

# Estimating Time to Contact and Impact Velocity When Catching an Accelerating Object With the Hand

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To catch a moving object with the hand requires precise coordination between visual information about the target's motion and the muscle activity necessary to prepare for the impact. A key question remains open as to if and how a human observer uses velocity and acceleration information when controlling muscles in anticipation of impact. Participants were asked to catch the moving end of a swinging counterweighted pendulum, and resulting muscle activities in the arm were measured. The authors also simulated muscle activities that would be produced according to different tuning strategies. By comparing data with simulations, the authors provide evidence that human observers use online information about velocity but not acceleration when preparing for impact.

When performing natural tasks, human beings are adept at predicting the future positions of objects that move within the environment. Such capabilities are a functional necessity given the significant delays in the transmission of information within the nervous system. In the case of catching an object with the hand, for example, an observer must anticipate future movements of the object to initiate and control motor responses at the appropriate time prior to impact.

Mechanisms used by human observers have been extensively studied for a variety of predictive behaviors, including interception tasks (Bootsma & van Wieringen, 1990; Lee, Young, Reddish, Lough, & Clayton, 1983; Savelsbergh, Whiting, & Bootsma, 1991; Savelsbergh, Whiting, Pijpers, & van Santvoord, 1993), predictive motion tasks (Kaiser & Phatak, 1993; Schiff & Detwiler, 1979; Schiff & Oldak, 1990), and relative judgment tasks (Bootsma & Oudejans, 1993; Kaiser & Phatak, 1993; McLeod & Ross, 1983). Such studies have clearly established that observers can access estimates of time to contact (TTC) on the basis of information contained in the available perceptual variables. The question remains open, however, as to the nature of the information used in such behaviors. Even without asking the question of which perceptual variables are actually used, one can question in a more abstract sense whether position, velocity, or acceleration information is used to coordinate motor responses with visual stimuli. In the study reported here, we addressed the issue in the aforementioned manner; that is, we asked the question: Is position, velocity,

or acceleration information used to adjust the timing and amplitude of muscle activities when catching objects that accelerate?

The formulation of this question is deceptively simple, but its meaning is ambiguous. How might one "use" velocity information to program a response, and how can one answer the question experimentally? One obvious test might be to see if responses vary appropriately according to the velocity of the moving object. If responses occur earlier (with respect to movement onset) for fast-moving than for slow-moving objects (from a fixed position), one might claim that the timing strategy adjusts for changes in velocity. But an affirmative response to this test does not mean that velocity information is explicitly measured during the task. If, for example, the observer simply triggers the response when the object reaches a fixed distance, the response will nevertheless occur earlier for the faster moving target because the object arrives at the threshold distance sooner. To accurately discuss these issues, one needs to have a clear definition of what it means to use position, velocity, or acceleration information to catch a moving object.

One possibility is to classify strategies mathematically, based on the temporal derivations embedded in the underlying control laws. As we will show, if  $P(t)$  describes the motion of the target object, a strategy can be called a zero-order, first-order, or second-order strategy, depending on which temporal derivatives of  $P(t)$  contribute to the control of the predictive behavior. With this convention, a zero-order strategy is said to use position information only, a first-order strategy uses position and velocity but not acceleration, and so on. In the remainder of this introduction, we first develop this nomenclature in more detail (see also Bootsma, Fayt, Zaai, & Laurent, 1997) and use it to compare experimental studies related to the problem of catching. We consider the synchronization of muscle activations to the moment of contact and the control of muscle activity amplitude to match the impending impact. Finally, we identify the open questions that motivated our experiments in which human observers caught an accelerating object (a swinging pendulum) with the hand.

## Response Timing

Consider the following perception–action task to be performed by a human observer. A mobile object is traveling toward the hand,

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This work was carried out under the auspices of the European Laboratory for the Neuroscience of Action. Financial support was provided by the French space agency Centre National d'Etudes Spatiales. We thank A. Berthoz, R. Bootsma, F. Lacquaniti, and M. Wexler for helpful comments on the experiments and manuscript; A. Treffel for the mechanical work on the pendulum; and F. Maloumian for help in producing the figures.

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which is held at a fixed position in space. The observer must generate a motor response to successfully arrest the movement of the object at the point of impact. This response must in general be triggered at some lead time ( $\lambda$ ) prior to the moment of impact ( $T_{\text{impact}}$ ). The amount of time before impact required for the task might, for instance, represent the time it takes for a motor command to travel from the central nervous system to the muscle, or it may represent the fact that perceptual information is delayed between acquisition in the periphery and processing in the central nervous system. The consequence of these delays is that the perceptuomotor system must predict the time of impact and trigger a response when there remains only  $\lambda$  seconds until impact.

How might this anticipatory response be generated? Suppose that the position of the object in relation to the hand at each moment in time is described by the function  $P(t)$ . With perfect advance knowledge of  $P(t)$ , it would be relatively straightforward to solve for  $T_{\text{impact}}$  such that  $P(T_{\text{impact}}) = 0$  and then trigger the motor response at  $t = T_{\text{impact}} - \lambda$ . In a realistic analysis, however, it is assumed that the observer does not have full veridical knowledge of the moving object's future trajectory. Hypothetically, one might instead suppose that the observer continuously estimates the future movement of the target based on current measurements of  $P(t)$  and its derivatives:

$$\tilde{P}(t + \delta) = P(t) + \dot{P}(t)\delta + \ddot{P}(t)\delta^2 + \dots \quad (1)$$

and then solves for TTC such that  $\tilde{P}(t + \text{TTC}) = 0$ . By analogy with a Taylor series expansion, the more temporal derivatives used in  $\tilde{P}$ , the more accurate will be the estimate of TTC. The classification of TTC estimates as zero, first, or second order is based on an analogy with this equation. Estimates of TTC will be progressively more accurate if they incorporate information about position, velocity, and acceleration. Note, however, that the use of this nomenclature does not necessarily imply that the observer explicitly performs the computations in Equation 1 or that the observer explicitly measures  $P(t)$  or its derivatives. Invariant relationships between quantities in the sensory input variables may permit the estimation of TTC directly without evaluating  $\tilde{P}$  at all. Nevertheless, the "order" of strategies can be assigned on the basis of the functional equivalence with Equation 1 in terms of information processing. This point becomes clearer in the examples of zero-, first-, and second-order timing strategies that are described in the following paragraphs.

### Strategies for Estimating TTC: What Is Good Enough?

The accuracy required for the estimate of TTC depends on the temporal constraints imposed by the predictive task. By definition of the task given earlier, the position of the hand is fixed, and the actions of the observer have no influence on the time course of  $P(t)$ . The job for the observer therefore reduces to that of triggering the response at a fixed time  $\lambda$  prior to impact:

$$T_{\text{response}} = T_{\text{impact}} - \lambda. \quad (2)$$

The precision required by this task may be described as a temporal window around the ideal response trigger. The error margin  $\varepsilon$  describing the temporal window need not, in the most general case, be symmetric. The action will be successful if

$$T_{\text{impact}} - \lambda - \varepsilon^- < T_{\text{response}} < T_{\text{impact}} - \lambda + \varepsilon^+. \quad (3)$$

A control strategy will be "good enough" if errors in the estimation of TTC are less than the error margin  $\varepsilon^\pm$ .

### Zero-Order Strategies

With measurements of the object's position, observers could initiate their response when the object passes a fixed reference position. In terms of Equation 1, this is a zero-order control strategy because no temporal derivatives of  $P(t)$  are used to estimate TTC. In fact, this strategy does not rely on any estimate of TTC at all, per se. TTC cannot be derived from  $P(t)$  without at least some a priori assumption of a nonzero approaching velocity. Despite this implicit assumption, we classify this strategy as "zero order" because it neglects all derivatives of  $P(t)$  in the equivalent *online*<sup>1</sup> estimate of TTC. Such a strategy is "good enough" if the difference between the implicit and true velocity across trials causes small variations in the time to move from the threshold distance to the impact point, where small is defined by the temporal window  $\varepsilon^\pm$ .

Certain anticipatory tasks may be successfully synchronized without any use of spatial information whatsoever. Observers could simply initiate the required response at a fixed reaction time following the detection of a trial's onset. Technically, this strategy cannot be related to Equation 1 because  $P(t)$  and its derivatives appear nowhere in the timing strategy. For convenience in this article, however, we call this a zero-order strategy because of the absence of higher order derivatives in the equivalent information processing. This strategy can be effective if the movement duration (i.e., the time lapse between the object's apparition and impact) varies less from trial to trial than the width of the temporal time window allowing for success. Observers may learn with practice to adopt a particular reaction time such that the response occurs on average  $\lambda \pm \varepsilon^\pm$  seconds prior to impact across trials. Or, if there is no penalty for initiating a trial early (e.g.,  $\varepsilon^+ > \text{max movement duration}$ ), the observer may adopt a reaction time appropriate for the shortest possible movement duration.

### First-Order Strategies

For an object approaching the impact point with time course  $P(t)$ , TTC may be estimated to a first-order approximation as the distance divided by the approach velocity:

$$\text{TTC}_1(t) = -P(t)/V(t), \quad (4)$$

where  $V(t) = \dot{P}(t)$ . In the case of constant velocity motion, this estimate of the true TTC will be exact, whereas  $\text{TTC}_1$  will over- or underestimate the true TTC for accelerated or decelerated movement, respectively. Such a strategy is "first order" because it uses online information about movement velocity (the first derivative of  $P(t)$ ). Note that explicit measurements of velocity need not be present to achieve a first-order strategy. Take, for example, the  $\tau$  strategy for a head-on approach. The optic variable  $\tau$  gives a direct

<sup>1</sup> We differentiate online information as stemming from measurements made by viewing the moving object *during* a given trial from a priori information that is acquired *before* the object first appears at the start of the trial (e.g., through learning, memory, and internal representations of physical laws).

estimate of TTC based on retinal information, without the need for an explicit estimate of object distance:

$$\tau = \frac{R(t)}{\dot{R}(t)} = -\frac{P(t)}{\dot{V}(t)}, \quad (5)$$

where  $R(t)$  is the size of the retinal image. It is the equivalence, however, between  $\tau$  and the distance divided by velocity that makes it a first-order strategy.<sup>2</sup> Thus, whereas the definition of a first-order strategy supposes the use of online velocity information, the implementation of the strategy may rely on other perceptual variables that provide an equivalent estimate of TTC.

First-order strategies as defined here are sometimes called *constant velocity strategies* (Bootsma et al., 1997; Tresilian, 1991) because  $TTC_1$  provides an accurate estimate of the true TTC only if velocity remains constant for the remainder of the movement. This does not necessarily imply that a strategy based on  $TTC_1$  will ignore acceleration altogether. If one truly believes that the motion will continue at constant velocity, one could make a single estimate of  $TTC_1$ , and then internally count down  $TTC_1 - \lambda$  seconds based on an internal clock. For an accelerating or decelerating system, if the single measurement of  $TTC_1$  occurs too far in advance of impact, the error induced by a first-order estimate of TTC may cause the response to be triggered too early or too late. This would explain why human observers do not adopt such strategies in predictive motion tasks (DeLucia & Liddell, 1998). Later measurements of  $TTC_1$  would, however, be progressively more accurate. If instead of counting down  $TTC_1 - \lambda$  the observer continuously recomputes  $TTC_1$  until it reaches the critical value of  $\lambda$ , errors induced by the first-order estimate would become progressively smaller. A first-order strategy based on  $TTC_1$  can therefore adjust for acceleration by continuously monitoring changes in velocity. Although a single estimate of  $TTC_1$  ignores acceleration, *behavior* based on  $TTC_1$  does not (Bootsma et al., 1997).

### Second-Order Strategies

Strategies for estimating TTC that include information relative to acceleration can be called “second order” because of the implication of the second derivative of  $P(t)$ . In analogy with the first-order strategy outlined earlier,  $TTC_2$  would be measured by an approximation that takes into account online measurements of  $\dot{P}(t)$  or an equivalent. Given an instantaneous measurement of acceleration, the second-order estimate of TTC is given by

$$TTC_2(t) = \frac{-V(t) + \sqrt{V(t)^2 - 2A(t)P(t)}}{A(t)}, \quad (6)$$

where  $A(t) = \dot{P}(t)$ .  $TTC_2$  is somewhat complex, and it may be unreasonable to assume that the sensorimotor system is capable of executing this computation exactly online. Nevertheless, just as the  $\tau$  hypothesis suggests a feasible implementation of a first-order strategy that does not explicitly compute velocity, one could imagine other computations based on available perceptual quantities, such as  $\dot{\tau}$  (Lee & Reddish, 1981; Yilmaz & Warren, 1995), that would nevertheless provide information about acceleration and thus improve the estimate of TTC.

### Experimental Evidence

Ample experimental evidence has been found to show that human observers use online perceptual information that is corre-

lated with position and velocity to estimate TTC. For example, the hypotheses that TTC information is given by the optical variable  $\tau$  (Lee, 1976) and via generalized  $\tau$ -functions (Bootsma et al., 1997; Lee, van der Weel, Hitchcock, Matejowsky, & Pettigrew, 1992) have received direct experimental support (Bootsma & Oudejans, 1993; Savelsbergh et al., 1991; Savelsbergh et al., 1993). Note, however, that the conclusions drawn from deflating-ball experiments (Savelsbergh et al., 1991; Savelsbergh et al., 1993) have been challenged on methodological grounds (Wann, 1996). Furthermore, it has been observed that these hypotheses are based on particular theoretical assumptions that may be irrelevant in most natural situations (Tresilian, 1991, 1999; Wann, 1996). Nevertheless, it seems to be generally accepted that  $\tau$  information contributes to estimates of TTC (see Wann 1996, p. 1043). It has also been shown that TTC can be derived from monocular and binocular information about velocity and distance (Cavallo & Laurent, 1988; Gray & Regan, 1998; Rushton & Wann, 1999; Tresilian, 1991, 1999). Furthermore, nonveridical cues to an object’s distance or velocity, such as size (Smith, Flach, Dittman, & Stanard, 2001), relative size (DeLucia & Novak, 1997; DeLucia & Warren, 1994), or background movement (DeLucia, Tresilian, & Meyer, 2000), can affect TTC estimates. Although these studies argue against  $\tau$  as the specific perceptual variable that is actually measured, all of these studies are consistent with the use of first-order estimates of TTC (Tresilian, 1991). But the stimuli in these studies actually did move with constant velocity and so did not explicitly test for the use of acceleration information.

Acceleration information may not, in fact, play an important role in guiding motor responses in interceptive tasks performed by human observers. Lee et al. (1983) proposed that when jumping to punch a falling (accelerating) ball, participants geared their limb movements to  $\tau$  rather than to the true TTC value. This strategy would ignore explicit online estimates of acceleration, such information being absent in the optical variable  $\tau$ . This paradigm has recently been repeated (Michaels, Zeinstra, & Oudejans, 2001), confirming that even if perceptual variables other than  $\tau$  are also used to estimate TTC, acceleration is ignored in this task. Bootsma and Oudejans (1993) showed that when asked to choose which of two accelerating or decelerating objects would pass a target line (a relative judgment task), participants used an estimate of TTC arising from a weighted combination of the relative rate of dilation of the objects’ optical contours and the relative rate of constriction of the optical gap separating the objects from the target position (see, however, DeLucia & Meyer, 1999). Again, the results were consistent with a first-order strategy that ignores online estimates of acceleration. Port, Lee, Dassonville, and Georgopoulos (1997), using an interception task in 2D space with accelerating and decelerating targets, concluded that participants “either did not have access to or were unable to fully utilize information concerning the acceleration of target motion” (p. 415). All of these results are consistent with the observation that the visual system is poorly sensitive to acceleration itself over short viewing times (Werkhoven, Snippe, & Toet, 1992).

<sup>2</sup> The optic variable  $\tau$  is exactly equivalent to distance/velocity only in the case of small angular extent of the image and in the case of a rigid body that either is radially symmetric or does not rotate (Lee, 1976).

Acceleration information has, however, been demonstrated to be available, albeit indirectly, through measurements of changes in velocity (Gottsdanker, 1952; Hecht, Kaiser, & Banks, 1996; Werkhoven et al., 1992). For motion extrapolation tasks in which the participant consciously reports where an object was last seen or expected to be seen, perception of acceleration has been supported by some (Jagacinski, Johnson, & Miller, 1983; Rosenbaum, 1975) and rejected by others (Gottsdanker, 1952; Runeson, 1975; Todd, 1981). Recently, Brouwer, Brenner, and Smeets (2002) showed that participants require viewing times of at least 300 ms to detect and verbally report velocity changes of 25%. They compared these results with data from real ball-catching tasks and found that participants initiated their movements earlier than the minimal delay required to be consciously aware of the velocity changes. Although experimental evidence exists to show that acceleration information may be used in perceptual tasks involving predicted motion, coincidence anticipation, or relative judgment, such is not the case for interceptive actions that are characterized by short viewing times, short execution times, and short visuomotor delays. It has therefore been proposed that perceptuo-motor processes differ for these two classes of timing behavior (Tresilian, 1995).

In fact, it has been argued that human behavior need not have evolved past the complexity of first-order timing strategies that ignore acceleration; errors elicited by using such estimates would be minimal for the magnitudes of acceleration that are likely to be encountered (Tresilian, 1999). An interesting empirical exception, therefore, is the task of catching a falling ball in the outstretched hand (Lacquaniti & Maioli, 1989b). On the basis of electromyographic (EMG) data, it was shown that initiation of anticipatory activity in arm muscles relative to impact was too precise to be generated by a first-order strategy alone. These results pose a dilemma: If the human visual system is insensitive to acceleration for short viewing periods, how could the timing strategy be improved? Lacquaniti, Carrozzo, and Borghese (1993, p. 389) proposed that "a priori knowledge on the most likely path and law of motion" may be used to anticipate the influence of gravity on the ball. Thus, TTC could be more accurately predicted by combining online measurements of height and velocity with an a priori assumption that acceleration will be equal to 1 g. This proposal constitutes an internal model in the sense of a "constraint characterizing a class of trajectories" (Jagacinski et al., 1983, p. 44) but with a twist: The essential parameter that makes this strategy second order, that is, the assumed nonzero acceleration, would be set not through direct perception of the ball's acceleration across trials but rather through cognitive knowledge about the actions of gravity on a falling object. This hypothesis brings to mind the concept of "representational physics" (Freyd & Finke, 1984) in which implicit knowledge of movement dynamics (internalization of environmental invariants), and more specifically, a priori knowledge about gravitational acceleration (Hubbard, 1990), can influence visual perception. Hubbard (1990) showed that the extrapolation in the reporting of 2D target position was a function of movement direction with respect to gravity: A disappearing target moving downward was extrapolated lower and a target moving upward extrapolated higher. The hypothesis of an internal model can be interpreted as an extension of these ideas to that of TTC estimation. Taken in this perspective, the ball-drop experiments (Lacquaniti & Maioli, 1989b) suggest that, in addition to its influence on perceptual judgment tasks (DeLucia & Liddell, 1998;

Tresilian, 1995), representational physics may as well intervene in relatively low-level (almost reflexive) sensorimotor behaviors.<sup>3</sup>

### Response Amplitude

An equally important but less-often studied aspect of catching involves the programming of muscle activities such that the hand will absorb the shock of impact without rebound. For this aspect, it is reasonable to assume that the required muscle activity would be related to the force of impact or to the kinetic energy of the ball, given that the movement must be stopped within a finite distance.<sup>4</sup> This implies that the observer is able to predict both the mass and the final velocity of the ball at impact. If the observer has prior knowledge of the mass (through practice, manipulation of the ball, etc.), then only impact velocity (hereinafter referred to as  $V_{\text{impact}}$ ) needs be estimated based on available sensory cues.

### *Strategies for Estimating $V_{\text{impact}}$ : What Is Good Enough?*

Muscle activation used to stop a moving object can have one of three effects: First, muscle activity could be programmed to generate a precise braking force. In this respect, one would expect to need a force within a given range; too much force and the object will be propelled backward, too little and the object will simply push the hand to the limit of arms' reach. A second effect of muscle activity is the regulation of limb impedance. Without explicitly programming a braking force, the observer could program hand stiffness and viscosity to absorb and dissipate the energy of the ball. Again, the required activity would seem to be bracketed by a minimum of stiffness, below which there is no resistance to impact momentum, and a maximum stiffness, above which the object will rebound off the rigid hand. A final option may be to impart an anticipatory momentum to the hand and limb. If precisely tuned, this momentum may be used to counteract the momentum of the object, resulting in a net momentum change of zero at impact. In any of these three cases, the required muscle activity must fall within an acceptable range. Whether or not a strategy to estimate the impact velocity is "good enough" will depend on the mechanical constraints of the task. And just as timing strategies may be characterized by the temporal derivatives of the object's position used to estimate TTC, strategies used to estimate the final velocity may also be classified by these criteria. The principle is the same: The more derivatives used, the greater the likelihood that a given strategy will produce responses that are correctly tuned to impact.

<sup>3</sup> Whereas data on predictive motion tasks are consistent with more or less accurate internal representations of momentum (Freyd & Finke, 1984) and gravity (Hubbard, 1990), it has also been noted that intuitive reasoning about the laws of motion is sometimes "naïve," leading to erroneous reporting of observed motions (Kaiser, Jonides, & Alexander, 1986; Kaiser, Proffitt, & McCloskey, 1985; McCloskey & Kohl, 1983; McCloskey, Washburn, & Felch, 1983). Such erroneous internal representations would presumably be detrimental to performance if applied to perception-action coupling. For a discussion of these issues, see Hubbard (1995).

<sup>4</sup> Given a large enough range of motion for the hand after impact, even a minimal amount of braking force (muscle activity) would be sufficient to stop a ball having any amount of kinetic energy, but such a solution is not reasonable for the limited reach of the human arm.

### Zero-Order Strategies

The simplest possible strategy for controlling EMG amplitude consists of programming a constant amplitude muscle activation for all possible impact velocities. This strategy makes use of no information related to  $P(t)$  or its derivatives. Analogous to the constant-reaction-time strategy described for response timing, we consider this strategy to be zero order because of the lack of dependence on online velocity or acceleration information. This strategy will be good enough if there is a large margin of error in response amplitude relative to the possible momentum at impact.

### First-Order Strategies

A more sophisticated strategy is to continuously measure the object's velocity during the trial. When the motor command is programmed at some time prior to impact (to take into account sensorimotor delays), the measured velocity at that instant will be used as an estimate of the final velocity, with the implicit assumption that there will be no subsequent acceleration or deceleration, that is,

$$\tilde{V}(t + \delta) = V(t). \quad (7)$$

### Second-Order Strategies

Estimates of impact velocity may also be improved by including information about the object's acceleration: In fact, including acceleration in the estimate of final velocity is in some sense easier than incorporating a direct estimate of acceleration in the calculation of TTC. Whereas the formula for converting distance, velocity, and acceleration is somewhat complex (see Equation 6), the task of projecting  $V$  a fixed time into the future is relatively simple:

$$\tilde{V}(t + \delta) = V(t) + \delta A(t). \quad (8)$$

A second-order strategy that incorporates acceleration could conceivably be used to tune the response amplitude even if the TTC estimate that triggers the response is first order.

### Interactions With TTC Estimates

To the extent that the ball's velocity and acceleration determine both TTC and  $V_{\text{impact}}$  (assuming that the hand is at rest at impact), response timing and amplitude are clearly related. Both components of the task require the anticipation of a kinematic variable at impact based on sensory information at some earlier point in time. Furthermore, the ability to predict the velocity at impact using the second-order estimate described in Equation 8 implies that an estimate of TTC is also available, to be multiplied by the current estimate of acceleration. Yet these two aspects of the task could conceivably be treated separately by the sensorimotor system. Indeed, the mere fact that a given timing strategy is equivalent to a first-order approximation of TTC does not necessarily mean that  $V(t)$  is explicitly computed (e.g., the  $\tau$  hypothesis). If the strategy used to synchronize responses with impact is performed with a direct estimate of TTC, then the velocity information required to tune the response amplitude would have to be provided elsewhere. It is important, therefore, to ask the question of how the control of

response amplitude is linked to strategies used to control response timing.

### Experimental Evidence

It has been shown empirically that anticipatory changes in the grip force used to hold a tool when striking a moving object covary with the force of impact when such information is available in advance (Johansson & Westling, 1988; Turrell, Li, & Wing, 1999). It is clear that human observers adopt predictive strategies to program the required muscle activities. When catching a falling object, EMG activity in the braking muscles has been shown to be directly correlated with the momentum (Lacquaniti & Maioli, 1989b) or the kinetic energy (Bennis, Roby-Brami, Dufosse, & Bussel, 1996) of the ball at impact. When vision is occluded, the correlation between impact momentum and anticipatory response amplitude disappears (Lacquaniti & Maioli, 1989a). This implies that the observer is able to estimate the final velocity of the ball on the basis of visual information. The question arises again: How can the sensorimotor system accurately predict the velocity at impact if the perceptual system is insensitive to the ball's acceleration? In the case of a falling object, it was also proposed that an internal model of gravitational acceleration could be used to more accurately predict the final ball velocity (Lacquaniti et al., 1993).

### Open Questions

The debate is not closed on what kinds of information may be used to anticipate impact when catching. The results of Lacquaniti et al.'s original ball-dropping experiments (Lacquaniti et al., 1993; Lacquaniti & Maioli, 1989b) suggest the use of an internal model of gravity that anticipates a default 1-g acceleration rather than measuring the actual acceleration. Although clearly provocative, the results from Lacquaniti et al. cannot be considered as conclusive evidence for the internal model hypothesis. While the visual system appears to be insensitive to accelerations for verbally reported perceptual tasks, one cannot exclude the possibility that participants were nevertheless able to incorporate an online estimate of the ball's actual acceleration into a quasi-automatic sensorimotor response. Such a result would be in conflict with the previously cited experiments that argue for first-order strategies for movement timing, but these apparent conflicts could be attributed to a number of differences between tasks and experimental conditions.

First, the adequacy of first- or second-order estimates of TTC and impact velocity depends on whether they are used in prospective or predictive behaviors. Whereas jumping or reaching to punch a falling ball permits online adjustments once the response is initiated, the burst of muscle activity that occurs 100 ms prior to impact leaves little time for additional tuning. Although a first-order estimate of TTC may be good enough to direct a prospective movement strategy that converges toward impact, the precise tuning of the EMG burst could conceivably require a more accurate predictive strategy based on a second-order TTC estimate or better.

Second, viewing conditions may play a primary role in determining if acceleration information is available. In contrast to looming experiments, in which the ball approaches directly along

the sight line and for which acceleration seems to be ignored, the balls in Lacquaniti and colleagues' experiments (Lacquaniti et al., 1993; Lacquaniti & Maioli, 1989b) followed an oblique path from the drop point to the outstretched hand. Estimates of TTC are in some cases more accurate for oblique (bypass) versus head-on trajectories (Schiff & Oldak, 1990), but sensitivity to acceleration was not explicitly tested. It is possible that the displacement of the ball across the retinal image or the tracking movements of the eyes provide enough information to allow an online estimate of acceleration during the trial. The capacity to extract TTC for oblique trajectories was already tested for motion prediction and for absolute and relative judgment tasks (Bootsma & Oudejans, 1993; Kaiser & Phatak, 1993). The results of these experiments argue against the explicit use of acceleration information in perceptual tasks, but data are lacking for motor tasks. One cannot exclude the possibility that acceleration information is available to the sensorimotor system without being consciously perceived (Goodale, Milner, Jakobson, & Carey, 1991; Goodale, Pelisson, & Prablanc, 1986).

Finally, practice may provide an alternative explanation of how gravitational acceleration appears to have been incorporated into strategies for catching a falling ball. Trials in Lacquaniti et al.'s experiments (Lacquaniti et al., 1993; Lacquaniti & Maioli, 1989b) were performed in blocks of 13, and the first 3 trials from each block were excluded from the analysis. Because the drop height and initial velocity remained constant within a given block, participants may have learned to produce an appropriate response for the later trials within a block. Thus, the apparently higher precision

revealed by these participants may have been achieved not through the use of an internal model of gravity, but instead by tuning a parametric internal model through practice (Jagacinski et al., 1983). Participants may have even adopted zero-order strategies in this situation to control muscle activity based on experience from previous trials.

With these points in mind, we arrive at the specific questions posed in our experiments. Do human observers use online position, velocity, or acceleration information to control muscle activity during catching when these types of information cannot be foreseen in advance? The task and the experimental measurements we performed were in many ways similar to those in Lacquaniti et al.'s experiments. First, we studied the timing and amplitude of muscle activations used to arrest a moving object. Second, the visual conditions for this task, while not exactly the same as in the case of the falling ball, contained common characteristics, including movement of the image across the retina, the possibility of tracking eye movements, and an oblique path toward an intercept point located away from the eyes of the observer. The key difference between the protocols lay in the use of a pendulum equipped with a hidden counterweight (see Figure 1), which allowed us to vary the object's acceleration. We compared measurements of EMG timing and amplitude to the simulated performance of zero-, first-, and second-order control strategies that could be used to stop the pendulum. We show that online information about velocity but not acceleration was used to control muscle activities in the anticipation of impact.

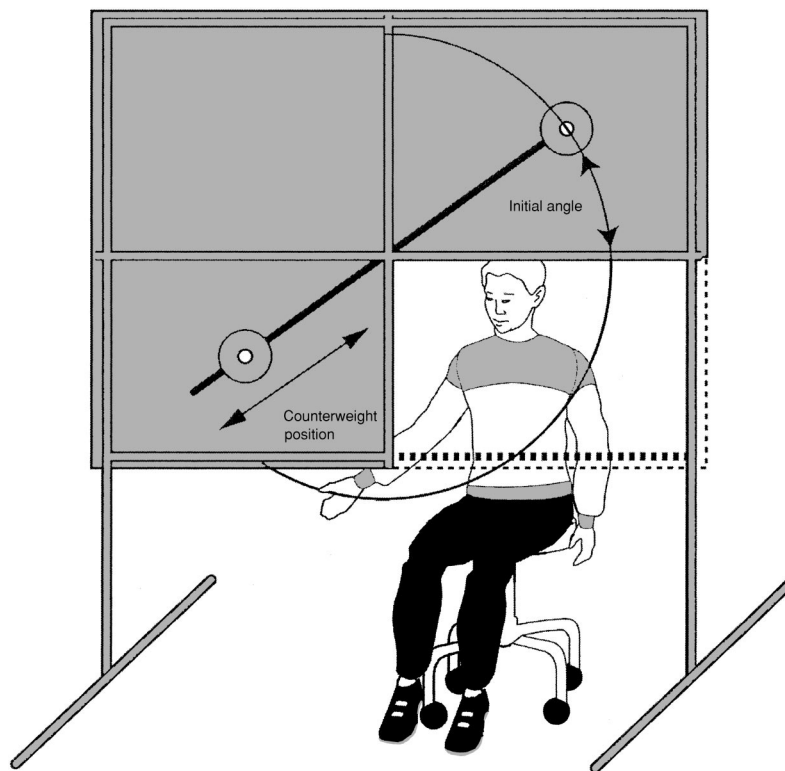


Figure 1. Experimental device.

## Method

### Apparatus

The experimental device (see Figure 1) consisted of a 1.2-m rod attached at the center to a pivot point, allowing rotations of the rod in the fronto-parallel plane. At the end of one arm of the rod was attached a padded 1.55-kg weight, thus forming a pendulum. A counterweight of equal mass was attached to the opposite arm. The position of the counterweight could be changed by the experimenters from trial to trial. The trajectory of the padded weight and rod was partly hidden behind a square wooden panel (1.3 m  $\times$  1.3 m) with a cutout in the lower left quadrant. The panel was used to limit in space and time the visibility of the pendulum as it swung downward and to the right from the upper-left corner of the window (as viewed by the participant) toward the participant's hand. The panel also hid the position of the counterweight. The participant positioned the hand to catch the swinging pendulum at a point directly under its axis of rotation. Because the size of the panel cutout and the hand position were fixed across trials and experimental conditions, the angular distance traveled by the padded weight in the visible area was always the same. The pendulum position  $\alpha$  (Figure 2A) was defined to be 90° horizontal (i.e., when the padded weight first appears from behind the screen) to 0° vertical (nominal position for hand contact). If  $T_0 = 0$  is the time of appearance of the pendulum at  $\alpha = 90^\circ$  and  $T_{\text{impact}}$  the time when it is stopped by the hand at  $\alpha = 0^\circ$ , the visible swing duration ( $D_{\text{swing}}$ ) is then equal to  $T_{\text{impact}} - T_0$  (Figure 2D). The pendulum's acceleration was maximal (most negative) when it was in the horizontal position and reduced to zero as it approached the vertical position (Figure 2C).

To clarify, we can distinguish what variables were controlled by the experimenter and what variables could potentially be available to the observers. First, the experimenter could voluntarily control the moment of inertia and the torque due to gravity acting on the pendulum, and thus its acceleration profile, by adjusting the position of the counterweight. The counterweight position was varied between conditions but was held fixed throughout a single trial. Consequently, each condition was partly characterized by its initial acceleration ( $A_0$ ) at  $\alpha = 90^\circ$ . Increasing the counterweight eccentricity decreased acceleration (acceleration became less negative; Figure 2C). Second, the starting angular position of the pendulum (hidden by the panel) could also be varied by the experimenter. For a given counterweight position, changing the starting angular position changed the initial velocity ( $V_0$ ) of the pendulum when it first appeared from behind the panel at  $T_0$ . Increasing the release angle increased the initial velocity for the same counterweight position (Figure 2B). Thus, each condition was also characterized by its initial visible velocity. Finally, because the visible angular distance traveled by the pendulum was constant from trial to trial, the duration of the trial ( $D_{\text{swing}} = T_{\text{impact}} - T_0$ ) was dependent on the combination of the initial velocity and acceleration that characterized each experimental condition (Figure 2A). In addition, as the object to be stopped was supported against gravity by the pendulum's axis, observers had no direct sensory information about its mass or moment of inertia. However, the acceleration profile, initial velocity, and swing duration, although not available prior to the start of a trial, were potentially available to the observers during the visible course of the pendulum's swing.

### Protocol

Participants were seated on a chair in front of the open part of the panel. They were asked to put their right hand on the path of the padded weight, forearm parallel to the floor, with their hand directly under the rotation axis of the pendulum. They were informed that the pendulum would always move counterclockwise toward their hand along a circular path in the fronto-parallel plane, but no further information about its velocity or acceleration was given. A few seconds after a vocal signal, the pendulum was released, traveled through the hidden part of the trajectory, and then became visible as it continued on its path toward the participant's hand.

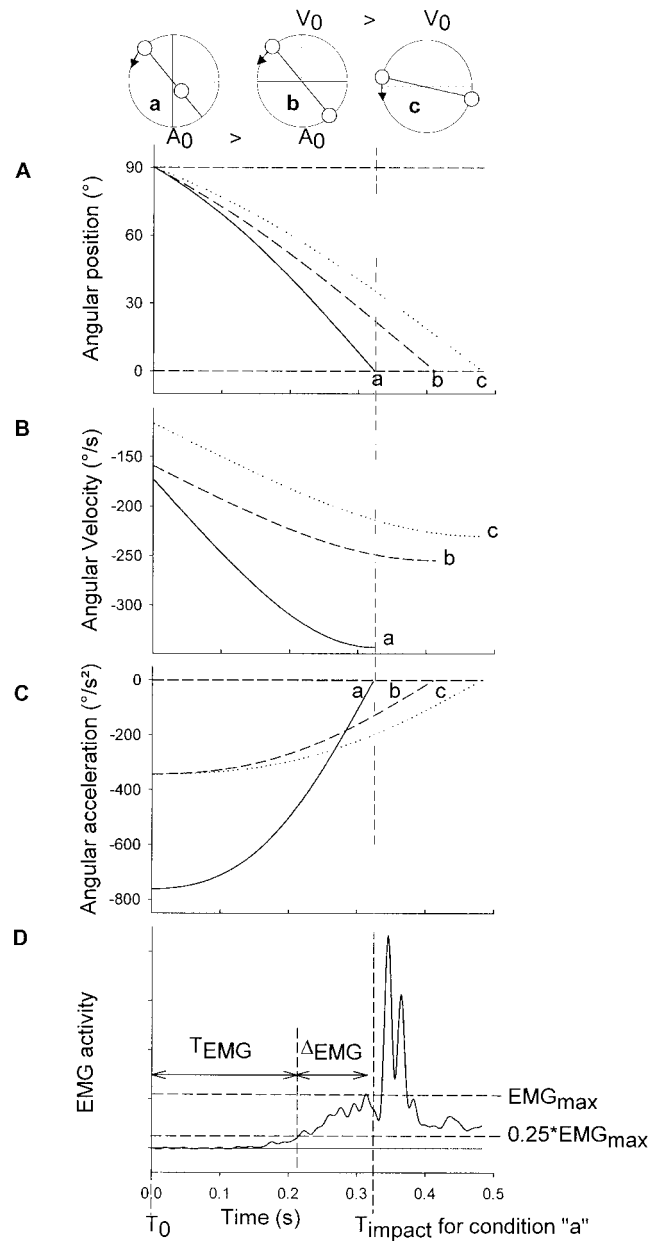


Figure 2. Effect of counterweight position (a vs. b) and initial angle (b vs. c) on the angular (A) position, (B) velocity, and (C) acceleration as a function of (D) time and quantification of anticipatory electromyographic (EMG) activity in flexor carpi radialis (wrist flexor) prior to impact.

The task was to stop the pendulum while trying to maintain the initial position of the hand. This latter instruction was given to encourage participants to stop the padded weight in the defined catching area corresponding to the vertical position of the pendulum. Participants repositioned their hand at the correct initial location before each trial. No instruction was given about where they should look, and each participant was free to choose his or her own response strategy. They only knew where the pendulum was to appear and what path it was to follow until it arrived in their hand.

The time course of the pendulum's movement was computed for each condition with a Matlab mathematical simulation and verified by compar-

ison with calibration data acquired from the swinging pendulum. Twenty-four different profiles corresponding to different combinations of counterweight position and the starting angular position were chosen to provide a large range of swing durations and kinematic profiles.  $D_{\text{swing}}$  varied between 256 and 491 ms,  $V_0$  between 48°/s and 273°/s,  $A_0$  between 255°/s and 761°/s<sup>2</sup>, and  $V_{\text{impact}}$  between 225°/s and 403°/s. The 24 conditions were presented five times each in a pseudo-randomized order.

### Participants

Seven healthy right-handed volunteers (3 female, 4 male; ages 20–35 years old) were recruited to perform the experiment after giving informed consent. Experiments were performed in conformance with local and international standards for the use of human participants.

### Data Acquisition and Processing

EMG activity was recorded using bipolar surface electrodes placed on the skin over the flexor carpi radialis (FCR). The exact time of impact was determined through a three-axis accelerometer attached to the back of the hand. Hand acceleration and EMG data were recorded with the Kinelite recording system (Centre National d'Etudes Spatiales/Matra Marconi Space). Analog EMG signals were bandpass-filtered from 3 to 330 Hz and sampled at 800 Hz. Digitized EMG signals were rectified and then low-pass filtered (10th-order Butterworth, 50 Hz cutoff frequency) to measure the EMG envelope (muscle activation). The rectified EMG signals recorded from FCR clearly showed a biphasic functional pattern with an anticipatory burst before impact and a reflex burst following impact (Figure 2D), in agreement with previous data (Lacquaniti & Maioli, 1989b). Following the same quantitative procedures as our predecessors, the initiation time ( $T_{\text{EMG}}$ ) of the anticipatory activity was defined for each condition as the time relative to  $T_0$  when the mean activity reached and remained above 25% of the preimpact maximum. The 25% threshold applied to the rising edge of the EMG envelope provides a good estimate of the timing of the EMG burst. Lower thresholds would be too sensitive to baseline variations in the intrinsically noisy EMG signals. The magnitude of the anticipatory burst of muscle activity ( $M_{\text{EMG}}$ ) was computed by integration of the rectified EMG signal over the 50 ms preceding impact for each condition.

### Analyses and Model Predictions

**Response timing.** We set out to determine if and how participants incorporated velocity and acceleration information into estimates of TTC. Following the general analysis outlined in the introduction, we considered four hypothetical strategies that could be used by the participant to synchronize EMG activity to the arrival of the pendulum at the vertical position (where  $H$  = hypothesis):

$H_T$ : A constant-reaction-time strategy. This strategy implicitly assumes a constant swing duration across all trials. The muscle command would be triggered at a fixed time delay after the apparition of the pendulum.

$H_D$ : A constant-distance strategy. In this strategy, muscle commands would be triggered when the pendulum reaches a fixed angle with respect to either the initial visible position (90°) or the impact position (0°). For this experiment, these two situations are identical, because the visible swing distance is constant.

$H_1$ : A first-order strategy. This strategy uses online estimates of velocity to estimate TTC. The pendulum velocity and angle, or some correlate, is measured during the trial and used to update a first-order estimate of TTC.

$H_2$ : A second-order strategy. This strategy uses an online acceleration information during a trial to better estimate TTC.

Figure 3 shows how these four hypotheses can be distinguished by numerical simulation of what would be the onset of EMG activity produced by each of these strategies:

1. A constant-reaction-time strategy ( $H_T$ ) is easily distinguished from the other three possibilities by plotting simulated EMG onset ( $T_{\text{EMG}}$ ) versus swing duration ( $D_{\text{swing}}$ ) for each condition (Figure 3A).  $H_T$  predicts a constant  $T_{\text{EMG}}$  for all conditions, whereas for any of the other possibilities,  $T_{\text{EMG}}$  will be positively correlated with  $D_{\text{swing}}$ .
2. The constant-distance strategy ( $H_D$ ) can be distinguished from the other first- and second-order strategies by plotting the angle of the pendulum at the moment of EMG initiation ( $\alpha_{\text{EMG}}$ ) as a function of  $D_{\text{swing}}$  (Figure 3B).
3. The remaining two hypotheses ( $H_1$  and  $H_2$ ) both result in a positive correlation between  $T_{\text{EMG}}$  and  $D_{\text{swing}}$  and a negative correlation between  $\alpha_{\text{EMG}}$  and  $D_{\text{swing}}$ . To distinguish between these remaining hypotheses, one must look at the small variations in the timing of the response with respect to the moment of impact ( $\Delta_{\text{EMG}} = T_{\text{impact}} - T_{\text{EMG}}$ ).
  - A first-order estimate of TTC that measures instantaneous velocity online but that assumes zero acceleration for the subsequent movement ( $H_1$ ) will systematically overestimate the true TTC for an accelerating system (the object will arrive *earlier* than predicted).
  - A second-order estimate of TTC that measures both instantaneous velocity and acceleration ( $H_2$ ) will tend to underestimate the true value for a swinging pendulum (the object will arrive *later* than anticipated) because the acceleration of the true system gradually decreases as the pendulum approaches the vertical position.

Figure 4A illustrates the relationship between estimated and true TTC as a function of the initial pendulum acceleration and velocity. One can see that both hypotheses  $H_1$  and  $H_2$  converge to the true TTC value as the pendulum approaches impact. Thus, the greater the required TTC threshold ( $\lambda$ ), the greater the error in response timing. One can also see that the discrepancy between estimated and true TTC is relatively unaffected by the pendulum's initial velocity but that for a given TTC threshold, changes in the pendulum's acceleration profile (i.e., changes in the position of the counterweight) have a much stronger effect.

Figure 4B illustrates how these observations can be used to test for online measurements of acceleration in the estimation of TTC. Figure 4B plots the expected  $\Delta_{\text{EMG}}$  relative to impact versus  $A_0$  for a response triggered at a fixed  $\lambda$ . A first-order estimate of TTC ( $H_1$ ) results in a smaller  $\Delta_{\text{EMG}}$  than the ideal value, and there is a negative, almost linear correlation between the predicted response and the pendulum's acceleration. The magnitude of the slope of the relationship depends on the value of the TTC threshold  $\lambda$  but is always negative. The greater the  $\lambda$ , the steeper the slope. On the other hand, a second-order TTC estimate that uses online measurements of both velocity and acceleration results in a correlation between  $\Delta_{\text{EMG}}$  and  $A_0$  that is always positive.

The simulated second-order strategy shown in Figure 4B assumes that the observer has simultaneous information about velocity and acceleration to estimate TTC at Time  $t$ . One could imagine a host of alternatives in which, for instance, acceleration is estimated with some time lag with respect to velocity estimates, based on changes in velocity measured earlier during a trial. We also considered a strategy in which the observer uses information from the first few milliseconds of a trial to estimate acceleration  $A_0$ , which is then assumed to be constant for the remainder of the trial. This is nevertheless online information about acceleration, because it



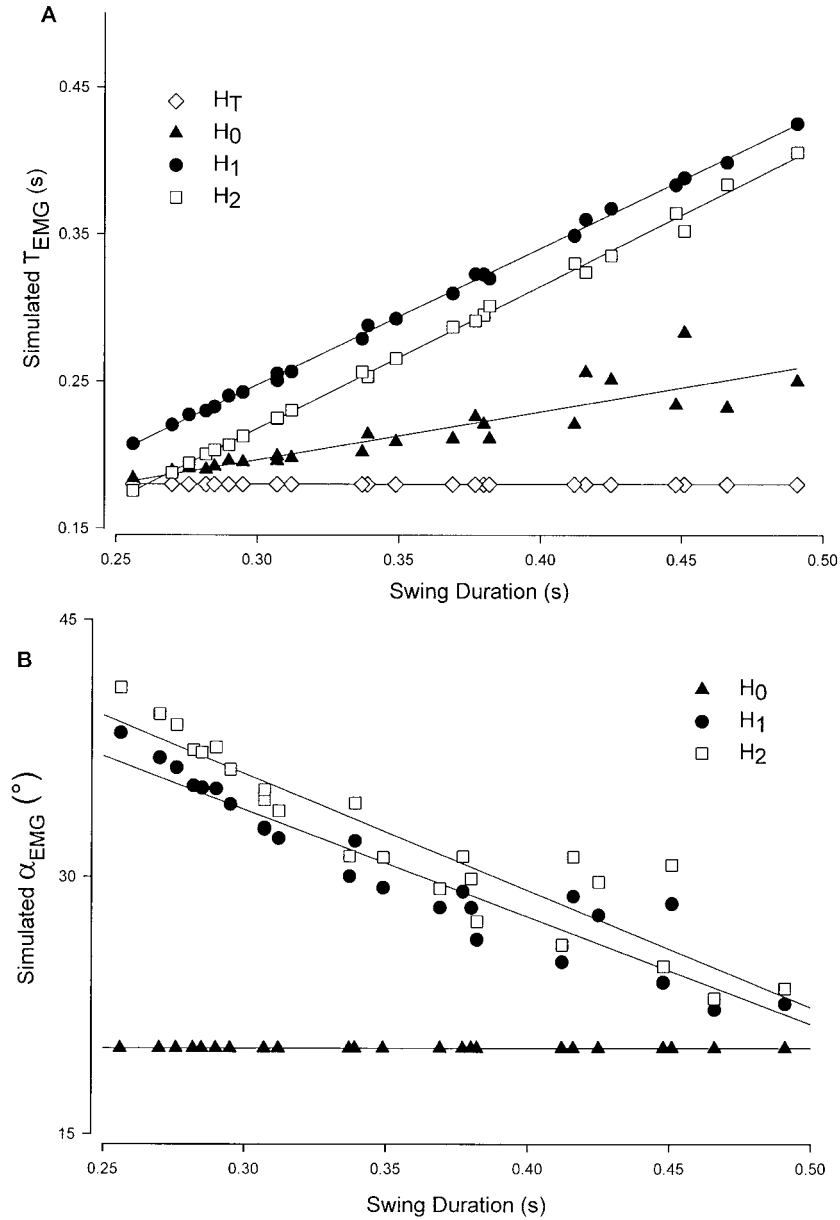


Figure 3. (A) Simulated  $T_{EMG}$  and (B)  $\alpha_{EMG}$  versus swing durations for hypotheses in Table 1. EMG = electromyographic activity; H = hypothesis.

is acquired through observations of the pendulum's movement. A second-order strategy based on this estimate of initial acceleration (least up-to-date) and continuously monitored velocity information (most up-to-date) would still predict a positive correlation between  $\Delta_{EMG}$  and  $A_0$ . Idem for the limiting case in which the least up-to-date online information about velocity and acceleration is used to estimate TTC: Even if the observer computes  $TTC_2$  based on an initial estimate of  $A_0$  and  $V_0$  and then triggers the response after counting down  $TTC_2 - \lambda$  s,  $\Delta_{EMG}$  will still show a positive correlation with  $A_0$ .

These simulations provide the key test for determining whether online information about acceleration is used to estimate TTC. Whereas the lack of significant correlation between measured  $\Delta_{EMG}$  and  $A_0$  would be inconclusive (an underlying correlation may be hidden in the noise), a

statistically significant positive or negative correlation would be compelling evidence that participants do or do not incorporate online measurements of acceleration, respectively, when estimating TTC for the swinging pendulum.

Table 1 summarizes the rationale behind our experiments and analysis of response timing. For each hypothesis, the use of position, velocity, or acceleration information is described, and the predicted results of each test ( $T_{EMG}$  vs.  $D_{swing}$ ,  $\alpha_{EMG}$  vs.  $D_{swing}$ , and  $\Delta_{EMG}$  vs.  $A_0$ ) are indicated. We performed each of these regression analyses to determine the order of the TTC estimate used to initiate the EMG responses. We then performed an additional analysis to determine the value of  $\lambda$  used to trigger these responses. We accomplished this by simulating the expected  $\Delta_{EMG}$  values for different hypothetical values of  $\lambda$ . A regression of measured versus

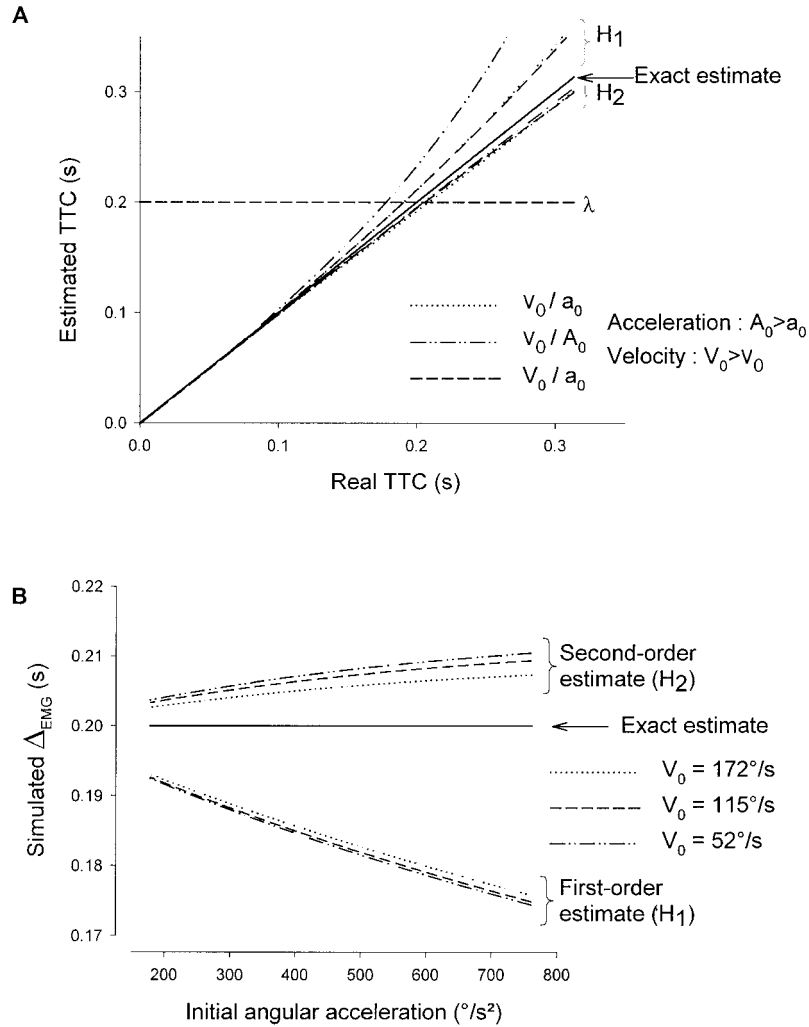


Figure 4. Effect of initial acceleration ( $A_0$ ) and velocity ( $V_0$ ) on first- and second-order estimates of (A) time to contact (TTC) and (B)  $\Delta_{EMG}$ . H = hypothesis; EMG = electromyographic activity.

simulated  $\Delta_{EMG}$  should give a slope of 1 when the simulated data are based on the correct model (zero, first, or second order) and on the correct value of  $\lambda$ .

*Response amplitude.* In a similar vein, we set out to determine how participants incorporated velocity and acceleration information into estimates of impact momentum so as to scale the muscle activities accordingly. Following the classification outlined earlier, we considered three different

hypothetical strategies that could be used to adjust the amplitude of muscle activation:

*HH<sub>0</sub>:* A zero-order strategy that makes no adjustment for object velocity at all when computing the amplitude of the muscle response. Muscle commands would have the same amplitude for all trials:  $M_{EMG} = M$ .

Table 1  
Experiment Predictions for Specific Hypotheses About Strategies for Response Timing

Hypothesis	Online information used			Predicted correlation		
	Position	Velocity	Acceleration	$T_{EMG}$ vs. $D_{swing}$	$\alpha_{EMG}$ vs. $D_{swing}$	$\Delta_{EMG}$ vs. $A_0$
H <sub>T</sub>	No	No	No	—	—	—
H <sub>0</sub>	Yes	No	No	↗	—	—
H <sub>1</sub>	Yes	Yes	No	↗	↘	↘
H <sub>2</sub>	Yes	Yes	Yes	↗	↘	↗

Note. EMG = electromyographic activity;  $T_{EMG}$  = initiation time;  $D_{swing}$  = swing duration;  $A_0$  = initial acceleration.

*HH<sub>1</sub>*: A first-order strategy that uses online estimates of velocity to estimate  $V_{\text{impact}}$ . Pendulum velocity is measured during the trial and used as the estimate of final velocity. At  $t = T_{\text{impact}} - \kappa$ , the activation amplitude is programmed on the basis of the current estimate of velocity, assuming no further acceleration or deceleration:  $M_{\text{EMG}} \propto \hat{V}(T_{\text{impact}} - \kappa)$ .

*HH<sub>2</sub>*: A second-order strategy that allows for online measurements of both velocity and acceleration during a trial to better estimate final velocity. At  $t = T_{\text{impact}} - \kappa$ , the activation amplitude is programmed on the basis of the current estimate of velocity and acceleration:  $M_{\text{EMG}} \propto \hat{V}(T_{\text{impact}} - \kappa) + \kappa A(T_{\text{impact}} - \kappa)$ .

Figure 5 shows the prediction of each of these hypotheses for a motor command that is programmed  $\kappa = 200$  ms prior to impact. If EMG amplitude ( $M_{\text{EMG}}$ ) is proportional to the estimated velocity at impact, a zero-order strategy with a presumed fixed final velocity (*HH<sub>0</sub>*) can be distinguished from the other possibilities by the lack of correlation between  $M_{\text{EMG}}$  and  $V_{\text{impact}}$ . However, even a first-order strategy that scales activity to the velocity measured at some time prior to impact would show a reasonable positive correlation between  $M_{\text{EMG}}$  and  $V_{\text{impact}}$  for sufficiently small values of  $\kappa$ . This is because  $V(T_{\text{impact}})$  and  $V(T_{\text{impact}} - \kappa)$  are linked through finite accelerations. The kinematics of the pendulum provide a decrease of the acceleration as it approaches the vertical position, which in our case was the impact point. In general, this means there will be a correlation between the pendulum velocities recorded at different fixed times prior to the moment of impact.

To determine whether acceleration is explicitly used in the estimation of  $V_{\text{impact}}$ , one must effectively decorrelate the estimated final velocity at time  $T_{\text{impact}} - \kappa$  from the real final velocity. To do this, we performed an analysis on the parameter  $M_{\text{EMG}}$  as follows: We selected pairs of conditions (A and B) in which the A elements start faster but accelerate less than the B elements, such that the order of velocities is reversed (from  $A > B$  to  $B > A$ ) at some moment before impact. Figure 6 illustrates an example of one such pair in which the order of velocities reverses about 200 ms prior to impact. A first-order estimate of  $V_{\text{impact}}$  (Figure 6B) will be *greater*

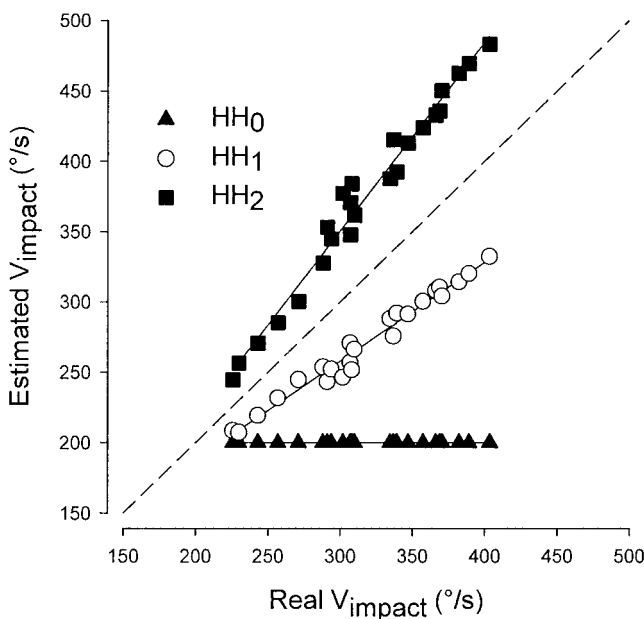


Figure 5. Predicted correlation between estimated and real impact velocity ( $V_{\text{impact}}$ ) for zero-, first-, and second-order estimates of  $V_{\text{impact}}$ . HH = hypothesis.

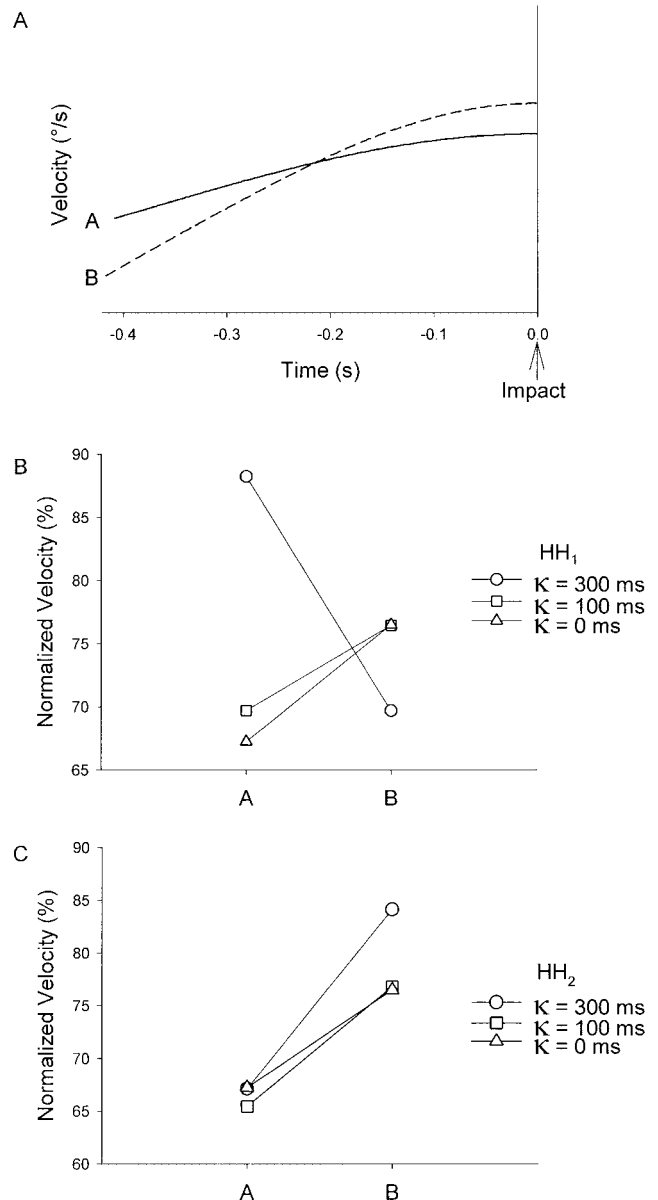


Figure 6. Rationale for pairwise test of hypotheses (HH) for estimating impact velocity.

for Trial A than for Trial B in each pair if the velocity used to scale the activity is measured prior to the crossover point ( $\kappa > 200$  ms), but *less* for Trial A than for Trial B if measured at a later time ( $\kappa < 200$  ms). Because a second-order estimate of  $V_{\text{impact}}$  makes use of an estimate of the acceleration (Figure 6C), it will reflect the true relative magnitudes for  $V_{\text{impact}}$  when applied at any time prior to impact in the range shown; that is, estimated  $V_{\text{impact}}$  will be *less* for Trial A than for Trial B for all values of  $\kappa$ . These observations make specific predictions on the relative magnitude of EMG for A versus B elements, depending on the order of the estimate used to predict  $V_{\text{impact}}$ . If  $M_{\text{EMG}}$  is based on a first-order estimate applied more than 200 ms prior to impact ( $\kappa > 200$  ms),  $M_{\text{EMG}}$  will be *greater* for the A element than for the B element of each pair. However, if the first-order estimate is applied at a later time ( $\kappa < 200$  ms), or if a second-order estimate can be used to predict the velocity at impact at any

time during the trial,  $M_{EMG}$  values will be pairwise *less* for the A elements than for the B elements. In this example, an observation of greater  $M_{EMG}$  values for A than for B would allow us to reject  $HH_2$  and accept  $HH_1$ . However, a single performance of this test does not specify the critical time before impact ( $\kappa$ ) at which the first-order estimate is applied. In this example, A greater than B would be predicted for any  $\kappa > 200$  ms. Furthermore, an observation of B greater than A is not conclusive evidence of a second-order estimate of  $V_{impact}$  unless it can be shown that a first-order estimate is inadequate for even the smallest reasonable values of  $\kappa$ . This ambiguity can be resolved through a process of elimination by repeating this procedure for different pairs of conditions in which the instantaneous velocities cross at different times prior to impact.

### Statistical Analyses

Three independent linear regression analyses were planned to determine whether the timing strategy is zero, first, or second order:  $T_{EMG}$  versus  $D_{swing}$ ,  $\alpha_{EMG}$  versus  $D_{swing}$ , and  $\Delta_{EMG}$  versus  $A_0$  (see Table 1). Additional regressions of simulated versus measured  $\Delta_{EMG}$  were performed to estimate  $\lambda$  for the first-order strategy, but these relationships were neither independent of the linear regression of  $\Delta_{EMG}$  versus  $A_0$  nor required to accept or reject the hypotheses  $H_T$ ,  $H_0$ ,  $H_1$ , and  $H_2$ . A single regression analysis of  $M_{EMG}$  versus  $V_{impact}$  was planned to accept or reject hypothesis  $HH_0$ , and a single paired comparison between conditions in Group  $A_1$  and  $B_1$  was required to distinguish between hypotheses  $HH_1$  and  $HH_2$ . Test results were considered significant for a comparisonwise criterion of  $p < .01$ , corresponding to an experimentwise error rate of  $p < .049$  for the five independent tests (based on the Dunn–Sidak correction).

## Results

### Response Timing

EMG onset was synchronized with the time of impact. Figure 7A displays the regression of  $T_{EMG}$  averaged across participants versus  $D_{swing}$  for the 24 conditions, showing a strong correlation between these two variables. We found a positive correlation for each participant and for the average across participants, with a linear regression slope approximately equal to 1,  $F(1, 22) = 507.42$ ,  $R^2 = 0.96$ ,  $p < .01$ . This indicates that participants were able to use TTC information so as to synchronize at least approximately EMG onset with impact. Participants built up their anticipatory activity 45 to 112 ms relative to impact whatever the experimental condition. We can thus reject hypothesis  $H_T$ , that is, that participants initiate EMG activity at a fixed time after the appearance of the pendulum.

Nor did participants use strategy  $H_0$ , which would trigger a response at a fixed pendulum angle from the impact position. We computed  $\alpha_{EMG}$  corresponding to the pendulum position at  $t = T_{EMG}$ . If participants had used a constant-angle strategy, we should have observed the same angular position whatever the swing duration. The plot of  $\alpha_{EMG}$  versus  $D_{swing}$  (Figure 7B) for average data across participants shows a tendency toward a decrease in the angular position at EMG onset, although this tendency was not statistically significant,  $F(1, 22) = 3.77$ ,  $R^2 = 0.14$ ,  $p > .05$ . However, if one considers that the observed EMG activity must be triggered at some prior time to account for transmission delays in the nervous system, we find clear evidence that participants did not trigger the motor command at a fixed angular position. By assuming a fixed delay between the triggering of the response by the central nervous system and the onset of EMG activity, one can calculate what the position of the pendulum was

when the response was triggered. If we consider a minimal transmission delay of as little as 30 ms (which is an acceptable estimate of the time lag between cortex and hand muscles; Salenius, Portin, Kajola, Salmelin, & Hari, 1997), we observe a significant negative correlation between  $\alpha_{EMG}$  and  $D_{swing}$ ,  $F(1, 22) = 20.08$ ,  $R^2 = 0.47$ ,  $p < .01$ , statistically justifying our conclusion that EMG initiation is not triggered on the basis of a fixed threshold applied to the pendulum's position.

At this stage of the analysis, we can conclude that motor activity involved in stopping a swinging pendulum is triggered by a timing strategy that uses some estimate of TTC or equivalent (rejecting  $H_T$  and  $H_0$ ). To test the remaining two hypotheses, we plotted measured  $\Delta_{EMG}$  as a function of initial acceleration (to be compared with Figure 4B). Figure 7C shows measured  $\Delta_{EMG}$  values for each condition averaged across participants. The negative correlation of  $\Delta_{EMG}$  versus  $A_0$  was significant,  $F(1, 22) = 42.69$ ,  $R^2 = 0.66$ ,  $p < .01$ , and explained a reasonable amount of the variance between conditions. The remaining variability is most likely due to uncertainty in estimating EMG onset. For an average EMG response computed from only five trials, the computed envelope of EMG activity rises nonmonotonically (see Figure 2D). Calculations of onset time based on a threshold are thus expected to vary considerably between participants and trials. To reduce this problem, we recomputed ensemble averages for trials from groups of four conditions having the same initial acceleration and thus having very close to the same predicted  $\Delta_{EMG}$ . We then computed  $\Delta_{EMG}$  for each of four such blocks from these ensemble averages based on the 20 trials within each block. This significantly smoothes the rising edge of the EMG envelope and thus increases the signal-to-noise ratio in the measurement  $\Delta_{EMG}$ . With these calculations, a negative correlation between  $\Delta_{EMG}$  and  $A_0$  was confirmed with a reduced variability for the linear regression, as would be expected,  $F(1, 2) = 472.37$ ,  $R^2 = 0.99$ ,  $p < .01$ .

Note that for the ensemble of 24 conditions tested in this experiment, there was a correlation between  $A_0$  and  $D_{swing}$ . If  $\Delta_{EMG}$  is somehow affected by the total duration of the trial, one might also expect to see a significant correlation between  $\Delta_{EMG}$  and  $D_{swing}$ . To test whether trial duration contributes to, or is the sole source of, the variations in  $\Delta_{EMG}$ , we performed a multiple linear regression on  $\Delta_{EMG}$  with both  $A_0$  and  $D_{swing}$  as independent variables. This regression was significant,  $F(2, 21) = 18.329$ ,  $R^2 = 0.64$ ;  $A_0$  accounted for significant amounts of the variance in  $\Delta_{EMG}$  ( $p < .01$ ), but  $D_{swing}$  did not ( $p > .90$ ).

The regressions described above reject the hypothesis that EMG is initiated based on a second-order approximation of TTC and support the hypothesis of a first-order TTC estimate. Having identified the first-order TTC estimate as a good candidate for explaining performance on this task, we then used the predictions of the first-order hypothesis to evaluate the magnitude of the TTC threshold  $\lambda$ . If EMG timing is based on a first-order estimate of TTC, simulated  $\Delta_{EMG}$  for a first-order strategy should predict the magnitude of the variations in measured  $\Delta_{EMG}$ . Thus, a regression between the measured values and those simulated with the correct value of  $\lambda$  should give a slope of 1. If the  $\lambda$  used to simulate  $\Delta_{EMG}$  is greater than the true  $\lambda$  value, variations of simulated  $\Delta_{EMG}$  will be greater than the true variations of  $\Delta_{EMG}$ . Therefore, regressions of measured  $\Delta_{EMG}$  (independent variable) versus measured values  $\Delta_{EMG}$  (dependent variable) based on  $\lambda$  values greater than the true  $\lambda$  should give regressions slopes less than 1, and vice versa.

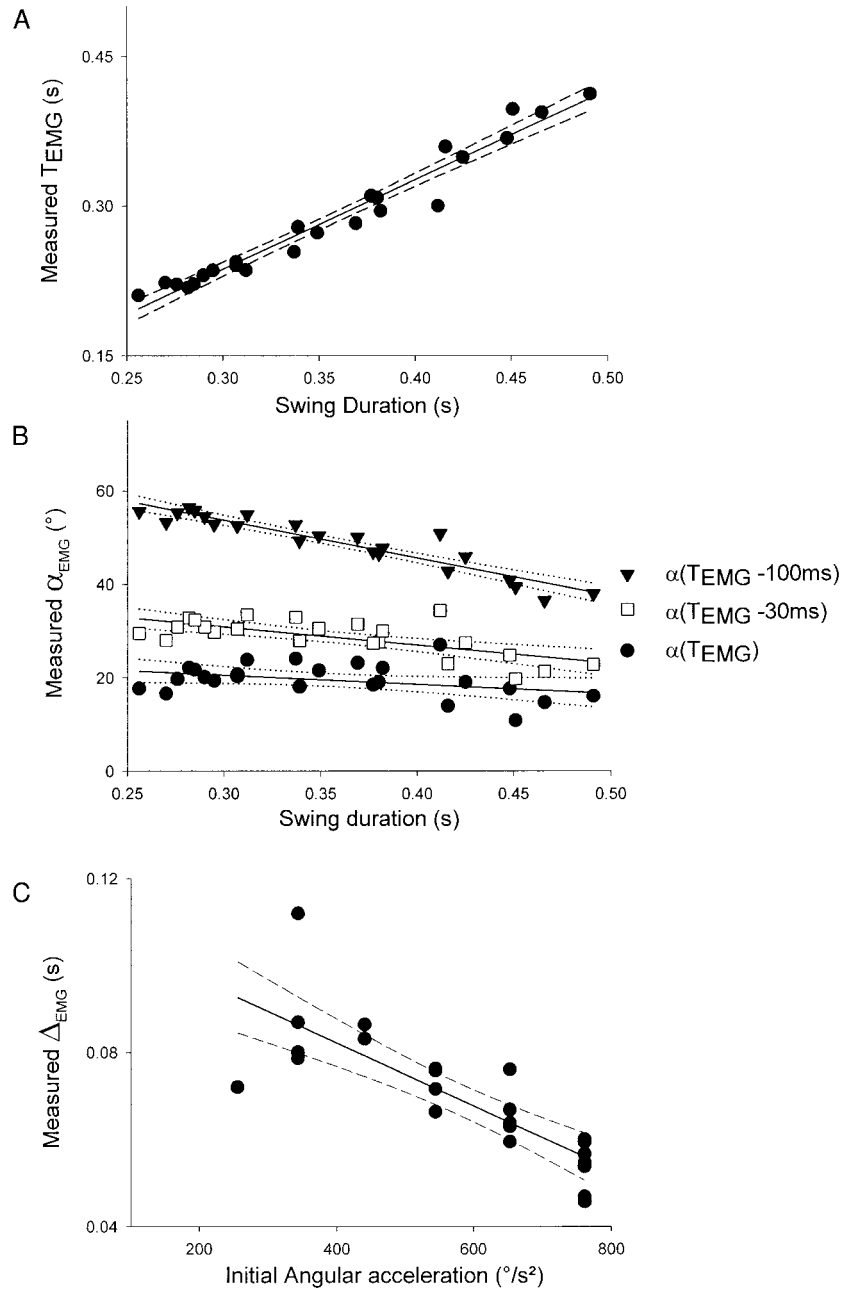


Figure 7. (A) Measured values of  $T_{EMG}$  versus swing duration, (B)  $\alpha_{EMG}$  versus swing duration, and (C)  $\Delta_{EMG}$  versus initial acceleration, to be compared with model predictions in Table 1. EMG = electromyographic activity.

To find the critical value of  $\lambda$ , we simulated  $\Delta_{EMG}$  values for a first-order strategy and a range of TTC thresholds. We tested  $\lambda$  values every 10 ms between 100 and 400 ms. The curved lines in Figure 8 depict the slope of the regression line (ordinate) versus the  $\lambda$  value used in the simulation (abscissa) plotted on a semilog scale. The regression of simulated versus measured  $\Delta_{EMG}$  for different  $\lambda$  values was in all cases significant ( $p < .01$ ). Error bars at  $\lambda = 100, 200, 300,$  and  $400$  ms indicate the 95% confidence limits for the regression slope calculated at the corresponding

value of  $\lambda$ . For analyses based on the entire data set (Figure 8, solid line, open symbols), the regression slope crosses 1 for  $\lambda = 300$  ms.

Some experimental conditions had  $D_{swing}$  values inferior to 300 ms. If at the beginning of a trial the very first estimate of TTC were to be below threshold ( $TTC_1[0] < \lambda$ ), the observer would presumably initiate the response as soon as possible after the pendulum first appears ( $TTC_1$  is already below threshold). Responses would be triggered less than the optimal amount of time prior to impact but might still fall within the margin of error. One would not,

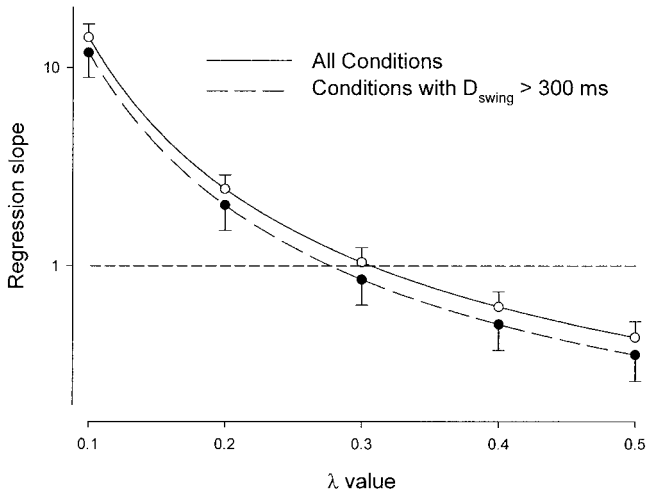


Figure 8. Effect of time-to-contact threshold ( $\lambda$ ) on regression slopes values for measured  $\Delta_{EMG}$  versus simulated  $\Delta_{EMG}$  predicted by a first-order strategy. EMG = electromyographic activity.

however, expect the predicted relationships of a first-order strategy (Table 1) to hold for all conditions, because the observer would essentially be implementing a zero-order, constant-reaction-time strategy for the short duration trials. One could expect, therefore, to have different slopes for the regression of  $\Delta_{EMG}$  versus  $A_0$ , depending on the duration of the trial.

The predicted relationship between  $\Delta_{EMG}$  and  $A_0$  will hold, however, as long as  $TTC_1$  starts out above threshold. This was the case in our experiment; the first-order estimate  $TTC_1$  at  $t = 0$  was always greater than 300 ms, even if  $D_{swing}$  was less than 300 ms for some conditions. Because the response will not be triggered until  $TTC_1$  reaches the critical value of  $\lambda$ , the time of response onset with respect to impact will vary according to the predictions of the first-order model even in this regime, and, depending on the margin of error, success may still be achieved. Including or excluding short duration trials ( $D_{swing} < 300$  ms) should have no effect on the regression slope. To confirm this point, we repeated the analysis using data from a subset of experimental conditions for which  $D_{swing}$  was greater than 300 ms (Figure 8, dashed line, filled symbols). For this subset of data, the slope reaches unity for  $\lambda = 275$  ms, but the difference between the two curves is not statistically significant (based on the 95% confidence interval for the estimated regression slopes).

### Response Amplitude

EMG amplitude was observed to be scaled with impact velocity. Figure 9 shows a significant positive correlation between the EMG amplitude ( $M_{EMG}$ ) integrated over the 50 ms prior to impact and the instantaneous angular velocity of the pendulum at impact,  $F(1, 22) = 48.86$ ,  $R^2 = 0.69$ ,  $p < .01$ . Thus we can reject the simplest hypothesis that the participants produced the same EMG amplitude for all trials. Participants used at least an approximate estimate of final velocity to scale the EMG amplitude.

To distinguish between first- and second-order strategies for estimating  $V_{impact}$ , we applied the pairwise analysis described in Figure 6. We selected a set of seven condition pairs, for which a

first-order estimate of  $V_{impact}$  applied 200 ms prior to impact predicts higher  $M_{EMG}$  values for Group A<sub>1</sub> elements than for Group B<sub>1</sub> elements (Figure 10A). Conversely, the true  $V_{impact}$ , a second-order estimate of  $V_{impact}$  applied at  $T_{impact} - 200$  ms, or a second-order estimate of  $V_{impact}$  applied at  $T_{impact} - 300$  ms, predicted higher  $M_{EMG}$  for B<sub>1</sub> elements than for A<sub>1</sub> elements. Even using a second-order estimate based on data acquired in the first few milliseconds of each trial ( $V_0$  and  $A_0$ ) predicts that  $M_{EMG}$  will be higher for B<sub>1</sub> elements than for B<sub>2</sub> elements (predictions not shown for this case because they are indistinguishable from the predictions of HH<sub>2</sub> for  $\kappa = 300$  ms). We then compared  $M_{EMG}$  for Elements A and B of each pair. Measured values of  $M_{EMG}$  were indeed greater for Group A<sub>1</sub> than for Group B<sub>1</sub> (Wilcoxon signed rank test,  $N = 49$ ,  $Z = 2.70$ ,  $p < .01$ ). Thus, we can reject hypothesis HH<sub>2</sub> and accept hypothesis HH<sub>1</sub>, wherein EMG magnitude is tuned to an estimate of  $V(t)$  measured at some time  $\kappa$  prior to impact, with the implicit assumption of no further changes in velocity.

We applied such an analysis two more times to establish a range of possible values for the critical time factor  $\kappa$ . In a second set of six condition pairs (Figure 10B), the first-order estimate of  $V_{impact}$  for  $t = T_{impact} - 300$  ms predicts higher EMG activity for Element A<sub>2</sub> than for Element B<sub>2</sub> in each pair. Conversely, a first-order estimate of  $V_{impact}$  performed at  $t = T_{impact} - 200$  ms predicts lower EMG magnitudes for Group A<sub>2</sub> than for Group B<sub>2</sub>. Measured values of  $M_{EMG}$  were indeed lower for Group A<sub>2</sub> than for Group B<sub>2</sub> ( $N = 42$ ,  $Z = 2.93$ ,  $p < .01$ ).  $M_{EMG}$  is therefore tuned to a first-order estimate of  $V_{impact}$  applied less than 300 ms prior to impact. To establish a lower bound for the critical value of  $\kappa$ , we performed a final pairwise comparison on a set of six condition pairs (Figure 10C) for which a first-order estimate of  $V_{impact}$  applied at  $T_{impact} - 250$  ms was higher for elements in Group A<sub>3</sub> than for the corresponding element in Group B<sub>3</sub>, but for which the inverse was true for a first-order estimate applied at  $T_{impact} - 200$  ms. In this test,  $M_{EMG}$  was higher for the A<sub>3</sub> elements than for B<sub>3</sub> elements. Although this difference was not statistically significant (velocities change very little over 50 ms, resulting in very small

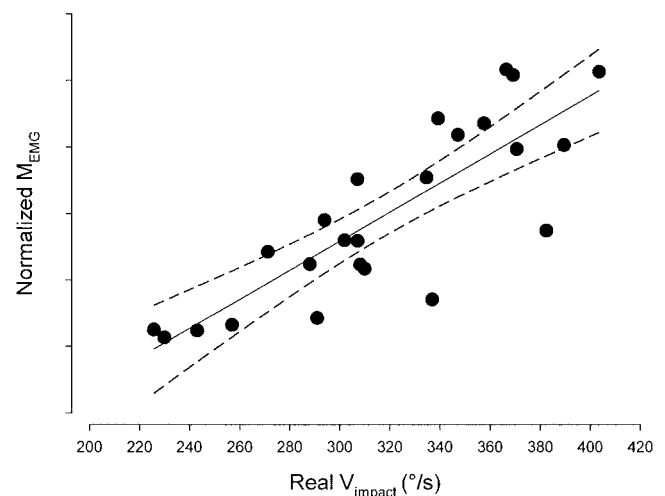


Figure 9. Electromyographic (EMG) amplitude versus impact velocity ( $V_{impact}$ ).

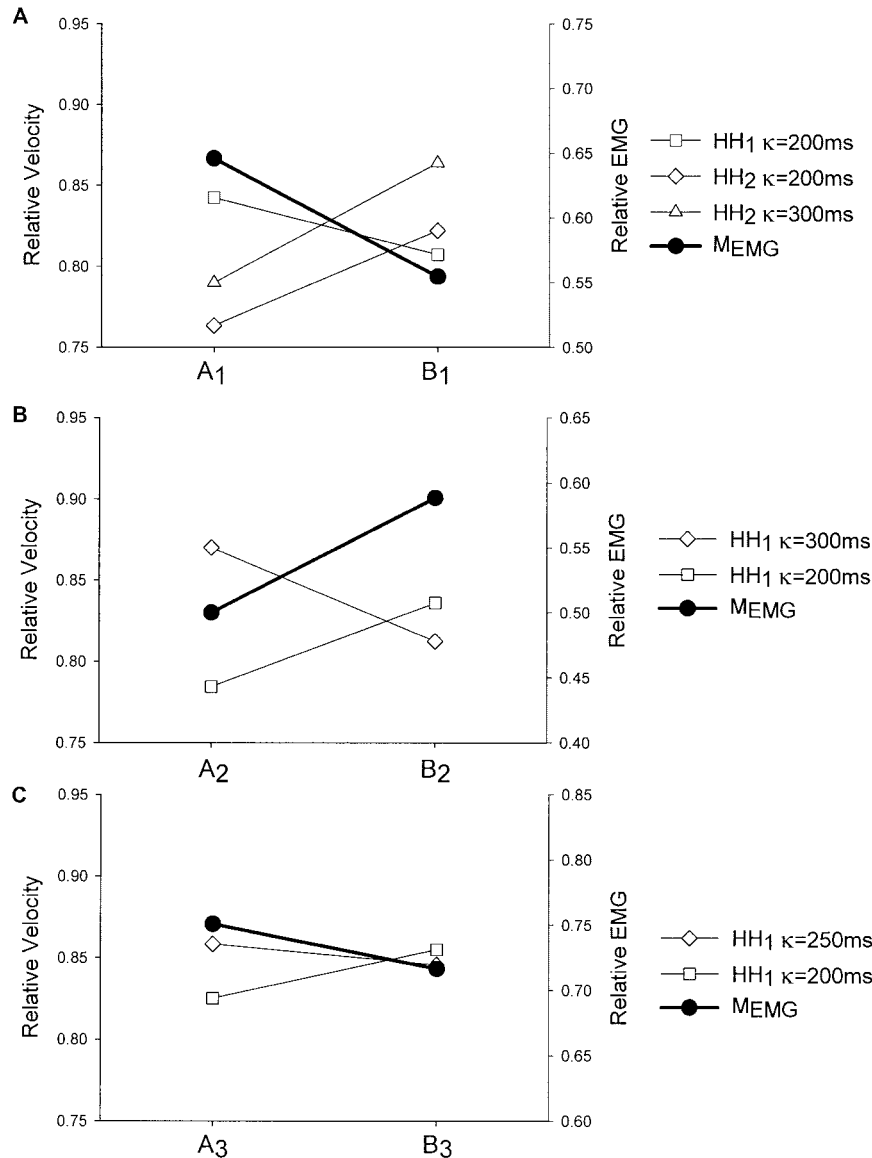


Figure 10. Comparison of relative EMG amplitude ( $M_{EMG}$ ) values versus model predictions for three paired comparisons. EMG = electromyographic activity; HH = hypothesis.

changes in EMG amplitude), this result suggests that the EMG magnitudes are tuned to a first-order estimate applied more than 200 ms prior to impact. From these two comparisons (Figures 10B and 10C), it follows that the critical value of  $\kappa$  falls somewhere between 200 and 300 ms prior to impact.

Finally, we ask whether duration, rather than velocity information, is the factor that determines the amplitude of the EMG response. By testing different combinations of  $A_0$  and  $V_0$ , duration and  $V(T_{impact} - \kappa)$  were not strictly correlated, although there was a general tendency for low  $V_0$  values to produce longer duration swings. A multiple linear regression analysis with  $D_{swing}$  and  $V(T_{impact} - 250 \text{ ms})$  as independent variables and  $M_{EMG}$  as the dependent variable was significant,  $F(2, 21) = 51.256$ ,  $R^2 = 0.83$ . The angular velocity measured 250 ms prior to impact accounted for a significant part of the variance in  $M_{EMG}$  ( $p < .015$ ), whereas

$D_{swing}$  did not ( $p < .7$ ). Thus, pendulum velocity, rather than total swing duration, appears to be the dominant factor that determines the amplitude of the muscle response.

## Discussion

To stop the swinging pendulum with their hand, participants built up an anticipatory EMG activity in wrist flexors just prior to impact. This motor response was similar to those observed previously for participants who caught a free-falling ball (Lacquaniti & Maioli, 1989b; Lang & Bastian, 1999). The buildup of flexor activity is presumed to cause an anticipatory increase of limb impedance that is timed to coincide with the contact between hand and ball and thus aid in absorbing the impact (Lacquaniti, Borghese, & Carrozzo, 1993). EMG activity in the concerned muscles

was elicited at approximately the same time relative to impact; furthermore, participants were always successful in catching the pendulum in the hand. Thus, participants estimated TTC well enough to perform this specific task. But a more detailed analysis revealed systematic variations in the timing of EMG responses, consistent with the use of a first-order approximation of the pendulum's motion to estimate TTC. Although the first-order model does not explain all the variability in the timing of EMG responses, one would not expect to find the statistically significant negative correlation between  $\Delta_{\text{EMG}}$  and  $A_0$  if the participant had access to better estimates of TTC.

Quantitatively, a first-order estimate of TTC explains the systematic variations in EMG onset using physiologically reasonable model parameters. For instance, the slope of the regression line in Figure 4B is determined by the choice of  $\lambda$ , and the best results were obtained with a  $\lambda$  of 275–300 ms (Figure 8). Note that while there was a good correlation between simulated and measured  $\Delta_{\text{EMG}}$  for this  $\lambda$  value, there is significant offset between the predicted and simulated  $\Delta_{\text{EMG}}$  (simulated  $\Delta_{\text{EMG}}$  values are longer than the measured values by about 170 ms). This can be explained by delays in the neural transmission of the sensory signal and motor command. Simulated  $\Delta_{\text{EMG}}$  values are based on when the estimated TTC falls below the TTC threshold  $\lambda$ . Taking into account the time required for sensory information to reach the brain from the eyes and the time for the motor command to reach the muscles from the brain, measured  $\Delta_{\text{EMG}}$  values should occur somewhat later. A delay of 170 ms from vision to muscles is entirely compatible with delay times that might be expected within the central nervous system (Thorpe, Gegenfurtner, Fabre, & Bulthoff, 2001). Furthermore, the identified range for  $\lambda$  is consistent with what is known about the critical viewing window required to catch a ball (Savelsbergh et al., 1993). Thus, we conclude that the participants triggered the EMG response when a first-order estimate of TTC dropped below a TTC threshold of about 300 ms.

When stopping the moving pendulum, participants modulated the amplitude of their anticipatory EMG responses as a function of the pendulum's final velocity, in agreement with the observed EMG responses when catching a falling ball (Bennis et al., 1996; Lacquaniti & Maioli, 1989b) and with the observed increase in grip force when striking one object with another (Turrell et al., 1999). We have demonstrated how this correlation may be obtained by using a first-order predictor of the true final velocity that ignores accelerations. In an analysis that corrects for the inherent correlation between pendulum velocities at different times prior to impact, we found that EMG amplitude was better correlated with the pendulum's velocity at some time before the impact ( $200 \text{ ms} < \kappa < 300 \text{ ms}$ ) than with the velocity at impact. Our results suggest that the participants did not extrapolate changes in velocity to correctly estimate the final true value. Instead, the participants seem to have adopted a strategy that measures the current velocity up to the last possible instant and then assumed that there will be no further changes until impact.

The results from our two analyses (timing and amplitude) are consistent with a common first-order control process. Indeed, estimates for  $\lambda$  fall within the estimated range of values for  $\kappa$ . Thus, it is possible that an observer triggers the EMG response when the first-order estimate reaches its threshold value of approximately 275–300 ms and that the amplitude of the response is programmed at the same time, based on the instantaneous velocity

at that moment (i.e., that  $\kappa = \lambda$ ). We cannot rule out, however, modifications to the EMG amplitude that could occur between 200 and 300 ms prior to impact, generated by a prospective strategy that adjusts the amplitude of the ongoing activity based on first-order TTC estimates. In this way, some, but not all, changes in velocity that occur after response initiation could still be accounted for by modulating the motor response based on updated, first-order TTC estimates.

Do human observers completely lack the capacity to estimate accelerations based on visual information, or is such information conceivably available yet ignored for this task? Although the visual system seems unable to detect directly instantaneous accelerations, observers are clearly able to detect modulations of speed over time. According to data from Werkhoven et al. (1992), velocity modulation detection is carried out in a two-stage process that involves a low-pass filter stage (time window of 100–140 ms) followed by a discrimination stage sensitive to velocity changes of as little as 17% (Werkhoven et al., 1992). We saw that anticipatory EMG activity linked to impact began about 75 ms before impact. As the viewing time for the different conditions in our experiment varied between 256 and 491 ms, participants should have had enough time to detect some level of acceleration, at least at the beginning of the trial. In half of our conditions, the pendulum accelerated with an increase in velocity of 17% or more during the period between the appearance of the pendulum up to 300 ms prior to impact. Limiting the analysis to a subset of trials in accordance with the “17% rule” did not change the results, indicating that acceleration information was not used even for the conditions in which it was potentially available. Thus, these results indicate that the timing of EMG activity in anticipation of impact is best described by the predictions of a first-order approximation for estimating TTC, as compared with a second-order estimate of TTC or better.

The study of TTC evokes fundamental questions such as: What environmental properties are used in the performance of a given task, and how are they perceived by an observer? Differing experimental conditions and available sensory cues might explain apparent discrepancies between experimental studies, thus the importance of specifying what we are talking about (Bootsma et al., 1997). For a catching task, the property of the environment–actor system that is of interest is the TTC between the hand and the approaching object. In a general case, TTC could be detected through measurements such as the magnitude and rate of closure of the optical gap between the hand and the object and the rate of expansion of the approaching object's retinal image (Bootsma et al., 1997). The original experiments by Lee (1976) were limited to objects approaching along the sight line. Therefore, the optic variable  $\tau$  was one of the few pieces of information available to participants under these conditions (see Tresilian, 1999). However, Lacquaniti's experiments involved catching a ball that fell into the participant's outstretched hand (Lacquaniti et al., 1993; Lacquaniti & Maioli, 1989b). In the latter case, participants had additional retinal and extraretinal information on which to base their TTC estimates. Thus, the ability to estimate object acceleration could conceivably be related to the available sensory cues. In our study, the movement of the pendulum occurred entirely in the fronto-parallel plane. Expansion of the image on the retina should have played a minor role, with the optical gap providing the dominant source of information. Even under these viewing conditions, we



observed responses consistent with a first-order model, as described by Lee and others (Lee, 1976; Lee et al., 1983; Savelsbergh et al., 1991; Savelsbergh, Whiting, Burden, & Bartlett, 1992). Therefore, the ability to account for accelerations does not seem to be strictly dependent on the viewing conditions. Nevertheless, we have not attempted in this study to determine exactly which optical or visuomotor signals are used by the central nervous system to represent the estimated TTC. Instead, we addressed the more general question of whether participants use information about acceleration in available cues to estimate TTC.

What, if anything, do our experiments have to say about the “internal model of gravity” hypothesis for estimating TTC of a falling object? Obviously, our results do not support the use of a general purpose internal model of acceleration for the case of a moving pendulum. Nevertheless, the results from our experiments give corroborating evidence that an internal model of the specific acceleration due to gravity may indeed have been used to catch a falling ball. Our reasoning on this point is as follows: In our experiment we found no evidence that participants used information about acceleration to improve EMG timing. The visual conditions and the task constraints were similar to those of the ball-drop experiments and cannot explain the difference. Therefore, if EMG responses for catching a falling ball do indeed take into account the acceleration due to gravity, it must be through an alternative mechanism. It is known that a priori knowledge (i.e., information given prior to the start of the trial) can improve control—motor responses in anticipation of impact are better tuned when the participant handles the projectile prior to release (Bennis et al., 1996; Johansson & Westling, 1988) or when verbal information about the magnitude of the impending impact is given in advance (Turrell et al., 1999). In the case of a falling ball, an internal model of gravity could provide additional a priori information based on a lifetime of experience in Earth’s natural environment. Participants could apply this model by default as the most likely solution when interacting with a downward moving object. Evidence supporting this hypothesis was derived from an experiment in which participants caught a downward moving ball in the presence or absence of gravity (McIntyre, Zago, Berthoz, & Lacquaniti, 2001). Differences in the timing of catching responses between the two gravitational conditions suggest that the synchronization strategy makes use of a second-order internal model of gravity that assumes a downward 1-g acceleration by default. In the present experiment with the pendulum, we varied the acceleration profile and initial velocity randomly from trial to trial. Not only were the dynamics of the pendulum more difficult to model than that of an object in freefall, but we also removed any prior knowledge of the initial velocity or acceleration and we limited the possibility that participants might tune the timing of their responses through practice. Even if observers used data from the first few milliseconds of a trial to generate an internal model of the pendulum’s acceleration, performance should have been better than the observed first-order behavior. A hypothesis consistent with all of these experiments states that participants may use second-order TTC estimates when an internal model can be formulated, for example, in the case of gravitational acceleration or when a priori information is given about the specific conditions of a catching trial. When such information is not readily available, the system resorts to a simpler, first-order strategy that relies only on the accessible sensory cues.

Is first-order good enough for this task? Our data are best explained by the use of first-order strategies for controlling the anticipatory EMG required by the task, yet participants always succeeded in trapping the pendulum in the hand. It is clear, therefore, that first-order strategies were good enough to perform this operation. It could therefore be argued that the precision demanded by our task was not high enough to force participants to use a more accurate strategy. One might even question whether there is any need for accurate prediction at all in this task. The hand was placed on the path of the swing, so interception was assured 100%. Participants could have been satisfied by the level of performance provided by a first-order strategy knowing that the padded weight would not be missed whatever the condition. The consequences of a miss-tuned response in this experiment are therefore not obvious. In this respect, the allowable margins of error for the timing and amplitude of the EMG responses studied here are ill defined, as compared with other interceptive tasks for which an early or late response results in out-and-out failure. The mere fact, however, that participants synchronize responses to impact, rather than applying a fixed-latency, fixed-amplitude strategy for all trials, indicates that the correct tuning of the response is indeed of some importance for the task. Furthermore, the observation that a 1-g internal model may be used to produce more precisely tuned responses in the case of a falling ball (Lacquaniti et al., 1993; McIntyre et al., 2001) suggests that precision is maximized to the limits allowed by the available information. The incentive for increased accuracy under these circumstances may therefore be linked more to the minimization of some cost function, such as energy consumption, than to hard constraints that determine the success or failure of a trial. Nonetheless, it remains to be shown whether the central nervous system can be pushed to form more accurate, higher order predictive mechanisms depending on the precision and cost functions demanded by different sensorimotor tasks.

## Conclusions

The data from our experiment provide further insight into the anticipatory strategies used by humans when catching accelerating objects with the hand. The use of the variable velocities and accelerations afforded by the pendulum allowed us in this experiment to clearly distinguish among zero-, first-, and second-order control laws, based on systematic variations in response timing and amplitude according to the velocity and acceleration of the object. We found that the strategies implemented by human observers to control muscle activity were compatible with predictions for simulated first-order, but not second-order, control strategies. We conclude, therefore, that in the absence of a priori knowledge about the object’s movement, online information about velocity but not acceleration is used to estimate TTC and impact velocity.

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Received May 21, 2001

Revision received June 4, 2002

Accepted June 25, 2002 ■