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Perception–action coupling and expertise in interceptive actions

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Abstract

The goal of this experiment was to show that expertise in interceptive actions can be explained by a shorter delay in movement regulation. In this contribution, we tested tennis experts and non-experts using a simulated interceptive task. The experimental device simulated linear motion of an object toward a target on a horizontal runway. Participants had to intercept the simulated moving object with their right hand holding a cart that could slide along a horizontal track perpendicular to the runway. Three different velocity conditions were used: a constant velocity condition that maintained the initial velocity (2 m/s) constant until arriving on the target; the decelerated and accelerated velocity conditions, in which the velocity suddenly changed (400 ms before its arrival on the target) from 2 to 1 m/s or 3 m/s, respectively. Timing accuracy and movement correction after the unexpected velocity change were analysed. The experts were more accurate in the decelerative case (−29 and −124 ms respectively), in the accelerative case (69 and 116 ms respectively), but not in the constant velocity case (2 and 13 ms respectively). Findings can be explained by the shorter visuo-motor delay (VMD: the time required to adapt the movement to the new velocity) for the experts (162 ms) than for the non-experts (221 ms). This shorter VMD offers more time to adapt the interceptive movement to the new velocity. These results can be interpreted as an optimization of the perception–action coupling with expertise.

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1. Introduction

Interceptive skills require the ability to coordinate body and arm movements with (action-related) environmental information. Consider, for example, the tennis player who runs to catch a drop shot or the baseball player who moves to catch a fly ball. In such skills, the window for accurate interception can be less than 10 ms (e.g., McLeod, McLaughlin, & Nimmo-Smith, 1986). This level of accuracy suggests a very precise and efficient relationship between perceptual and motor processes so that the actor may detect and use information to continuously adapt his/her action to the approaching ball. The action is organized for the adaptive regulation movement on the basis of a continuous coupling between the perceptual and motor systems (Warren, 1988).

Bootsma, Houbiers, Whiting, and van Wieringen (1991) proposed a "funnel like type of control" metaphor to describe more closely the operation of this type of control. A discrepancy between the current behaviour and the required behaviour to succeed in the task would give rise to regulations. The higher the vicinity of contact, the more systematic regulations in order to cancel this discrepancy (see also the results of Montagne, Cornus, Glize, Quaine, & Laurent, 2000a which are in agreement with the funnel metaphor).

Peper, Bootsma, Mestre, and Bakker (1994) proposed the required velocity model to explain visual control in interceptive tasks. This model links hand acceleration to an optical invariant which specifies the discrepancy between the current hand velocity and the required hand velocity to succeed in the task. The actor has to regulate his/her action according to the required hand velocity, which acts as a reference value. The results presented by Montagne, Laurent, Durey, and Bootsma (1999) provide support for this model (but see Dessing, Bullock, Peper, & Beek, 2002 and Beek, Dessing, Peper, & Bullock, 2003 for an optimization of this model).

Bootsma and van Wieringen (1990) illustrated this perception–action coupling in ball sports by analyzing the timing of attacking forehand drives produced by high-level table tennis players. They showed that the variability in racket orientation across trials was greater at the beginning of the movement than at the moment of ball–racket contact. The large decrease in movement variability with the approach of the ball and the extreme accuracy of contact in expert players were interpreted by the authors as being the result of a continuous regulation of the movement with the approach of the ball or, in other words, as the result of a strong coupling between perception and action (see also Bootsma et al., 1991). This hypothesis was also suggested by Tresilian (1995) who argued that the nature of perception–action coupling could become more specific with practice. A more specific coupling could be for experts to produce more adapted and accurate regulations tuned to the approach of the ball.

On the temporal level, expertise in ball sports could be linked to shorter latencies in the perception–action coupling or to shorter visuo-motor delays (VMD) in the regulation of actions. VMD[1] is generally defined as the time period between visually registering some information to be used to produce an adjustment and the resulting observable movement (e.g., Brenner, Smeets, & Lussanet, 1998; Carlton & Carlton, 1987; Tresilian, 1993). In interceptive actions, VMD has been estimated to lie somewhere between 100 and 200 ms, depending on various factors (e.g., Michaels et al., 2001). Whiting, Gill, and Stephenson (1970) showed, in a ball-catching experiment in which the final part of the trajectory was occluded, that catching performance was affected by occlusion conditions as short as 100 ms, implying that visual information was used within this period. Bootsma and van Wieringen (1990), in their table-tennis ball-striking task, as well as Savelsbergh, Whiting, and Bootsma (1991) using a catching task, observed that the variability of the movement across trials was minimal about 100 ms before contact. They concluded that the phase of minimal variability corresponded to the very end of the regulation window and that this time interval might correspond to VMD.

In contrast with these results, some researchers have shown longer VMD in interceptive actions. Lee et al. (1983) suggested that VMD could be longer when information was used to initiate the action than when it was used to control an action already in progress. This suggestion was confirmed by Michaels et al. (2001) as well as Benguigui, Ripoll, and Broderick (2003) who showed that the VMD between the occurrence of the critical information to start action and the beginning of the action was indeed around 200 ms.

After having established that the direction in which the hand moved was continuously adjusted on the basis of the perceived position of the target, with a 110 ms delay (Brenner & Smeets, 1997), Brenner et al. (1998) showed longer VMDs in a hitting task. In their task, the velocity of the moving target (4.5 or 7.5 cm/s) could change suddenly, with an increase or a decrease of 3 cm/s. Movement adaptation, which corresponded in this case to the acceleration pattern of the hand, was noticeable 200 ms after the change in target velocity. Brenner et al. (1998) argued that the longer VMD could originate from the time required to detect the unpredictable velocity change (for a similar proposition, see Bootsma & van Wieringen, 1990).

In sum, the duration of VMD appears to depend on the subsequent manner in which the information is used. It can be as short as 100 ms when information is used

[1] Even if some authors have recently introduced the term "interval" to replace the term "delay" (Caljouw, van der Kamp, & Savelsbergh, 2004a, 2004b; Michaels, Zeinstra, & Oudejans, 2001, note 4) we prefer to keep the term visuomotor delay which was initially proposed by Lee in his initial work on interceptive actions (e.g., Lee, Young, Reddish, Lough, & Clayton, 1983). The term "delay" has been rejected by Michaels et al. (2001, note 4) as well as by Caljouw et al. (2004a, 2004b) because it could suggest minimization and fixed amplitude. Even though we share the idea that delay can vary from one individual and situation to another as a function of task constraints, level of attention given to the source of information, intention of the actor as well as individual factors, we do not see anything in the term "delay" that would prevent translating this variability. Regarding the idea of minimization, we think that this experiment suggests that the inertia of the visuo-motor system is an important variable that constrains efficiency in interceptive actions and that the use of the term "delay" translates this idea rather well.

during the on-line regulation of the movement, but can reach values near 200 ms when information is used to produce more discrete movements, such as the beginning of the movement or some important correction of that movement. Moreover, longer delays of adjustments could be due partly to the inertia of the limbs to be overcome, for example in an action of striking a ball with a cricket bat (McLeod, 1987). The increase in VMD for discrete movements could be due to the increase in the complexity of the motor commands and/or to the increase in the inertia of the limbs to be overcome (McLeod, 1987).

If the duration of VMD clearly depends on the type of regulation involved, one can suppose that it also depends on the level of expertise of the performer. McLeod (1987) was the first to test the idea that experts in ball sports could have a shorter VMD. He analyzed the movement of high-level cricket batters and hypothesized that they would be able to adapt their action to an unexpected deviation of the ball on the ground in a time shorter than implied through traditional measures of experimental reaction time (RT), as measured on a press-button response (e.g., Keele & Posner, 1968). The proposed VMDs for correction were in the order of 190–240 ms. These values partially confirmed the hypothesis and were not very different from a simple experimental RT (e.g., Hick, 1952). However, these values could be deemed to be very short if one takes into account the weight of the bat and the inertia that must be overcome in order to start a correction, and the unpredictability of the change in ball trajectory. Furthermore, VMD should be compared to multiple choice RT, that is a function of the number of possible responses, and is typically greater than 200 ms (e.g., Hyman, 1953).

McLeod's (1987) results were confirmed by Carlton, Carlton, and Kim (1991, reported by Carlton, 1992) in an experiment in which expert tennis players had to carry out forehand shots to execute balls that could bounce unexpectedly fast or slow. The various rebounds were obtained by placing on selected portions of the court surface either smooth tape or a rough texture surface. Participants were able to adapt their responses (i.e., acceleration or deceleration of their swing) in the time interval between 150 and 190 ms.

It should be noted that the data obtained from these two studies do not make it possible to determine if the delay in adapting the action can truly be regarded as one of the determinants of expertise in ball sports because the comparison was not carried out according to the players' level of expertise. An important issue is whether experts may demonstrate faster VMD when faced with unexpected events. We could speculate that the necessary delays due to the perception–action coupling in all catching or hitting actions are shorter in experts. Shorter delays would, in the end, explain why experts are more precise when carrying out such actions.

The purpose of this study, inspired by McLeod's (1987) and Carlton's (1992) results, was to test this assumption. Tennis experts and non-experts were tested in an interception task in which the velocity of the stimulus to be intercepted could vary in an unexpected way (acceleration or deceleration). We aimed to show that experts managed to preserve higher levels of accuracy than non-experts in these constraining conditions. If this is confirmed, it would validate our assumption that experts display better perception–action coupling, allowing them to be better tuned to the new stimulus velocity. The origin of the expert's enhanced perception–action coupling could be twofold. A first assumption (*temporal hypothesis*) is that the experts' greater accuracy comes from faster corrections, thus leaving more time to adjust their movement to the new velocity. A second assumption (*kinematic hypothesis*) states that the enhanced accuracy is the result of more adapted corrections. Some examples of this latter hypothesis would include larger accelerations of the hand in an accelerated condition, and conversely larger decelerations of the hand in a decelerated condition. It may even be that the expert's superiority over the novice comes jointly from faster (temporal hypothesis) and better adapted (kinematic hypothesis) corrections.

2. Method

2.1. Participants

Twenty right-handed males between 18 and 30 years of age (mean of 23 years) participated in the experiment. Two groups were created: a group of 10 expert tennis players and a group of 10 non-experts. Experts were French tennis players ranked in the top 1000 players in the country. Non-expert participants had never practiced any type of ball sport outside of school.

2.2. Apparatus

The experimental device consisted of a runway (4 m long, 7 cm deep and located 1.2 m above the ground), with 200 light-emitting diodes (LEDs) that simulated a linear motion of an object, and a cart that could slide along a horizontal track perpendicular to the runway. Participants had to intercept the simulated moving object with their right hand holding a cart moving on the rectilinear track. The interceptive movement was carried out at a distance of 0.80 m of the track (see Fig. 1).

The successive illumination of the LEDs, that were positioned at fixed intervals, simulated an apparent movement of an approaching object. The illumination frequency ranged from 50 to 150 Hz depending on the stimulus velocity presented in the experimental conditions. The stimulus moved horizontally from left to right toward a target situated at the extreme far end of the runway. The target was represented by two green[2] LEDs, placed above and below the last LED. The same apparatus has been previously used by Benguigui et al. (2003).

Forty-one contactors, placed 2 cm apart under the cart's path, were used to detect the position and timing of the sliding cart on the track. The first contactor, placed on the track at the beginning of the cart trajectory, allowed the recording of movement initiation. The last contactor, placed on the track at the point of contact between the mobile and the cart, was used to compute the accuracy of the interception. The

[2] For interpretation of the references in colour in this figure, the reader is referred to the web version of this article.

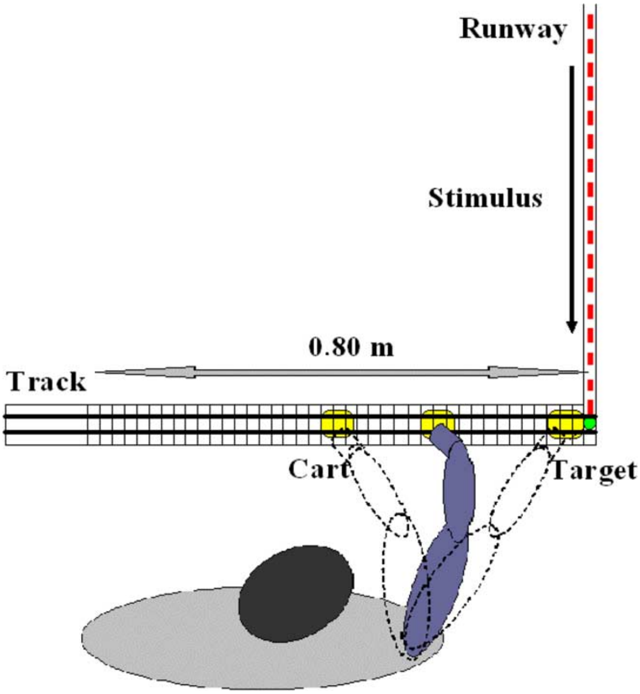

Fig. 1. The experimental device employed.

illumination timing of the LEDs, the trial onset and the data acquisition on the position and timing of the cart were synchronized using the Labview software at a sampling frequency of 200 Mhz. The time interval between the effective arrival of the moving stimulus and the cart on the target corresponded to the constant error (CE). When the car reached the target before the arrival of the stimulus, CE was marked with a negative sign. When it reached the target after the stimulus, CE was marked with a positive sign. Velocity and acceleration of the cart were calculated using the first- and second-order time-derivatives of the cart's position, respectively. The accuracy of the system depends on the actor's movement velocity, because the higher the velocity, the more numerous the data. When the change in velocity occurred, the velocity of the hand for all participants was generally increasing and at least 1 m/s. This means that the frequency of acquisition at and after that moment was equal or superior to 50 Hz.

2.3. Velocity conditions

Three different velocity conditions were used during the test. They all had the same initial velocity (IV = 2 m/s). The constant velocity condition maintained the initial velocity constant until arriving on the target. The stimulus was presented during a total time (TT) of 1450 ms. In the two other velocity conditions, the velocity of

Table 1
Characteristics of the stimulus velocity

Experimental conditions	Constant velocity condition (2 m/s)	Decelerated velocity condition (2–1 m/s)	Accelerated velocity condition (2–3 m/s)
IV: Initial velocity	2	2	2
TVC: Time after which the velocity changes		1050	1050
FV: Final velocity	2	1	3
TTC-IV: Time-to-contact based upon initial velocity	400	400	400
TTC-FV: Time-to-contact based upon final velocity	400	800	266
ECE: Expected constant error which would be obtained if no correction were produced	0	−400	133
TT: Total time during which the stimulus was visible	1450	1850	1316

the moving stimulus suddenly changed 1050 ms after the beginning of the trial or, equivalently, 400 ms before its arrival on the target, based on initial velocity. This time was called the time-to-contact based on initial velocity (TTC-IV). In the decelerated velocity condition, the velocity changed from 2 to 1 m/s. After the velocity change, the time-to-contact based on final velocity (TTC-FV) changed to 800 ms. The total time (TT) of the stimulus displacement was 1850 ms. In the accelerated velocity condition, the velocity changed from 2 to 3 m/s. After the velocity change, the time-to-contact based on final velocity (TTC-FV) changed to 267 ms. The total time (TT) of the stimulus displacement was 1317 ms. In both conditions of velocity change, it was possible to calculate a CE which would be obtained if no correction were produced by the participants (the expected constant error: ECE). ECE corresponded to the difference between TTC-IV and TTC-FV. ECE was −400 ms in the decelerated velocity condition and 133 ms in the accelerated velocity condition. Table 1 summarizes the various conditions of stimulus velocity.

The amount of velocity change was selected to be well above the threshold value that is generally found to be sufficient to allow the perception of a variation. It has been shown that a velocity change of 20–25% is necessary to detect acceleration or deceleration (e.g., Babler & Dannemiller, 1993; Benguigui et al., 2003; Brouwer, Brenner, & Smeets, 2001). In our experiment, the velocity changes were set at 50% (2–1 m/s in the decelerated velocity condition and 2 to 3 m/s in the accelerated velocity condition).

2.4. Procedure

The test was preceded by two blocks of training with six trials in each block. Each block contained four constant velocity trials (2 m/s), one decelerative trial (2–1 m/s), and one accelerative trial (2 to 3 m/s). The training session was considered to be successful when the participant was able to produce at least four responses out of six with CE lying in the interval [−100 to +100 ms]. All participants met these requirements after two blocks of practice.

The experimental session followed the practice period and contained two blocks of 20 trials. A block contained 10 trials of constant velocity, and 5 trials in each condition of velocity change. Trials were randomly presented within the first block and in opposite order in the second block, so as to ensure that the order of presentation was counterbalanced. After each trial, the experimenter informed the participant of the level of accuracy achieved (in ms). The experiment lasted approximately 1 h.

3. Data analysis and results

3.1. Errors

For each participant and in each velocity condition, CE and variable error (VE) were calculated. CE values were used as an indicator of response accuracy. VE corresponded to the standard error calculated from the signed errors. VE provided information about the dispersion of the errors.

CE and VE scores were statistically analyzed using an Expertise (experts, non-experts) × Velocity (constant, accelerated, decelerated) analysis of variance (ANOVA), with repeated measures on the second factor. The level of significance was fixed at .05. The effect size (η^2) is reported and Newmann–Keuls post hoc analysis was used when necessary to detail main effects and interactions.

CE: Mauchly's test of sphericity highlighted a significant violation of the sphericity assumption for repeated measures ANOVA, $\chi^2(2) = 30.55$, $p < .05$. We used the Greenhouse–Geisser procedure to adjust the degrees of freedom with $\varepsilon = .55$. The ANOVA on CE shows a significant effect for velocity ($F(1.09, 19.63) = 52.39$, $p < .05$, $\eta^2 = .74$). The Expertise × Velocity interaction was significant ($F(1.09, 19.63) = 9.98$, $p < .05$, $\eta^2 = .36$). Post hoc analysis revealed a significant difference between experts and non-experts in the change in velocity conditions, with the experts being more accurate than the non-experts in the decelerative case (respectively −29 and −124 ms), in the accelerative case (respectively 69 and 116 ms), but not in the constant velocity case (respectively 2 and 13 ms) (Fig. 2).

In the decelerated velocity condition, a one-tail independent samples t-test comparing CE for non-experts (−124 ms) and experts (−29 ms) to ECE (−400 ms) showed that both groups had lower CE than ECE ($t(9) = 5.85$, $p < .05$, $\eta^2 = .39$ and $t(9) = 47.65$, $p < .05$, $\eta^2 = .84$, respectively). In this condition, all participants had enough time to produce corrections in their movement to reduce errors. In the accelerated velocity condition, the same type of analysis showed that CE for experts (69 ms) differed from ECE (133 ms) ($t(9) = -7.91$, $p < .05$, $\eta^2 = .47$), while no significant difference was found for non-experts (116 ms) ($t(9) = -1.20$, $p > .05$, $\eta^2 = .12$). In this condition, the time length after the velocity change was probably too short for non-experts to produce corrections in their movements.

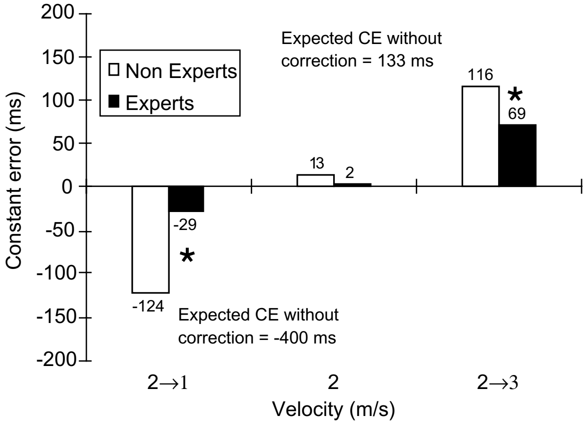

Fig. 2. CE for experts and non-experts as a function of the velocity conditions ($2 \rightarrow 1$: decelerated velocity condition; 2: constant velocity condition; $2 \rightarrow 3$: accelerated velocity condition). The stars indicate significant differences ($p < .05$). Expected CE without correction are given in the figure.

VE: Mauchly's test of sphericity highlighted a significant violation of the sphericity assumption for repeated measures ANOVA, $\chi^2(2) = 36.79$, $p < .05$. We used the Greenhouse–Geisser procedure to adjust the degrees of freedom with $\varepsilon = .53$. The ANOVA on VE showed a significant effect for expertise ($F(1,18) = 16.45$, $p < .05$, $\eta^2 = .48$), and for velocity ($F(1.06, 19.10) = 37.76$, $p < .05$, $\eta^2 = .68$). The Expertise × Velocity interaction was also significant ($F(1.06, 19.106) = 10.07$, $p < .05$, $\eta^2 = .36$). Post hoc analysis indicated a significant difference between experts and non-experts only in the decelerated velocity condition (57 and 134 ms respectively, see Fig. 3). This suggests a greater amount of regulation in that condition and more difficulties for the non-expert participants to regulate their movement.

3.2. Testing the temporal hypothesis (TH)

Three temporal variables (TV) were calculated to test the TH. Each one of these variables corresponds to a time interval between two distinct events.

(TV1): VMD was calculated for each participant. VMD was the time separating the discrete velocity change of the stimulus from the first functional consecutive movement adaptation. To calculate VMD, we compared across each of the three velocity conditions, using an ANOVA test, the values of the cart acceleration at each contactor, for all trials of the same participant. Movement adaptation was detected by the appearance of a significant difference among accelerations in the three velocity conditions (see Fig. 4).

(TV2): The time (T) necessary to reach the minimal velocity (V_{min}) or the maximal velocity (V_{max}) after the velocity change (VC), ($T[VC_{to} V_{min}]$ and $T[VC_{to} V_{max}]$), was also calculated.

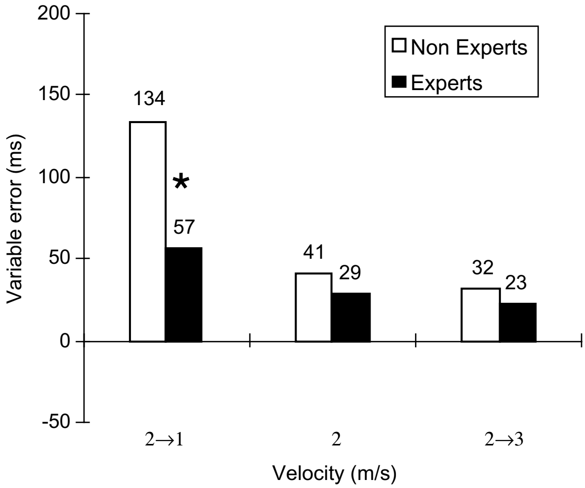

Fig. 3. VE for experts and non-experts as a function of the velocity conditions ($2 \rightarrow 1$: decelerated velocity condition; 2: constant velocity condition; $2 \rightarrow 3$: accelerated velocity condition). The star indicates a significant difference ($p < .05$).

(TV3): Similarly, the time (T) necessary to reach $V_{\min}$ or $V_{\max}$ after the first functional movement correction (VMD), ($T[\mathrm{VMD}_{\mathrm{to}}V_{\min}]$ and $T[\mathrm{VMD}_{\mathrm{to}}V_{\max}]$), was calculated.

VMD scores were analyzed with an independent samples t-test comparing the experts and the non-experts while $T[\mathrm{VC}_{\mathrm{to}}V_{\min}]$ and $T[\mathrm{VC}_{\mathrm{to}}V_{\max}]$ and $T[\mathrm{VMD}_{\mathrm{to}}V_{\min}]$ and $T[\mathrm{VMD}_{\mathrm{to}}V_{\max}]$ were analysed with an Expertise (experts, non-experts) × Velocity (accelerated, decelerated) ANOVA, with repeated measures on the second factor.

VMD (TV1): The t-test revealed a significant effect of the expertise factor on VMD ($t(18) = 4.77$, $p < .05$, $\eta^2 = .21$). The VMD reached 221 ms for the non-experts (ranging from 185 to 298 ms) and 162 ms for the experts (ranging from 127 to 185 ms). The experts had, on average, a VMD 59 ms shorter than the non-experts.

$T[\mathrm{VC}_{\mathrm{to}}V_{\min}]$ and $T[\mathrm{VC}_{\mathrm{to}}V_{\max}]$ (TV2): ANOVA indicated no significant effect for expertise. The time needed by the experts to reach $V_{\min}$ or $V_{\max}$ after the velocity change was not significantly different from that of the non-experts (442 vs 466 ms). There was however a significant effect for velocity ($F(1,18) = 138.68$, $p < .05$, $\eta^2 = .89$): The time needed to reach $V_{\min}$ and $V_{\max}$ after the change in velocity was respectively 575 and 333 ms, in the decelerated and accelerated velocity conditions. This difference is due to the TTC values after the velocity change (800 ms in the decelerated velocity condition vs 267 ms in the accelerated velocity condition). The Expertise × Velocity interaction was not significant.

$T[\mathrm{VMD}_{\mathrm{to}}V_{\min}]$ and $T[\mathrm{VMD}_{\mathrm{to}}V_{\max}]$ (TV3): ANOVA revealed a significant effect for expertise ($F(1,18) = 4.75$, $p < .05$, $\eta^2 = .21$). The time needed to reach $V_{\min}$ or $V_{\max}$ after the VMD was longer for experts than that for non-experts (280 vs 245 ms). Moreover, a significant main effect was also found for velocity ($F(1,18) = 197.14$, $p < .05$, $\eta^2 = .92$), indicating that the time needed to reach $V_{\min}$

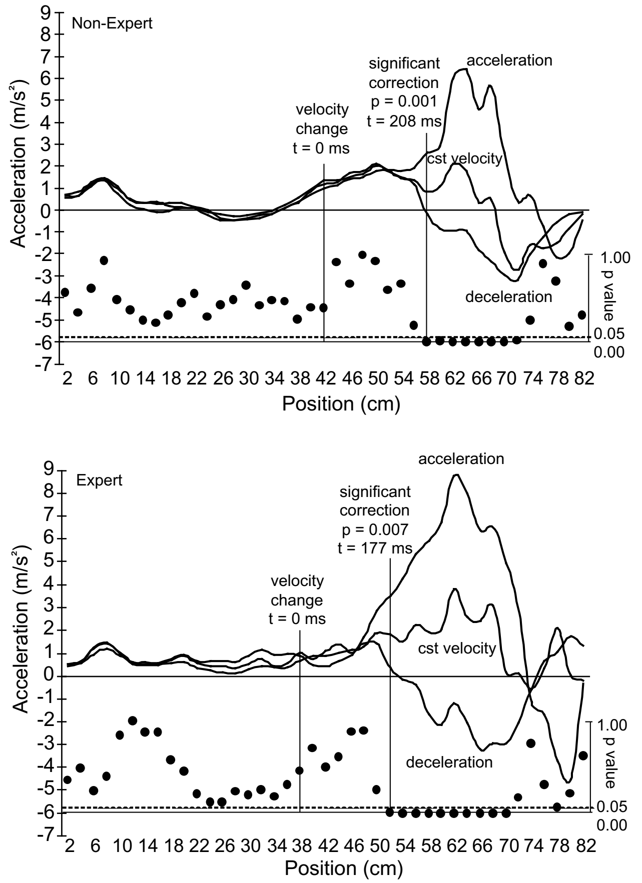

Fig. 4. Typical acceleration of the cart and p value given by an ANOVA (constant velocity vs acceleration vs deceleration) according to its position for one non-expert (above) and one expert participant (below).

and V_{max} after the VMD was 384 and 141 ms, in the decelerated and accelerated velocity conditions, respectively. The Expertise × Velocity interaction was not significant.

3.3. Testing the kinematic hypothesis (KH)

To check if differences appeared between experts and non-experts in movement kinematics, several kinematics variables (KV) were calculated:

(KV1): We analysed V_{min}, reached after the velocity change in the decelerated velocity condition, and V_{max}, reached after the velocity change in the accelerated velocity condition.

(KV2): We also computed, in the decelerated and accelerated velocity conditions, the average deceleration and the average acceleration of the hand (H_{dec} and H_{acc}),

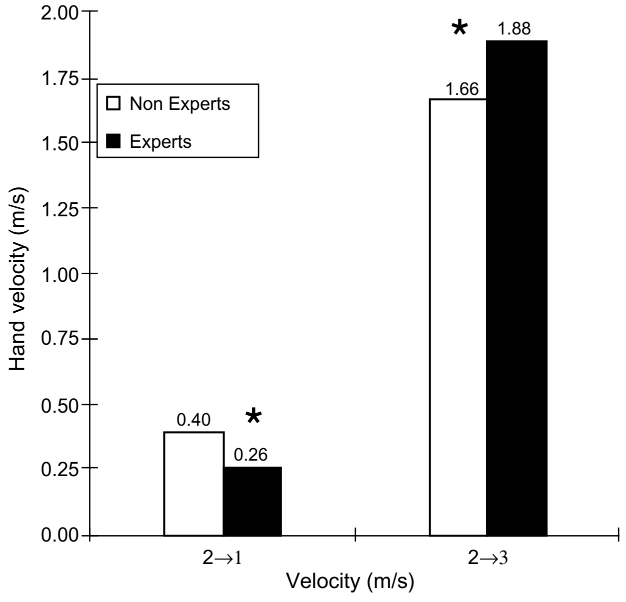

Fig. 5. V_{min} (left) and V_{max} (right) of experts and non-experts as a function of the velocity conditions ($2 \rightarrow 1$: decelerated velocity condition; $2 \rightarrow 3$: accelerated velocity condition). The stars indicate a significant difference ($p < .05$).

after the first functional movement correction (VMD) and until the reaching of V_{min} or V_{max} (respectively $H_{dec}[\mathrm{VMD}_{to}V_{min}]$ and $H_{acc}[\mathrm{VMD}_{to}V_{max}]$).

The data sets for both variables were analysed using an Expertise (experts, non-experts) × Velocity (accelerated, decelerated) ANOVA, with repeated measures on the second factor.

V_{min} and V_{max} (KV1): ANOVA showed a significant effect of velocity ($F(1,18) = 392.46$, $p < .05$, $\eta^2 = .96$). A Expertise × Velocity interaction was also observed ($F(1,18) = 6.25$, $p < .05$, $\eta^2 = .26$, see Fig. 5). Post hoc analysis indicated a significant difference between experts and non-experts in the two velocity conditions. The experts' V_{min} values were lower than those for the non-experts when there is a deceleration (respectively 0.26 and 0.40 m/s), conversely, their V_{max} values were higher when there is an acceleration (respectively 1.88 and 1.66 m/s).

$H_{dec}[\mathrm{VMD}_{to}V_{min}]$ and $H_{acc}[\mathrm{VMD}_{to}V_{max}]$ (KV2): ANOVA indicated a significant effect for velocity ($F(1,18) = 57.49$, $p < .05$, $\eta^2 = .76$): Participants had an average deceleration of -1.88 m/s^2 after VMD when the stimulus decelerated, and an average acceleration of 5.99 m/s^2 after VMD when it accelerated. There was no effect of expertise, and no interaction.

3.4. Explaining CE of experts and non-experts

Finally, in order to incorporate the above results and estimate the proportion of variance for CE accounted for by temporal and kinematic variables, a forward stepwise regression was used. For each participant, we calculated the difference between CE in the accelerated velocity condition and CE in the decelerated velocity condition [$\Delta(CE_{acc} - CE_{dec})$]. Large differences meant less accuracy and little movement regulation after the sudden change in velocity. Five variables capturing movement adaptation following velocity change were used as predictors:

1. VMD (TV1);
2. $T[VC_{to}V_{max}]$ in the accelerated velocity condition and $T[VC_{to}V_{min}]$ in the decelerated velocity condition (TV2);
3. $T[VMD_{to}V_{max}]$ in the accelerated velocity condition and $T[VMD_{to}V_{min}]$ in the decelerated velocity condition (TV3);
4. difference between V_{max} of the hand (measured in the accelerated velocity condition) and V_{min} of the hand (measured in the decelerated velocity condition), $\Delta(V_{max} - V_{min})$. This variable is related to what can be called the "length of the movement adaptation" (KV1);
5. difference between acceleration of the hand (measured in the accelerated velocity condition) and deceleration of the hand (measured in the decelerated velocity condition) Δ(Acc–Dec); This variable is related to what can be called the "intensity of movement adaptation" (KV2).

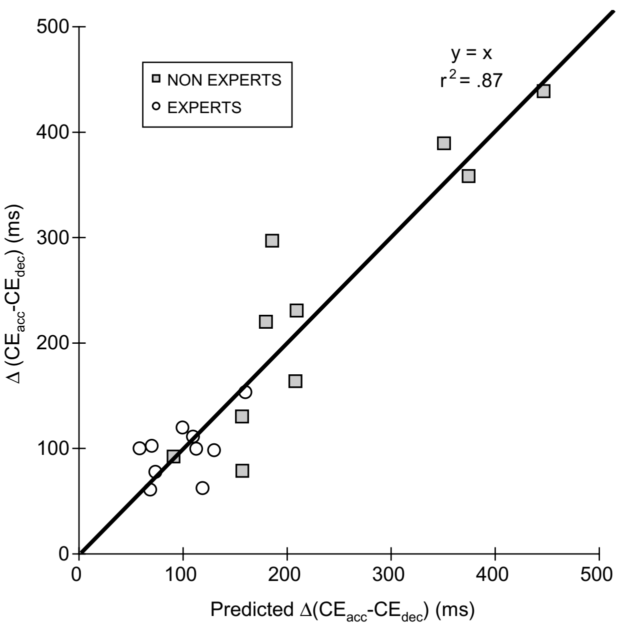

Fig. 6. The observed difference between CE in the accelerated velocity condition and CE in the decelerated velocity condition [$\Delta(CE_{acc} - CE_{dec})$] as a function of the predicted difference calculated on the basis of a multiple regression analysis with VMD, $T[VMD_{to}V_{min/max}]$, and "length of the movement adaptation" as predictors. The equation can be written as follow: $\Delta(CE_{acc} - CE_{dec}) = [1.38 \times VMD] - [0.65 \times T[VMD_{to}V_{min/max}]] - [86.75 \times \Delta(V_{max} - V_{min})] + 201$.

In the first step, VMD was the best predictor of $\Delta(CE_{acc} - CE_{dec})$ with a significant correlation of. 88 [$F(1,18) = 59.98$], which explained 77% of the total variance. In the second step, $T[VMD_{to} V_{min/max}]$ entered the equation. VMD ($\beta = .694$) and $T[VMD_{to} V_{min/max}]$ ($\beta = -.29$) explained 82% of the total variance with a significant correlation of .91 [$F(2,17) = 38.67$]. Finally, in the third and last step, the "length of the movement adaptation" entered the equation. VMD ($\beta = .486$), $T[VMD_{to} V_{min/max}]$ ($\beta = -.39$) and "length of the movement adaptation" ($\beta = -.28$) explained 87% of the total variance with a significant correlation of .93 [$F(3,16) = 35.72$]. The equation of the multiple regression analysis is detailed on Fig. 6 and can be expressed as follow: $\Delta(CE_{acc} - CE_{dec}) = [1.38 \times VMD] - [0.65 \times T[VMD_{to} V_{min/max}]] - [86.75 \times \Delta(V_{max} - V_{min})] + 201$.

This analysis indicates that a shorter VMD allows for better accuracy because it leaves more time to reach high velocity and low velocity in the accelerated and decelerated velocity conditions, respectively. The longer time period is used to better adapt the movement to the velocity change. Fig. 6 shows that experts are clustered together while non-experts are scattered along the regression line. Three non-experts have errors that resemble the expert errors, but the majority of the non-experts have greater errors that are very well predicted by the three components of the multiple regression.

4. Discussion

The goal of this experiment was to examine whether expertise in interceptive actions is explained by more refined perception–action coupling. By carrying out this experiment away from the tennis court and grounding it in a simplified task that kept the major perception–action properties of the real game, we had the advantage of eliminating various type of procedural knowledge related to sports activity that certain participants possessed. The purpose of this procedure was to capture one of the essential and most basic determinants of expertise. We expected fewer or no errors from experts due to faster corrections (temporal hypothesis) and/or more adapted corrections (kinematic hypothesis).

The results for CE show that experts, and non-experts, have the ability to adapt their movement to a sudden change in velocity, but not sufficiently to obtain an accuracy equivalent to that obtained with constant velocity. This is due to the late occurrence of the velocity change (400 ms before the contact). In these constraining conditions, experts show greater adaptive abilities than non-experts. These abilities allow them to minimize CE, since they are more accurate (−29 vs −124 ms in the decelerated velocity condition and 69 vs 116 ms in the accelerated velocity condition). This first result confirms our assumption and suggests a more efficient perception–action coupling in experts than in non-experts.

Similarly, the results for VE indicate that experts exhibit more stability than non-experts (36 vs 69 ms, all conditions mixed). This is particularly true in the decelerated velocity condition, which leaves much time to adapt the action to the new velocity (respectively 57 vs 134 ms for experts and non-experts). This finding could mean that experts manage with more ease and regularity to reduce the discrepancy between their current behavior and the required behavior to succeed in the task after the velocity change (Bootsma & van Wieringen, 1990; Peper et al., 1994).

To explain the origin of the differences between experts and non-experts, one can use the VMD analysis as a reference. The VMD values obtained in the current experiment ranged between 125 and 295 ms for all participants (mean = 192 ms) and are in agreement with those obtained in similar experiments (e.g., Benguigui et al., 2003; Brenner et al., 1998). The most interesting result is the great discrepancy between experts and non-experts (162 vs 221 ms). Experts spent on average 59 ms less (i.e., 31% of the VMD) to start to adapt their movement to the velocity change. VMD values measured for experts are shorter than those reported by McLeod (1987), ranging between 190 and 240 ms, and Carlton (1992), between 150 and 190 ms, undoubtedly because there was less inertia to be overcome in our task than in an action of striking a ball with a cricket bat or tennis racket. The measurement of VMD in a behavioral study indeed depends upon the action performed and the effector used (e.g., Benguigui et al., 2003; Michaels et al., 2001).

The shorter VMD for experts enable them to spend more time on regulation. The amount of time needed after VMD to reach V_{min} (by decelerating the hand velocity in the decelerated velocity condition) or V_{max} (by accelerating the hand velocity in the accelerated velocity condition) was greater in experts than in non-experts (280 vs 245 ms). This makes it possible for the experts to reach a lower V_{min} than the non-experts (0.26 vs 0.40 m/s) in the decelerated velocity condition and a higher V_{max} (1.88 vs 1.66 m/s) in the accelerated velocity condition. In doing so, experts have a longer time for regulation. It should be noted that in the decelerated velocity condition, experts reached V_{min} well before the end of their movement, leaving themselves more time (204 vs 94 ms for the non-experts, $p < .05$) to accelerate their movement one more time (increase in speed of 0.26 vs 0.10 m/s for the non-experts, $p < .05$). This undoubtedly leads to better accuracy (−29 vs −124 ms) and confirms our assumption that experts are able to be better tuned again to the required behavior to succeed in the task after the velocity change. On the other hand, experts do not show a better ability to produce greater acceleration or deceleration in their movement after the velocity change than non-experts. For example, more important accelerations would have made it possible for experts to much more minimize their errors in the accelerated condition (69 ms). From this point of view, experts' corrections are not better adapted. Thus, the kinematic assumption can be rejected in this experiment.

In sum, these results show a better perception–action coupling in experts and extend the works of McLeod (1987), Bootsma and van Wieringen (1990) and Carlton (1992) by clearly showing that experts are better than non-experts in a task which requires large adaptations. Furthermore, these results highlight the temporal nature of the observed difference between experts and non-experts. Experts are more accurate in their interceptions because they have less temporal inertia in their regulation loop. The reduced inertia in perception–action coupling allows a more accurate control in interceptive actions. It provides the opportunity to improve on-line regulations and to adapt these regulations at later stages before contact. This additional amount of time could be linked to perceptual strategies, which would be more suitable to pick up the information on a more continuous mode and to detect more quickly the velocity change (see Rodrigues, Vickers, & Williams, 2002). The additional amount of time could also be linked to cerebral mechanisms. These latter would be more appropriate to couple information and movement in a faster way. Thus, it could optimize the functioning of the necessary law of control (Peper et al., 1994).

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