and refinement of cortico-cortical communication with motor planning regions as observed in experts relative to novice target shooters (Deeny et al., 2009; Haufler et al., 2000), the magnitude of noise in the AP trajectories was significantly less than that observed in the trajectories of novices. However, the similarity seen between ability in groups in strategic control processes to achieve the aiming performance was unexpected.

7. The distance-time profile in both phases can be mimicked by a feedback control system corresponding to some modification of a differential equation of geometric Brownian motion.

Regular and Random Components in Aiming and Relation Between Them

Various functional motor subsystems are active during shooting. We emphasized two: tracking and trigger pulling. During the first phase of the movement, lasting to the moment of approximately 0.6s–0.8s prior to shooting, it appears that only the motor subsystem accomplishing tracking (servo system) is active without involvement of the trigger pulling subsystem. The activity of the tracking subsystem is revealed in the regular component of aiming trajectory, approximating the aiming point to target and random component accompanying it. We characterized the regular component by the mean (across trials and participants) time profile of distance, $d(t)$, between aiming point and target (see Figure 2), and the random component by the time profile of standard deviation of the distance, $SD(t)$. Such a direct characterization allows for some interpretation of the results. We related the regular component to the functioning of a deterministic tracking system and considered the random component as originating from perceptive and motor processes. Our data did not allow for discrimination between their contributions, and we could characterize only their joint effect measured by standard deviation $d(t)$. The average relation between the regular and random compo-

nents was expressed in the CV for which the values changed insignificantly during the course of aiming (the respective standard deviations were approximately 10% of means; see Table 2). According to Table 2, the CVs calculated across participants are less for novices than for experts, pointing to the greater relative differences in experts' skill or qualification. However, experts in their trials are more consistent than are the novices (the CVs across trials are greater for novices than for experts). These peculiarities can be seen in the coordinates x and y of AP and in the distance between AP and target. Table 2 shows that CV means across trials (M_T) are greater than means across participants (M_P). In particular, for the distances for novices, $M_T = 0.62$ ms versus $M_P = 0.38$ ms, and for experts, $M_T = 0.56$ ms versus $M_P = 0.47$ ms (see Table 2, with means and standard errors). Figure 2 shows this with examples of distance-time profiles in individual trials in which the deviation from the mean distance could be several times greater than that of the value of the mean, which indicates the huge contribution of the random component to aiming.

A linear regression model applied to the dependence of distance versus time, $d(t)$, affirmed the regularity of approximation to the target. In spite of the magnitude of statistical significance of the models, the coefficients of determination (R^2) were modest (see Table 1), which may be explained by noisy data but also by some degree of nonlinearity of the real relation, $d(t)$. The regression parameters also showed that the aiming movement is slower in experts than in novices (the mean values of the rate are 5.6 mm/s vs. 14 mm/s, respectively; see Table 1).

The joint consideration of the mean distance d and $SD(d)$ allows for an additional conclusion about their properties. A regression model applied to the d and $SD(d)$ relation showed that they obeyed the Weber-Fechner law (see Table 1). This follows from the visual estimation of the distance value (Johnson, Hsiao, & Yoshioka, 2002; Kunimoto, Miller, & Pashler, 2001) and from the functioning of the motor system, also demonstrating properties similar to the Weber-Fechner law (Newell & Carlton, 1993).

Presumable Events in Phase 2, Generated Because of Control Strategy of Aiming

The properties that we examined of the random component of aiming and the linear regression of distance on time and distance standard deviation on distance were revealed in the phase of regular approximation to the target (Phase 1). However, in some critical moment, the average rate of travel to the target appeared to increase. We suggest that this moment corresponds to the change in the aiming control strategy from Phase 1 to Phase 2. The new control strategy was accompanied by the generation of several events. However, because we were not able to study these events directly from our data, we can define them only by the differences in the kinematic properties of aiming and then speculate about their functionality.

The reorganization of the control strategy appeared just before the visible part of Phase 2 when the system prepared to form the final intensive approximation to target and alerted the trigger-pulling motor subsystem. The pulling subsystem is alerted when the distance achieves the threshold, around the minimum of the negative semiwave of $d(t)$, at 0.3s–0.15 s prior to shooting (see Table 3). If the pulling process continues for approximately 0.3s–0.15s, the shot would then come in the final moment of 0 s, which is in accordance with our data (see Figure 5).

We can thus define the following five events of Phase 2: (a) the intrinsic change of control strategy, (b) the intensification of tracking by perfection of the tracking system (or simultaneous awaiting for a random negative semiwave), (c) the activation of pulling motor subsystem, (d) the pulling and shooting, and (e) the final relaxation. These events correspond approximately to the five intervals defined previously, in accordance with the statistical properties of the distance–time profile in Phase 2 (see intervals: onset, pre.min, glob.min, post.min, relax; see Figure 5 and Table 3). These events seem to comprise the major processes of the aiming system during these intervals.

Hypothetical Mechanisms Accelerating Approximation AP to Target in Phase 2

We hypothesized that the following two mechanisms used for the accelerating are the improvement of the tracking system and the waiting mechanism. The first improves the properties of the servo system responsible for the regular approximation AP to target. Doubtless, the efforts to keep the servo system in perfect condition could be quite costly (e.g., it could be connected with complete concentration of attention on shooting and loss of control upon outer environment), so it is reasonable to engage it only during the short time at the end of aiming (during Phase 2).

The second mechanism, the waiting one, is effective if the precision of perceptual processes is greater than that of motor processes. Under the conditions of our experiments, we defined the *motor accuracy* as the relation

between the standard deviation of the aiming point in the area of the global minimum in Phase 2, $SD(d_{\min})$, and the distance between the marksmen's eyes and the target, D . This relation represents the scatter of the aiming angle in the planes that are orthogonal to the target plane. In our experiments, $D = 5,000$ mm, whereas for experts, we estimated that the $SD(d_{\min}) = 10$ mm. The angle of scatter originated from the involved motor activity can thus be estimated in 2×10^{-3} radians, whereas the absolute threshold for vision in human beings is less than 2×10^{-4} radians (McIlwain, 1996). The accuracy of visual perception is 10-fold greater than the involved motor processes are in experts (and even greater than those in novices). Thus, the waiting strategy could be applied to any shooting system with a similar relation between the accuracy of the visual and motor subsystems in which it is profitable to wait until the random fluctuation brings the AP closer to the target and then allows for pulling the trigger. The apparent criterion for choosing the appropriate fluctuation is the sufficient closeness of the AP to the target defined by an assigned threshold. The mechanism of waiting for the random approximation to the target is indeed not a standard way of motor control, but it works effectively in the described circumstances. We illustrated these processes in terms of the analytical model.

The waiting mechanism allowed us to relate the shooting system to the systems with stochastic resonance. These are systems that enhance the information content of a signal with the help of noise interference. Examples are systems that improved the perceived sound effect and visibility of digitized images by dithering, increasing effectiveness of statistical decision theoretical systems (Kosko, 2006; Moss, Ward, & Sannita, 2004), and enhancing tactile sensation (Collins, Imhoff, & Grigg, 1996). As in the case of the aiming or shooting system in the present study, such systems use noise benefit to improve their performance.

Tracking and Triggering Motor Subsystems in Aiming Phases 1 and 2

The data that we obtained creates an impression that the tracking and trigger-pulling motor subsystems inhibit each other. During Phase 1, the tracking system is active, but the trigger-pulling system is not. The evidence in support of this conclusion is that the global minimum achieved during Phase 1 for the AP is significantly closer to the target than the global minimum achieved during Phase 2 (see Table 4). Meanwhile, the trigger is not pulled, and the pulling system is not activated (or inhibited). The process of pulling apparently begins at the moment when the two conditions are satisfied. First, the pulling system gets permission for the shot (i.e., it is activated), and second, the distance between the AP and the target is less than the assigned threshold. However, for the time passed from this moment to the end of trigger pulling (electro-mechanical delay; Bell & Jacobs, 1986), the AP moves away from

the target, substantially distorting the accuracy of shooting (see Table 4: the global minimum in Phase 2 was less than the hitting distance, 2.48 times greater than for novices, and 2.4 times greater than for experts). Researchers can expect that to avoid this delay, the system would precede the pooling. However, it appears that the system does not use its anticipatory possibilities efficiently; or alternatively, it means that the pulling process somehow mechanically distorts the position of AP.

Similarities in Novices' and Experts' Strategies of Aiming

The difference in the kinematic quality of the AP trajectories in the novices and experts is obvious. Besides the main difference in shooting accuracy, it was expressed in the lower values of the mean distance to the target, the lower level of the random component, and the lower rate of approximation to the target in the experts. In the literature, researchers can find indications of dependency of other characteristics on the level of shooter expertise, for example, in the type of visual strategy (Ripoll et al., 1985), brain slow potentials (Konttinen et al., 1998), other EEG parameters (Hatfield et al., 2004; Haufler et al., 2000), and different times of attack and stabilization (Ripoll et al.). However, our data suggest that although the elements differ in the two groups, their kinematic control strategies are similar. We can find the same peculiarities (patterns) in the distance–time profiles determining Phases 1 and 2, and the same intervals of Phase 2 in both groups (see Figures 2, 3, 5). As examples of not distinguishing values of parameters in novices and experts, we can point out moments $T(DGM)$ in Phase 2 (see Table 4), mean cosines across Phase 1 (see Table 3), CVs of AP coordinates and distance to target (see Table 2), and relation between global minimums of Phases 1 and 2 (see Table 4). Therefore, we suggest the same model of strategic approach to shooting for both groups of marksmen, providing it with different values of parameters.

Connection Between EEG Characteristics and Kinematic Properties of Shooting

The interpretation outlined in the previous section informs the potential explanations for the development of expertise in target shooting, and perhaps self-paced visuomotor aiming tasks in general, when considered in tandem with brain-imaging studies of target shooting performance (Hatfield et al., 2004). That is, Haufler et al. (2000) observed significantly lower levels of cerebral cortical activation across the scalp topography in expert marksmen during the aiming phase, compared with those observed in novices. This difference was revealed by a comparison of power spectral densities of the various frequency bands (i.e., theta, delta, alpha, beta, gamma). In addition, Deeny et al. (2009) observed that the relative economy areas of brain activity in experts were accompanied by relatively lower levels of EEG coherence between various associative or perceptual regions with the motor planning

regions. These findings imply a reduction in nonessential inputs during this particular task from various cortical areas to the motor regions, which would ultimately result in less interference with intended action. Thus, the relative economy noted in the brain processes of the experts, along with the more refined yet similar pattern of kinematic qualities of their AP trajectories, suggests that skill development in target shooting is characterized by adoption of a core or common strategy (i.e., similar in experts and novices) and that gradual refinement or dropping out of nonessential activity occurs over time with deliberate practice. That is, both groups are trying to do the same thing, but the novice is burdened with noisy inputs to the motor system that are reflected in the qualities of the aiming trajectory. The attenuation of the neuromotor noise then emerges to affect the higher quality aiming movement. This likely underlies the greater accuracy and consistency of target shooting noted in the experts.

Formal Model Mimicking Kinematics of Aiming: Tracking System

The aiming strategies formulated from the experimental observations provide for a model mimicking the aiming and shooting process of a marksman (see Figure 7). We could also use this model as a concise but efficient description of the results of our experimental data analysis. To model the kinematic qualities of Phase 1, we used a tracking system implementing the regular approximation to target on the background of considerable noise. This part is described by our modification of the geometric Brownian motion differential equation (Bellman, 1960; Borodin & Salminen, 2002; Karatzas & Shreve, 1991) and the correspondence of the system with feedback (see Figure 7). In Equation 11, the equation of the tracking system, $\dot{z}$ is tangential velocity of the aiming point, and $z - z_{tar}$ is a feedback signal formed from visually estimated target and AP positions (see the rest denotations in Figure 7). The deterministic matrix A and random matrix V were respectively responsible for the regular and random behaviors of the model. The relation between parameters μ and σ reflects the contribution of the random component in aiming. Integration as shown in Figure 7 is an actual physical process of the traveling or excursion of the AP on the target plane. In Figure 8, there are results of modeling the distance–time profiles $d(t)$, and the parameters that we used follow: $A = I$ (identity matrix); entries of V were samples of white noise (distributed as $N(0,1)$) filtered on Butterfield low-frequency filter, with $f_c = 8.5$ Hz, $n = 4$; $\mu = 1$ during Phase 1; μ in the Phase 2 increased and then fell down as the dashed–dotted line in Figure 8 shows; $\sigma = 10$; and initial values of $z = (x, y)$ in each trial were not correlated variables $N(0,50)$. The number of trials was 30, and we calculated the mean and standard deviation of the distance shown in Figure 8 across these trials.

The simulated data demonstrate regular and random components of AP trajectory similar to the data obtained in exper-

iments (see Figure 8A) and show significant linear regression ($p < .000$) of distance standard deviation on distance: the Weber–Fechner law (with $R^2 = .96$). This law is demonstrated because the noise in Equation 11 is represented in multiplicative form (the random matrix V is multiplied with the state variable z). The equation with an additive noise is not able to demonstrate the linear dependence between d and $SD(d)$, which is the issue of the Weber–Fechner law.

The linear dependence of distance on time is also significant ($R^2 = .8$). Meanwhile, the theory prompts not linear dependence but exponential dependence of approximation of AP to target (Bellman, 1960). This, side by side with the data noise, can explain the low R^2 values in linear regression of the distance versus time in experimental and model data.

Formal Model Mimicking Kinematics of Aiming: Trigger-Pulling System

To satisfy Phase 2, we added the logic of the trigger-pulling system control:

$$t_{pull} = \text{"decision making"} \ \& \ "d(t) < thr", \quad (12)$$

where variables "decision making" and t_{pull} , and the proposition " $d(t) < thr$ " could take logical values *yes* or *no*

(t_{pull} is the command starting the trigger pulling). Thus, the trigger is pulled ($t_{pull} = \text{yes}$) if the pulling motor system is alerted ("decision making" = *yes*) and the distance to target is less than the threshold thr , " $d(t) < thr$ " = *yes*.

Therefore, Equations 11 and 12 described the model. The part of the model controlling the pulling contains a decision maker that defines the moment when pulling subsystem should be alerted, and a generator of threshold value (see Figure 7). The nature of the decision maker can be different: The marksman can formulate the decision intrinsically or after some stimulus or commands from outside. After the marksman makes a decision, the mean course of aiming changes and AP accelerate the approximations to target. We considered two possible mechanisms of this acceleration: active and passive. In the active mechanism, the system changed its parameters, making them more effective (see Hypothetical Mechanisms Accelerating Approximation AP to Target in Phase 2 section). The example in Figure 8A shows how it could be achieved by a special time profile of drift term, $\mu(t)$. The second mechanism is reduced to the passive waiting for the distance random negative semiwave approximating AP to target (see Figure 8B and Hypothetical Mechanisms Accelerating Approximation AP to Target in Phase 2 sec-

FIGURE 8. Analytical model of shooting process: Time profiles of distance between aiming point and target mimicking the experimental results. The vertical dotted-dashed lines denote the boundary between Phases 1 and 2, defined by the decision maker. The empty circle is the moment of shooting. (A) Time profiles obtained with the help of a modification of the geometric Brownian motion equation. The thick dotted line is the drift term $\mu(t)$ time profile providing Phase 2. $d(t)$ is unitless. (B) Demonstrates the appearance of Phase 2 because of waiting strategy, consisting in waiting of distance random negative semiwave approximating aim point to target. The distance-time profiles of individual trials (thin lines) were aligned to the moment of shooting and averaged; the result (the thick line) is a specific mean time profile analogous to the one shown on experimental data. $d(t)$ and t are unitless.

tion). In both cases, Phase 2 shows the valley analogous to the one found previously in experimental data (see Figure 2). Details of Phase 2 timing in the model (formation of its duration, asymmetry of the valley) and connection between the model and structures and functions of real shooting system are out of scope of this work.

Conclusions

Kinematic analysis properties of aiming and shooting action allowed us to conclude that the AP trajectory consists of two components, the first being the actual target search and the second being a random component. During the course of trajectory, the aiming process can be divided into two phases: initial active search and a random approxi-

mation. During the first phase, the aiming motor subsystem is active, whereas the triggering subsystem is inhibited, so that a marksman does not shoot even when close to target. During the second phase, the triggering motor subsystem is alerted, and the marksman's strategy of trigger pulling is to wait until the aiming point gets close to the target, which is acquired through random movement, and then trigger. The strategy corresponds to the fundamental property of visuomotor system: The accuracy of vision is significantly greater than the motor action precision. The act of triggering interferes with aiming and distorts the accuracy of shooting. In the two phases, the sensory system plays different roles. Initially, it controls convergence between AP and target (demonstrating Weber-Fechner law), but then, it compares the distance with the threshold of triggering. We also concluded that the control strategies novices and experts used are similar and are distinguished only by the values of parameters. The experimental results were illustrated on an analytical model of shooting that successfully mimicked the two phases of AP trajectory, Weber-Fechner law properties, and the waiting strategy of triggering. We hope that athletes can improve their shooting performance by using the notion of waiting strategy explicitly formulated in the present article.

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