8 Intercepting accelerating projectiles

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For actions involving interception and, more generally, for any action requiring tracking of moving projectiles, the performer's essential problem consists of co-ordinating his/her actions with the movements of the projectile. One of the unanswered questions in this domain concerns how humans adapt their actions to accord with the accelerating or decelerating trajectories of projectiles. This question is essential since one can easily observe that, in dynamic sport environments, the velocity of projectiles that need to be intercepted is rarely uniform. For example, in sports such as cricket and tennis, the trajectories of approaching balls are influenced either by decelerations due to air resistance, gravity, surface resistance, or accelerations due to muscular or mechanical impulsion or gravity. One can conceive, as did Rosenbaum (1975), that individuals adapted to the environment are capable of using strategies that allow them to cope with variations in velocity of moving projectiles.

In examining the work on perception of movements of non-constant velocity, one finds apparently rather contradictory results. One of the first scientists to address this problem was Gottsdanker (1952). The results of his study, obtained using a visual–manual pursuit task, requiring extrapolation of the displacement of a moving target after its disappearance, showed that the participants were more precise in their extrapolations for movements at constant velocity than for accelerated movements. This observation led Gottsdanker to speculate that human beings are incapable of regulating their actions in accordance with an accelerating projectile.

This conclusion was later questioned by Rosenbaum (1975) in his analysis of the nature of Gottsdanker's experimental task. According to Rosenbaum, it is conceivable that the incapacity of the participants to pursue the accelerating projectile was due to the complexity of the task itself, rather than to a general incapacity to perceive (and act on) a projectile's accelerating movements. To eliminate this ambiguity, Rosenbaum sought to diminish the motor response component by using a prediction–motion task in which the participant only had to press a switch to indicate his/her estimation of the moment of arrival of a ball at a target after the occlusion of the final part of the ball's trajectory. In the second experiment reported, three constant velocities (0.19, 0.43, and 0.73 m/s) and three accelerations (0.23, 0.39, and 0.44 m/s^2) were used. The participants were as precise in their estimates of constant velocities as for accelerations, suggesting that people are able to follow and estimate arrival of an accelerating projectile. Nevertheless, there are still some remaining questions about the generality of the results, since the lack of difference between the two conditions could have been due to the relatively low rates of acceleration used.

Other work on perception and action with respect to non-constant velocity includes an experiment by Jagacinski, Johnson, and Miller (1983). Projectile displacement, simulated by an oscilloscope, was at first visible right to left, then occluded on its return from left to right. The results demonstrated that the participants were apparently capable of taking account of a projectile's accelerations when the time required for extrapolation was less than 500 ms, but apparently, when greater than this, it was no longer possible.

Thus, the results of early studies left many questions unanswered about perception of variations in velocity. More recent studies have provided some clarity, without, it is clear, providing an unequivocal answer.

Perception and identification of acceleration

One way to examine the problem consists of determining a human being's capacities for detection of acceleration. A number of studies have addressed this specific question by testing people's sensitivity to accelerating and decelerating trajectories (Babler and Dannemiller, 1993; Calderone and Kaiser, 1989; Mateeff, Dimitrov and Hohnsbein, 1995; Regan, Kaufman and Lincoln, 1986; Werkhoven, Snippe and Toet, 1992). In these studies, the task consisted of determining whether there was a variation in the velocity of a projectile. The main **projectileive[?]**was finding a detection threshold under the form of Weber's Law corresponding to the difference between final and initial velocity with respect to mean velocity (e.g. Calderone and Kaiser, 1989; Regan, Kaufman and Lincoln, 1986). This quantity, known as the velocity ratio (v_{ratio}), corresponds exactly to a percentage of the variation of velocity (e.g. Babler and Dannemiller, 1993). Even though the results are somewhat different in each studies of this body of work, it emerges that a human being is capable of detecting a projectile's changes in velocity when the v_{ratio} exceeds 20 per cent (e.g. Werkhoven, Snippe and Toet, 1992; Babler and Dannemiller, 1993).

Nevertheless, it is one thing to find in such studies that people are capable of perceiving and identifying acceleration or deceleration of a projectile when they are sufficiently obvious, and another to show that such variations of velocity can be grasped and utilized in the regulation of an interceptive action. Indeed, the detection of acceleration demonstrated in these experiments does not imply that people can necessarily use the information available in the quantitative change of velocity of a projectile to precisely regulate an interceptive action.

To better understand this problem, one may refer to the work of Werkhoven, Snippe and Toet (1992) suggesting that human beings are not equipped with a visual receptor that would permit them to directly perceive acceleration. Instead, the detection of acceleration might be connected to a second-order process consisting of comparing at different instants the velocity of a projectile. As a consequence, it appears difficult to imagine that the mechanisms implicated in the identification of acceleration are equally implicated in interceptive tasks.

Making reference to the two visual streams identified at the neuro–functional level (e.g. Goodale and Milner, 1992), Dubrowski and Carnahan (2000) suggested that the characteristics of a moving projectile can be treated either in the ventral (cognitive) visual stream or in the dorsal (motor) visual stream as a function of the response to be produced (for discussions see Chapter 12 by Keil and Bennett; Keil, Holmes, Bennett, Davids and Smith, 2000; Michaels, 2000; Tresilian, 1995, 1999b). As Keil and Bennett indicate in their chapter, for verbal responses requiring the identification of acceleration, the cognitive stream may be sufficient, whereas for actual interceptive actions the motor stream would be implicated. As Tresilian (1999b) emphasized, the function of the motor stream is largely automatic and non-conscious. If accepted, this argument means that perception in the sense of utilisation of information (including acceleration information) for interception actions must be viewed differently from tasks of perceptual discrimination (see Chapter 1).

Perception and utilisation of acceleration information in interceptive actions

In the case of interceptive actions, the perception and utilisation of acceleration information can be considered at two different levels (Michaels and Oudejans, 1992). Such information can be used by the performer both for regulating locomotion into a zone permitting catching or hitting a ball in flight, and for regulating the catching or hitting movements themselves.

Locomotor displacement and catching: optical acceleration cancellation (OAC)

As Michaels and Zaal point out in their chapter, since the initial work of Chapman (1968), a number of studies have hypothesized that the locomotor displacements necessary to catch a ball in flight depend directly on the perception of acceleration of the ball (e.g. see Babler and Dannemiller, 1993; Michaels and Oudejans, 1992; McLeod and Dienes, 1993). According to these studies, the performer's strategy for catching a ball consists of seeking, by his/her own appropriate movements, the vertical optical acceleration cancellation (OAC strategy). The optical acceleration is specifically determine by the relation $d^2(y)/dt^2$, with y corresponding to the height of the ball (Michaels and Oudejans, 1992), or in other form, $d^2(\tan \alpha)/dt^2$ with α corresponding to the angle formed at the point of observation with the ball and a point on the ground directly under the ball (e.g. McLeod and Dienes, 1993). Theoretically, the OAC strategy can explain all displacements of the performer when the ball moves in a plane that includes the performer himself/herself. A positive optical acceleration means that the catcher is situated behind the landing point, and a negative optical acceleration indicates that the catcher is in front of the landing point, while a zero optical acceleration indicates that the catcher is standing at the landing point. The optical acceleration indicates, therefore, the action necessary (advance, reverse, do not move) for moving to catch the ball. By searching to keep the optical acceleration at zero, the performer can regulate his/

her displacement to place himself/herself at the right place and time for performing the catch (Michaels and Oudejans, 1992; McLeod and Dienes, 1993).

It is worth remarking that the data on this concept are at the present time somewhat tentative for at least three reasons. The first problem is linked to the fact that the data that seem compatible with the model do not permit effective testing of the utilisation of information concerning a projectile's vertical variation in velocity. The reason for this is that there has been no experimentation to specifically manipulate the optical quantity $d^2(\tan \alpha)/dt^2$ to examine whether the performer's behaviour is completely determined by this variable. The second difficulty is linked to the fact that this strategy necessitates in the performer a rather extreme sensitivity to the variations in velocity of a projectile since it requires a kind of 'online' cancelling of optical acceleration. However, some previous studies have suggested that the visual system has very little sensitivity to this type of information (see e.g. Calderone and Kaiser, 1989; Werkhoven, Snippe and Toet, 1992). Finally, the concept of OAC only allows explanation of the displacement of a performer in situations where the performer is, at the beginning of the task, aligned in the vertical plane of a projectile's trajectory. In other words, its explanatory power currently lies in very narrow task constraints, and it does not account for constraints under which lateral displacements of a performer are necessary for catching a ball in flight. Other more general models that do not include the perception of vertical acceleration have since been proposed to explain this type of displacement (McBeath, Schaffer and Kaiser, 1995). In light of these questions, further research is necessary to validate or reject the OAC hypothesis. One recent study has suggested the possibility of a type of extra-retinal perception of vertical acceleration (see Oudejans, Michaels, Bakker and Davids, 1999). In this experiment, Oudejans, Michaels, Bakker and Davids (1999) showed that it was possible to run and catch a luminescent ball in the dark. This finding suggested that a visual background was not necessary to succeed in catching; rather, information from the vestibular system could be used to detect the vertical acceleration of the ball. Without background visual information, the data imply that another functional strategy consists of moving the head in order to maintain a stationary image of the ball on the retina. The information from the semicircular canals of the vestibular system can be used for detecting the acceleration of the head in fixating the ball.

Timing of the effector: estimating time to contact

With respect to time, it is generally believed that effector control in interceptive action necessitates estimation of time to contact (TC) information, that is, to the time remaining before the arrival of the projectile at the performer or a point in space adjacent to the performer (e.g. Lee, 1976; Peper, Bootsma, Mestre and Bakker, 1994). Estimation of TC requires the perception and utilisation of information relative to the displacement of a projectile. An interesting question concerns how the performer takes into account the relevant kinematic properties of the projectile for timing interceptive actions.

Hypotheses for regulating interception of projectiles travelling at non-constant velocity

For interceptive actions, two hypotheses can be proffered for explaining the mechanisms of regulating interception of accelerating and decelerating projectiles: (i) the performer is capable of accessing information to account for variations in projectile velocity utilising second-order TC (TC2); and (ii) the performer does not have this capacity and continually regulates action on the basis of first-order TC (TC1).

The latter hypothesis comes from the initial work of Lee (1976), based on the principle that perception and action can be coupled by utilisation of a first-order optic variable called tau (τ). This optic variable, as defined initially by Lee (1976), in situations of radial approach, corresponds, from the point of view of the observer, to the inverse of the rate of dilation of the optical contour of the approaching projectile. This optical quantity is expressed mathematically by $\tau(t) = \varphi / \dot{\varphi}$, in which φ corresponds to the angle formed by the point of observation and the approaching projectile and $\dot{\varphi}$ corresponds to the variation of this angle with respect to time. This optical quantity is directly available on the retina of the performer and necessitates no additional cognitive treatment as it is not necessary to engage in computations of the distance and the velocity of the approaching projectile. The essence of this quantity is that it directly provides information on the temporal relation between the performer and the approaching projectile. More precisely, it allows the performer to access a temporal variable that Lee and Young (1985) called the 'tau-margin' that permits the performer to regulate interceptive actions. More recently, Bootsma, Fayt, Zaal and Laurent (1997) proposed to denote this variable as the first-order time to contact (TC1) suggesting that this variable corresponds to a first-order temporal relation between the performer and the moving projectile. Indeed, it appears that this variable is equal to TC solely when the projectile moves at constant velocity.[1] For non-constant velocities, this relation does not exist, since TC1 does not take into account variations in projectile velocity. It was this point that led Tresilian (1994a, 1995) to define this variable as a first-order approximation of TC.

It must be noted, however, that this approximation of the temporal relation between the projectile and the performer does not prevent the performer from producing appropriate actions, since, according to the hypothesis, the utilisation of TC1 implies a continuous coupling between the perceptual system and the motor system. This coupling permits 'on-line' adjustment of movement characteristics as a function of the evolution of the value of TC1 (e.g. see Chapter 7 by Montagne and Laurent; Montagne, Fraisse, Ripoll and Laurent, 2000). This conceptualization is strengthened by the fact that the value of TC1 more closely approximates the value of TC2 as the projectile approaches the point of contact (Figure 8.1).

With this perspective, Lee, Young, Reddish, Lough and Clayton (1983) were interested in the timing of action using a task of hitting an accelerating ball. The task consisted of jumping up to hit a ball dropped from different heights above the participant. The analysis of Lee, Young, Reddish, Lough and Clayton (1983), who

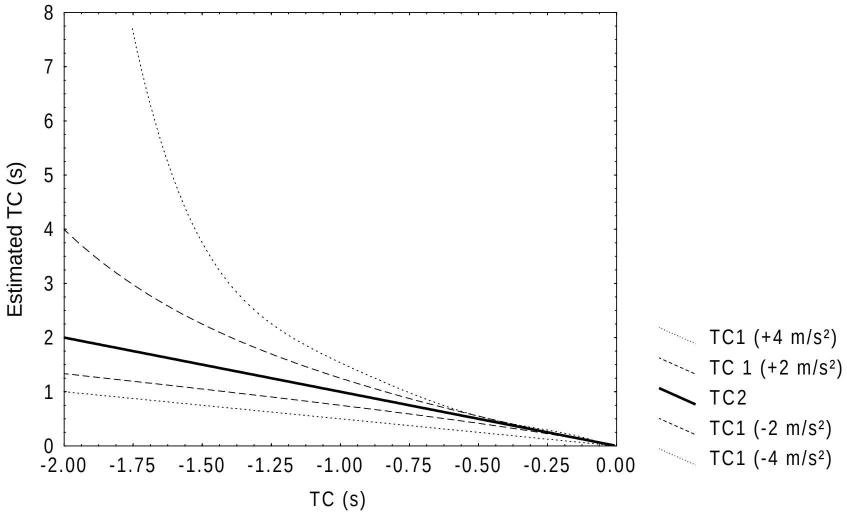

Figure 8.1 Representation of the evolution of TC1 and TC2 for accelerating and decelerating trajectories as a function of time to contact (TC) for four trajectories having different accelerations (+4, +2, –2, –4 m/s^2, with initial velocities respectively of 0, 2, 6, 8 m/s and final velocities respectively of 8, 6, 2, 0 m/s). As TC diminishes, the difference between TC1 and TC2 diminishes.

measured the angular variations of the ankle and the knee during the extension phase, showed that the temporal regulation of the action could be described independently from the height of the drop by a function relying on the performer's utilisation of TC1.[2]

Generalizing this hypothesis to non-radial approaches of projectiles, Bootsma, Fayt, Zaal and Laurent (1997, note 1), after Bootsma and Oudejans (1993, p. 1043, equation 9), defined an information source combining the relative velocity of the expansion of the optical contour of the projectile with the relative velocity of the constriction of the optical angle formed at the point of observation by the projectile and the point of interception. This information variable, permitting specification of TC1 at any point in space, is formalized by:

$$\frac{1}{\text{tau margin}} = \frac{\dot{\varphi}}{\sin\varphi} - \frac{\dot{\theta}}{\sin\theta} = -\frac{1}{\text{TC1}},$$

where $\dot{\varphi}/\sin\varphi$ can be assimilated to the inverse of the optical variable tau as it is defined by Lee (1976) when φ is small (when $\varphi \leq 10^\circ, \sin\varphi \approx \varphi$), θ corresponds to the angle formed at the point of observation by the projectile and the point of interception, and $\dot{\theta}$ corresponds to the variable of this angle as a function of time (Figure 8.2).[3]

On the basis of this relation, Bootsma and Oudejans (1993) designed a forced-choice task in which the participants had to predict as quickly as possible the order of arrival of two projectiles moving toward the same target. They demon-

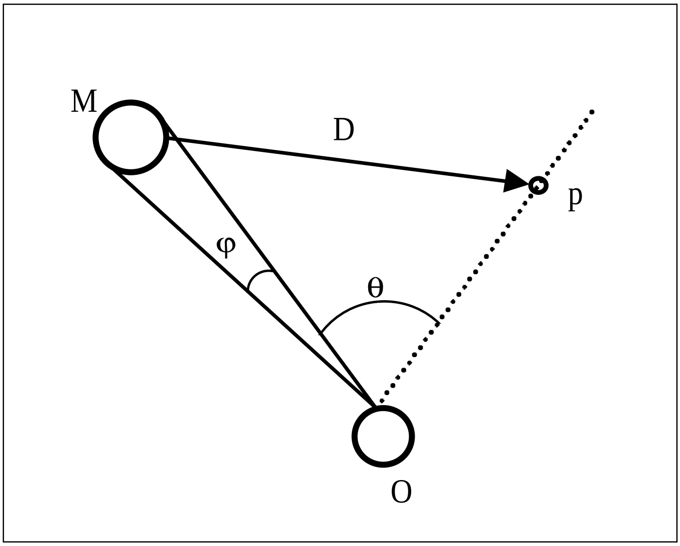

Figure 8.2 Geometrical relations between an observer O and a projectile M that moves distance D toward point p.

strated that neither acceleration nor deceleration were accurately judged. Participants committed more errors when one of the projectiles or both projectiles moved at a non-constant velocity.

These results were partially confirmed by Kaiser and Hecht (1995, experiment 1) in a prediction–motion task. In their experiment, the participants were required to estimate the arrival time of a simulated approaching target star which was presented in a flow field of constant-sized stars. The approach of the star was either accelerating, decelerating, or at constant velocity. The utilisation of these different conditions should have induced overestimates of arrival time in the case of accelerating approaches and underestimates in the case of decelerating approaches. The results of this experiment confirmed the hypotheses in the deceleration condition but not in the acceleration condition. In order to explain this absence of overestimation in the former condition, Kaiser and Hecht (1995) suggested that the values of accelerations and the durations of occlusion utilized in the experiment were not sufficiently great to produce the expected results.

In a study using a virtual interception task, Port, Lee, Dassonville and Georgopoulos (1997) addressed the question of the use of information from a projectile's acceleration or deceleration. The task consisted of intercepting a projectile on a computer screen using a cursor controlled by a manipulandum with movement in two dimensions. The projectile moved either with acceleration (six different trajectories from 5.84 to 129.41 cm/s^2), constant velocity (six trajectories from 8.84 to 35.35 cm/s), or deceleration (six trajectories from 5.84 to 129.41 cm/s^2). A trial was considered successful if the cursor entered the interception zone (0.6 cm radius) within ± 100 ms of the arrival of the projectile within the interception zone. Trials in which the cursor arrived more than 100 ms before the projectile were considered early errors, and trials in which the cursor arrived more than 100 ms after the projectile were considered late errors. Only 41.3 per cent of the trials were successful under these criteria. The large majority of the early errors were produced for decelerating trajectories while the large majority of late errors were produced for accelerating trajectories. These results, which have been confirmed by Ripoll and Latiri (1997) in a coincidence-timing task using a simple button press, reveal difficulty in dealing with variations in velocity when co-ordinating responses to projectile movement. The results also suggest that, in this task, the participants were unable to compensate completely for the effect of acceleration by means of a continuous regulation mechanism.

In another study using the same task, Lee, Port and Georgopoulos (1997) looked at the kinematic characteristics of the cursor displacement and observed different velocity peaks, notably in response to slow accelerations and decelerations. The authors suggest that the different peaks result from the production of sub-movements whose goal was to adjust to the characteristics of the target specifically adjusting to the first-order estimate of target position and velocity. It can be speculated that no information concerning the variation in velocity of the target is truly perceived as part of the production of interception movements.

The only research evidence that supports the possibility of humans being able to adequately pick up and use acceleration or deceleration information of a moving projectile during interception, was provided by Lacquaniti, Carozzo and Borghese (1993). In their experiment, the timing precision observed in participants when asked to catch balls falling from a height less than or equal to 1.5 m had to be due, the authors argued, to the participants' use of acceleration information. Nevertheless, it is also possible to explain this result by maintaining that the visual system does not permit the direct perception of acceleration information (Regan, Kaufman and Lincoln, 1986; Werkhoven, Snippe and Toet, 1992). Tresilian (e.g. 1993, 1997, 1999b) suggested that in free-fall situations where projectile acceleration is produced uniquely by the force of gravity (g), it is possible for a person to learn to integrate this value and to use it from the moment the height of the drop is known in order to produce and/or adjust the interception movement on the basis of a temporal variable of the type: $TC = \sqrt{2 \times h / g}$, in which h corresponds to the height of the drop and g to gravitational acceleration.

Some recent relevant experiments

Even with the particularly interesting results reported in the study above, it is worth noting that the data were collected under rather specific task constraints that allow little generalisation to many typical situations requiring timing of action with the movement of a projectile. More generally, it appears that many actions can be correctly regulated, even if accelerations are ignored, by using a first-order estimate of TC. Nevertheless, it must be cautioned that this hypothesis is supported by very little direct empirical data and demands rigorous empirical testing (Tresilian, 1999).

It is precisely for this reason that two experiments were performed using two tasks allowing relative predictions for utilisation or non-utilisation of information about a projectile's variation in velocity (Benguigui and Ripoll, 2000). The goal of these experiments was to collect quantitative data about the nature of perception of temporal variation when projectile trajectory was accelerated or decelerated.

In the first experiment, the apparatus consisted of a ramp of lights (4 m length) that simulated projectile movement toward a target situated at the end of the ramp. The participants were required to estimate time of arrival by pressing a button at the moment the moving stimulus arrived at the target, but with the stimulus occluded during the final part of the trajectory. This prediction–motion task was used to measure prediction-estimation responses of an occluded moving projectile since it allowed quantitative predictions of estimation errors in cases where participants could not perceive information relative to a projectile's variation in velocity. The goal of this experiment was also to re-examine the contradictory findings of Rosenbaum (1975) and Kaiser and Hecht (1995) by using longer occlusion times and administering greater accelerations. Eight values for accelerations (range: –2.45 to +2.45 m/s^2) and eight values for occlusion times (range: 300 to 1110 ms) were applied.

To validate the hypothesis of the utilisation of TC1, the theoretical errors were calculated for each trajectory from the difference between TC1 and the real TC (i.e. TC2) of the projectile at the moment of occlusion. These theoretical errors were then compared by regression analysis to the errors committed by the participants.

The results of this analysis indicated an R^2 of 0.66 and a regression-line slope of 0.96 (Figure 8.3). These statistical analyses signify a direct relation between the errors committed by the participants and the predicted errors. The results confirm the most recent hypotheses of Bootsma, Fayt, Zaal and Laurent (1997) and Tresilian (1999a) that, in a prediction–motion task, humans cannot use information about the acceleration or deceleration of a projectile to estimate the time of arrival of the projectile based on TC1 perceived at the moment of occlusion.

A second recent experiment followed the same principle as the first but used an indirect interception task. This task consisted of projecting a ball a distance of 2 m in order to intercept a moving target. The purpose of this task was to require, as in the prediction–motion task, a response produced on the basis of predictive information picked up before the projectile's arrival at the interception point. In this type of action, contrary to classic interception actions (catching or hitting a ball), it is not possible to control the effector movement at the moment preceding contact. One can, therefore, predict that if the participants produced their action on the basis of TC1, they will commit the error of attempting to intercept the ball too soon for decelerated trajectories and too late for accelerated trajectories.

In this experiment, nine values for accelerations/decelerations (range : –2.4 to +2.4 m/s^2) were used for a total of 54 trials. To validate the predictions relative to the utilisation of TC1, TC and TC1 of the projectile with respect to the point of interception at the instant of ball release were calculated. These calculations allowed a prediction of error for each trial conforming to the TC1 hypothesis.

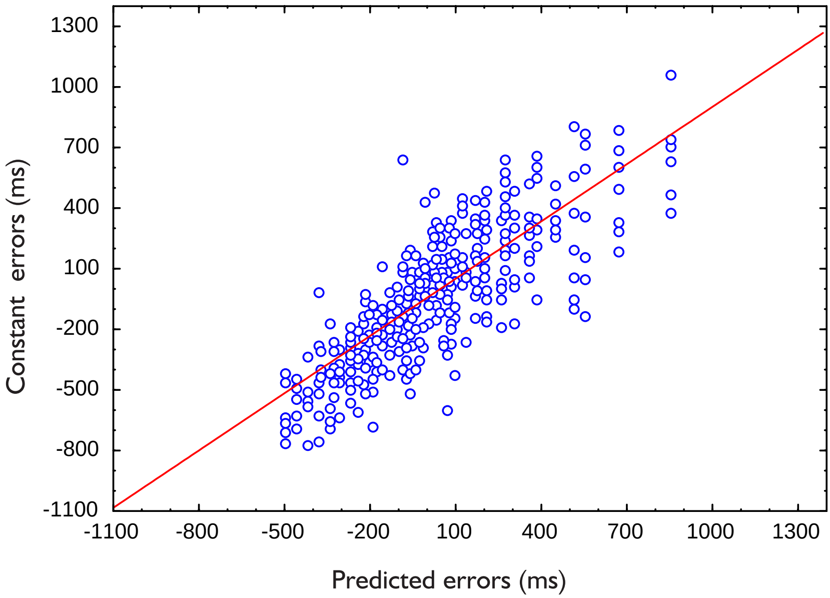

Figure 8.3 Errors committed (measured error) as a function of predicted errors. The equation of the line of regression is: Measured Error = 44 + 0.96 × Predicted Error, with $R^2 = 0.66$.

These theoretical errors were then compared with the participants' errors by regression analysis.

The results show an R^2 of 0.65 with a regression-line slope of 1.72 (Figure 8.4). The errors committed by the participants confirmed that information relative to the projectile's acceleration was not used. The participants committed some errors with over- and under-estimations higher than the model predicted**.** This finding could mean that, under these task constraints, the information used to produce action could be picked up at a pre-motor stage, the moment before release of the ball. Indeed, in this type of task, if the participants used information uniquely specifying the projectile's velocity (i.e. TC1), then the earlier the information was perceived, the greater the magnitude of errors.

In the course of these two experiments, it was shown that, the participants made temporal estimates (in the prediction–motion task) and produced action (in the indirect-interception task) on the basis of TC1. The results of our two experiments, considered in relation to the most relevant work in this domain (Bootsma and Oudejans, 1993; Kaiser and Hecht, 1995; Lee, Young, Reddish, Lough and Clayton, 1983; Lee, Port and Georgopoulos, 1997; Port, Lee, Dassonville and Georgpoulos, 1997; Tresilian, 1999a), served to underscore the validity of their quantitative predictions and confirmed the effective utilisation of TC1. On the perceptual side, the results clearly indicated that people perform poorly in tasks requiring accurate perception of information about a projectile's acceleration or deceleration. The results also confirm the observations of

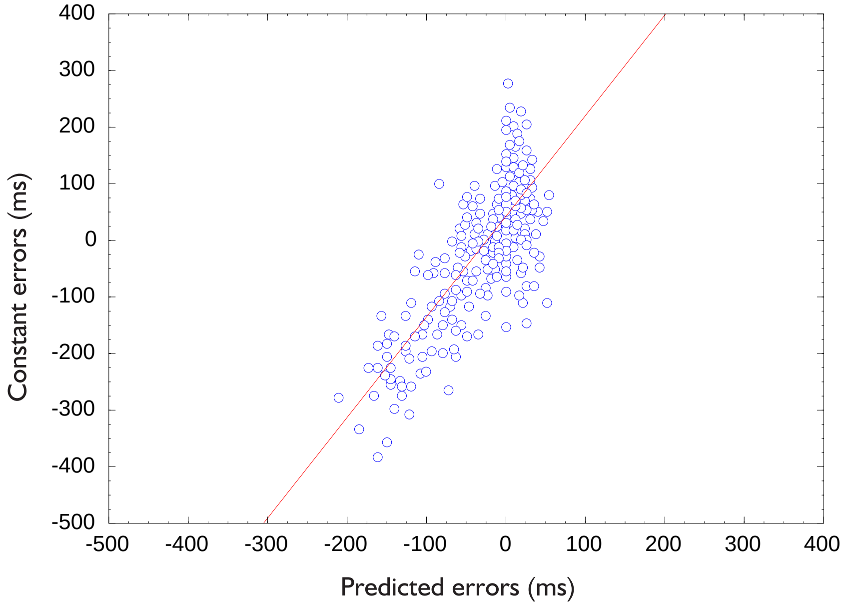

Figure 8.4 Errors committed as a function of predicted errors. The regression equation is: Measured Error = 39 + 1.72 × Predicted Error, with R^2 = 0.65.

Werkhoven *et al*. (1993) that the visual system is not equipped to directly detect acceleration.

Conclusions

Some experimental findings have indicated that people are capable of identifying variations in velocity (e.g. Babler and Dannemiller, 1993; Calderone and Kaiser, 1989; Mateeff, Dimitrov and Hohnsbein, 1995; Regan, Kaufman and Lincoln, 1986; Werkhoven, Snippe and Toet, 1992). Moreover, the experiment of Lacquaniti, Carozzo and Borghese (1993) suggested the possibility that performers could take into account the vertical acceleration in a ball-catching task. Nevertheless, it appears that for most interception tasks, people do not use information relative to acceleration or deceleration. The optical quantity defined by Bootsma, Fayt, Zaal and Laurent (1997, equation 2) is a good candidate for explaining how interceptive actions are produced and regulated. This optical quantity permits a person to specify TC1 in any situation. It is, nevertheless, not currently possible to draw more definitive conclusions since there has not been a direct demonstration of the use of this variable. New experiments are therefore necessary to evaluate the effective use of this source of information.

A last point to be discussed concerns the errors produced in the final two experiments presented, where the magnitude of variations in velocity increases were as high as 800 ms (Benguigui and Ripoll, 2000). This means that TC1 is approximate as soon as the participant is unable to pick up and use information to support an interceptive action right up until the point of arrival of a projectile. One can nevertheless say that these situations are extremely rare and that, in most interceptive actions, the regulation of the action is possible up until time of contact with an approaching object. It is not necessary to have information relative to the variation in velocity of the projectile. It seems that the human visual system does not need to quickly and accurately measure accelerations, since such an ability would not confer a significant survival advantage (Tresilian, 1999a). The on-line systems of regulation based on the perception of first-order information suffice in the production of motor acts adapted to dynamic environments in which projectiles typically move at non-constant velocities.

Notes

1 Lee (1976, pp. 440, 441, equations 5, 6, 7, and 8) demonstrated that for a rectilinear displacement at constant velocity, $\tau(t) = \varphi/\dot{\varphi} = Z/\dot{Z} = \mathrm{TC}$, with Z corresponding to the distance between the observer and $\dot{Z}$ at the velocity at which this distance diminishes. Note here that tau margin corresponds to the relation $Z/\dot{Z}$.

2 Michaels, Zeinstra and Oudejans (2000) found a number of failures in this experiment and criticized the conclusions made by Lee, Young, Reddish, Lough and Clayton (1983) (see also Tresilian, 1993 and Wann, 1996, for criticisms of this study). They attempted to rectify these problems by examining elbow extension only in seated punchers. The results of this experiment suggest that different kind of variables could be used to control action. The flexion of the elbow appeared to be initiated and regulated by the expansion velocity of the ball, rather than by the tau-margin (i.e. TC1). For the extension movement, it was not possible to clearly identify the variable utilized. Finally, Michaels, Zeinstra and Oudejans (2000) concluded that different variables could be used depending on availability of information and depending on the organisation of action. However, no suggestions were offered for the possible use of information regarding the variation of velocity of the ball.

3 It appears that this formalization combines a function of radial tau $(\varphi/\dot{\varphi})$ and a function of tangential tau $(\theta/\dot{\theta})$ when φ and θ are small (less than 10°).

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