The Use Of On-Line Perceptual Invariants Versus Cognitive Internal Models For The Predictive Control Of Movement And Action

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Abstract-**An important and ongoing debate in the study of human motor behavior concerns the complexity of neural processing used to control our actions. On the one hand, neural systems could mimic geometric and dynamic laws to estimate the current and future movements of one's self and of objects within the environment (a cognitivistic viewpoint). Conversely, the nervous system may exploit perceptual invariants in sensorimotor signals to rapidly elicit actions with little computational overhead (the ecological-perception school of thought). In this paper we propose a hybrid solution to the classical problem of intercepting a falling object. We demonstrate how control strategies that rely on first-order, real-time estimates of time-to-contact can be tuned based on a priori knowledge about gravity to provide more effective control with little or no additional computations. We propose this solution as one way in which the central nervous system might implement "pretty good" internal models of laws of motion for the predictive control of motor actions.**

***Keywords* - Prediction, interception, TTC, motor control**

I. INTRODUCTION

Consider a simple hitting task to be performed by a human or robotic actor: a ball is travelling along a predictable trajectory towards a predetermined point of interception. The task is to trigger a motor response at the right time so as to stop the ball or deflect it from its original trajectory. If we leave aside the spatial aspects of the prediction (i.e. where is the interception point?) and concentrate on the temporal problem (i.e. when will the ball arrive?), the motor response must in general be programmed to start at some lead time prior to the moment of arrival. The lead time might, for instance, represent the time it takes for a motor command to travel from the central nervous system to the muscle plus the electro-mechanical delay between electrical activation of muscle and its mechanical effect on the hand and the limb. The consequence of these delays is that the perceptuo-motor system must predict the moment of impact based on sensory information available at some earlier point in time. If we further restrict the analysis to predictive all-or-nothing tasks, such as pressing button to trigger a fixed-duration response, success or failure will be entirely determined by the ability to accurately estimate the time-of-arrival (ETA) of the ball.

The task of catching a falling ball has been extensively studied by experimental psychologists and human physiologists alike. According to the theories of Ecological Perception [1], all the information used to drive behavior should be contained in the sensory signals that arise from the task. In the case of visually-guided interception, this means that the required information about ETA should be contained in visual signals. However, it is known that the visual system is a poor discriminator of object acceleration [2]. Accordingly, if only position and velocity information is contained in the optic flow pattern, then the timing of motor actions should at best be based on a first-order estimate of ETA that ignores acceleration. The τ hypothesis proposed by David Lee [3] has therefore become a standard bearer of the Gibsonian school of thought. Because the retinal signals $r(t)$ and $\dot{r}(t)$ are readily available, the perceptual variable τ provides a direct, first-order estimate of ETA for an object approaching head-on without resorting to more complex processing. Experimental evidence suggests that human subjects indeed use τ rather than a higher-order estimate of ETA when jumping to punch a falling ball [B4]. The hypothesis that first-order estimates are used has also been extended to viewing situations other than the head-on approach required for τ [5,6,7,8].

On the other hand, human subjects who caught a falling ball in the outstretched hand activated arm muscles in coordination with the arrival of the ball in the hand independent of the drop height [9,10]. The precise timing of these responses with respect to impact indicate that the subjects were able to take into account the acceleration of the ball due to gravity when estimating ETA. Rather than supposing that these subjects somehow had access to *on-line* information about acceleration, however, Lacquaniti and colleagues proposed that subjects may use an *a priori* assumption about the most likely pattern of movement, based on implicit knowledge about the laws of physics, i.e. that downward moving objects will accelerate at 1g. Evidence from a recent experiment performed in space flight provides support for this latter hypothesis [11]; systematic shifts in the timing of muscle activity during catching were consistent with an *a priori* second-order estimator that combines on-line information about position and velocity with an assumed 1g acceleration to predict ETA. Nevertheless, the use of this kind of strategy appears to be counter-intuitive for the most general case. Should the CNS continue to adopt such a strategy when 1g acceleration is not the only possibility? This question can be posed as a sort of optimization problem – if the brain is constrained to use an *a priori* assumption of a fixed acceleration, what acceleration value should be used to optimize the chances of success?

II. METHODOLOGY

To evaluate the optimal strategy that may be employed to intercept or catch a falling object, we simulated the following situations that typify the range of catching or

Supported by grants from the French Space Agency CNES and the Italian Space Agency ASI.

intercepting tasks that a human actor may encounter: A ball is projected along a straight line toward the actor. The catch zone is assumed to be pre-determined, i.e. the actor must correctly time his or her responses to the ETA of the ball, but the position of the interception is determined by the task. In a *catching* task, the hand is placed at the interception point, palm perpendicular to the ball's trajectory. The actor must generate an impulse-like response, such as a muscle stiffening, timed to occur at the same moment as the arrival of the ball plus or minus some margin of error. In a *hitting* task, the actor must trigger the displacement of a racquet along a path perpendicular to the ball's flight line so as to intersect the path of the ball when it is within the area covered by the racquet.

A. Temporal Characteristics

For the purposes of the simulations described here we wished to consider a range of plausible ball trajectories that might be encountered in real-life situations. To allow for a direct comparison with experimental studies on catching or hitting a falling ball, we considered trajectories of the ball in which the acceleration is held constant within a given trial. The trajectory of the ball may therefore be characterized by the initial distance from the interception point, the initial velocity when the ball is launched from this point and the constant acceleration applied to the ball over its entire flight.

$$p(t) = p_0 - \dot{p}_0 t - \tfrac{1}{2}\ddot{p}_0 t^2 \qquad (1)$$

The critical factor determining the "interceptability" of the ball is the reaction time allowed to the actor from when the ball first appears. From previous studies is known that humans need at least 300 ms viewing time to successfully catch a thrown ball. This establishes a minimal duration for an "interceptable" ball. We assumed a normalized initial distance p_0 equal to 1 m and accelerations $\ddot{p}_0$ within the range of ±1 ms^{-2}. We then calculated initial ball velocities $\dot{p}_0$ so that the total flight time was at least 0.3 s. By appropriate scaling, the results generalize to other distances, velocities and accelerations, so long as the minimum time window is respected. It was assumed that 1.0 s is well in excess of the required ETA threshold so that information arriving more than 1.0 s prior to arrival will have no effect on the timing of the response. Thus, we considered flight times only up to 1 s. Flight times greater than this value can be re-cast in terms of a flight initiated at a closer position with a greater initial velocity.

B. Simulated Timing Strategies

We assumed that the actor adopts a timing strategy in which ETA is continuously computed via a second-order estimate based on on-line measurements of position $p(t)$ and velocity $\dot{p}(t)$ and a fixed *a priori* value of acceleration a_0. The assumed future trajectory of the ball at any time t is therefore:

$$\tilde{p}(t+\Delta) = p(t) - \dot{p}(t)\Delta - \tfrac{1}{2}a_0\Delta^2 \qquad (2)$$

and the estimated ETA is given by:

$$\Sigma^{2a}(t) = \begin{cases} \dfrac{p(t)}{\dot{p}(t)}, & a_0 = 0 \\ \dfrac{\dot{p}(t) + \sqrt{\dot{p}(t)^2 + 2a_0 p(t)}}{a_0}, & otherwise \end{cases} \qquad (3)$$

The actor is free to choose the specific value of acceleration a_0 used in the estimate of ETA, but the value a_0 must remain fixed across all trials. The actor will trigger a response when $\Sigma^{2a}(t)$ drops below the ETA threshold λ.

C. Variability and Error Margins

We wished to identify the values of a0 and λ that will optimize performance, where performance is defined as the percentage of successful trials for repeated measures across the range of possible true ball velocities and accelerations. The rate of success will depend on the accuracy of the ETA estimate, variability in the timing of responses and the allowable margin-of-error. We characterized the variability as Gaussian noise added to the response timing predicted by $\Sigma^{2a}(t)$. The catching and interception tasks differ conceptually in terms of the margin-of-error for the accuracy of timing. In the catching task it was assumed that the response must occur within a fixed temporal window, independent of the velocity or acceleration of the ball. In the interception task, the ball will traverse the region swept out by the racquet more or less quickly, depending on the final velocity of the ball. In the latter case, the margin-of-error varies as a function of the ball's velocity and acceleration, and as a function of racquet and ball size.

III. Results

Errors in timing were computed as a function of total flight time induced when the assumed acceleration a_0 is not equal to the true acceleration $\ddot{p}_0$ of the approaching object. Success depends on the ETA threshold λ and the margin-of-error in the timing of the response. For small values of λ, any choice of a_0 would allow the actor to intercept balls with any of the possible true accelerations (timing errors are within the margin of error for any value of a_0). For large λ values, the actor would be able to hit only balls undergoing acceleration equal to the assumed value a_0. For intermediate values of λ, depending on the level of noise in the responses, the actor would be able to hit a percentage of all 3 accelerations, with the percentage on a given true acceleration depending on the choice of a_0.

Fig. 1 illustrates how a_0 may be selected to optimize the total success. Fig. 1A shows the simulations of the hitting task in which the error margin depended on the size of the ball and racquet and on the final speed of the ball at the interception point. Results were similar for the catching task in which the error margin around the ideal onset time is fixed. For low values of λ it is clear that the optimum choice

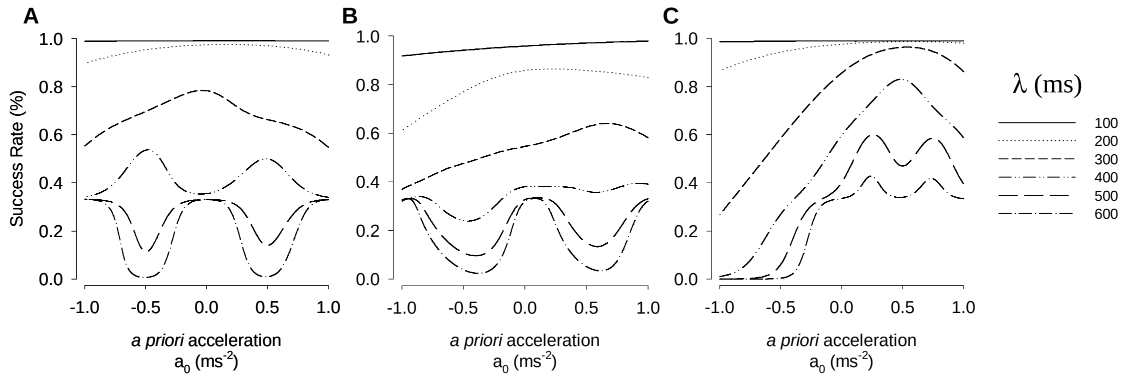

Figure 1: Effect of assumed constant acceleration (a_0) and response lead (λ) on success rate. For an equal likelihood of all 3 possible true accelerations (**A**), patterns of success rate vs. a_0 vary from unimodal for short λ with a maximum at $a_0 = 0$, to trimodal for long λ. For asymmetric error margins with more tolerance for early rather than late responses (**B**) or for true accelerations restriced to positive values (**C**), the optimal value of a_0 is positive, in between 0 and 1 ms^{-2}.

of a_0 is 0 ms^{-2}. At this value a maximum percentage of all balls would be hit successfully. A curious effect occurs for λ = 400 ms. Here the rate of success profile was dual peaked, with values of $a_0 = \pm 0.5$ ms^{-2}. This may have implications for an adaptation strategy in which a_0 is found through gradient descent. The final value of a_0 will depend on the initial guess.

Fig. 1B illustrates how an asymmetric error window can modify the optimal value for a_0. If being early is more tolerable than being late, the actor will achieve greater overall success by assuming that the ball will accelerate somewhat, although not at the maximum possible rate. Fig. 1C shows how the expected distribution of real accelerations can influence the optimal choice of a_0 even for the case of symmetric error margins. Obviously, if only accelerating balls will be encountered, the actor can improve success by choosing an intermediate value of a_0 between 0 and +1.

Adjusting a_0 is not the only free parameter available to the actor in these examples. It was assumed that the motor responses at the effector occur at a fixed time delay μ after the response is triggered in the brain, i.e. muscle stiffening at the hand occurs at a fixed time delay after the neural command is triggered and that the racquet moves with a constant duration from a fixed starting point to the interception point. Thus, for both catching and hitting one might naturally assume that the actor must trigger the response μ s prior to the arrival of the ball at the interception point. It make sense that if the estimate of ETA is exact, the threshold ETA value λ used to trigger the response should be equal to the required lead time μ. But in fact, the actor is free to choose a different λ to account for certain errors that may arise in the case of an approximate estimate such as $\Sigma^{2a}(t)$. For instance, if responses are consistently too late, the actor could increase λ to compensate. Timing strategies were therefore characterized by two free parameters, the assumed acceleration a_0 and the ETA threshold λ.

Fig. 2 shows how adjusting λ can improve the overall success rate even for a non-optimal value of a_0. In Fig. 2A, optimal performance was achieved for $a_0 = 0$ and λ = μ, but overall performance with $a_0 > 0$ could nevertheless be improved by setting λ slightly lower than the ideal value μ. Furthermore, it can be shown that for an asymmetric error margin (Fig. 2B) or for an asymmetric distribution of true accelerations (Fig. 2C), the actor may achieve equally good performance for any choice of a_0 by simply adjusting the value of λ.

IV. Discussion

The simulations described in this paper provide insight into how a actor system can optimize strategies for intercepting moving objects when limited temporal information is available. If observations are limited to on-line measurements of position and velocity, the actor is constrained to make a best-guess estimate of what the ensuing acceleration will be if success is to be optimized. In previous studies of psychophysics, it has been suggested that in the most general case human actors use first-order estimates of ETA which implicitly suppose that acceleration of the object is equal to zero. In at least one group of studies, however, it has been proposed that when an acceleration is predictable, such as in the case of gravitational acceleration, human actors may use an *a priori* assumption of non-zero acceleration to maximize chances of success. This phenomena has been described as an “internal model” of the affects of gravity on the ball.

The analysis of optimal strategies presented here provides a alternative interpretation of the term “internal model of the effects of gravity”. It is clear that when all accelerations are equally likely, the best guess for the assumed acceleration is zero, consistent with the first-order hypotheses for estimates of ETA. If a non-zero acceleration is more likely to occur, success is improved by biasing the assumed value of acceleration toward the expected true mean. Furthermore, the actor may take advantage of asymmetry in the margins of error. If it is better to be early rather than late, as in the case of stiffening the hand to absorb the impact with a ball, the optimal strategy is to assume a

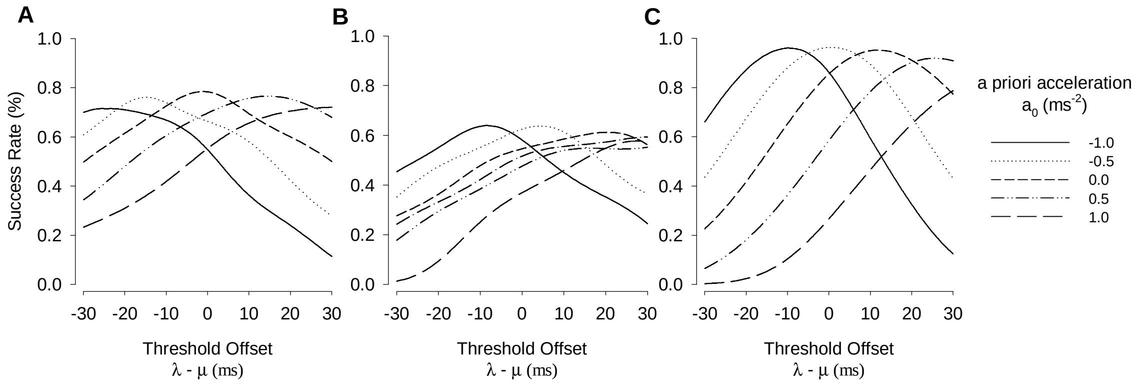

Figure 2: Effect of shifting λ with respect to the ideal lead time μ. In the general case, best performance achieved with $a_0 = 0.0$, but letting λ<>μ may improve performance for any value of a_0 (**A**). For an asymmetric error margin (**B**) or a biased distribution towards accelerating objects (**C**), optimal performance is achieved with $a_0 = 1$ and $\lambda = \mu - 10$ ms.

positive acceleration. Note, however, that the optimal strategy is not to adopt the greatest possible acceleration. An *a priori* guess of ½g acceleration potentially provides a better compromise for the range of accelerations normally observed on Earth. While such a strategy may no longer constitute an internal model of 1g gravitational acceleration *per se*, it nevertheless reflects an internal model of what accelerations are most likely to be expected for a downward moving object in a normal environment.

The form of the curves in Figs. 1 and 2 also have implications for learning strategies based on past performance. One might assume that the actor will update the free parameters a_0 and λ based on feedback as to whether a given response was too early or too late. One insight to be drawn from the simulations shown here is that success rate as a function of these two parameters are not always single-peaked. Thus, the optimal solution may not necessarily be found and/or the system may settle into one of several equally advantageous solutions based on the initial guess. Further insight is obtained by observing the interaction between λ and a_0. While the true optimal may only be reached by correctly adjusting a_0, significant improvements may be obtained simply by increasing λ when responses are too late and decreasing λ when responses are too early.

V. Conclusion

The predictions of the simulations presented here remain to be tested for human actors performing intercepting tasks. Preliminary experiments suggest that humans indeed select intermediate values of a_0, depending on the range of expected ball accelerations. Furthermore, one may naively act on the choice of the ETA threshold λ, rather than on the assumed acceleration parameter a_0 when incorporating knowledge about the most likely acceleration of the ball. The simulations presented here and the experiments that they suggest promise to provide further insight into the workings of the human brain when performing predictive interceptive tasks.

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