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Visuo-motor delay, information–movement coupling, and expertise in ball sports

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Abstract

We compared the performance of tennis experts and non-experts using a simulated interceptive task, in which the ball could be unexpectedly deviated 400 ms before contact. The results showed that experts were more accurate than non-experts when intercepting balls that deviated in their trajectory and that this could be explained by their shorter visuo-motor delay in adapting their interceptive movement. In addition, multiple regression analyses revealed that visuo-motor delay was a good predictor of accuracy in this task. Finally, accuracy in the simulated interceptive task was shown to be a reasonable predictor of expertise in tennis assessed by national ranking. In combination, the present results suggest that an important component of expertise in interceptive skills is fast information–movement coupling, which corresponds to a reduced delay in integrating vision and action. Our findings highlight the potential of the virtual interceptive task used here to predict performance in tennis.

Keywords: *Interception, information–movement coupling, expertise, ball sports*

Introduction

In many sports, the best athletes reach extraordinary levels of control and give the impression of pushing back the functional limits of the perceptual and motor systems. This is the case, for example, in ball sports in which players have to coordinate their actions with fast moving objects. The successful completion of interceptive actions, such as hitting or catching balls, requires extremely accurate control of the rapid effector movement and is dependent on adaptive processes involving the perception of various properties of the ball trajectory. The necessary accuracy of such actions, which is generally defined by the various dimensions of the spatio-temporal window in which the contact occurs (McLeod, McLaughlin, & Nimmo Smith, 1986), has been estimated at ± 2 cm (Tresilian, 2004) and ± 5 ms (Regan, 1997) in baseball.

The difficulty of fast interceptive actions is exacerbated by uncertainty regarding the ball trajectory. For instance, although ball trajectory is initially defined by a velocity vector with a given value and direction, once the ball is in flight it is exposed to various forces (gravity, wind resistance, Magnus force of rotation inducing curve trajectories, friction during bouncing). The perceptual consequences of these events are not easily accessible to the visual system (for the use of information about acceleration, see Benguigui, Ripoll, & Broderick, 2003) and not easily extrapolated by the central nervous system (for a reconsideration of internal models to predict ball trajectory, see Baurès, Benguigui, Amorim, & Siegler, 2007). Uncertainty of ball trajectory is, therefore, an important consideration for a prospective control model of interceptive actions, which has been defined in various forms in recent years (e.g. Arzamarski, Harrison, Hajnal, & Michaels, 2006; Bootsma, Fayt, Zaal, & Laurent, 1997; Dessing, Bullock, Peper & Beek, 2002; Jacobs & Michaels, 2006; Michaels, Jacobs, & Bongers, 2006; Montagne, Laurent, Durey, & Bootsma, 1999). According to the general principles of this model, success in interceptive actions depends on the use of control laws, which allow continuous adjustment of free parameters of the action on the basis of relevant information picked up in the environment (Warren, 1988; for an analytical example, see Peper, Bootsma, Mestre, & Bakker, 1994). Accordingly, success on an interceptive action depends more on the accuracy of on-line adaptations than on anticipated knowledge of the spatio-temporal characteristics of the contact zone. In this respect, information pick-up is

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critical to minimize the difference between current and required behaviours.

Despite the success of prospective models of control in explaining interceptive actions, surprisingly few researchers have considered the issue of expertise. One exception is the study of Bootsma and van Wieringen (1990), who analysed the timing of attacking forehand drives produced by expert table tennis players. Their results showed that expert players were able to minimize movement variability with great consistency as the moment of the ball–racket contact approached. This finding was interpreted as evidence for optimized continuous control, with refined integration between information and movement up to the moment of contact.

Another way of testing the efficiency of information–movement coupling is to study the capacity to cope with the more or less predictable transformations of the environment (Savelsbergh & van der Kamp, 2000). In such situations, the time required to adapt movement to the environmental transformation can be considered as a determinant of performance. In this respect, many pointing and interceptive studies have shown that changes in target location or object trajectory require movement adaptations with an identifiable visuo-motor delay to maintain performance. Visuo-motor delay is generally defined as the time between the occurrence of a relevant visually detectable event in the environment and the initiation of the respective adjustment to the ongoing movement (e.g. Day & Lyon, 2000; Teixeira, Lima, & Franzoni, 2005b), and has been shown to vary between 100 and 300 ms, depending on the task, availability of information about trajectory change, and the inertia to be overcome (Benguigui, Baurès, & Le Runigo, 2008).

McLeod (1987) was the first to use the ball-deviation paradigm to study expertise in interceptive actions. McLeod analysed the behaviour of high-level cricket batters confronted by balls that could be deviated after hitting the ground and making contact with dowels located under a ground cloth. Delays between the moment the ball left the ground and the first detected difference between the two types of bat trajectories were between 190 and 240 ms. These results were confirmed by Carlton, Carlton, and Kim (1991; cited by Carlton, 1992), who showed that expert tennis players were able to adapt their shot to the bounces on various surface textures with delays between 150 and 190 ms. These "visuo-motor delays" could be regarded as very short when considering the weight of the bat or the racket, and the unpredictability of the change in ball trajectory. Indeed, visuo-motor delay should be compared with multiple-choice "reaction time", which is a function of the number of possible responses, and is typically greater than 200 ms (e.g. Hyman, 1953).

An important implication of the above two studies is that a short visuo-motor delay could enable better information–movement coupling and thereby in part determine expertise in ball sports. For instance, improved coupling might allow an individual to minimize the gap between the current and the required movement for hitting a moving ball, hence leading to more accurate responses. However, as both of these studies did not compare experts and non-experts, it remains to be confirmed whether the observed on-line adaptations can truly be linked to expertise in ball sports.

Some preliminary support for this position is evident in the work of Le Runigo and colleagues (Le Runigo, Benguigui, & Bardy, 2005), who examined experts and non-experts in tennis intercepting a simulated target moving on a horizontal 4-m long runway with movement performed across a perpendicular path. The target moved either at a constant velocity ($2 \text{ m} \cdot \text{s}^{-1}$) to the interception position at the end of the runway, or had an unexpected change in velocity (i.e. instantaneous decrease in velocity from 2 to $1 \text{ m} \cdot \text{s}^{-1}$ or increase from 2 to $3 \text{ m} \cdot \text{s}^{-1}$) 400 ms before its arrival. The results showed that visuo-motor delays between velocity change and movement adaptation were shorter in experts than in non-experts (162 vs. 221 ms). These shorter visuo-motor delays provided experts with more time to regulate their movement, and thereby more opportunity to adapt their interceptive movement to the new velocity. Therefore, the difference between experts and non-experts was interpreted as an optimization of the information–movement coupling required to achieve expertise in ball sports. This result contrasts with those obtained in reaction time tasks, where no clear differences were observed between experts and non-experts in ball sports (Abernethy, 1991, 1994; Rowe & McKenna, 2001). It was reasoned that unlike the discrete response in a reaction time task, the corrections involved in an ongoing movement appear to be made faster by experts, suggesting that the involvement in action and in information–movement coupling is a determinant of expertise in ball sports.

Accordingly, the aim of the present study was to determine whether differences in interceptive timing, and the associated information–movement coupling, exist between expert and non-expert tennis players. Participants were required to complete a laboratory task in which high spatio-temporal constraints were obtained with the use of unexpected deviations in the trajectory of a virtual ball. First, we wished to confirm that it was unnecessary to use a task that literally reproduces tennis situations to reveal the specific ability of experts to adapt more precisely and/or more quickly their movement, but instead adopt an action in which information–movement coupling

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is significantly engaged. Second, we formulated two hypotheses regarding the visuo-motor control of expert and non-expert participants. One (temporal) hypothesis was that the greater accuracy of experts originates from earlier corrections, and hence from a shorter visuo-motor delay, providing a longer period to adjust movements to deviation of the target trajectory. The other (kinematic) hypothesis was that experts are more accurate because they make well-adapted movement corrections. Accordingly, higher peak velocity and peak acceleration of the interceptive movement should be observed in experts compared with non-experts if the change in ball trajectory makes the interception zone further from the hand than expected based on the initial part of the trajectory. Furthermore, higher deceleration of the movement should be observed in experts if the change in the trajectory makes the interception zone closer to the hand than initially expected, or if the trajectory requires a reversal in movement to achieve the interception. The temporal and kinematic hypotheses are not necessarily exclusive. It could be that the superiority of experts over non-experts comes jointly from earlier (temporal hypothesis) and better-adapted (kinematic hypothesis) corrections. Having examined the strategy used to adapt to an unpredictable change in object trajectory, we then determined whether the capacity to adapt to unforeseeable changes in trajectories (1) discriminates between high-standard players and (2) reflects their level of performance in tennis.

Methods

Participants

Twenty-one right-handed individuals, who were in good health and had normal or corrected-to-normal vision, participated in the experiment. A group of experts in ball sports comprised 11 French tennis players (9 males, 2 females) aged 24.0 ± 3.8 years (mean ± *s*). We chose tennis as the ball sport of interest mainly because the national federation's classification is well established and representative of competitive standard. The tennis players were ranked from 2500 to 89 (out of a total of 387,940 players) in the national federation's classification. Proportionally, the selected players were among the best 0.64% in the country. A group of 10 non-experts in ball sports (8 males, 2 females), aged 23.0 ± 2.2 years, was comprised of individuals who had never practised tennis or any other type of ball sport, or indeed any sport that requires fast reactions beyond the regular activities in physical education in a school setting.

Experimental device for simulating a moving object

The experimental device consisted of a system simulating interception in a virtual environment. Experimental conditions were realized using custom-written software, "Interceptor", which was used to generate images of a 2.5-cm diameter ball (target) that was displaced vertically on a 3 × 4 m screen. The task required participants to intercept the vertically moving target with a virtual effector (3 cm diameter), which corresponded to manual movements made by participants on a horizontal axis. Participants sat at a table in front of the screen and were instructed to intercept the simulated moving target with the virtual effector by moving a wooden cart along a horizontal, rectilinear track (Figure 1). Manual movements were directed from left to right, although the participants were allowed to move the effector backward if they deemed it necessary, such as in the case of overestimating the interception point. A electromagnetic sensor (flock of birds, Ascension Technology©) was connected to the cart, which was sampled at 120 Hz to provide position data that were then used to update in real-time the virtual effector on the screen; the position data were stored for later processing. The device was configured with a gain of 1, so that the movement of the virtual effector on the screen corresponded to the movement of the cart. The latency between the movement produced with the cart and the outcome on the screen was measured with a photoelectric cell and was equal to 30 ms. This value was lower than the threshold identified by Vogels (2004), who showed that the latency between a haptic stimulus and a visual stimulus had to be lower than 45 ms if the two stimuli were to be regarded as synchronous. Moreover, a preliminary experiment showed that familiarization with the apparatus was very fast. After five trials, accuracy did not improve in intercepting a moving target on rectilinear trajectories and with constant velocities.

Experimental conditions

The target moved vertically from the top to the bottom of the screen, over a distance equal to 120 cm, at a constant velocity of $1 \text{ m} \cdot \text{s}^{-1}$. The moving target reached the interception axis 1.2 s after its onset. In half of the trials target direction was maintained throughout, whereas in the other half of the trials the trajectory was unexpectedly deviated such that there was a lateral shift to the right- or to the left-hand side. To increase uncertainty and task difficulty, two magnitudes of target deviation were used, leading to a left or right displacement from the original interception position of 12.3 and 27.2 cm. The deviation of the trajectory occurred 800 ms after

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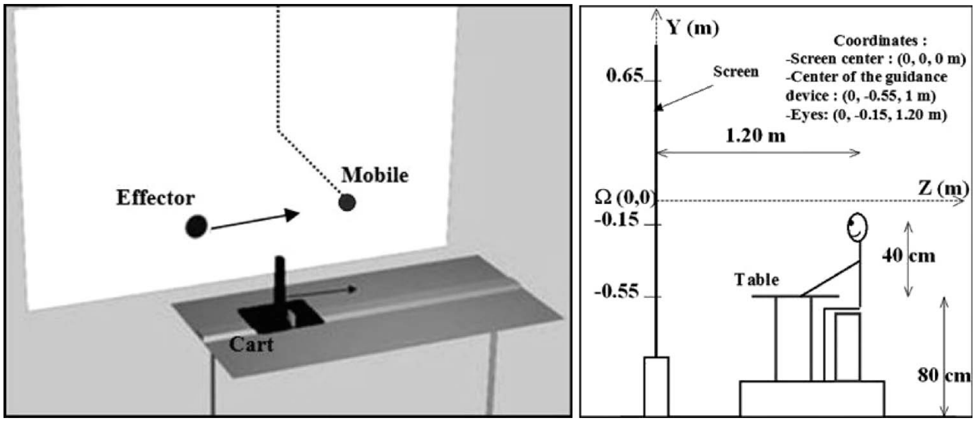

Figure 1. Three-dimensional (left panel) and two-dimensional lateral view (right panel) representations of the experimental device. The right-hand panel indicates the spatial organization of the experimental room. Ω corresponds to the origin of the distances for configuring the experimental trajectories.

Table I. Characteristics of the moving target trajectories.

Time (ms)	X (m)	Y (m)	v_x (m · s^{-1})	v_y (m · s^{-1})	α(°)	X (m)	Y (m)	v_x (m · s^{-1})	v_y (m · s^{-1})	α(°)
	Large deviation on the left					Large deviation on the right				
0	0	0.65	0	−1	0	0	0.65	0	−1	0
800	0	−0.15	−0.68	−1	0	0	−0.15	0.68	−1	0
1200	−0.272	−0.55	−0.68	−1	−34.23	0.272	−0.55	0.68	−1	34.23
	Small deviation on the left					Small deviation on the right				
0	0	0.65	0	−1	0	0	0.65	0	−1	0
800	0	−0.15	−0.308	−1	0	0	−0.15	0.308	−1	0
1200	−0.123	−0.55	−0.308	−1	−17.11	0.123	−0.55	0.308	−1	17.11
	No-deviation									
0	0	0.65	0	−1	0					
800	0	−0.15	0	−1	0					
1200	0	−0.55	0	−1	0					

Note: X and Y symbolize the abscissa and the ordinate of the moving target referred to the origin Ω (0, 0 m), v_x and v_y the horizontal and vertical velocities, α the angle between the vertical and the moving target direction after the deviation. The moving target reached the interception axis 1.2 s after its onset. The deviation of the trajectory occurred 800 ms after onset of the moving target and 400 ms before it reached the interception axis.

motion onset and 400 ms before reaching the interception axis. The kinematic parameters of the target trajectories are shown in Table I and Figure 2. The resulting four deviations were pseudo-randomly presented across trials.

Initially, participants were provided with a training block of 13 trials, which contained five rectilinear trajectories, followed by four deviated trajectories randomly alternated with four rectilinear trajectories. The purpose of the training block was to familiarize the participants with the various trajectories and enable them to determine the properties of the simulated effector. Participants then completed the main experimental session, which consisted of 48 randomly presented trials, 24 with rectilinear trajectories (50% of the trials) and 24 with deviated trajectories (50%) presented six times each (4 × 12.5%).

Dependent variables

For each trial, timing accuracy was calculated as the difference between the effective arrival time of the moving target and the effector at the interception point. The absolute error and constant error were then calculated on the basis of these timing data. "Absolute error" corresponded to the unsigned errors and was used to provide a measure of the overall accuracy in performance. "Constant error" was calculated using the signed errors, and was positive when the cart reached the interception point after the simulated moving target (the effector arrived too late) and negative when the cart reached the interception point before the simulated moving target (the effector arrived too early). Constant error was used to identify a possible bias in the estimations (i.e. under- or overestimations). The constant error value was displayed on the screen after

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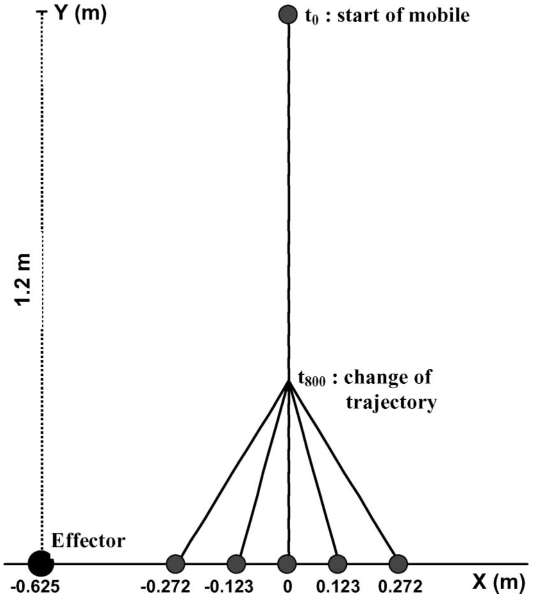

Figure 2. Representation of the different target trajectories. The large black disk on the left-hand side represents the position of the effector at the beginning of the trial. The arrival point of the moving target on the horizontal interception axis (X) could be -0.272, -0.123, $0, +0.123$ or $+0.272$ m from its initial direction.

each trial, thus providing participants with knowledge of results.

Five other variables were calculated to test between the temporal hypothesis (see below "visuo-motor delay", "time to reach peak velocity", and "time to reach peak acceleration") and the kinematic hypothesis (see below "peak velocity" and "peak acceleration"):

1. *Visuo-motor delay* was the interval (ms) between the change of target direction and the first functional adaptation of the movement following this change. To calculate the visuo-motor delay, we used the same method as Le Runigo et al. (2005). For each participant, we compared the values of hand acceleration at each instant (i.e. every 8.33 ms) across the entire movement duration, using an analysis of variance (ANOVA) with trajectory as a repeated measure with five conditions. As there were six trials in each deviated trajectory condition and 24 trials in the condition without deviation, we randomly selected six trials in this latter condition to maintain a symmetrical design. A functional adaptation in the movement was detected by a significant difference in acceleration values in the five conditions (see Figure 3). Before running this analysis for calculating the visuo-motor delay, we used the same method to determine whether there were any differences in the onset timing of movements across the various trajectory conditions.
2. *Time to reach peak velocity* was the time (ms) required to reach peak velocity after the change of target direction in the deviated trajectory conditions.
3. *Time to reach peak acceleration* was the time (ms) required to reach peak acceleration after the change of target direction in the deviated trajectory conditions.
4. *Peak velocity* was the peak velocity ($\mathrm{m \cdot s^{-1}}$) of the effector after the change of target direction in the deviated trajectory conditions (Figure 3, middle).
5. *Peak acceleration* was the peak acceleration ($\mathrm{m \cdot s^{-2}}$) of the effector after the change of target direction in the deviated trajectory conditions (Figure 3, bottom).

Absolute and constant errors were analysed using an Expertise (experts vs. non experts) × Trajectory (Left/Large, Left/Small, No-Deviation, Right/Small, Right/Large) analysis of variance (ANOVA), with repeated measures on the second factor. Peak velocity, time to reach peak velocity, peak acceleration, and time to reach peak acceleration were analysed using an almost identical mixed-factorial ANOVA but with only four trajectory conditions (Left/Large, Left/Small, Right/Small, Right/Large). To compare the visuo-motor delay of experts and non-experts, these data were analysed with an independent samples t-test.

Having examined differences in discrete kinematic variables between groups as a function of the different trajectory conditions, we then evaluated the origin of constant error for each participant using a forward stepwise regression with the various dependent variables as predictors. A similar forward stepwise regression was performed on the data for experts only to determine which variables predicted national ranking. Statistical significance was set at $P < 0.05$ for all tests. Newmann-Keuls *post hoc* analyses were used when necessary to decompose main effects and interactions.

Results

Absolute error

Analysis of absolute error showed a significant main effect for Expertise ($F_{1,19} = 12.27$, $P < 0.05$, $\eta^2 = 0.39$), with an absolute error of 60 ms for the experts and 103 ms for the non-experts. There was also a significant main effect for Trajectory ($F_{4,76} = 14.04$, $P < 0.05$, $\eta^2 = 0.42$). *Post hoc* analysis revealed that absolute error was higher in the two larger deviation conditions (left and right) than the three other trajectories. The Expertise × Trajectory interaction was also significant ($F_{4,76} = 2.71$,

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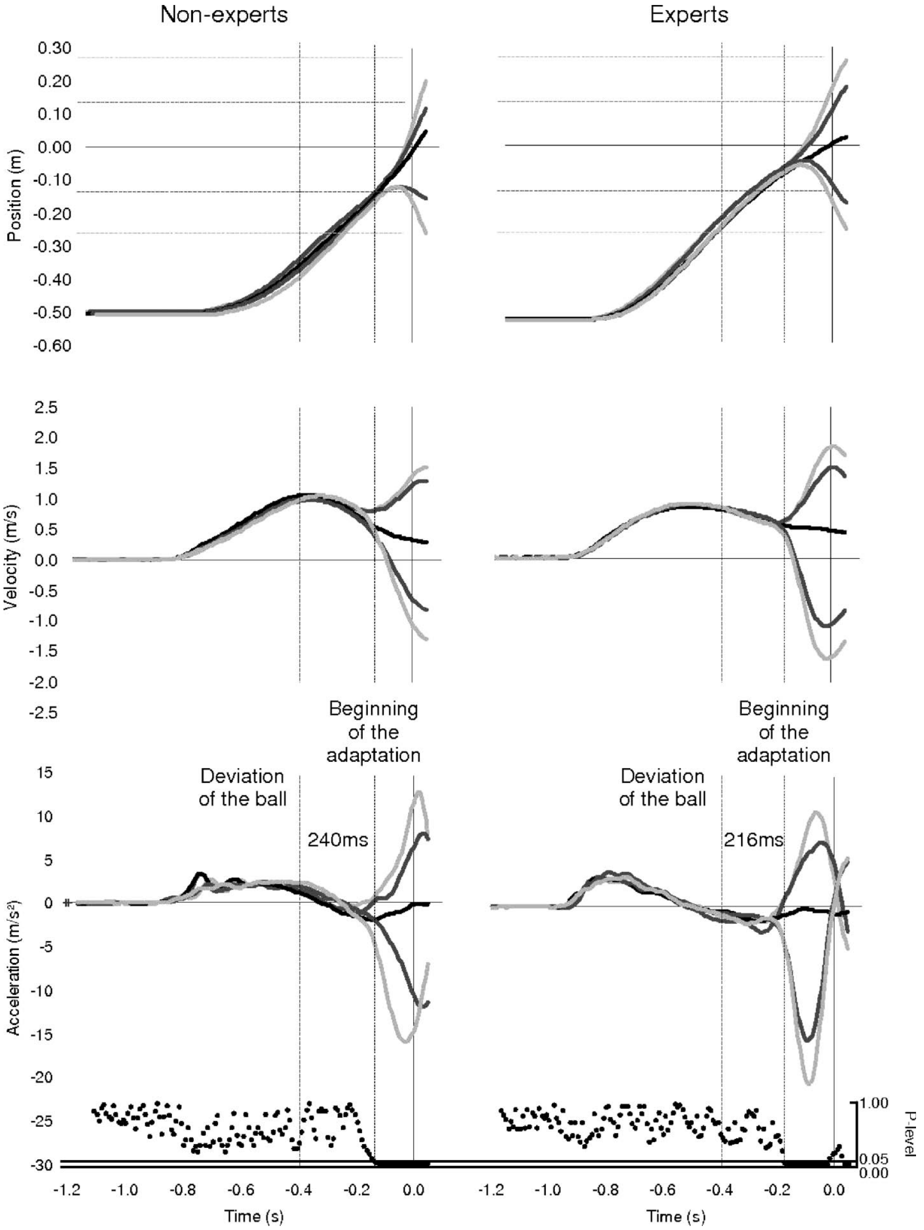

Figure 3. Mean profiles of position (up), velocity (middle), and acceleration (bottom) of the hand as a function of time in the five trajectory conditions, for the 10 non-experts on the left and the 11 experts on the right. Time = 0 corresponds to the arrival of the ball on the interception axis. The horizontal dashed lines at the top of the figure correspond to the position for the interception in the deviated trajectory conditions. The P-value at the bottom of the figure arises from an ANOVA test that was used to compare, across each of the five velocity conditions, the acceleration of the cart for all trials of the same participant, at each instant (i.e. every 8.33 ms). After ball deviation, which occurred at $t = -0.4$ s, the first functional adaptation of the movement is determined when the $P < 0.05$.

$P < 0.05$, $\eta^2 = 0.12$) (Table II). Absolute error was smaller for the experts than for the non-experts in the Left/Large trajectory condition (63 vs. 150 ms). No differences were observed in the other conditions.

Constant error

Analysis of constant error revealed a significant main effect for Expertise ($F_{1,19} = 16.17$, $P < 0.05$, $\eta^2 = 0.46$). Constant error reached 39 ms for the experts and 84 ms for the non-experts. The results also revealed a significant main effect for Trajectory ($F_{4,76} = 29.98$, $P < 0.05$, $\eta^2 = 0.61$), showing that error increased almost linearly as the target direction moved away from the central position (No-Deviation) (Newman-Keuls $P < 0.05$). For left deviations, the delay observed included a reversal in movement direction. The Expertise × Trajectory interaction was also significant ($F_{4,76} = 3.55$, $P < 0.05$, $\eta^2 = 0.16$) (Table II). A *post hoc* test on this interaction showed that constant error was lower

Table II. Absolute error (AE), constant error (CE), visuo-motor delay (VMD), peak velocity (v_{peak}), time to reach peak velocity ($T_{v\text{peak}}$), peak acceleration (A_{peak}), and time to reach peak acceleration ($T_{A\text{peak}}$) as a function of expertise and type of trajectory.

		Deviation on the Left			Deviation on the Right		
		Large	Small	No-Deviation	Small	Large	Mean
AE (ms)	Experts	63	43	58	37	101	60
	Non-experts	150	84	80	62	139	103
CE (ms)	Experts	59	8	−6	35	101	39
	Non-experts	149	76	−4	62	139	84
VMD(ms)	Experts			216			
	Non-experts			240			
v_{peak} ($\text{m} \cdot \text{s}^{-1}$)	Experts	2.15	1.60		1.83	2.29	1.97
	Non-experts	1.53	1.11		1.70	1.90	1.56
$T_{v\text{peak}}$ (ms)	Experts	417	429		356	427	407
	Non-experts	479	500		324	344	412
A_{peak} ($\text{m} \cdot \text{s}^{-1}$)	Experts	29.71	27.02		23.13	28.96	27.20
	Non-experts	27.32	23.42		16.74	20.08	21.89
$T_{A\text{peak}}$ (ms)	Experts	380	470		440	460	440
	Non-experts	490	440		370	370	420

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for the experts than for the non-experts for the Left/Large trajectory condition (59 vs. 149 ms). For the Left/Small trajectory condition, constant error was marginally lower for the experts than for the non-experts (8 vs. 76 ms, $P = .06$). No differences were observed in the other conditions. Note that constant error showed a very similar pattern to absolute error. However, constant error showed that the increase in absolute error with the more important deviations corresponded to late responses. It also showed that experts were able to minimize this lateness.

Visuo-motor delay

A *t*-test revealed a significant main effect for Expertise ($t_{19} = 8.59$, $P < 0.05$, $\eta^2 = 0.31$), with a visuo-motor delay of 216 ms for the experts and 240 ms for the non-experts. As expected according to the temporal hypothesis, experts demonstrated a shorter visuo-motor delay than non-experts, and hence an ability to correct more rapidly their movement in response to deviations in the target trajectory.

Peak velocity

Analysis of peak velocity showed a significant main effect for Expertise ($F_{1,19} = 6.58$, $P < 0.05$, $\eta^2 = 0.26$), with experts exhibiting a higher peak velocity than non-experts ($1.97\ \text{m} \cdot \text{s}^{-1}$ and $1.56\ \text{m} \cdot \text{s}^{-1}$, respectively). There was also a significant main effect for Trajectory ($F_{3,57} = 19.32$, $P < 0.05$, $\eta^2 = 0.50$), which was the result of participants reaching a higher peak velocity for the large deviations (Left/Large and Right/Large) than for the small deviations (Left/Small and Right/Small), irrespective of direction (Table II).

Time required to reach peak velocity

Analysis of time to reach peak velocity showed a significant main effect for Trajectory ($F_{3,57} = 15.58$, $P < 0.05$, $\eta^2 = 0.45$). *Post hoc* comparisons showed that participants reached their peak velocity later for the left trajectories (Left/Large and Left/Small) than for the right trajectories (Right/Large and Right/Small). The Expertise × Trajectory interaction was significant ($F_{3,57} = 6.58$, $P < 0.05$, $\eta^2 = 0.26$). Experts reached their peak velocity sooner than the non-experts for deviations on the left, whereas the opposite was observed for deviations on the right. However, a *post hoc* test on this interaction showed no significant difference between experts and non-experts for the four deviated trajectory conditions (Table II).

Peak acceleration

Analysis of peak acceleration showed a significant main effect for Trajectory ($F_{3,57} = 5.77$, $P < 0.05$, $\eta^2 = 0.23$). *Post hoc* testing showed that peak acceleration was higher in the Left/Large condition than in the other three conditions, and that it was lower in the Right/Small condition than in the other three conditions (Table II). This indicates that the Left/Large condition was the most constraining because high peak acceleration can be considered as an attempt to compensate for large differences between the required and the current velocity of the hand.

Time required to reach peak acceleration

An ANOVA performed on time required to reach peak acceleration showed no significant main effects for Expertise and Trajectory and no interaction.

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Origin of constant error for experts and non-experts

The analysis presented above provides some evidence that interceptions were more accurate without deviation and deteriorated with the amplitude of the deviation. However, experts demonstrated increased accuracy when facing the deviated trajectories and presented shorter visuo-motor delays than non-experts. To estimate the origin of constant error accounted for by the temporal and kinematic variables, we used a forward stepwise regression. For each participant, the mean constant error calculated from the four conditions with deviated trajectories was used as a dependent variable. Constant error was used instead of absolute error because the *F*-values obtained from the previous ANOVA showed that the effect of Expertise as well as that of the Expertise × Trajectory interaction was higher for constant error than for absolute error. Consequently, constant error was considered to be a better indicator of expertise. Five independent variables, capturing adaptation of the movement following deviation of the moving target, were used as predictors: mean visuo-motor delay, peak velocity, time to reach peak velocity, peak acceleration, and time to reach peak acceleration. Note that the predictors were not or only moderately correlated.

In the first step, visuo-motor delay was the best predictor with a significant correlation of 0.78 ($F_{1,19} = 29.33$), and hence explained 61% of the total variance. In the second and final step, peak velocity was entered into the predictive equation and was found to explain an additional 17% of the total variance. In the final equation, visuo-motor delay ($\beta = 0.584$) and peak velocity ($\beta = -0.52$) explained 84% of the total variance, with a significant correlation of 0.92 ($F_{2,18} = 46.94$) (Figure 4).

Differentiating the experts

In an attempt to classify the experts on the basis of temporal and kinematic variables, forward stepwise regression analysis was conducted with national ranking as a dependent variable and the six independent variables as predictors: mean constant error, visuo-motor delay, peak velocity, time to reach peak velocity, peak acceleration, and time to reach peak acceleration (see Table III for correlations between these predictors).

In the first and last step of the forward stepwise regression, constant error was the best predictor of the players' rankings, with a significant correlation of 0.66 ($F_{1,10} = 6.86$), and hence explained 43% of the total variance (Figure 5).

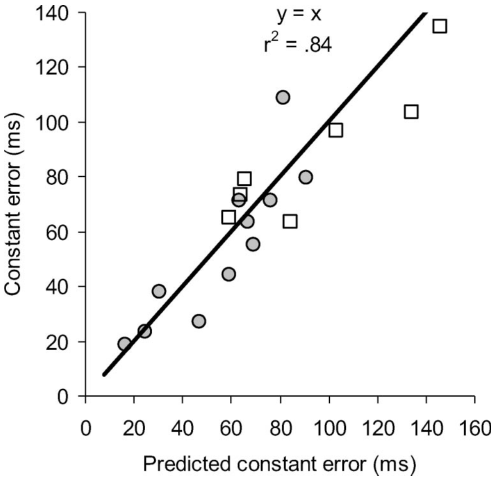

Figure 4. Constant error (CE) as a function of predicted constant error on the basis of the multiple regression analysis with visuo-motor delay (VMD) and peak velocity (v_{peak}) as predictors. The equation can be written as follows: $\text{CE} = [1.064 \times \text{VMD}] + [-52.143 \times v_{\text{peak}}] + [-70.143]$. White squares and grey circles represent non-experts and experts respectively.

Discussion

The main purpose of this study was to identify the adaptive and prospective regulating mechanisms leading to expertise in interceptive actions. To achieve this objective, we used a simulated interceptive task in which virtual falling balls were unexpectedly deviated from their regular trajectory. Analysis of absolute error and constant error showed that timing accuracy when intercepting balls falling in a central (i.e. non-deviated) rectilinear direction was very similar in experts and non-experts. For the deviated trajectories, accuracy decreased for all participants, with the larger deviation resulting in larger error, but experts minimized the error compared with non-experts, especially for the leftward deviated trajectories. Thus, our interceptive task was completed with greater accuracy by experts than non-experts in the most constraining conditions. These results confirm previous findings by Le Runigo et al. (2005), and show that experts have a higher adaptive capacity to adjust their movement when faced with a sudden change in ball trajectory (Carlton et al., 1991; McLeod, 1987).

To identify the origin of these differences in timing accuracy between experts and non-experts, analyses showed visuo-motor delay and peak velocity to be the most significant variables. These analyses indicated that, compared with non-experts, experts reacted earlier (216 vs. 240 ms) and had higher hand peak velocity (1.97 vs. 1.56 m · s^{-1}). The delays obtained in the current experiment were in a similar range to those reported by McLeod (1987), but are longer than those recorded in pointing tasks (125 ms: Day & Lyon, 2000) as well as in the study of Le

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Table III. Correlation coefficients (*r*) between the six predictors in the second regression analysis: constant error (CE), visuo-motor delay (VMD), peak velocity (v_{peak}), time to reach peak velocity ($T_{v\text{peak}}$), peak acceleration (A_{peak}), and time to reach peak acceleration ($T_{A\text{peak}}$).

	CE	v_{peak}	$T_{v\text{peak}}$	A_{peak}	$T_{A\text{peak}}$	VMD
CE	—	−0.56	0.41	−0.66*	−0.12	0.55
v_{peak}	−0.56		−0.10	0.53	−0.45	0.20
$T_{v\text{peak}}$	0.41	−0.10		−0.47	0.11	0.35
A_{peak}	−0.66*	0.53	−0.47		0.29	−0.48
$T_{A\text{peak}}$	−0.12	−0.45	0.11	0.29		−0.35
VMD	0.55	0.20	0.35	−0.48	−0.35	

Note: There were only one significant correlation (*).

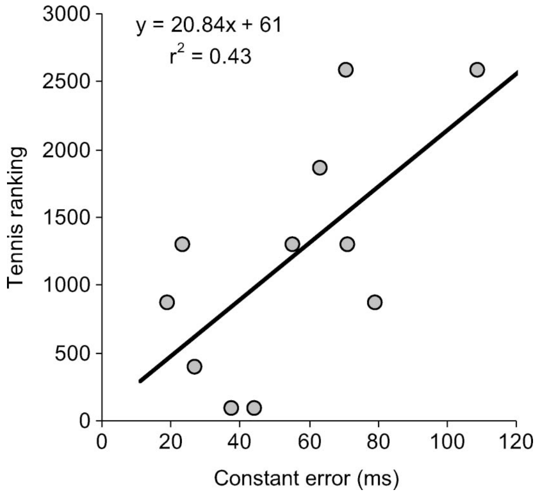

Figure 5. Correlation between national tennis ranking and constant error.

Runigo et al. (2005). This difference between tasks should not be regarded as inconsistent use of an adaptive strategy, but rather can probably be explained by the inertia required to overcome the movement of the cart along the track. The important point to emphasize, then, is that the measure of visuo-motor delay depends on the task, on the effector used, and on the type of regulation involved (e.g. Benguigui et al., 2003; Michaels, Zeinstra, & Oudejans, 2001).

We also found that the leftward deviated trajectories were characterized by a longer time to reach peak velocity and higher peak acceleration. These results indicate that larger differences occurred between the required and the current velocity of the hand, and suggest accordingly that this condition was the most constraining. These results are consistent with those obtained previously (Le Runigo et al., 2005; Teixeira, Franzoni & Da Silva, 2005a; Teixeira et al., 2005b) and can be explained by the fact that it is easier to carry out a correction in the direction of the ongoing movement (acceleration gain by the agonist muscles) than to slow down and reverse movement direction (inverting the relationship between agonist and antagonist muscles). It is interesting to note that the difference between experts and non-experts in timing accuracy also appeared to be greatest in the most constraining condition.

In an effort to explain the higher accuracy of experts, forward stepwise regression indicated that while the primary predictor (for both experts and non experts) was visuo-motor delay (61% of the total explained variance), there was also a significant contribution from individuals' capacity to reach a high velocity of the hand after ball deviation (84% of the variance explained by these two variables; Figure 4). Because time to reach peak velocity and peak acceleration were not found to be predictors of constant error, and were not different in experts and non-experts, we can assume that the additional time due to a reduced visuo-motor delay was used to reach a higher peak velocity by producing similar acceleration over a longer period. In other words, the extra time provided by a shorter visuo-motor delay was used to better adapt the interceptive movement to the deviation of the trajectory. Thus, these results are more likely to support the temporal hypothesis (i.e. experts reacted earlier) than the kinematic hypothesis (i.e. experts have a better control of actions in producing higher accelerations), even if the temporal benefit was used to reach a higher peak velocity. Moreover, a part of the variance in constant error was independently explained by peak velocity. This result suggests that in spite of our main interpretation, the kinematic hypothesis cannot be rejected.

Our results suggest that visuo-motor delay somehow reveals the efficiency of information–movement coupling and that a short visuo-motor delay enables a reduction of the discrepancy between current and required behaviour to succeed in a task (Montagne et al., 1999; Peper et al., 1994). Although the 24-ms difference in visuo-motor delay between experts and non-experts in the current study could be considered rather small, it is important to note that this reduction represents 10% of the duration of the visuo-motor delay. Therefore, if visuo-motor delay is considered to facilitate improved accuracy in

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interceptive performance by allowing more accurate control of the action based on more recent information, a gain of 10% should not be regarded as negligible. For instance, in a sport such as tennis, a reduction in visuo-motor delay by a few milliseconds could provide better accuracy in each individual stroke, which when multiplied by the several hundred strokes that comprise a single tennis match could provide a significant advantage.

Moreover, the interception accuracy in this task was a reasonable predictor of expertise as assessed by national ranking, explaining 43% of the total variance (Figure 5). This result is particularly interesting when considering that tennis performance emerges from the interaction of a myriad of parameters, and therefore that a single factor cannot in itself explain the differences in performance between experts. This is also of interest when considering that important individual differences can emerge in experts (Ripoll & Benguigui, 1999). This was the case in the current study, in that we found that while the experts had in general a constant error that was under 70 ms, two experts were above this threshold. A possible interpretation is that these two experts developed their expertise on the basis of other factors that are important in tennis, such as strength, speed in their displacement, and efficient coordination.

When considering inter-individual differences and the multiple factors involved in tennis performance, our results suggest that the visuo-motor capacities involved in a coincidence timing task could play a significant role in climbing the rankings, and that our task is a reliable indicator of these visuo-motor capacities. Thus we achieved our aim of distinguishing between experts, an enterprise that has rarely been tackled in previous investigations of ball sport expertise (but see Gray, 2002, for an analysis of simulated baseball). Although these results need to be confirmed and reproduced on a larger scale (i.e. with more players and young experts in a longitudinal design), the paradigm of deviated trajectories appears, even in simulated conditions, to be a means of identifying expertise in ball sports and of contributing to talent detection.

It has to be noted that in spite of the use of a simplified interceptive task, which was quite distinct from the circumstances that tennis players face on the court (rectilinear instead of parabolic trajectories with speeds that were significantly lower than the speeds of a tennis ball in match-play), this experiment revealed clear differences not only between experts and non-experts but also among experts. Although the task was much simplified, and the use of spatio-temporal constraints only permitted a 400-ms window in which to adapt movement after a deviation that could occur in 50% of the trials with four different possible directions, it was sufficient to reveal expertise. Contrary to what is frequently proposed, here it is not the ecological validity of the task that was essential to capture the determinants of expertise, but rather the involvement of the processes capturing expertise at a sufficient high level of constraints (Ericsson, 2003).

It is important to comment on the origin of such increased accuracy and short visuo-motor delay in expert interceptions. As noted above, it is important to emphasize that the origin of expertise is a complex issue. Our results do not allow us to speculate about some potential intrinsic individual differences that could have influenced adaptive behaviour. However, it is quite clear that intensive practice is necessarily involved in differences between experts and non-experts. With practice, the relationship between the actor and the environment evolves with the establishment and refinement of more accurate information–movement couplings. Arguing in favour of this viewpoint, Savelsbergh and van der Kamp (2000) considered that sport training starts with the emergence and the strengthening of a coupling between information and movement. With further practice, this coupling is reinforced or transformed according to the relevant constraints. Thus, new couplings can be set up to replace those discovered to be inappropriate during practice. Expertise can thus depend either on a capacity to exploit the various visuo-motor couplings and to switch from one to another to be more efficient in particular circumstances, or on a capacity to optimize one or more specific control laws in the search for increased movement accuracy. In this experiment, we explored this second aspect of expertise in revealing a strengthened coupling in experts with shorter delays between the perception of temporal information in ball trajectory and movement regulation.

In summary, our results show that the deviated ball paradigm can lead to significant differences between experts and non-experts in tennis. Experts were able to minimize errors, especially for the leftward deviated trajectories, to react earlier and to produce movements with a higher hand velocity. These results confirm the hypothesis previously suggested by McLeod (1987) and Carlton et al. (1991) that experts have higher adaptive capacities to adjust their movement when faced with a sudden change in ball trajectory. In addition, our multiple regression analysis revealed that a shorter visuo-motor delay, associated with the capacity to reach a higher velocity of the hand after ball deviation, consistently explained interception accuracy. Finally, this accuracy was a reasonable predictor of expertise. Thus, visuo-motor delay somehow reveals the efficiency of the information–movement loop, with a short visuo-motor delay allowing a reduction in the discrepancy between current and required behaviours.

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