Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Vision Research xxx (2007) xxx–xxx
Vision Research
www.elsevier.com/locate/visres

Intercepting free falling objects: Better use Occam's razor than internalize Newton's law

Robin Baurès *, Nicolas Benguigui, Michel-Ange Amorim, Isabelle Anne Siegler

Université Paris-Sud, UPRES EA 4042, Contrôle Moteur et Perception, 91405 Orsay, France

Received 22 December 2006; received in revised form 12 July 2007

Abstract

Several studies have recently provided empirical data supporting the view that gravity has been embodied in a quantitative internal model of gravity thereby permitting access to exact time-to-contact (TTC) when intercepting a free falling object. In this review, we discuss theoretical and methodological concerns with the experiments that supposedly support the assumption of a predictive and accurate model of gravity. Having done so, we then propose that only a "qualitative implicit physics knowledge" of the effects of gravity is used as an approximate pre-information that influences timing of interceptive actions in the specific case of free falling objects. Clear evidence remains to be provided to define how this knowledge is combined with optical information for on-line timing of interceptive actions.

Keywords: Interceptive action; Motor timing; Internal model of gravity; Qualitative implicit physics knowledge

1. Introduction

Throughout human evolution, phylogenesis has embodied many durable environmental constraints that humans meet. Gravity (g) is one of these major and durable constraints. The most notable consequence of gravity is to accelerate any object in free fall, by a relatively constant value (about 9.81 m/s^2 at sea level, with a <1% maximum variation with latitude and/or altitude (Zago & Lacquaniti, 2005b)). McIntyre, Zago, Berthoz, and Lacquaniti (2001) proposed that the relative constancy of gravity enables it to be taken into account in interceptive actions through the application of an internal model of gravity. This internalization would enable individuals to overcome the well known visual failure to perceive the acceleration of objects (Werkhoven, Snippe, & Toet, 1992) and thus would permit an exact prediction of the time-to-contact of a free falling object; TTC is the time remaining before the object reaches the observer or a specific point of interception.

In this paper we review studies that purportedly support the use of an internal model of gravity (e.g., Zago et al., 2004). Subsequently, we discuss why these works do not present unequivocal evidence for such a model. We then argue that humans' only use qualitative "implicit physics knowledge" of gravity effects to facilitate interception of free falling objects rather than a quantitative internal model of gravity.

1.1. Studies supporting the internal model of gravity

The hypothesis of the internal model of gravity in interceptive actions has been addressed in a large number of studies beginning with the seminal work by Lacquaniti and Maioli (1989a, 1989b). In a first experiment, Lacquaniti and Maioli (1989a) showed that the onset of anticipatory EMG in wrist and elbow muscles occurred at the same time before contact (e.g., 150 ms in case of the biceps) regardless of the initial height of the ball (ranging from 0.2 to 1.6 m). This result was interpreted by the authors as evi-

---

[*] Corresponding author. Present address: Université Paris-Sud11, UFR STAPS, Bâtiment 335, 91405 Orsay Cedex, France. Fax: +33 (0)1 69 15 62 37.
E-mail address: robin.baures@u-psud.fr (R. Baurès).

0042-6989/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2007.07.024

dence for the use of TTC obtained from an internal model of gravity (TTCg) instead of TTC obtained from a first order information such as $\tau(\theta)$,[1] neglecting the acceleration of the moving object (TTC1). Indeed, Lacquaniti and Maioli (1989a) argued that if responses were produced on the basis of a constant value of TTC1, as was proposed earlier by Lee, Young, Reddish, Lough, and Clayton (1983), then EMG peak activity would not have occurred at a constant value of TTC. In a second experiment with the same task, Lacquaniti and Maioli (1989b) showed that participants were able to time the grasp of the ball without seeing it during free fall and implied that they used instead the height of fall and an auditory cue that signalled the time of release. This result was interpreted as evidence that participants stored in memory the specific value of gravitational acceleration, and then used it to predict the exact TTC of the ball.

The use of an internal model of gravity was also tested as part of a Neurolab space shuttle mission (McIntyre et al., 2001) in which astronauts had to catch balls projected "vertically" to their hand by a ball machine with three different initial velocities. A first session was carried out on Earth (1 g condition), followed by a second session during the flight in space (0 g condition). On Earth, anticipatory catching responses (weak rotation of the arm and EMG peak of the biceps) were well synchronized with the arrival of the ball, independent of the initial projection velocity, confirming the previous results of Lacquaniti and Maioli (1989a, 1989b). In Space, anticipatory responses occurred earlier (with respect to impact time) than in 1 g condition (i.e., at a greater TTC than in the 1 g condition). These results led McIntyre et al. (2001) to reject both Eq. (1) control of the anticipatory responses on the basis of TTC1; in this case, anticipatory responses should have occurred later in the 0 g condition than they did, and Eq. (2) direct perception of the acceleration of the ball; in this case, no difference should have been observed between 0 and 1 g conditions. McIntyre et al. (2001) came to the conclusion that the brain anticipates the gravitational acceleration of downward moving objects, even in outer space where no gravity applies.

Zago and Lacquaniti (2005a), Zago et al. (2004, 2005) tested the validity of the internal model of gravity using a virtual system to simulate free falling balls. In these experiments, the fall of the virtual ball was coupled with the release of a real ball by an electromagnet behind a screen. The two balls arrived in synchrony at the interception point, situated just below the lower border of the screen, and participants were required to punch the real ball. With the real ball being hidden by the screen, participants had to produce their movement using the information provided by the virtual ball. In a first study with two conditions of acceleration (0 and 1 g), Zago et al. (2004) showed initial high performance for the 1 g motion with a low improvement of the success rate with practice; 80% for the first five trials and 92% for the last five trials. Initial performance for the 0 g motion was weak at 20% but there was a large improvement of success rate to 59%, although it did not reach the level exhibited in the 1 g condition. Maximum velocity of the hand was attained at the time of impact in 1 g condition (-2 ± 24 ms), whereas it was reached earlier (with respect to impact time) in the 0 g condition (-93 ± 78 ms). According to Zago et al. (2004), these results demonstrated that the internalization of Newton's laws in the internal model of gravity allows perfect timing for the interception of a ball in free fall.

However, the use of an internal model of gravity in interceptive actions seems to be context-dependent, as shown by Zago et al. (2004) in a second experiment. Participants were asked to press a button when the virtual target reached an interception point. As in the first experiment, the virtual target was either presented with a 0 or 1 g acceleration but now there was no real ball was falling at the same time behind the screen. Results indicated that better performance was obtained for 0 g motion (timing error of 0 ± 31 ms) than for 1 g motion (21 ± 40 ms). This observation led Zago et al. (2004) to conclude that the 1 g model is activated only with real balls to be intercepted while a 0 g model is used for virtual objects which are seen as having no mass and thus not subjected to the effect of gravity.

Further research was carried out by Senot, Zago, Lacquaniti, and McIntyre (2005), who tested the use of an internal model of gravity when facing congruent or contradictory visual and proprioceptive information. In this study, participants immersed in a virtual environment (head-mounted display) had to press a button to start the movement of an interceptor in order to collide with a ball. The ball could either fall from the ceiling (above condition) or rise from the ground (below condition). To add proprioceptive information that contributed to orientation, participants had to look up (head pitched up) to intercept balls falling from above or to look down (head pitched down) to intercept balls rising from below. The ball could adopt three accelerations: coherent (downward accelerating or upward decelerating motion) or incoherent (downward decelerating or upward accelerating motion) with gravity, and constant velocity motion (zero acceleration). Results showed that interception success rate was greater in constant velocity condition than in accelerated and decelerated conditions, regardless of motion direction. However, motion direction interacted with acceleration condition such that for both the above and below conditions, success rate was higher when ball motion was coherent with the effect of gravity. Moreover, response initiation timing was near ideal for constant velocity motion but significantly earlier for the above condition (87 ± 105 ms prior impact) than for the below condition (62 ± 102 ms prior impact) independent of acceleration. These results indicate that participants improve their performance when

---

[1] $\tau(\theta)$ is the inverse of the rate of expansion of the angle θ formed by the object with respect to the observer (Lee, 1976). Theoretically, τ can be used to optically specify the exact TTC for objects moving at constant velocity and an approximation of TTC for objects accelerating (Tresilian, 1995).

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

acceleration is coherent with direction of motion, by initiating the response earlier when the ball falls from the ceiling and later when the ball rises from the ground. The role of head pitch was confirmed in a control experiment that used identical visual scenes but with participants required to maintain their head parallel to the ground. Like in the primary experiment, success rate was higher for 0 g motion than for 1 or −1 g motions. However, there was no longer any significant interaction between direction of motion and acceleration. Senot et al. (2005) concluded that an internal model of gravity is only used when visual and proprioceptive information are congruent, leading to anticipated responses when the ball comes from above and delayed responses when the ball comes from below.

Finally, Indovina et al. (2005) undertook an fMRI experiment to identify the neural substrates of the 1 g model. The experimental setup involved virtual balls displayed on a screen with pseudo-realistic cues to provide indications about up and down (e.g., a woman holding a basket above her head, and standing in front of a building) and about the distance travelled by the ball in order to make the scene more natural. Balls moved "down" with either a 1 or −1 g acceleration. Participants were asked to press a button when the virtual ball reached the fixation point. Data showed that the insulae and the temporoparietal junctions located in the vestibular cortex were activated when the visual acceleration matched gravity. In contrast, when facing a −1 g acceleration this area was not activated but there was a significantly stronger response around the lateral occipital sulcus in the middle and inferior occipital gyri, an area known to be sensitive to visual movement (Orban et al., 2003). The activation of the vestibular cortex in the 1 g condition led Indovina et al. (2005) to conclude that it provides a neural substrate to the internal model of gravity.

In summary, it appears that the internal model of gravity has been investigated extensively and that a large amount of empirical data converges to demonstrate the effective use of this implicit knowledge in the timing of interceptive actions (Zago & Lacquaniti, 2005c). This model can be defined as a predictive forward model (Wolpert, Ghahramani, & Flanagan, 2001) and would permit the exact estimation of TTC for the production of a movement programmed on the basis of this estimation. However, we will argue that some questions regarding the involvement of this model have not always been addressed correctly and that the role of this internal model has been considerably exaggerated. We will highlight some methodological and theoretical problems that call into question whether this model, especially in its quantitative form, plays such an important role in catching.

In the next section, a critical examination of the methods used in the above mentioned studies will be presented and some alternative interpretations to the obtained results will be proposed. Then, we will examine the theoretical limits of the quantitative internal model of gravity. Finally, we will explain how a qualitative internal model of gravity could be used in very specific situations to modulate the timing of interceptive actions.

1.2. Methodological limits and alternative interpretations of empirical and neurophysiological data

Using EMG analyses, Lacquaniti and Maioli (1989b) showed that participants were able to time the grasp of a ball in free fall without seeing it after release. Instead, it was proposed that they timed the grasp using knowledge of the height of fall in combination with an auditory cue signalling the time of release. This result was interpreted as evidence that priori knowledge of g provided an estimation of the time of fall. However, this catching task can be interpreted as a time retention task, in which participants could simply learn during the initial trials the temporal interval between two sensory cues, one auditory and the other tactile. This would then provide a representation of a simple relationship between ball release height and time of fall, which after training would enable participants to produce a motor response to coincide with the tactile cue at a given time after the auditory one. Indeed, some studies have shown that people have good representations of short durations, especially when the estimation is made shortly after the presentation of the temporal interval (e.g., Clément & Droit-Volet, 2006), such as in Lacquaniti and Maioli (1989b).

Another important finding which seems to support the internal model of gravity concerns the constant timing observed in tasks with different drop heights (Lacquaniti & Maioli, 1989a). We would like to point out that this observation is not true for all muscles. Lacquaniti et al. (1989a) observed that the moment of anticipatory EMG **Q1** activity in wrist extensor varied depending on the height of release, as predicted by the TTC1 hypothesis. Further, for other muscles in which the initiation of anticipatory EMG activity was made at constant time before contact, alternative explanations are once again possible. First, in these studies, the three lowest drop heights (0.2, 0.4 and 0.8 m) were characterized by very short presentation times (202, 286 and 404 ms, respectively). For objects released from such a low drop height, and hence with a very short time of presentation, it can be suggested that the participant must simply react as fast as possible to have any chance to catch the ball. The implication, therefore, is that no information about the kinematics of the moving object was used after its release. For the two highest drop heights (1.2 and 1.6 m), time of presentation was long enough to permit the use of visual feedback from the ball's kinematics (495 and 571 ms, respectively). However, it is well known since Lee et al. (1983), that when an accelerating ball approaches contact, the difference between TTC1 and TTC2 (i.e., the temporal relationship between an object and an observer, based on a second order information such as g) is very small (see Fig. 1). For instance, in Lacquaniti and Maioli's experiment (1989a), with an actual TTC of 150 ms before contact (i.e., when the bursts of EMG begin)

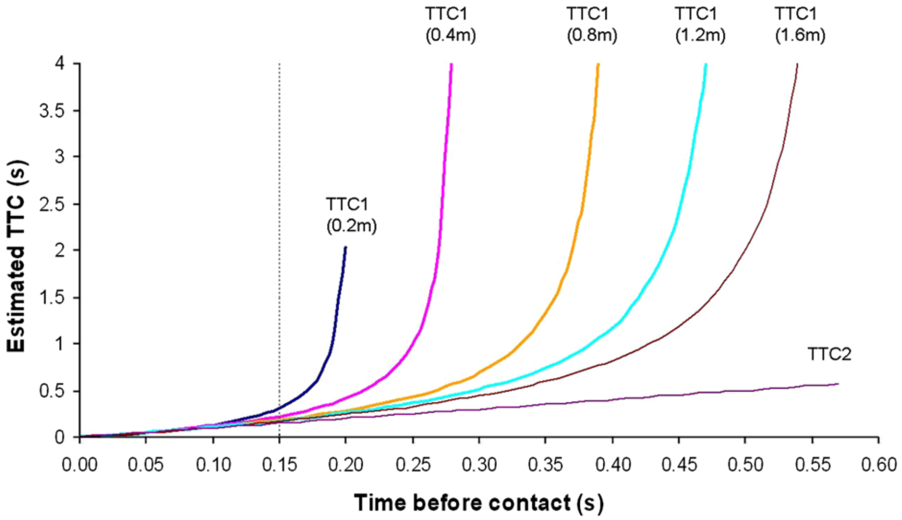

Fig. 1. Evolution of TTC1 as a function of TTC2 for the five drop heights. At 150 ms before the contact (see dashed line), values of TTC1 are 164, 174, 184, 221 and 310 ms for the highest to lowest drop heights, respectively. Except for the shortest drop height, for which an alternative strategy is possible, values of TTC2 and TTC1 are too close to determine experimentally whether TTC1 or TTC2 is used.

the difference between TTC1 and TTC2 was 14 and 24 ms for a 1.6 and 1.2 m drop height, respectively. This difference is certainly too small to be distinguished on the bases of the EMG analysis used by Lacquaniti and Maioli (1989a). Therefore, the use of an optical variable giving access to TTC1, even if not demonstrated, cannot be excluded and could explain equally well the timing of EMG responses.

Similarly, in the experiment of McIntyre et al. (2001), the difference obtained in the timing of EMG activity in space or on Earth was very small (about 30 ms). The use of the quantitative internal model of gravity should have led to differences between hand and ball timing of 234, 517 and 1781 ms for initial velocities of 2.7, 1.7 and 0.7 m/s, respectively. Consequently, these findings on EMG activity do not provide a quantitative validation of the use of g for the timing of interceptive action. The 30 ms difference only showed that in absence of gravity, interceptive movements were triggered a little sooner (with respect to impact time) than in 1 g condition. The only conclusion that one can draw from this small difference in timing, is that qualitative knowledge of gravity had a weak modulating effect on the timing of interception action. We do not believe that it should be viewed as a clear and unquestionable proof for the use of a quantitative internal model of gravity.

Other methodological limits exist in the experimental design developed by Zago and Lacquaniti (2005a); Zago et al. (2004, 2005). A real ball was released behind a screen while a virtual ball was projected on the screen with various velocities and accelerations. This experimental design was used Eq. (1) to suggest to the participants that the ball had a mass and was submitted to the gravity and Eq. (2) to enable the experimenters to manipulate the acceleration of the visual stimulus. Although technically advanced, this device is not bias-proof. Indeed, the main problem comes from the differences in the velocity between the virtual and real balls at the point of interception, which induce differences in the time window available to make a precise and successful contact. The time window can be expressed as follows:

$$\text{Time window} = (S_\text{b} + S_\text{i})/V_\text{b}, \tag{1}$$

where S_b is the size of the ball, S_i the size of the interceptor and V_b the velocity of the ball when entering the interception zone. This corresponds to the time interval during which the object remains in the interceptive zone, and thus represents the temporal precision required for intercepting a moving object (McLeod, McGlaughlin, & Nimmo-Smith, 1985; Tresilian & Lonergan, 2002). Because this very important constraint was not controlled in their experiments, the conclusion provided by Zago et al. is questionable. For instance, in these experiments participants had to deal with both an expected time window that corresponded to the virtual ball they could see *and* a real time window that corresponded to the real ball they had to intercept. When the virtual ball was released with an acceleration of 1 g, the difference in velocity at the interception point was small, and the expected time window and real time window were quite similar (Fig. 2a).This led participants to very quickly reach a good timing performance. When the virtual ball fell with an acceleration of 0 g, the difference in velocity at interception point was large and the expected time window and real time window were very different (Fig. 2b); 214 ms for the virtual ball and 24 ms for the real ball in the 0 g condition with an initial velocity of 0.7 m/s. It is perhaps not surprising to observe large errors in participants' responses in trials with such discrepancies between expectancies about the accuracy required in the interceptive action according to the virtual ball and the accuracy required to intercept the real ball. Moreover, the conflict that existed between the visual information

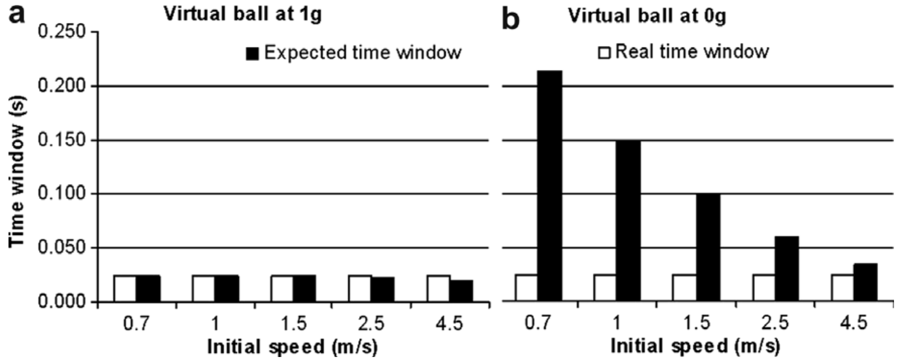

Fig. 2. (a and b) Differences in expected time windows from the virtual ball and the real ball falling behind the screen in the 1 g condition (panel a) and in the 0 g condition (panel b) with different initial velocities. Time windows are calculated for an interceptor of 6 cm and a ball of 9 cm after a 2.04 m fall, and taking friction due to air resistance into account.

available on the screen and the representation of the falling ball behind the screen that participants would have defined after trials in the 0 g condition, could also explain why participants did not approach the level of accuracy and the consistency in timing observed in conditions with no conflict between time windows (i.e., the 1 g condition). Consequently, it is possible to question the conclusions of Zago et al. about the use of a quantitative internal model of gravity which would explain why participants adopt a perfect timing in the 1 g condition.

Interestingly, our interpretation is supported by the second experiment carried out by Zago et al. (2004). In this experiment there was no real ball falling behind the screen, and hence there was no conflict between the expected time window and real time window. Under such conditions, the timing accuracy at 0 g was clearly better than at 1 g. In contrast to the authors, we believe that rather than assuming the virtual ball was considered as having no mass and therefore not submitted to gravity, the results could be due to the absence of a discrepancy between the expected time window and real time window. Hence, participants could perform better at 0 g because of the inability of the visual system to take acceleration into account (e.g., Benguigui, Ripoll, & Broderick, 2003 for a similar result).

Another line of evidence belying Zago et al's., 2004 results comes from studies showing that a target's velocity strongly affects movement time (MT) in interceptive actions (e.g., Brenner & Smeets, 2005; Brenner, Smeets, & de Lussanet, 1998; Tresilian & Plooy, 2006). Because this effect of target's velocity on MT, the use of a virtual simulation with a velocity different from the velocity of the real ball to be intercepted will necessarily induce inadequate movements and errors in timing.

Finally, in the studies of Zago and Lacquaniti, changes in velocity and/or acceleration of the ball were not compensated for by changes in viewing distance (VD) to maintain viewing time (VT) constant across all conditions. It has been shown that a decrease in V associated with an increase of VT induces an increase in MT and variability (Brenner & Smeets, 1996; Carnahan & MacFadyen, 1996). This provides an alternative explanation for the larger variability observed in motor responses in the 0 g condition, characterized by a greater VT and a slower velocity of the simulated target. Conducting the same experiment and maintaining an equal VT and time window in the interception zone, would avoid this conflict. This could be achieved by varying the release of release of the virtual and real balls in such a way that they enter the interception zone at the same time and with the same velocity. However, because the real ball accelerates at g, the difference between expected time window and real time window can only be minimized and not completely avoided as in the case of a virtual ball falling with a 0 g.

Results obtained by Senot et al. (2005) also do not provide undeniable proof for the use of a quantitative internal model of gravity. Indeed, even if a small effect of gravity was highlighted when visual and proprioceptive information were coherent, results showed that timing accuracy was better in 0 g condition (constant velocity) than in the most coherent conditions of acceleration and deceleration. The use of a quantitative internal model of gravity should have led to a better accuracy in the 1 g conditions with congruent proprioceptive information than in the 0 g. Instead, the results are more consistent with the use of qualitative version, which would allow a reduction of errors for targets accelerating or decelerating under the effect of gravity. For instance, timing of interceptive actions could be modulated, by anticipating the time taken when the object moves downward and then delaying the response when the object moves upwards.

Moreover, the conclusion of Senot et al. (2005) regarding the importance of coherence between visual and proprioceptive information for the possible use of an internal model of gravity, questions the neuroimaging study by Indovina et al. (2005) where visual gravity did not coincide with proprioceptive gravity. In this fMRI experiment, participants were required to lie supine on a bed while viewing the scene through a tilted mirror, which resulted in visual motion orthogonal to gravity, and corresponding to the control experiment of Senot et al. (2005) in which no evidence was found for the use of the quantitative internal model of gravity (see also Nagai, Kazai, & Yagi, 2002 for a similar result).

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

There is another problem in the work of Indovina et al. (2005) related to the use a photograph of surroundings to provide realism and visual cues to counterbalance the discrepancy between visual and proprioceptive gravity. The use of a virtual simulation contradicts the conclusion of Zago et al. (2004) who stated that virtual balls are regarded as having no mass and thus do not involve the quantitative internal model of gravity. If the hypothesis of Zago et al. (2004) is valid, it still remains to be proved that the addition of surroundings to provide realism to the simulation would be sufficient enough to make participants perceive the ball as having a mass in this virtual environment.

To summarise this section, we suggest that together these methodological limits in studies aimed at demonstrating the role of a quantitative internal model of gravity, cast some doubts on its effective use in interceptive actions. We propose that these doubts are reinforced in the following section, where we present a critical examination of the real capacity of such a model to provide accurate timing for the interception of falling objects.

1.3. Theoretical limits of the quantitative model of gravity

In the studies supposedly supporting the quantitative internal model of gravity, little is said about how this knowledge is used in the timing of interceptive actions. One can understand that it provides information to obtain TTC. If this idea is developed, one can suppose that an integrated knowledge of gravity (g) would be computed with a perception of the falling distance (d) and the velocity of the fall (v) to obtain TTCg, the time of fall, on the basis of the following equation:

$$\mathrm{TTCg} = \frac{-v + \sqrt{v^2 + 2g \times d}}{g} \tag{2}$$

(Senot et al., 2005). This time would then be used to program a response at a time equal to TTCg.

Adhering strictly to the use of a quantitative internal model of gravity, one might question the constancy of the value of g on Earth. Even if one agrees with Zago and Lacquaniti (2005b) that the variation of g with latitude or altitude has little effect on the value of g, a second factor can have an important effect upon gravitational acceleration: air resistance. The assumption of the quantitative internal model of gravity fits well with the theory of Galileo according to whom the time to fall and the vertical velocity of a falling object is independent of its weight and only dependent on the force of gravity. But this principle is true only in the vacuum or on the moon (where there is no atmosphere and gravity is about $1.62\ \mathrm{m/s^2}$) or for an object whose density is sufficiently high for air resistance to be neglected. However, there are many cases of interception in which air resistance is opposed to the force of gravity and cannot be neglected. The effect of air resistance, as a function of the mass of the object, is seldom acknowledged in articles about the quantitative internal model of gravity. Some of these works have simply mentioned the effect of mass on air resistance (Zago & Lacquaniti, 2005a; Zago et al., 2004, 2005) whereas other articles did not even comment (Lacquaniti & Maioli, 1989a, 1989b; Senot et al., 2005; Zago & Lacquaniti, 2005b, 2005c). Because of the lack of interest on this factor, and because an acceleration of precisely 1 g is as scarce as a constant velocity motion, the effect of air resistance and the factors which are involved in this effect must be clarified.

If no air resistance was applied to a falling object, the only force acting would be its weight ($\vec{w}$, with a vertical axis oriented downwards). According to Newton's second law

$$\left(\sum \vec{Forces} = m \times \vec{a}\right),\ \text{we know that}: \vec{w} = m \times \vec{a} \tag{3}$$

in which $\vec{a}$ is the acceleration vector and m the mass of the ball. We also know that $\vec{w} = m \times \vec{g}$ and obtain by insertion and simplification:

$$\vec{g} = \vec{a} \tag{4}$$

Thus, the value of the acceleration of the ball is equal to the constant value of the terrestrial acceleration.

With air resistance, a friction force $\vec{f}$ is also applied to the ball. The second law of Newton still applies, therefore:

$$\vec{w} + \vec{f} = m \times \vec{a} \tag{5}$$

By insertion and simplification, we obtain:

$$\vec{a} = \vec{g} + \frac{\vec{f}}{m} \tag{6}$$

As we can see from Eq. (6), ball acceleration depends on ball mass. Furthermore, in the case of a ball falling vertically, Eq. (6) leads to the following differential equation (from which the kinematics of the ball can be obtained):

$$\frac{\mathrm{d}v}{\mathrm{d}t} = g - \frac{kv^2}{m}, \tag{7}$$

where $k = 0.5 \times \mathrm{Cr} \times \mathrm{Rhau} \times \mathrm{A}$, Cr being the drag coefficient of a ball, Rhau the air density and A the cross-sectional area of the ball.

With air resistance affecting acceleration, velocity and TTC are also affected. One could argue that the difference between the TTC estimation neglecting friction and the real TTC when action is triggered, is small enough to permit successful interception. However, this statement is doubtful. For instance, the TTC of a table tennis ball falling from a height of 2 m with and without air resistance would be 671 and 638 ms, respectively; a difference between both TTCs of 33 ms. Even if corrected during the fall by visual information about ball's position and velocity, the TTC estimation using a constant value of $9.81\ \mathrm{m/s^2}$ as given by the internal model of gravity would prevent the ball interception. For example, 300 ms before the ball reaches the interception point, its acceleration has decreased due to air resistance to $8.06\ \mathrm{m/s^2}$. The use of an acceleration value of $9.81\ \mathrm{m/s^2}$, specified at the moment of ball release, would lead participants to estimate a TTC of 280 ms, cor-

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

responding to an error of 20 ms in timing. These differences are quite important when one considers that the timing accuracy of interception can be as small as 5 ms (Regan, 1997). Hence, the effect of air resistance should not be neglected, especially in the case of light balls. The implication is that the use of a quantitative internal model of gravity should be complimented by the use an internal model of friction and knowledge of ball's mass to obtain accurate estimates of TTC. The use of such knowledge is theoretically possible even if it seems to be quite complex (Craig, Berton, Rao, Fernandez, & Bootsma, 2006; Oberle, McBeath, Madigan, & Sugar, 2005). Evidence remains to be provided in support of this position.

Another limit of the quantitative internal model of gravity is related to the very small perimeter in which it could be brought into play. In other words, its use seems to be limited to the unique case of balls in free fall. In the numerous studies on this topic, no generalisation to other situations with parabolic trajectories has been envisaged. Regan (1997) claimed that ignorance of gravitational acceleration in cricket prevents the batsman from determining precisely if the ball will contact the wicket and bounce before being struck. This difficulty n predicting ball flight on a parabolic trajectory is said to be one of the reasons why it is not easy to time the hitting of a cricket ball. Similar difficulties have been reported in baseball for estimating the height of pitch to hit the ball (Gray, 2002). The non-use of the internal model of gravity with parabolic trajectory limits considerably its interest. It would be quite surprising that the brain would have developed such an accurate but complex strategy only for situations of vertical fall which are neither frequent nor critical for the survival of the species or for success in high speed ball game.

2. Discussion

In this article, we have reviewed empirical evidence supposedly supporting the internal model of gravity. We have shown that these studies have methodological problems and that alternative interpretations exist. In addition, we showed that the internalization of a single value of g (i.e., 9.81 m/s^2) does not permit accurate interception of a free falling ball submitted to air resistance because the acceleration of the ball decreases during its fall and the use of a constant value of g would impair the estimation of TTC. We believe that these issues question the use of a quantitative internal model of gravity or at least minimize its relevance for interceptive actions.

However, this article does not call into question the fact that representations (whether implicit or explicit) or a priori expectations could be used to intercept moving objects. Strong evidence for this position is reported by de Lussanet, Smeets, and Brenner (2002), who showed that the characteristics of a trial (velocity of the object, abrupt and unpredictable change of the position of the target) or context (change in resistance applied to the interceptive movement) influence the next interception movement (initial direction of motion and spatial error). In fact, we agree with Proffitt and Kaiser (1998) that the geometrical properties of objects (e.g., conservation of the shape of an object during its motion) are internalized and may be used to estimate TTC (López-Moliner, Brenner, & Smeets, in press). However, although we can accept that an implicit knowledge of physics may bias our spatial memory of an object that abruptly disappeared (Hubbard, 1995), we still wonder whether internalized gravity is used in interceptive actions even though gravity is omnipresent and there is a theoretical advantage to be gained if it can be perceived. This statement is consistent with observations of Todd (1981), who argued that all information or perceptual strategies potentially available for controlling actions were not systematically used.

Nevertheless, since there is no definite evidence in favour of a quantitative internalization of gravitational acceleration, one of the issues that remain to be explored concerns how humans adjust their actions to objects accelerating and decelerating under gravitational influence when trying to intercept. Concerning the timing of the effector, a few studies have investigated whether an optical variable(s) may initiate or guide interceptive movement. Lee et al. (1983) studied the information used when punching a ball accelerated by gravity and concluded that the evolution of knee and elbow angles during the fall of the ball could be explained by the use of $\tau(\theta)$. The authors argued that even if $\tau(\theta)$ gives access to TTC1 and not to the exact TTC, TTC1 is accurate enough when it is used with a type of control in which a continuous coupling between perceptual and motor systems allow on-line adjustments of action; as previously mentioned here, TTC1 converges towards TTC in the course of time (Fig. 1) and therefore the difference becomes negligible.

Unfortunately, however, the study of Lee et al. (1983) has not been without criticism. Wann (1996) argued for his part that results showing the use of $\tau(\theta)$ could simply be due to an artefact of the analysis. Other methodological problems led Michaels, Zeinstra, and Oudejans (2001) to reproduce the same experiment with a better control of the independent variables. The results partly contradict those of Lee et al. (1983) since Michaels et al. (2001) found that the optical variable used to initiate and guide knee and elbow angles was θ' (the expansion velocity of the ball) rather than $\tau(\theta)$, even if $\tau(\theta)$ fitted better the data of certain participants in specific conditions. Still, it is important to note that this experiment did not reveal any evidence for the use of TTC2, which would be consistent with the involvement of an internal model of gravity. Moreover, the two optical variables identified in this experiment avoid the theoretical criticism of the effect of air resistance on the estimation of TTC addressed to the internal model of gravity. This is obvious for θ', which does not give access to TTC and thus cannot lead to a wrong estimation of TTC because of air resistance. The use of $\tau(\theta)$ involves a continuous regulation of action to minimize potential

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

errors of a first order information and thus also avoids air resistance influence.

Results of authors such as Michaels et al. (2001), and van der Kamp, Savelsbergh, and Smeets (1997) also highlighted differences between monocular and binocular viewing conditions, suggesting the exploitation of different optical cues depending on viewing conditions. Caljouw, van der Kamp, and Savelsbergh (2004) proposed that multiple optical variables are implicated in the regulation of interceptive actions. According to these authors, the environmental and organic constraints that determine the specificity of the task would lead to the use of either a single source of information among several alternatives, or a combination of these multiple sources of information [e.g., $\tau(\theta)$, θ', binocular disparity, relative size of the object, occlusion, η (a combination of optical size and rate of expansion, López-Moliner & Bonnet, 2002)]. This combination could be made either by summation or multiplication of several weighted sources of information, with the weights being attributed according to task constraints (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003; Rushton & Wann, 1999; Smith, Flach, Dittman, & Stanard, 2001).

It has thus been demonstrated that ecological invariants picked-up from the environment (Gibson, 1979) are not the only base for timing interceptive actions and that other information, such as perceptual cues or prior knowledge of the behaviour of the target, could be taken into consideration.

To summarize, if the initial idea of an exclusive one-to-one mapping between information and movement is now rejected by many researchers (e.g., Caljouw et al., 2004), a prospective type of control presents several advantages in comparison to a predictive one supported by an internal model of gravity. A prospective control establishes a particular relationship (a law of control, Warren, 1988) between information and movement (e.g., Dessing, Bullock, Peper, & Beek, 2002). Accordingly, action needs on-line control on the basis of information specifying the relationship between the actor and the environment (e.g., Michaels, Jacobs, & Bongers, 2006). The value of the information, which can vary with time, is used as a continuous guide for action timing. In interceptive actions, continuous guidance is used to reach the right place at the right time without any a priori knowledge of this time and this place (Peper, Bootsma, Mestre, & Bakker, 1994). Predictive models give rise to predictions of time and/or place of contact, which are used to program the movement before its initiation. The movement may be corrected (or re-programmed) if necessary during the unfolding of the act on the basis of a comparison between expected and actual sensory feedbacks (e.g., Pisella et al., 2000; Teixeira, Chua, Nagelkerke, & Franks, 2006). Zago et al. (2004) argue that the internalization of gravity is combined with on-line visual information about position and velocity of the object to predict the exact TTC. Consequently, TTC predictions could be corrected during the fall of the object, which could overcome the possible modification of TTC caused by air resistance. However, even if position and velocity information may be updated during the fall of the ball, the change in the acceleration value is not updated, which would prevent access to exact TTC when the specific value of 9.81 m/s^2 does not match the real acceleration (Fig. 3). A prospective type of control would allow accurate timing when the ball is submitted to the effect of air resistance, as opposed to the use of a constant value of acceleration in a predictive model. Moreover, it would allow a more economical type

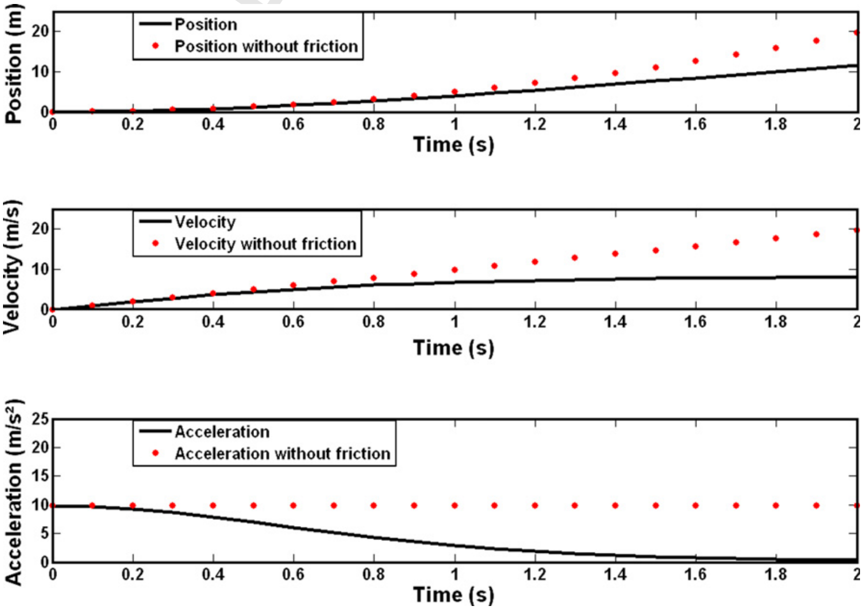

Fig. 3. Evolution in time of acceleration, velocity and position for a table tennis ball in free fall (diameter 4 cm and mass 2.7 g, International Table Tennis Federation regulation). At 0.726 s after the release of the ball, the acceleration has been divided by two, and 2 s after the release, the acceleration is no more than 0.3 m/s^2.

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

of control in which it is not necessary to learn and store an exact value of g and in which no complex calculation is required to predict the exact TTC.

Here, we claim that timing of interceptive actions cannot be based on an internal model of gravity that would give a quantitative and perfect prediction of the real TTC. However, we agree that a basic knowledge of the effect of gravity could be used in specific situations to modulate the timing of interceptive actions. We suggest that this is an example of using "qualitative implicit physics knowledge" to describe the motor advantage it could provide in reacting faster or earlier when the ball is expected to accelerate under the effect of gravity (e.g., McIntyre et al., 2001; Senot et al., 2005). This conclusion is in agreement with the work of Hecht (Hecht, 2001; Hecht & Bertamini, 2000; Hecht, Kaiser, & Banks, 1996). Theoretically, an observer could use the constancy of the value of gravity to estimate the absolute size and distance of a free falling object. However, Hecht et al. (1996) showed that even if participants internalize some abstraction of gravity, they do not use this specific knowledge to a degree sufficient enough to succeed in their judgement.

Because knowledge of the effect of gravity could only be used in very specific situations when intercepting objects in free fall, we believe that the role of gravity has been considerably exaggerated. The effect of gravity could belong to one of the environmental constraints proposed by Caljouw et al. (2004), and could be used in combination with other sources of information to intercept the object (DeLucia et al., 2003). The weight applied to this information could take a zero value when for example a ball rolls on the ground (e. g., in football), or a value of one when the ball is moving vertically (e. g., in the jump ball in basketball). Hence, the motor system would be "warned" that the timing of action should be modulated and that the interceptive movement should be adapted to begin earlier and or to be executed faster in case of downward motion of the ball and conversely; the opposite applies in the case of upward motion. For these reasons, we prefer to define this process as a qualitative implicit physics knowledge rather than as an internal model: people only know the effect of gravity and do not really have internalized this constant.

3. Conclusion

We have shown that evidence presented to support the assumption of a predictive and accurate internal model of gravity in the timing of interceptive actions can be called into question, and that the use of an internal model of gravity to access the exact TTC of a falling object should embody air resistance effects, which has been neglected by the proponents of a quantitative internal model of gravity. However, some results suggest a qualitative modulating effect of gravity (e.g., McIntyre et al., 2001; Senot et al., 2005) in which this knowledge might simply lead to the expectation of an increase of velocity for a ball in free fall. Consequently, we reject the actual demonstration of the use of a quantitative internal model of gravity. Instead, we propose that a prospective type of control based on multiple sources of visual information, combined with a qualitative knowledge of the basic effect of gravity, could be sufficient to intercept an object in free fall. Hence, the existence of a quantitative internal model of gravity is unlikely according to Occam's razor principle, which states that "entities should not be multiplied beyond necessity". We propose that the brain follows Occam's razor principle rather than internalizing Newton's laws. The challenge for future research is to measure how qualitative implicit physics knowledge affects timing of interceptive actions, especially by identifying the movement parameters that are modified (e.g., initiation time, movement velocity). This research could examine how optical variables used to initiate or guide interceptive actions may be modulated by an a priori qualitative knowledge of the effect of gravity.

References

Benguigui, N., Ripoll, H., & Broderick, M. P. (2003). Time-to-contact estimation of accelerated stimuli is based on first-order information. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 1083–1101.

Brenner, E., & Smeets, J. B. J. (1996). Hitting moving targets: Co-operative control of 'when' and 'where'. *Human Movement Science, 15*, 39–53.

Brenner, E., Smeets, J. B. J., & de Lussanet, M. H. E. (1998). Hitting moving targets: Continuous control of the acceleration of the hand on the basis of the target's velocity. *Experimental Brain Research, 122*, 467–474.

Brenner, E., & Smeets, J. B. J. (2005). Intercepting moving targets: Why the hand's path depends on the target's velocity. In B. E. Rogowitz, T. N. Pappas & S. J. Daly (Eds.), *Human Vision and Electronic Imaging X*. Vol. 5666 (pp. 374–384).

Caljouw, S. R., van der Kamp, J., & Savelsbergh, G. J. P. (2004). The fallacious assumption of time-to-contact perception in the regulation of catching and hitting. In H. Hecht & G. J. P. Savelsbergh (Eds.), *Time-to-contact* (pp. 443–474). Amsterdam, the Netherlands: Elsevier Science Publishers.

Carnahan, H., & MacFadyen, B. J. (1996). Visuomotor control when reaching toward and grasping moving targets. *Acta Psychologica, 92*, 17–32.

Clément, A., & Droit-Volet, S. (2006). Counting in a time discrimination task in children and adults. *Behavioural Processes, 71*, 164–171.

Craig, C. M., Berton, E., Rao, G., Fernandez, L., & Bootsma, R. J. (2006). Judging where a ball will go: The case of curved free kicks in football. *Naturwissenschaften, 93*, 97–101.

de Lussanet, M. H., Smeets, J. B., & Brenner, E. (2002). The relation between task history and movement strategy. *Behavioural Brain Research, 129*, 51–59.

DeLucia, P. R., Kaiser, M., Bush, J., Meyer, L., & Sweet, B. (2003). Information integration in judgements of time to contact. *Quarterly Journal of Experimental Psychology Human Experimental Psychology, 56*(A), 1165–1189.

Dessing, J. C., Bullock, D., Peper, C. L., & Beek, P. J. (2002). Prospective control of manual interceptive actions: Comparative simulations of extant and new model constructs. *Neural Networks, 15*, 163–179.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

Gray, R. (2002). Behavior of college baseball players in a virtual batting task. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1131–1148.

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024

Hecht, H., Kaiser, M. K., & Banks, M. S. (1996). Gravitational acceleration as a cue for absolute size and distance? *Perception & Psychophysics, 58*, 1066–1075.

Hecht, H., & Bertamini, M. (2000). Understanding projectile acceleration. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 730–746.

Hecht, H. (2001). Regularities of the physical world and the absence of their internalization. *Behavioral and Brain Sciences, 24*, 608–617.

Hubbard, T. L. (1995). Cognitive representation of motion: Evidence for friction and gravity analogues. *Journal of Experimental Psychology: Learning, Memory and Cognition, 21*, 241–254.

Indovina, I., Maffei, V., Bosco, G., Zago, M., Macaluso, E., & Lacquaniti, F. (2005). Representation of visual gravitational motion in the human vestibular cortex. *Science, 308*, 416–419.

Lacquaniti, F., & Maioli, C. (1989a). The role of preparation in tuning anticipatory and reflex responses during catching. *Journal of Neuroscience, 9*, 134–148.

Lacquaniti, F., & Maioli, C. (1989b). Adaptation to suppression of visual information during catching. *Journal of Neuroscience, 9*, 149–159.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*, 437–459.

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 35*(A), 333–346.

López-Moliner, J., & Bonnet, C. (2002). Speed of response initiation in a time-to-contact discrimination task reflects the use of η. *Vision Research, 42*, 2419–2430.

López-Moliner, J., Brenner, & E., Smeets, J. B. J. (in press). Effects of texture and shape on perceived time-to-passage: knowing "what" influences judging "when". *Perception & Psychopysics.*

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience, 4*, 693–694.

McLeod, P., McGlaughlin, C., & Nimmo-Smith, I. (1985). Information encapsulation and automaticity: Evidence from the visual control of finely-timed actions. In M. Posner & O. Marin (Eds.). *Attention and Performance* (Vol. XI, pp. 391–406). Hillsdale, NJ: Lawrence Erlbaum Associates.

Michaels, C. F., Zeinstra, E. B., & Oudejans, R. R. (2001). Information and action in punching a falling ball. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 54*(A), 69–93.

Michaels, C. F., Jacobs, D. M., & Bongers, R. M. (2006). Lateral Interception II: Predicting hand movements. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 459–472.

Nagai, M., Kazai, K., & Yagi, A. (2002). Larger forward memory displacement in the direction of gravity. *Visual Cognition, 9*, 28–40.

Oberle, C. D., McBeath, M. K., Madigan, S. C., & Sugar, T. G. (2005). The Galileo bias: A naïve conceptual belief that influences people's perceptions and performance in a ball-dropping task. *Journal of Experimental Psychology: Learning, Memory and Cognition, 31*, 643–653.

Orban, G. A., Fize, D., Peuskens, H., Denys, K., Nelissen, K., Sunaert, S., Todd, J., & Vanduffel, W. (2003). Similarities and differences in motion processing between the human and macaque brain: Evidence from fMRI. *Neuropsychologia, 41*, 1757–1768.

Peper, L., Bootsma, R. J., Mestre, D. R., & Bakker, F. C. (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 591–612.

Pisella, L., Grea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., & Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: Toward reinterpreting optic ataxia. *Nature Neuroscience, 3*, 729–736.

Proffitt, D. R., & Kaiser, M. K. (1998). Mental structure hypothesized as internalized physical structure. In J. Hochberg (Ed.), *Perception and cognition at century's end: History, philosophy, theory* (pp. 169–197). Orlando, FL: Academic Press.

Regan, D. (1997). Visual factors in hitting and catching. *Journal of Sports Sciences, 15*, 533–558.

Rushton, S. K., & Wann, J. P. (1999). Weighted combination of size and disparity: A computational model for timing a ball catch. *Nature Neuroscience, 2*, 186–190.

Senot, P., Zago, M., Lacquaniti, F., & McIntyre, J. (2005). Anticipating the effects of gravity when intercepting moving objects: Differentiating up and down with non-visual cues. *Journal of Neurophysiology, 94*, 4471–4480.

Smith, M., Flach, J., Dittman, S., & Stanard, T. (2001). Monocular optical constraints on collision control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 395–410.

Teixeira, L. A., Chua, R., Nagelkerke, P., & Franks, I. M. (2006). Use of visual information in the correction of interceptive actions. *Experimental Brain Research, 175*, 758–763.

Todd, J. T. (1981). Visual information about moving objects. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 795–810.

Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction motion and relative judgment tasks. *Perception & Psychophysics, 57*, 231–245.

Tresilian, J. R., & Lonergan, A. (2002). Intercepting a moving target: Effects of temporal precision constraints and movement amplitude. *Experimental Brain Research, 142*, 193–207.

Tresilian, J. R., & Plooy, A. (2006). Systematic changes in the duration and precision of interception in response to variation of amplitude and effector size. *Experimental Brain Research, 171*, 421–435.

van der Kamp, J., Savelsbergh, G. J. P., & Smeets, J. B. (1997). Multiple information sources in interceptive timing. *Human Movement Science, 16*, 787–821.

Wann, J. P. (1996). Anticipating arrival: Is the tau-margin a specious theory? *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1031–1048.

Warren, W. H. (1988). Actions mode and laws of control for the visual guidance of action. In O. G. Meijer & K. Roth (Eds.), *Complex movement behavior: « The » motor-action controversy* (pp. 339–380). Amsterdam: North-Holland.

Werkhoven, P., Snippe, H. P., & Toet, A. (1992). Visual processing of optic acceleration. *Vision Research, 32*, 2313–2329.

Wolpert, D. M., Ghahramani, Z., & Flanagan, J. R. (2001). Perspectives and problems in motor learning. *Trends in Cognitive Sciences, 5*, 487–494.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2004). Internal models of target motion: Expected dynamics overrides measured kinematics in timing manual interceptions. *Journal of Neurophysiology, 91*, 1620–1634.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2005). Fast adaptation of the internal model of gravity for manual interceptions: Evidence for event-dependent learning. *Journal of Neurophysiology, 93*, 1055–1068.

Zago, M., & Lacquaniti, F. (2005a). The internal model of gravity for hand interception: Parametric adaptation to zero-gravity visual targets on Earth. *Journal of Neurophysiology, 94*, 1346–1357.

Zago, M., & Lacquaniti, F. (2005b). Visual perception and interception of falling objects: A review of evidence for an internal model of gravity. *Journal of Neural Engineering, 2*, 198–208.

Zago, M., & Lacquaniti, F. (2005c). Cognitive, perceptual and action-oriented representations of falling objects. *Neuropsychologia, 43*, 178–188.

Please cite this article in press as: Baurès, R. et al., Intercepting free falling objects: Better use Occam's razor ..., *Vision Research* (2007), doi:10.1016/j.visres.2007.07.024