Neural prediction of complex accelerations
for object interception

Aymar de Rugy¹, Welber Marinovic¹,², Guy Wallis¹,³

¹ Centre for Sensorimotor Neuroscience, School of Human Movement Studies,
University of Queensland, Brisbane, QLD 4072, Australia
² School of Psychology, University of Queensland, Brisbane, QLD 4072, Australia
³ Queensland Brain Institute, University of Queensland, Brisbane, QLD 4072, Australia

Correspondence should be directed to: Aymar de Rugy
Centre for Sensorimotor Neuroscience
School of Human Movement Studies
Room 424, Building 26
University of Queensland
St Lucia QLD, 4072
Australia
Tel: +61 7 3365 6104
Fax: +61 7 3365 6877
aymar@hms.uq.edu.au

Running head: Internal model for object interaction

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Abstract

To successfully intercept or avoid moving objects, we must compensate for the sensorimotor delays associated with visual processing and motor movement. While straightforward in the case of constant velocity motion, it is unclear how humans compensate for accelerations, as our visual system is relatively poor at detecting changes in velocity. Work on free falling objects suggests that we are able to predict the effects of gravity, but this represents the most simple, limiting case in which acceleration is constant and motion linear. Here, we show that an internal model also predicts the effects of complex, varying accelerations when they result from lawful interactions with the environment. Participants timed their responses with the arrival of a ball rolling within a tube of various shapes. The pattern of errors indicates that participants were able to compensate for most of the effects of the ball’s acceleration (~85%) within a relatively short practice (~300 trials). Errors on catch trials in which the ball’s velocity was unexpectedly maintained constant, further confirmed that participants were expecting the effect of acceleration induced by the shape of the tube. A similar effect was obtained when the visual scene was projected upside down, indicating that the mechanism of this prediction is flexible and not confined to ecologically valid interactions. These findings demonstrate that the brain is able to predict motion on the basis of prior experience of complex interactions between an object and its environment.

Keywords: internal model; anticipatory timing; interception; motor control; motion extrapolation.
Humans are capable of producing astonishingly fine tolerance motor movements demanding both high spatial and temporal accuracy. It has been demonstrated that we can easily hit falling balls with a bat within a time window of ± 10 ms (McLeod et al 1986) and the temporal accuracy to hit a home run in a baseball match may be as little as ± 2 ms (Regan 1992). The processes by which the human brain converts visual information into motor movements of this kind remains poorly understood, but however it is done, the system needs to contend with internal delays between visual detection and motor movement which can run to the order of a hundred milliseconds (Marinovic et al 2008; 2009; McLeod 1987). There is gathering evidence that part of the process of honing motor behaviour involves the development of an internal model for motion extrapolation, and recent studies have looked into the neural substrate of such a model (Bosco et al 2008; Cerminara et al 2009; Indovina et al 2005; Miller et al 2008; O'Reilly et al 2008) and how timing might be controlled (Billington et al 2011; Field & Wann 2005). An active area of current debate is the form this model takes and the types of information about a target and its motion which such a model might contain. What we do know from the smooth pursuit eye movement literature, is that humans are relatively good at tracking objects moving at a fixed velocity, but that we are actually poor at detecting and estimating changes in velocity i.e. accelerations (Watamaniuk & Heinen 2003; Werkhoven et al 1992). This is a problem because, in real life, even inanimate moving objects experience changes in velocity due to wind resistance, gravity, changes in terrain etc. It would therefore seem expedient to be able to internalise predictions about velocity changes. To date, what little evidence we do have, has come from the study of objects falling under gravity. Evidence points to the fact that we take the effects of gravity-driven acceleration into account when timing the interception of a falling ball for example (Indovina et al 2005; McIntyre et al 2001; Zago et al 2009). The question remains, however, as to whether this is a system that has developed especially for this purpose. Free fall involves a simple linear acceleration which permits extrapolation of location at any point along the object’s line of movement (Zago et al 2009). But perhaps humans possess a much more flexible system for dealing with accelerations in a more general manner. Here, we show that a human observer’s internal model of target motion is capable of predicting the effects of far more complex variations in acceleration that result from interaction of an object with its environment in both ecological and uneccological, but lawful, ways.
Materials and Methods

Participants

Ten participants (six of them male, aged 22 – 43) volunteered for this experiment. All were right handed with normal or corrected to normal vision. They all gave informed consent prior to the experiment, and the experiment itself was approved by the local ethics committee and conformed to the Declaration of Helsinki.

Task

The task required the participant to precisely time a discrete action (i.e., an abduction force produced with the index finger) when a moving ball passed through a specific location. Participants sat in a chair with their eyes at 85 cm from a computer display (48 × 30 cm, 1920 × 1200 pixels resolution, 66 Hz refresh rate) positioned at eye level (Figure 1A). The participants were required to abduct their right index finger against a force transducer, placed beside their right hand on the hand rest, at the precise moment they judged the red moving ball (30 pixels diameter) would pass through a green stationary line (6 pixels width) positioned on the right-hand side of the screen (Figure 1B and C). The movement of the ball corresponded to a ball rolling under the effects of gravity within a tube (32 pixels width) of varying slope. The effects of rolling resistance were also accurately simulated.

After each trial, the onset of the abduction force was determined using a standard onset peaking algorithm (Teasdale et al 1993), as described in Tresilian et al., (1997): (a) locate the sample (sample 1) at which the force time series first exceeds 10% of its maximum value \((V_{\text{max}})\); (b) working back from this point stop at the first sample (sample \(S\)) which is \(\leq\) \([(V_{\text{max}}/10) – (V_{\text{max}}/100)]\); (c) find the standard deviation of the series between sample 1 and sample \(S\) (SD); (d) working back from sample \(S\), stop at the first sample which \(\leq\) (sample \(S–SD\), this is the onset. The timing error between this onset and the ball passing through the target line was then calculated and displayed on the screen as feedback to the participants. All spatial measures are reported in pixels, with a pixel’s width of 0.25 mm corresponding to 0.0169º at the centre of the screen and 0.0156º at the left and right edges. Natural gravity (i.e., 9.81 m/s²) was used in the physical space of the simulation, and this space was scaled by 0.12 to be projected on the computer display. In this context, the 48cm width of the display represents 4m of simulation, which corresponds to a visual scene viewed from approximately...
Rolling ball simulations

Because the ball was restricted to move along the path of the tube, its motion was determined from Newton’s second law of physics using the projections of all forces acting along the direction of motion. In our case, gravity ($F_g$) and rolling resistance ($F_r$, the resistance associated with the surfaces’ deformation, which is a function of the normal force at the rolling object) were the only forces considered as having a component in that direction. The equation of motion is therefore given by

$$m\ddot{p} = F_g - F_r$$

which develops into

$$m\ddot{p} = mg \sin(\alpha) - C_r m g \cos(\alpha)$$

Where $\ddot{p}$ is the acceleration (and $p$ is the position) of the ball along the tube’s path, $m$ is its mass, $\alpha$ is the slope of the tube, and $C_r$ is the rolling resistance coefficient.

The acceleration of the ball was therefore determined by the slope of the tube. Figure 2 shows typical examples of tube configurations used. These configurations can be separated into three phases: A small initial ramp, followed by a constant slope for most of the trajectory, and finally a Gaussian deflexion (upward in Figure 1B and downward in Figure 1C) just before the crossing of the target line. With the ball released at zero velocity, the initial ramp was designed to accelerate the ball until it reached a fixed velocity (960 pixel/s), which was maintained constant by the specific inclination of the flat section of tubing (i.e., at this velocity, the force of gravity was exactly compensated by the rolling resistance such that overall acceleration was nil). Then, the deflexion was introduced to elicit the pattern of
varying acceleration. The starting position was determined randomly for each trial between
the left edge of the screen (e.g., Figure 1B) and 672 pixels on its right, such that the
movement time associated with a particular tube profile was varied by up to 700 ms from one
trial to the next.

In addition to a profile $d_0$ that has no deflection, ten conditions of upward deflection (from $d_1$
to $d_{10}$) and thirty condition of downward deflection (from $d_1$ to $d_{30}$) were used. There was
therefore a total of 41 simulated profiles used between the highest upward deflexion ($d_{10}$ in
Figure 1B, which represents a deflexion of 96 pixels) and the lowest downward deflexion ($d_1$
in Figure 1C, which represents a deflexion of 288 pixels). Figure 2 displays the profiles of
velocity (Figure 2A) and acceleration (Figure 2B) associated with each deflexion. As can be
seen from this figure, upward deflexions undergo a phase of deceleration followed by a phase
of acceleration, whereas the opposite occurs for downward deflexions. Overall, the average
velocity for an upward (downward) deflexion is therefore lower (higher) than the constant
velocity operating with no deflexion, and the passage of the target line will be delayed
(advanced) as compared to what it would have been under constant velocity.

Catch trials and predictions
To test whether the pattern of varying acceleration of the ball dictated by its interaction with
the environment was taken into consideration by the participants to time their responses, we
conducted constant velocity catch trials for four specific tube profiles ($d_8$, $d_{-8}$, $d_{-18}$, and $d_{-28}$),
within a block of normal trials (i.e., velocity and acceleration profiles are indicated Figure 2)
on their direct neighbours tube profiles. Figure 2C indicates that for upward deflection, the
ball should take longer to go through the deflection part of the tube than if the tube was flat
(e.g. $\delta t = 164$ ms for $d_8$; black arrow Figure 2C). This is due to the combined effect of
changes in tube’s length and ball’s kinematics over the deflexion. Conversely, the ball takes
less time to go through small downward deflexions, and longer time again for more important
downward deflexion (e.g., $\delta t = 6$ ms, 76 ms, and 155 ms for $d_8$, $d_{18}$, and $d_{28}$, respectively).
This is because for these higher downward deflexions, the increase in tube’s length overrides
the effect of acceleration such that more time is necessary for the ball to go through the
deflexion despite its higher averaged velocity. If participants are able to predict the effect of
acceleration over those deflexions, they should compensate for the differences in timing and
produce successful responses for every case (prediction for normal trials Figure 3A). Figure 2C also indicates the difference in timing for constant velocity catch trials. For instance, the ball would take less time (i.e., 115 ms less) to go through the upward deflexion $d_8$ in a catch trial than is a normal trial (red arrow figure 2C). If the participants expect a normal acceleration on these catch trials, they should therefore be mistaken and produce late responses (prediction for catch trials Figure 3A). Conversely, the ball takes longer to go through downward deflexions on catch trials than if acceleration is normal, by an amount that increases with the size of the deflexion. Earlier responses on these downward catch trials would therefore indicate that participants expect the effect of the correct, normal acceleration. It should be noted that in effect, the first changes in trajectory between catch trials and normal trials could occur as early as approximately 500 ms before the expected response time (visible in Figure 2). This leaves time for participants to partially correct their behaviour on the bases of ongoing information, and we therefore expect only a fraction of the error predicted in Figure 3A.

**Procedures and design**

Each participant was tested two times with the same protocol. On one occasion the scene was projected normally, with gravity pointing down (i.e., Normal Gravity), and on another, upside down, as if gravity was acting upward (i.e., Reversed Gravity). These two sessions were conducted on separated days interspersed by at least 1 week, and the order of the sessions was counterbalanced between participants.

Prior to each experimental session, the participants were given two blocks of practice trials to familiarize themselves with the task. The first consisted of 20 trials with no deflexion ($d_0$), in order to enable them to experience the apparatus and the task (i.e., synchronize their response with the ball) in the simple case of constant velocity. The second familiarisation block consisted of 3 consecutive sets of 41 trials (i.e., one trial per each of the 41 different deflexions) presented in a randomized order (total 123 trials). Then, the main experimental session was conducted. This session consisted of 8 consecutive sets of 20 trials (160 trials total), including 4 catch trials of different profiles ($d_8, d_{-8}, d_{-18}, \text{and } d_{-28}$) and 16 non catch trials consisting of the 4 closest neighbour profiles of each catch trial (e.g., neighbour profiles $d_6, d_7, d_9, \text{and } d_{10}$ for catch trial $d_8$) presented in a randomized order.
Data reduction and analysis

For each trial, the timing error was calculated as the difference between the onset of the force response and the passage of the ball through the target line, with negative errors indicating early responses. For each participant, the mean of the timing errors was then calculated separately for each of the 4 different profiles of catch trials and their associated normal trial neighbours. The resulting values were analysed using 3 way repeated measures ANOVAs (2 Gravity [Normal vs Reverse] × 2 trial type [Normal vs Catch] × 4 deflexion [$d_8$, $d_{-8}$, $d_{-18}$, and $d_{-28}$]). For each deflexion condition, paired sample $t$-tests were conducted to compare timing error between trial types (i.e., Catch and Normal) within the same gravity condition (i.e., Normal or Reverse), and between gravity conditions within the same trial type. Because biases of variable magnitudes were observed in averaged timing error for the different participants, averaged errors for each deflexion and trial type were difficult to interpret individually, and we concentrated our analysis on relative changes between deflexions and trial types as indicated before. This inter subject variability might be due to the nature of the task, with a virtual interception providing less realistic feedback than hitting a real object (e.g., Zago et al, 2005). This variability should, however, not affect our results, because of the repeated measure design used.

The time course of the timing error was also assessed on both the familiarization block and the main experimental session. For the familiarization block, the summed squared error was calculated over each consecutive set 10 trials, giving 12 time values per participants (covering 120 trials, the last 3 trials were discarded). The resulting values were analysed using a 2 way repeated measure ANOVA (2 Gravity [Normal vs Reverse] × 12 Times). For the main experimental session, the summed squared error was calculated separately on normal and catch trials over each consecutive set 20 trials (i.e., 16 normal and 4 catch trials), giving 8 time values per participants. The resulting values were analysed using 2 way repeated measure ANOVAs (2 Gravity [Normal vs Reverse] × 8 Times). Sphericity was tested using Mauchly’s test, and the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity when the assumption for sphericity was violated. The significance level was set to $\alpha = .01$ for all tests.
The averaged patterns of error obtained for normal trials and for catch trials were also fitted with the patterns of errors indicated by arrows Figure 2C. First, the errors for normal trials were fitted with the pattern of error expected should participants neglect the differences in time taken by the ball to go through the various deflexions (Black arrows Figure 2C). Second, the errors for catch trials were fitted with the pattern of error predicted should the participants expect the correct effect of acceleration (red arrows Figure 2C and 3A). The values obtained for the first fit of the normal trials were used as a baseline to perform this second fit of the catch trials. In both cases, two parameters were varied to obtain the best fit (i.e. minimal residual variance): a bias and a proportion.

Control Experiment 1 Methods

Ten new participants (5 of them female, aged 25 - 53) volunteered in this control experiment. The protocol was the same as each session of the main experiment. The only difference was that the tube that determines the path of the ball, and therefore its kinematics, was made invisible. This manipulation withdrew any cue that could be used to predict in advance the ball’s trajectory and time course based on its interaction with the environment. This control was designed to test whether the differences between normal trials and catch trials observed in the main experiment was genuinely due to a prediction of the ball’s kinematics based on its path.

Control Experiment 2 Methods

Eight new participants (3 of them female, aged 23 - 44) volunteered in this control experiment. The same protocol was employed again, but this time with the ball’s acceleration that corresponded to the different simulated deflexions was played on a flat path, with no apparent deflexion (i.e., visible but flat tube). As for the precedent control experiment, any cue that could allow participants to predict the ball’s acceleration has been removed, but here, the additional confound induced by the altered path length that is due to the deflexion was also removed. This control was designed to test whether any effect on the previous control experiment could be due to the altered path length.
Results

Pattern of error

Figure 3B and D show a pattern of error that resembles that predicted in Figure 3A, whether the visual scene was projected normally (i.e., normal gravity), or upside down (i.e., reversed gravity). Statistical analyses reveal that the effects predicted are all significant, and that there is no difference between conditions of normal and reversed gravity. The three way repeated measures ANOVA (2 gravity × 2 trial type × 4 deflexion) indicates a main effect of trial type ($F(1, 9) = 55.87, P < .0005$), deflexion ($F(3, 9) = 17.70, p < .0005$), and an interaction between them ($F(3, 27) = 25.41, p < .0005$). No other main effect or interaction was detected. The difference between catch trials and normal trials was significant for all deflexions of the two gravity conditions (all $t$s (9) > 3.57, all $ps < .006$). On the other hand, no differences were found between timing errors of the two gravity conditions within each trial type and deflexion (all $t$s (9) < 1.46, all $ps > .18$).

There are, however, noticeable differences from the pattern predicted in Figure 3A. These include a pattern of errors for normal trials that is overall negative (i.e., early responses), and which varies with deflexion. A fit indicates that 98.0% variance of the errors is explained by a proportion of only 15.4% of the full pattern of error expected should participants neglect the differences in time taken by the ball to go through the various profiles (Figure 3C). The interpretation conveyed by this fit is that in normal trials, participants were correctly accounting for 84.6% of the combined effects of acceleration and tube length over the deflexions. With respect to early responses, the fitted response obtained for the deflexion for which a response closest to zero was expected (i.e., $d_s$) is only -9 ms. This could be easily explained by the fact that the very onset of the force was used in order to prevent eventual benefits from modulating the force response when too early or too late.

Another noticeable difference is the size of the errors predicted for catch trials, which is more important than the actual errors observed (notice the different scale use for panel A than for the 3 other panels of Figure 3). The best fit performed on catch trials account for 95.4% of
error’s variance using a proportion of 29% of the pattern of error predicted should participants mistimed their response by an amount that corresponds to the full effect of normal acceleration. This means that participants were building up an expectation of the effects of acceleration dictated by the interaction of the ball and the tube, and were unable to completely overcome that expectation during unexpected constant velocity catch trials, despite the availability of visual information throughout.

Time course of the performance

The two way repeated measures ANOVA (2 Gravity × 12 Time) conducted on the summed squared error calculated over the 12 consecutive sets of 10 trials of the familiarization block did not reveal any main effect or interaction (all ps > .77). Similarly, the two way repeated measures ANOVAs (2 Gravity × 8 Time) conducted on summed squared error calculated over the 8 consecutive sets of 20 trials of the main block did not reveal any main effect or interaction for normal trials (all ps > .48) nor for catch trials (all ps > .54). These analyses indicate that overall performance was stable throughout the experiment, although some degree of adaptation could have been masked by the trial-by-trial variability.

Control experiment 1: invisible path

Figure 4A show a pattern of error that resembles that of the normal trial of the main experiment, but for both the normal and the catch trials. Statistical analyses reveal a significant effect of deflexion ($F(3, 30) = 14.40, p < .0005$), but no effect of trial type ($F(1, 10) = 5.34; p = .043$), and no interaction ($F(1.99, 19.9) = 3.87; p = .038$). That normal trials and catch trials were no longer different when the path of the ball was made invisible indicates that differences observed in the main experiment are due to a prediction of the ball’s kinematics based on its interaction with the environment. The remaining effect of deflexion on timing error could be related to the altered path length induced by the deflexions, which has been removed in control experiment 2.
Control experiment 2: flat path

Figure 4B show that when the acceleration profiles were played on a flat path, there was no longer difference with deflexion types. There was no effect of deflexion ($F(3, 7) = 2.91, p = .058$), only a marginal effect of trial type ($F(1, 7) = 9.75, p = .017$), and no significant interaction ($F(3, 21) = 1.24, p = .32$). This indicates that the effect of deflexion on normal trials of the previous control, and part of the effect observed in the main experiment, were indeed related to changes in path length with deflexion. That performance was close for normal and catch trials, also indicates that participants were somehow able to compensate for the effect of unexpected acceleration based on online visual information.

Discussion

Here we show that when timing an object interception, humans are building up an expectation of the effects of complex, varying accelerations that result from interactions with the environment. The errors produced by participants timing their responses with the arrival of a ball rolling under gravity within a tube of various shapes indicates that, within a relatively short practice (~ 300 trials), they were able to compensate for most (~ 85 %) of the effects of a complex acceleration dictated by the movement of the ball within its tube. Errors on catch trials in which the velocity of the ball was unexpectedly maintained constant confirmed that participants were expecting the effect of acceleration normally induced by the shape of the tube. Control experiments in which predictive cues about the environment were removed also indicate that the task could be resolved, to a certain degree, by online feedback only. Yet, participants were not able to overcome their expectation of the effect of gravity when reliable predictive cues were available in the main experiment. Furthermore, we showed that these effects were identical whether the visual scene was projected normally or upside down, which indicates that the mechanism of this prediction is flexible and not confined to ecologically valid interactions.

A critical feature of the present finding is that the acceleration of the ball was induced by the interaction with its particular environment in a predictable fashion. This situation resembles
the study of Brown et al. (2007) in which learning to move in a force field was shown to improve timing interception of an object accelerating in the same direction of the force field. In this case, knowledge of the environment acquired through motor learning influenced predictions of the motion of the object as if the object was interacting with the same environment. However, an important difference with the present study is that in Brown and colleagues’ study (2007), no visual information about the environment was available to assist in the prediction of the outcome of its action on the object. In this context, the knowledge developed during motor practice might have been sufficient to elicit a meaningful effect because of the relatively restricted scenario used (i.e., only one constant acceleration of the object, tested after practice of one of two possible force field environments that differed, or not, in direction). Here, the patterns of accelerations were complex and variable, both within and between the multiple tube shapes tested, but each was entirely predictable from a projection of the ball’s behaviour onto its visible environment (i.e. the shape of the tube).

The present results are also in line with important studies that have demonstrated that we are able to take the effects of gravity driven acceleration into account when timing the interception of falling objects (Indovina et al 2005; McIntyre et al 2001; Zago et al 2009). However, the extension of this finding to a much broader range of cases and situations has important implications for the mechanism underlying the prediction. In the case of a free falling object, acceleration is constant and an internal model could simply be composed of a single (constant) estimate of gravity acceleration combined with online retinal information (Zago et al 2009); see also (Tresilian 1999). An internal model of this kind, however, would fall short in the present context in which the variations of acceleration result from specific interactions with the environment. The fact that we obtained similar results whether the visual scene was projected normally or upside down further indicates that the mechanism of this prediction is flexible and not confined to an evolutionarily prepared version of gravity. Previous studies investigating this issue in the context of free falling objects, found an effect of the direction of gravity, on both the behaviour and the neural substrate involved in the prediction (Bosco et al 2008; Indovina et al 2005; Miller et al 2008). It was also found, however, that the inclusion of more realistic scenery amplified this effect (Miller et al 2008). In our case, the scenery was kept very sparse, and this might have contributed to the apparent ease with which subjects were able to learn to cope with reverse gravity.
In summary, our findings demonstrate that for object interception, humans are capable of predicting complex interactions with the environment in a manner that is much more flexible than previously thought. However, the overall capabilities and the precise form of a putative internal model responsible for this type of prediction remain largely unknown. We believe that the task set presented here constitutes a novel paradigm that has great potential to address these issues.


Figure legends

Figure 1. A. Experimental apparatus. B and C. Examples of tube configurations used to simulate the rolling ball. The ball is released at the top of the initial ramp which serves to accelerate the ball until it reaches the phase of constant velocity. Then, it undergoes an upward (B) or downward (C) deflexion before crossing the target line. B and C represent the highest ($d_{10}$) and the lowest ($d_{-30}$) deflexion used, respectively. The starting point was randomly determined between the left edge of the screen and 672 pixels on its right, in order to vary movement time by up to 700 ms from one trial to the next.

Figure 2. Velocity (A) and acceleration (B) profiles for the 41 different deflexions used. The profiles that correspond to the deflexions used for the catch trials are highlighted in red (i.e., $d_8$, $d_{-8}$, $d_{-18}$, and $d_{-28}$). C. Difference in time ($\delta t$) taken by the ball to go through the various deflexion compared to a flat tube (i.e. no deflexion), for trials with normal acceleration (black square) and constant velocity catch trials (red circle). Black arrows indicate timing errors expected should participants neglect the differences in time taken by the ball to go through the various deflexions, and red arrows indicate timing errors expected should participants expect normal acceleration on catch trials.

Figure 3. Timing errors. A. Pattern of error predicted should the participants correctly account for the effect of acceleration over the entire deflexion, presented as a function of the deflexion used for the catch trials (i.e., for $d_8$, $d_{-8}$, $d_{-18}$, and $d_{-28}$). B and D. Timing errors (mean error ± SE) obtained in condition of Normal Gravity (B) and Reverse Gravity (D). C. Averaged pattern of error fitted with the best proportion of pattern of error expected should participants neglect the effect of acceleration over normal trials, and should they expect normal acceleration on catch trial (cf Methods and Results). Negative errors indicate early responses.

Figure 4. Timing errors in control experiment 1 (A, invisible ramp) and control experiment 2 (B, flat tube).