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On the Information-Based Regulation of Movement: What Wann (1996) May Want to Consider

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On the basis of a critical review of studies that examined the use of temporal information in the regulation of movement, J. P. Wann (1996) concluded that there is little evidence in favor of the use of tau. Although more experimental work is certainly needed, progress can only be made if (a) the conceptual confusion emanating from a lack of distinction between specification (i.e., information) and what is specified (i.e., relevant property of the environment–actor system) is resolved, and (b) the way in which information is used in the regulation of movement is reconsidered. It is argued that continuous control models incorporating first-order time-to-contact related information not only explain the results obtained but also allow testable accounts of the principles involved in kinematic trajectory formation.

A change in the relative distance between an observer and an object (or a surface) gives rise to a change in the optic angle subtended at the point of observation by the object. Thus, a change in the optic angle may be used by an observer to detect the existence of relative motion. Moreover, the pattern of change of the optic angle contains information about certain characteristics of the relative motion, signaling, for instance, whether the relative distance increases or decreases and, in the latter case, whether a collision is imminent (Schiff, 1965). Lee (1974, 1976, 1980) demonstrated that besides these qualitative aspects, the pattern of change of the optic angle also contains quantitative temporal information, signaling the time remaining until contact if the velocity of approach were to remain constant.

The identification of such quantitative temporal information in the optic flow pattern opened the door for the development of a theory of the (temporal) regulation of movement, and since then a large number of studies have been reported that attempted to test and/or further develop such a theory. Today, the optical flow pattern descriptor identified by Lee (1974, 1976, 1980)—which he coined τ (tau)—figures prominently in most textbooks on perception or movement. However, this by no means implies that the debate on the manner in which, if at all, such an optical variable is used in the regulation of movement is closed, as is exemplified by the critical article of Wann (1996).

On Distinguishing Specification From What Is Specified

Before entering into the argument about the use of τ-like variables in the timing of action, a persistent and pervasive conceptual confusion needs to be resolved first. This confusion is generated by the fact that, more often than not, students of perception and movement fail to distinguish between the property of the Environment–Actor System (EAS) that is thought to be relevant for the regulation of movement and its optical (or acoustical, mechanical, chemical, etc.) representation, that is, the distinction between what is specified (the property of the EAS) and its specification (the informative flow pattern that can be detected). In the introductory example above, the relative motion between an observer and an object is a property of the EAS that can be visually detected by registering the pattern of change in the optic angle subtended at the point of observation by the object.

In order for a property of the EAS to be perceived, two mapping operations should therefore be distinguished: The property of the EAS should give rise to a property of (change in) the optic (acoustic, etc.) array, and the registering system should be sensitive and attuned to the latter property. The former mapping entails specification; the latter, detection. Obviously, what is not specified cannot be detected. Hence, a first step in the development of a theory

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of information-based regulation of movement involves the formal identification of informative properties of the proximal flow patterns. Lee's (1974, 1976, 1980) analysis of the optic flow pattern generated by head-on approach between an actor and an object (or a surface) demonstrated that information about the time remaining until the two will meet—if the velocity of approach remains constant—is present, which allowed him to suggest that this information is used in the timing of action. In this analysis (see Figure 1A) the property of interest of the EAS is the first-order temporal relation between actor and object that is given by current distance Z divided by current approach velocity $-\dot{Z}$; the corresponding property of the optic flow pattern is the inverse of the rate of dilation of the optic angle φ subtended by the object at the point of observation. Both of the components distinguished above pose terminological problems, as the full descriptions are relatively long and cumbersome. Thus, Lee (1974, 1976) proposed to denote by the variable τ the informative optical pattern (i.e., the inverse of the rate of dilation of the optic angle: $\tau = \varphi/\dot{\varphi}$) and to denote by the tau-margin (Lee & Young, 1985) the relevant property of the EAS (i.e., the first-order temporal relationship of interest: tau-margin $= -Z/\dot{Z}$). In this terminology, whatever

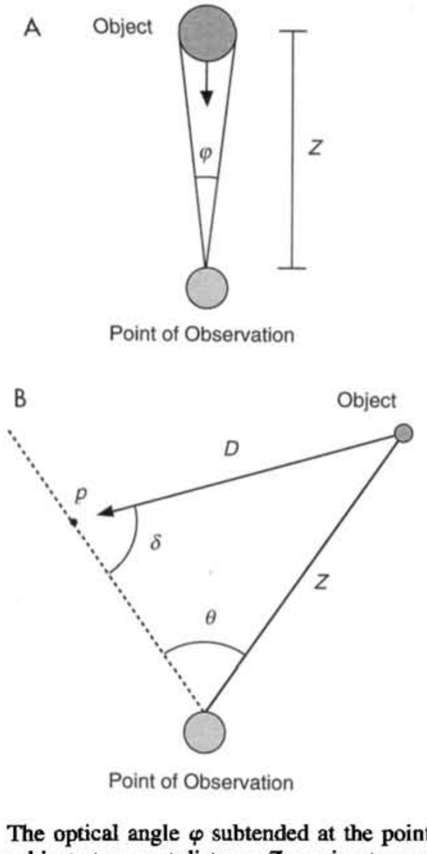

Figure 1. The optical angle φ subtended at the point of observation by an object at current distance Z moving toward the point of observation (A). The optical angle θ subtended at the point of observation by the gap separating a moving object from a target position p. The moving object approaches p under approach angle δ from current distance D (B).

the kinematic characteristics of the approach, in the case of head-on approach the optical variable τ specifies the tau-margin, the latter equaling the time-to-contact if the velocity of approach remains constant.

Subsequent work on the specification of first-order temporal relationships demonstrated that the flow analysis proposed by Lee could be generalized in the optical domain to non–head-on approaches (i.e., to approaches between two objects; see Bootsma, 1988, for a planar projection analysis, and Bootsma & Oudejans, 1993, Bootsma & Peper, 1992, and Tresilian, 1991, for polar projection analyses) as well as to acoustical (Erwin, 1995; Lee, Simmons, & Saillant, 1995; Shaw, McGowan, & Turvey, 1991), mechanical (Cabe & Pittenger, 1992), and other domains. This led to a reposing of the terminology problem, because τ-like variables were found to abound. Recently, Lee, Reddish, and Rand (1991) and Lee, Young, and Rewt (1992) proposed speaking of the τ-function of a perceptual variable to denote the informational quantity and of the τ-function of a physical variable to denote the state of the EAS. While we agree that there are certain advantages in this new terminological conception, we fear that, in failing to distinguish clearly between EAS and information, it will further the conceptual confusion rather than remedy it.

An example of the existing confusion can already be found in the question posed by Wann (1996, p. 1031) of whether the tau-margin is used in the judgment of arrival time: In light of the above-defined terminology, this phrasing of the question suggests that, contrary to the intention of his article, Wann is not interested in the informational support, because both the tau-margin and arrival time are variables of the EAS. Further confusion is generated when Wann suggests using the term tau-margin for any τ-function and using "$\tau(\varphi)$ when it is necessary to specify the stimulus" (p. 1031): When speaking of a tau-margin—written out or denoted τ_m—in this framework, it is by definition unclear whether one refers to an informational or an EAS property and, in either case, the relevant property is left undefined. In fact, Wann appears to have been confused by his own terminology, as may be clear from the fact that he proposes to limit his review to studies involving relatively direct approach toward an object or surface, because these would be the tasks most suited for the use of a tau-margin (p. 1032): If the tau-margin is meant to denote, in the framework of Lee et al.'s (1991, 1992) terminology, the τ-function of Z (the latter referring to the current distance in depth), the logic of this limitation can be understood. If, on the other hand, it is meant to describe any τ-function (and thus, as far as the EAS is concerned, not only that of Z), as proposed by Wann, the reasons for imposing such a limitation are much less obvious, because, as we noted above, first-order temporal relations abound both in the EAS and in the proximal flow patterns. A final example of the confusion that results is to be found in the argument (p. 1033) that the degree of deceleration required to stop before an obstacle would be specified by either $-\dot{Z}^2/2Z$, $-\dot{Z}/2\tau_m$, or $Z/2\tau_m^2$: Evidently, none of these three alternatives qualifies as a specification in the informational sense.

Apart from the conceptual confusion that may be provoked by the τ-function terminology, it also poses practical problems. Whereas the τ-function of the solid (i.e., two-dimensional) optic angle subtended at the point of observation by an object mathematically equals (half) $\tau(Z)$, transposing the analysis to the one-dimensional angle φ requires the assumption of small angles φ to allow establishing the identity-function $\tau(\varphi) = \tau(Z)$. If one is not willing to make this assumption,[1] the correct expression is $\sin \varphi/\dot{\varphi} = \tau(Z)$, in which the left-hand side is not exactly equal to the τ-function of φ.

Thus, given the conceptual and practical problems that arise from both the tau-margin and the τ-function terminologies, we propose to denote a first-order temporal relation TC_1(EAS), where EAS stands for the property of the EAS of interest that together with its first time derivative defines first-order time-to-contact TC_1, and to denote the informative flow pattern $\tau(I)$ (to be read as "tau of I"), where I stands for the informational flow quantity that together with its first time derivative specifies TC_1. In the case of head-on approach we will thus write $TC_1(Z) = \tau(\varphi)$, and in the case of an approach between two objects separated by current distance D, $TC_1(D) = \tau(\varphi, \theta)$ (see Footnote 1). In so doing we reserve the term τ for the specificational aspect and the term TC_1 for the EAS aspect, without reducing either of them a priori to the mathematical τ-function[2] proposed by Lee et al. (1991, 1992).

On the Use of $\tau(\varphi)$

Given the importance of the distinction between informational and EAS properties, the question addressed by Wann (1996) first of all needs to be separated into two: First, is the regulation of movement to be understood on the basis of a first-order temporal relation? Second, is the informational support for this relation provided by $\tau(\varphi)$?

Having distinguished these two questions, we can divide the review provided by Wann (1996) into two parts: a part in which the evidence in favor of the use of first-order temporal information (limited to the case of head-on approach) is evaluated, and a part in which the origin of this information is addressed. Of all the studies discussed, we suggest that only those in which the expansion patterns of approaching objects have been manipulated (Savelsbergh, Whiting, & Bootsma, 1991; Savelsbergh, Whiting, Pijpers, & Van Santvoord, 1993) bear on the latter question. On the basis of data digitized from a number of different figures presented in these studies, Wann concludes that the evidence they provide runs counter to the use of $\tau(\varphi)$ rather than being favorable to it. Whereas this might indeed eventually prove to be the case, we believe that one cannot on the one hand criticize the research on methodological grounds and on the other hand draw conclusions about the use of $\tau(\varphi)$ from the data it provides: As Wann himself remarks, his reconstruction of the expansion patterns of the deflating ball does not give the same results for the two studies. Whether this is due to errors in the original graphs presented or to the reconstruction method used is not at issue here. We suggest that a quantitative evaluation of specific predictions necessitates fine-grained analyses that cannot be made on the basis of the existing database.

We would nevertheless like to point to one issue that has, surprisingly, not been taken up in the criticisms of these studies. By using a deflating ball, Savelsbergh et al. (1991, 1993) dissociated the optical expansion pattern[3] from the spatio-temporal trajectory of the ball. Their results showed two main findings. First, the time of maximal hand closing velocity was delayed in the deflating ball condition. Second, the development of the magnitude of hand aperture during the grasping movement followed the magnitude of the deflating ball during the approach. While the former result can be interpreted as being consistent, at least qualitatively, with the use of $\tau(\varphi)$ for the regulation of timing, the latter casts doubts on this interpretation: The very movement patterns of the participants indicate that they somehow perceived the

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[1] Much has been made by Tresilian (1991, 1994a, 1994b) of the approximations often made for reasons of convenience in the analysis of one-dimensional angles. Let us therefore clarify this issue here with respect to the generalized τ-variable that has been proposed by Bootsma and Oudejans (1993): Let φ be the optical angle subtended by a moving object at the point of observation and let θ be the optical gap separating the center of the object from the point p toward which the object is traveling. The first-order temporal relationship of interest is that given by the current distance D between the moving object and the point p and its current rate of change over time $\dot{D}$ (Figure 1B). Without any approximation it follows that

$$-\frac{\dot{D}}{D} = \frac{\dot{\varphi}}{\sin \varphi} - \frac{\dot{\theta}}{\tan \theta}. \quad (1)$$

For head-on approaches $\dot{\theta} = 0$, and Equation 1 reduces to Lee's τ defined relative to the optical angle φ. For object movement that does not change the distance between object and observation point, $\dot{\varphi} = 0$, and the relevant information is specified by the rate of constriction of the optical gap θ. In all other cases it is the combination of the two that contains the information required. Thus, Wann's contention that the τ-function of φ constitutes a central component in the specification of the temporal relation is incorrect, because the relative importance of the two components is a function of the object motion trajectory.

[2] Lee's proposal to focus on the τ-function (i.e., the relation between a variable and its first time derivative; note the resemblance to a logarithmic function, Bootsma & Oudejans, 1993) has the virtue of stressing the symmetry in the relation between properties of the EAS and properties of the specificational flow patterns. Thus, when applied systematically (using, for instance, lowercase letters for flow quantities and uppercase letters for EAS quantities, with both quantities explicitly specified), this terminology certainly has merit. Nevertheless, for the practical reasons given, we maintain that our terminology is to be preferred.

[3] Savelsbergh et al.'s (1991, 1993) allusion to the temporal information contained in the expansion pattern generated by the deflating ball as being "non-veridical" is rather unfortunate, as this would, in the framework of the specification of EAS properties by proximal flow properties, imply a nonveridically deflating ball. What is meant is that the temporal information contained in the rate of dilation of the optical angle subtended by the ball does not correspond to that of a rigid body approaching at the same velocity along the same spatiotemporal trajectory.

ongoing change in the size of the ball. Whereas for the moment the information specifying the size of an approaching object is not clearly identified, the ongoing adaptation of the movement pattern indicates that participants did perceive the deflation. It would seem unlikely—although not impossible—that the diminishing size is integrated into one component of the action while it is not taken into account in another.

On the Logic of First-Order Temporal Information

Following Tresilian (1991, 1993, 1994a, 1994b), Wann (1996) proposes that the hypothesis that first-order temporal information—TC_1 in the terminology we propose—is used might be reformulated as a constant velocity approximation hypothesis. Behind this formulation seems to lie the idea that, because under non-constant-velocity approach conditions TC_1, which does not take into account upcoming changes in approach velocity, is not equal to "real" time remaining until contact (TC), information about TC_1 is only approximately correct in such situations (e.g., Tresilian, 1994a, 1994b; Wann, 1996, p. 1035). Indeed, if one assumes that a movement would need to be planned utilizing some type of optimization procedure (minimizing a cost function such as total jerk; Hogan, 1984, for example), exact knowledge of the time that will be spent in movement is needed (also see Zaal, Bootsma, & Van Wieringen, in press-b). Thus, if approach velocity is not constant, one might be led to search for "better" predictive temporal information. For head-on approach situations in which the rate of change of velocity (i.e., acceleration) is constant,[4] formulations for the optical specification of TC_2, the second-order temporal relation, have indeed been suggested (e.g., Bootsma & Peper, 1992; Lee & Reddish 1981; Tresilian, 1994a). However, neither for diving gannets (Lee & Reddish, 1981), nor for humans jumping off heights (Sidaway, McNitt-Gray, & Davis, 1989), nor for humans jumping up to hit a falling ball (Lee, Young, Reddish, Lough, & Clayton, 1983) was TC_2 at the moment of initiation of movement found to be constant. In fact, very few people would seem to hold the view that "real" TC is used in such a situation.

The issue of whether TC_1 should be considered approximate is, we believe, critical for understanding the control logic behind the hypothesis that movement is regulated on the basis of τ-like variables. Whereas during constant velocity approach $TC(X) = TC_1(X) = -X/\dot{X}$, the situation is different during a constant acceleration approach (because changes in velocity need to be taken into account), where $TC(X) = TC_2(X) = (-\dot{X} - \sqrt{\dot{X}^2 - 2X\ddot{X}})/\ddot{X}$, which reduces to $TC(X) = \sqrt{2X/\ddot{X}}$, if starting velocity $\dot{X}$ is zero. During an approach with a constant rate of change of acceleration, yet another expression for TC is found, $TC(X) = TC_3(X) = \sqrt[3]{6X/\dddot{X}}$, if both starting velocity $\dot{X}$ and starting acceleration $\ddot{X}$ are zero, and so on for other constant higher derivative approaches. Thus, in order for the perceiver to access the "real" TC, exact knowledge of the kinematic characteristics of the approach at hand would be required, and we may pose serious questions as to the feasibility of such a requirement. In light of the foregoing, it is important to note that for diving gannets, jumping humans, or falling balls, even the assumption that acceleration is constant can in fact not be maintained, because air resistance provides a friction force, scaling approximately with the velocity squared. Thus, using TC_2 information when confronted with natural free-fall situations would also only be approximate.[5]

The final point that we would like to make with respect to the issue of approximation is that in many situations it makes no sense to speak of "real" TC. In regard to the situations discussed above, the real time elapsed until contact is made will only correspond with the TC derived if the current kinematic characteristics pertain, that is, if the actor does nothing to change the current state of affairs! Drivers approaching an obstacle on the road in front will normally act in such a way so as to make sure that TC goes to infinity: They intend to avoid contact. Moreover, if the obstacle is another car, its driver's actions would also influence TC. Nevertheless, during the approach temporal relations do exist, and Lee (1976) has suggested that TC_1-related information may in fact be used to ensure that $TC \rightarrow \infty$.

Thus, we conclude that for many interactive situations "real" TC is a measure that can only be derived a posteriori. TC_1, on the other hand, always exists during the unfolding of the interaction and is always real. It should not be taken to represent an approximation of TC, but should be considered to be (one of) the temporal relation(s) of interest by itself. As already suggested by Lee and Young (1985), reliance on TC_1 information allows for the emergence of a strategy for controlling the interaction that is at the same time robust and flexible.

On the Use of First-Order Temporal Information

Having established the control logic behind the use of first-order temporal information, let us now turn to the issue of its use in the regulation of movement. In the recent series of critical analyses of the use of τ-like variables (Wann, 1996; but see also Tresilian, 1990, 1991, 1993, 1994a, 1994b), a number of assumptions are implicitly or explicitly made that need to be carefully examined. For instance, it has been suggested that the accepted view is that the EAS property of interest is specified by $\tau(\varphi)$. This assertion is then followed by an analysis of the types of error that "the old tau hypothesis" (Tresilian, 1995, p. 233) would produce,

[4] We denote the temporal relationship expressed by $-X/\dot{X}$ as being first-order because only the first time derivative of X is considered. A second-order relation thus includes $\ddot{X}$, a third-order relation $\dddot{X}$, and so on for higher-order relations.

[5] The only way out of this dilemma would be the use of a source of information that is in fact a series development (Kim & Effken, 1995) of a TC_1 source such as τ: $TC = \tau + f_1(\tau, \dot{\tau}) + f_2(\tau, \dot{\tau}, \ddot{\tau}) + \ldots$. As higher derivatives of velocity go to zero, the full expression approaches τ. However, for nonconstant acceleration approaches, the second time derivative of τ would already enter into the equation, and one might reasonably ask whether a perceptual system would be sensitive to such constituents.

and discussions are launched on the acceptability of these errors in different situations. Although we do not wish to deny that certain authors have indeed made bold statements concerning the status of Lee's τ (i.e., $\tau[\varphi]$) in the timing of action, this should not be taken to imply that this is the accepted view, embraced by all. For instance, the generalization of Lee's τ to other types of rectilinear approach that was proposed by Bootsma (1988; Bootsma & Oudejans, 1993; Bootsma & Peper, 1992; see Footnote 1) found its *raison d'être* in the observation that humans and other animals demonstrate accurate timing behavior in situations that do not involve head-on approaches (e.g., Bootsma & Van Wieringen, 1990; Lee, Lishman, & Thomson, 1982; Warren, Young, & Lee, 1986). As stipulated by Bootsma and Oudejans (1993) and reiterated in Footnote 1, the generalized τ-variable proposed reduces to Lee's τ in the case of head-on approach, thus rendering the latter but a special case of the former. If one takes this argument seriously, it implies that the discussions on the types of error that would result from the use of only part (i.e., $\tau[\varphi]$) of the complete expression (i.e., $\tau[\varphi, \theta]$) in situations in which $\dot{\theta} \neq 0$ in fact deal with a non-issue.

We suggest that fruitful experimentation and modeling start from an analysis of the observable action capabilities, giving rise to an ongoing search for the identification of the information used as well as the way in which it is used. A quest of this sort obviously implies a number of metatheoretical principles guiding what one is willing to accept as information and as the type of interface between information and movement. The ecological approach to perception and movement, to which we subscribe, holds that flow patterns may qualify as information if and only if they are in a univocal relation with the property of the EAS about which they are proposed to inform (as is the case for Lee's τ and its generalizations), because only then can sustained successful behavior be guaranteed. Concerning the coupling of perception and movement, the guiding principles are to be found in the proposed intricate and continuous interdependency of the two (Michaels & Carello, 1981). We will not develop these issues further here, but we simply want to point out that, without an adequate metatheory, modeling rapidly becomes unprincipled, insufficiently motivated, and ad hoc.

Let us now address the answers provided by Wann (1996) with respect to the question concerning the use of first-order temporal information. Without explicitly stating this, it is clear that in Wann's vision, use of a certain source of information implies that the attainment of a critical value of the informational variable is used to initiate the required movement and hence that the value of the EAS variable specified should be constant at the moment of initiation of the movement. Although we do not intend to fall into the trap of suggesting that this critical value hypothesis is the accepted view, it is true that this view has been predominant in the literature (e.g., Lee & Reddish, 1981). Without wanting to get too far ahead of our argument we suggest that, if this view proved to be untenable, this would not imply that the baby should be thrown away with the bath water: Rather than concluding that first-order temporal information is not used in the regulation of movement, we suggest that the way in which it is used should be reconsidered.

With respect to the data concerning the moment of initiation of movement,[6] Wann (1996) presents a multitude of arguments against actors using a constant value of $TC_1(Z)$. Because we agree with the position that movement onset is not the result of a decision to initiate movement, taken at a critical value of an informational quantity specifying $TC_1(Z)$, we will not take up all individual cases presented by Wann, and we limit ourselves to a few remarks. Contrary to what Wann suggests (p. 1033), there is evidence in the literature that human observers are sensitive to the relative rate of constriction of an optical gap (Bootsma & Oudejans, 1993), and the use of the generalized information source suggested by these authors (i.e., $\tau[\varphi, \theta]$, see Footnote 1) would seem to remedy most of the problems signaled by Wann in his analysis of the pigeon data of Lee, Davies, Green, and Van der Weel (1993). Thus, for the studies of movement normal to gravity discussed, only the data pertaining to the coefficients of variation remain, and these are certainly not without methodological problems. For the studies of movement with or against gravity, the argument goes no further than suggesting that an alternative control strategy, based on the relative change of distance, may explain the data available just as well. In the end, the case against the use of information on $TC_1(Z)$ is therefore not as strong as Wann suggests. In any case, whatever one's position, it is clear that what is needed is not more sophisticated modeling of (partial) data digitized from existing studies[7] but new experimental investigations that address specific predictions of the different control theories put forward.

On the Concept of Continuous Control

One control theory that is not explicitly addressed by Wann is based on the idea that one should not distinguish

[6] Note that the experimental procedure that consists in verifying whether $TC_1(Z)$ (or any other TC_1-variable) is implied in the control of action does not speak to the issue of specification and thus can only provide circumstantial evidence (Bootsma & Oudejans, 1993) for $\tau(\varphi)$, or any other τ-like variable. Such a procedure can therefore be but a first—albeit important—step in a more encompassing research program that must, at some stage, provide a more direct test of the information used by manipulating informational quantities (e.g., Savelsbergh et al., 1991, 1993).

[7] As we noted in the section "On the Use of $\tau(\varphi)$," only reproduction of the deflating ball experiments of Savelsbergh et al. (1991, 1993) with more fine-grained analyses and more experimental control will allow the evaluation of competing models (see Wann & Rushton, 1995, for an interesting attempt). The same holds for the experiment of Lee et al. (1983): Post hoc modeling of (part of) the action on the basis of data averaged over trials for only 3 participants (Tresilian, 1993, 1994b; Wann, 1996) simply cannot constitute a serious test of a theory. This latter experiment moreover suffers from the fact that, because only ankle and elbow angles were registered, insufficient data concerning TC_1 (Z) are available, as head displacement during the coiling and extension phases of movement was not taken into account.

movement initiation and movement execution. That is to say, the law of control guiding movement during the unfolding of the act is the same as the one that gave rise to the onset of movement. The idea of having a single law of control to account for both movement initiation and movement execution is what we understand to be implied by continuous control (cf. Bootsma & Van Wieringen, 1990; Peper, Bootsma, Mestre, & Bakker, 1994). Recently, Schöner (1994) has provided a general framework allowing the results of many of the studies discussed by Wann on the regulation of movement on the basis of first-order temporal information to be understood within a dynamical systems perspective implementing such continuous control. The basic idea of this framework is that the relative expansion function [i.e., $\tau(\varphi)^{-1}$] generated by head-on approach destabilizes one fixed point (corresponding to the initial state) in a system with two fixed-point attractors. This destabilization eventually leads the system to follow a limit-cycle regime until it stabilizes onto the other fixed point (corresponding to the final state), in line with the dynamical model for discrete movements that has been proposed (Schöner, 1990; see also Zaal, Bootsma, & Van Wieringen, in press-a, in press-b). In Schöner's (1994) model the inverse τ-function is the only informational component considered, and one might therefore argue that only temporal information is used. Because the cases with which Schöner deals all involve head-on approach situations in which only temporal uncertainty exists, such a limitation to temporal (TC_1-related) information may be warranted.

When considering tasks in which, besides a temporal constraint, a spatial constraint exists (implying that the object can be missed), that is, tasks requiring being at the right time at the right place, a complete reliance on purely temporal information would be insufficient. In an analysis of the lateral displacement of the hand in a catching task, Peper et al. (1994) found that balls converging toward the same interception point via different spatio-temporal trajectories gave rise to distinct kinematic profiles. This result led them to conclude that the actor did not first assess the future place of contact and the time remaining until the ball would reach it, followed by the execution of a movement programmed to reach this point at that time. Rather, they proposed a control strategy entailing a continuous regulation of the hand displacement velocity on the basis of (information that specifies) the velocity required to ensure interception. Simulations incorporating a threshold value for the detection of the required velocity gave rise to latencies and kinematic profiles that closely resembled the latencies and kinematic profiles that were experimentally observed.

Following up on this work, we are currently developing a more complete model that not only aims at providing realistic kinematics for tasks in which the goal is to be at the right place at the right time (as in catching tasks) but also can incorporate the constraint of arriving at a high velocity (as in hitting tasks). As a first step in this direction we have reformulated Peper et al.'s (1994) model as a set of two differential equations, one dealing with the establishment of the currently required velocity of the hand and the other dealing with the integration of this required velocity into the real velocity of the hand:

$$\dot{X}_{h\,req} = \frac{(X_h - X_b)}{(TC_1)_b} \quad (2)$$

$$\ddot{X}_h = \alpha \dot{X}_{h\,req} - \beta \dot{X}_h \quad (3)$$

where α and β are constants, $X_h - X_b$ is the current difference in position between hand and ball in terms of their relative progression toward the interception point,[8] $(TC_1)_b$ is the current (first-order) time remaining until the ball will reach the interception point, $\dot{X}_{h\,req}$ is the currently required hand velocity, and $\dot{X}_h$ and $\ddot{X}_h$ are the current hand velocity and hand acceleration, respectively. Basically, the model works in the following way: In order for the hand to arrive at the point of interception at the same time as the ball, the existing difference $X_h - X_b$ should be reduced to zero in the time span given by $(TC_1)_b$. Closing the gap too quickly would result in arriving too early at the interception point, while closing the gap too slowly would result in arriving too late. Thus, $(X_h - X_b)/(TC_1)_b$ represents the currently required velocity. Actual hand movement velocity is geared to this required velocity. Changes in ball velocity, trajectory, or both, will give rise to changes in the required hand velocity, which will then result in changes in the actual hand velocity, thus making the model suitable for examination under all sorts of ball approach conditions. For purposes of illustration, Figure 2 presents the results of simulations using this model with parameters α and β chosen to produce typical velocity profiles for catching (Figure 2A) and hitting (Figure 2B) actions.

Conclusion

Whatever one's opinion of the preliminary model presented above, it has the merit of demonstrating, as have the models proposed by Peper et al. (1994), Schöner (1994), and Tresilian (1994b), how first-order temporal information could be used in the regulation of movement. Given that the required velocity as described by Equation 2 depends on characteristics of the spatiotemporal ball trajectory on the one hand and on the current hand position on the other, Equation 3 in fact describes a simple second-order system, with β being the damping coefficient and α being the gain of a nonlinear stiffness function, in which both the equilibrium position ($X_h = X_b$) and the degree of supralinearity (through $1/[TC_1]_b$) are determined by the motion of the ball. In so doing, the model gives rise to what we have termed a funnel-like type of control (Bootsma, Houbiers, Whiting, & Van Wieringen, 1991; Bootsma & Peper, 1992), with

[8] The relation between the hand and the ball might also be described through the angle formed by the orientation of the ball–hand axis relative to the direction of movement of the hand, not unlike the gaze–movement angle identified in ego-motion (Cutting, Vishton, & Braren, 1995). Such a description would have the advantage of not necessitating a priori knowledge of the location of the interception point.

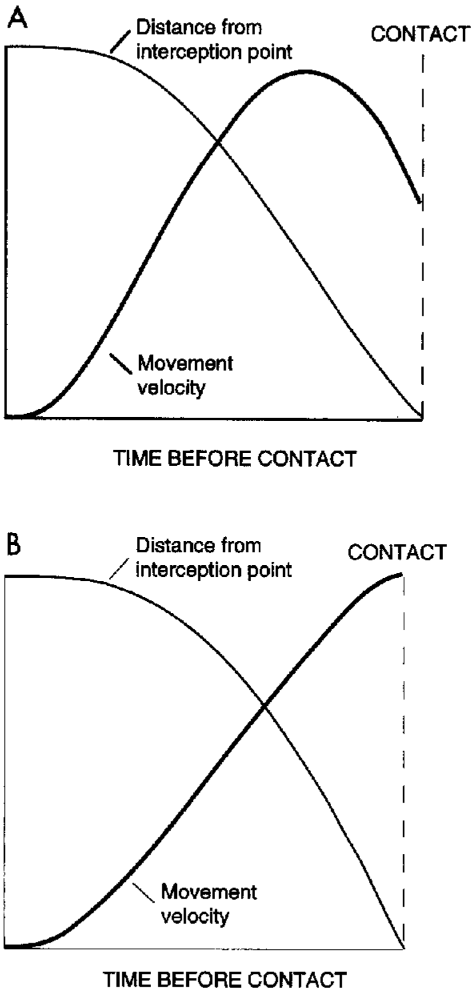

Figure 2. Simulated distance (thin lines) and velocity of the hand (thick lines) as it moves towards the point where the object (moving at constant velocity) will be intercepted ($X_h = X_b = 0$ at the moment $[TC_1]_b = 0$). Incorporating a 100-ms visuomotor delay, model parameters α and β were chosen so as to produce kinematic patterns that resemble those found in catching (A: α = 17, β = 5) and hitting (B: α = 11, β = 5) tasks.

between-trial variability (due to a noise term that can be added to Equation 3, for instance) decreasing as the moment of contact approaches.

The hypothesis that movement initiation would occur at some critical value of TC_1-related information has clearly been abandoned (Schöner, 1994; Zaal et al., in press-a). With the arguments of Wann (1996) in mind, it would seem that enough empirical evidence has been gathered by now to suggest that we move on to other things. In our view, the way to go is not to search for alternative variables, such as Wann's ξ-ratio, that could be used to initiate movement, because (a) the control logic behind the use of first-order temporal information and the possibility of applying the same logic in a number of different situations do not merit such a simple dismissal and (b) viable alternatives will have to address not only the reasons for the initiation of movement but also the mechanisms responsible for kinematic trajectory formation. The continuous control models that have been put forward, on the other hand, retain the control logic mentioned while explicitly dealing with the issue of kinematic trajectory formation.

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