The Influence of Environmental Information on Time to Contact Judgements: A Theoretical Model of Relative Tau

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Running Head: RELATIVE TAU MODEL

Abstract

A theoretical model is proposed that attempts to take into account the contribution of the environmental surround to the perception of time to contact of an object approaching an observer or performer. The proposed model is based on the assumption of direct approach at constant velocity, as is the case for Lee's tau model (Lee, Young, Reddish, Lough & Clayton, 1983). However, our theoretical model incorporates optical information from both the approaching object (as in Lee's τ model) and the surrounding environment (not included in Lee's τ model). This background optical information is contained in a new construct that we refer to as background tau (τ_{bg}). Both object tau (τ_{obj}) and τ_{bg} are measured in terms of the rate of expansion (or reduction) of the areas within the appropriate closed contours on the retina. Relative tau (τ_R) is defined in terms of τ_{obj} and τ_{bg} and reflects the rate of expansion (or reduction) of the retinal image of the object relative to that of an adjacent, surrounding background patch. We argue that perceived time to contact of the object with the observer is dependent on τ_R. Under conditions of a static environmental surround, our τ_R reduces to Lee's τ. However, we argue that perception of the object is still made with respect to this surrounding static environment. Our model makes additional predictions with regard to perceived time to contact of the object with the observer when the environmental flow field moves either toward or away from the observer or performer. In this paper, we indicate the implications of the model for the production of an interceptive motor action such as catching or hitting a ball, and offer some suggestions on how the model can be experimentally tested. While the model can be considered a refinement of Lee's τ model, we believe it offers a fundamentally different view of how the visual system works in the perception of time to contact in an interceptive action.

The Influence of Environmental Information on Time to Contact Judgements:

A Theoretical Model of Relative Tau

It has been nearly two decades since David Lee proposed that visual perception of time to contact (t_c) of an observer (or performer) with an approaching object is optically specified requiring no elaborate information processing computation (Lee, 1974). Lee defined t_c in terms of environmental information as the ratio of the distance to contact by the object velocity. Lee's theory (Lee, Young, Reddish, Lough & Clayton, 1983), influenced by the late J.J. Gibson's 'direct perception' approach, states that when an object approaches an observer (or vice versa) at a constant velocity, t_c is equal to tau (τ), defined as the inverse of the rate of dilation of the image of the approaching object on the retina. Thus, it is possible for the visual perception system to directly obtain t_c information without having to resort to computations of distance and velocity separately. Even under accelerative conditions where the relationship between t_c and τ is nonlinear (τ overestimates t_c with the overestimate increasing as t_c increases) it turns out that τ closely approximates t_c for $t_c < 300$ ms (Lee et al., 1983). As long as the performer has visual access to the approaching object for the last 300 ms or so before contact, he/she may be able to compensate for earlier overestimates and accurately time his/her response. Lee's research program has been devoted to establishing support for this simple, yet eloquent theory and over the years Lee and his co-workers have provided both naturalistic observations (Lee & Reddish, 1981) as well as experimental data (Lee & Young, 1985; Lee et al., 1983) in support of what has been referred to as the tau (τ) strategy. Considerable empirical support compatible with the τ strategy has also been obtained from other investigators (Laurent, Ding Phung & Ripoll, 1989; Savelsbergh, Whiting & Bootsma, 1991; Sidaway, McNitt-Gray & Davis, 1989; Wagner, 1982; Warren, Young & Lee, 1986). The τ theory is important for any understanding of motor control because it provides a way for the performer to pick up important visual information from the environment that can be used to help guide motor actions. There are a number of such actions or skills that require precise timing of performer's movements coincident with environmental objects such as walking over uneven terrain, braking an automobile at the correct time, and hitting or catching an object.

Lee's τ strategy provides an explanation of how the sequential timing of actions is controlled so that the body is in the appropriate dynamic state when it contacts some approaching object (Lee et al, 1983). The τ strategy states that all relevant action variables (such as joint angles) are functions of the latest available value of τ. The τ theory uses the expansion pattern of the retinal image of an approaching object, without regard to other retinal information provided by additional environmental features. However, these environmental features have been shown to affect perception of object velocity as is discussed later in this paper. The purpose of this paper is to propose a general perceptual τ model that attempts to account for optical interactions between an approaching object and its surrounding environment. While this proposed model can be viewed as a refinement or extension of Lee's tau model, we consider it to provide a fundamentally different approach to the functioning of the visual system during judgements of time to contact.

The format of this paper will include a discussion of Lee's definitions of tau, a review of some relevant work concerning the effect of the environment on the perception of the motion of an object, the rationale behind our definition of a general environmental tau model, a mathematical derivation of its relationship to time to contact, the predictions resulting from the model, and a general discussion of its implications.

Definitions of Tau

Lee introduces three definitions of the optical parameter τ that can be used in different situations to determine the time to contact of an approaching object with an observer (Tresilian, 1991). The first of these definitions, 'global tau', refers to the retinal image of the optical flow field of an observer moving relative to a rigid environment (or vice versa). For example, in Lee & Aronson's moving room experiment (1974), human infants were caused to sway or even fall backward or forward in response to slight forward or backward motion of a surrounding experimental room. This behavior was in response to information provided by global tau about the relative movement of an observer and the surrounding environment.

This paper specifically focuses on situations when an object approaches a stationary observer, as in interceptive actions such as catching or hitting. For these actions, Lee's 'local taus' provide appropriate estimates of time to contact. These two taus are referred to by Lee as 'dilation tau' (Lee, 1976) and 'spherical tau' (Lee & Young, 1985; Tresilian, 1991). Dilation tau is defined as the inverse of the rate of dilation of the retinal image of the approaching object, as shown in Figure 1. It can be written as r/r', where r denotes the retinal separation of two points on the object and r' denotes the rate of change of this separation. Spherical tau is defined as the ratio 2*A(t)/A'(t) where A(t) denotes the retinal area of the surface patch at time t and A'(t) denotes the rate of change of this area, as shown in Figure 2. These two definitions are defined locally to the image of an approaching object and are both equal to t_c under conditions of constant velocity and direct approach to the eye of the observer (Lee & Young, 1985).

Figures 1 and 2 about here

It is of interest to note that, as suggested by Fitch and Turvey (1977), an approaching object provides both an expansion pattern of the object and a **reduction** pattern of the surrounding environment on the retina. If all parts of the retina are equally sensitive to information about t_c, as found by Stoffregen & Riccio (1990), then t_c can be argued to be based as much on environmental changes as on object changes. This means that a given judgement of t_c can be reached either by using information from the relative expansion pattern of the approaching object on the retina or, equivalently, by using information from the complementary reduction pattern of the environmental information on the retina. The two effects are inseparable. Lee defines the perceptual variable tau only in terms of object information. To account for the complementary environmental effects, an analogous environmental tau can be defined. The importance of this environmental tau will be discussed later in this paper.

Environmental Effects

As discussed above, Lee's definitions of tau are stated only in terms of the approaching object itself without regard to any available environmental information. However, several perceptual studies have shown that the environment can have a considerable effect on the perception of an object and its motion. Information about the motion of an approaching object is obtained from two types of cues: absolute cues and relative cues (Gogel & McNulty, 1983). Absolute cues provide information regarding the motion of an object relative to an observer, and hence include no environmental effects. Lee's τ functions are examples of absolute cues. Relative cues, on the other hand, provide information regarding the motion of objects relative to each other, and hence make use of environmental effects. The distinction between absolute and relative cues is illustrated in studies involving the perceived motion of a test object, first presented alone and then simultaneously with a second moving object. Results of the studies indicate a difference in the perceived direction and/or magnitude of the motion of the test object in these two situations. Note that in the first scenario only absolute cues involving the object and the observer are available, while in the second case both relative cues (involving the two objects) and absolute cues (involving each object separately with the observer) are available (Gogel & McNulty, 1983). The phenomenon that motion of a surrounding object can induce apparent motion in a physically stationary test object is referred to as induced motion; the relative and absolute cues involved in induced motion have been studied extensively (Duncker, 1929; Wallach, 1959; Gogel,1979).

It has been observed for many years that the presence of noticeable reference marks in the environment increases the perceived velocity of a moving object (Brown, 1931).

Stated in terms of relative and absolute cues, perceived velocity from relative cues is usually greater than that from absolute cues (Gogel & McNulty, 1983). This implies that when background reference marks and a moving object are both visible, the perceived object velocity will be determined by the relative weights assigned to the relative and absolute cues.

What determines the weighting of the relative and absolute cues? According to Gogel & Mershon (1969), the adjacency principle plays a major role. The adjacency principle states that "the effectiveness of cues between objects in determining perceived object characteristics is inversely related to the relative separation of the objects" (p 13). As a result, the contribution of relative cues to the perception of motion increases as the separation of the objects decreases, either in a frontal or sagittal plane (Gogel, 1974). So, if an object passes near some interesting environmental landmarks (e.g., dense reference marks), the weighting from these relative cues should increase, and hence the perceived velocity of the test object should increase. If the background is uninteresting (e.g., has few reference marks) or if the object passes far from the background, the weighting given to the absolute cues should increase and the perceived velocity of the test object should decrease. Thus any model dealing with environmental influences should take into account the fact that nearby environmental cues are potentially more influential than far away cues. This is not accounted for in Lee's tau theory.

Proposed Relative Tau Model

As discussed earlier, Lee defines the perceptual parameter $\tau = \tau_A$ (absolute tau) in terms of absolute cues, since only information regarding the approaching object and the observer is included. The purpose of this paper is to propose a more general perceptual parameter τ_R (relative tau) that incorporates environmental perceptual information, that reduces to τ_A in the case of a stationary background, and that estimates t_c (time to contact) in the case of direct approach at a constant velocity. Although this proposed model has not yet been tested experimentally, several studies in the literature (to be discussed later), as well as the perceptual evidence cited in the previous section, provide evidence indicating the importance of the environment in interceptive actions such as catching and hitting. We begin this section with a mathematical derivation of the relative tau model, then examine it as an estimator of t_c, then explain how it deals with occlusion of background information, and finally present an explanation of how it is expected to operate.

Relative tau is a direct generalization of Lee's spherical tau, τ_A, described above. Recall that τ_A is defined as the ratio 2*A(t)/A'(t), where A(t) denotes the area of the retinal image of a surface patch on an approaching object in the environment, and A'(t) denotes its time derivative. Note that this definition only includes information about the interior of the closed contour defined by the image of the surface patch on the retina. Between this closed contour and the limit of the visual field there is some perceptual information that, we believe, also contributes to the judgement of time to contact of an approaching object with an observer. In particular, there are other closed contours corresponding to retinal images of surface patches from potential sources of environmental information. We will focus on a single closed contour that surrounds and is directly adjacent to the closed contour of the retinal image of the approaching object at a given time t (Figure 3). As time to contact of the object with the observer approaches zero, information about this impending collision will be contained in the changing relative patterns of the two closed contours on the retina.

Figure 3 about here

Just as τ_{obj} is defined as the relative rate of expansion of the retinal image of the object, τ_{bg} can be defined as the relative rate of expansion/reduction of the retinal image of the environmental patch. In the case of direct approach (towards or away from the observer) at constant velocity, τ_{bg} equals time to contact of the environmental patch with the observer. Note that τ_{bg} can assume a continuum of values between positive and negative infinity. Lee's absolute tau, which involves an approaching object and a stationary observer, corresponds to the special case where τ_{bg} is infinite, since a stationary background patch never reaches the observer. In this static case, the perception of the motion of the object is still judged relative to its background. As the object approaches the observer, the closed contour defining the retinal boundary of the background patch remains constant.

Relative tau also deals with situations involving a moving background. For example, if both the object and the background patch are approaching the observer, both contours will expand on the retina until eventually the contour corresponding to the background patch will expand beyond the limit of the visual field, and the retina will be completely filled by the interior of the closed contour corresponding to the object. On the other hand, if the background patch moves away from the observer as the object approaches, the closed contour corresponding to the object will expand as that corresponding to the background patch shrinks. Eventually, the background patch will be occluded by the approaching object, and that particular piece of environmental information will no longer be available. Such behavior should be included in a relative tau model. The model should also include transitions from relative tau to absolute tau in the two situations described above, when the background patch is no longer providing information on the retina.

With this introduction, relative tau (τ_R) can now be defined similarly to τ_A as the ratio 2A(t)/A'(t) where now:

$$A(t) = \frac{A_{obj}(t)}{A_{bg}(t)}.$$

Here, $A_{obj}(t)$ denotes the area of the retinal image of a surface patch on an approaching object at time t and $A_{bg}(t)$ denotes the area of the retinal image of a surface patch on a surrounding background object at time t. Note that in this definition both object and background areas are equally weighted; this results in an equal weighting of τ_{obj} and τ_{bg}.

An easy computation of A'(t) shows that

$$\tau_R(t) = \frac{2A_{obj}(t)A_{bg}(t)}{A_{bg}(t)A'_{obj}(t) - A_{obj}(t)A'_{bg}(t)} = \frac{1}{\frac{A'_{obj}(t)}{2A_{obj}(t)} - \frac{A'_{bg}(t)}{2A_{bg}(t)}}. \qquad (1)$$

The two terms in the denominator are readily identifiable as inverses of absolute taus, τ_{obj} and τ_{bg}. Hence,

$$\tau_R(t) = \frac{1}{\frac{1}{\tau_{obj}(t)} - \frac{1}{\tau_{bg}(t)}}.$$

This shows that τ_R is optically perceived as a function of τ_{obj} and τ_{bg}. Note that τ_R reduces to τ_A (or τ_{obj}) in the case when $A'_{bg}=0$ (Equation (1)). This occurs when the area of the background patch remains constant, i.e., when the background patch is stationary.

In the case when both the object and background patch move at constant velocities on a collision course with the eye of the observer, the τ functions are the same as time to contact. In terms of t_c, τ_R can be expressed as:

$$\tau_R(t) = \frac{1}{\frac{1}{t_c} - \frac{1}{t_c + \delta}} \qquad (2)$$

where δ denotes the difference between times to contact of the background patch and the object. Since both the object and the background patch are assumed to move at constant velocities (not necessarily the same), δ depends only on the velocities and initial physical separation between the object and the background patch. It does not vary with time. There are two situations in which δ can be negative: 1) when the background patch is moving away from the observer and the approaching object, and 2) when the background patch is moving toward the observer at a velocity high enough that it overtakes the object before reaching the observer. This second case is not permitted in our model. The fact that δ is negative in the first case follows from the fact that time to contact for a backward moving object is negative.

Equation (2) can be further simplified to

$$\tau_R(t) = t_c + \frac{t_c^2}{\delta}. \qquad (3)$$

The final term, t_c^2/δ, can be regarded as an error term that is introduced by using environmental cues since t_c is the time to contact of the object with the eye of the observer. Note that the largest errors occur for small values of δ, i.e., in situations where the times to contact of the object and background patch are almost equal. This is consistent with the adjacency principle, since in those situations the two patches are close together (in terms of time to contact) so the background has a larger effect on the perception of time to contact. In this case, relative cues are used more than for large values of δ, where the object and background have a greater separation (in terms of time to contact). This effect may be regarded as a generalization of the adjacency principle since the concept of separation in terms of times to contact of two patches includes both the physical distance and velocity separation of the patches.

The curves representing τ_R as a function of t_c for various values of δ are shown in Figure 4. Note that the curves corresponding to $\delta > 0$ lie above the line $\tau = t_c$, which corresponds to Lee's τ_A, while the curves corresponding to $\delta < 0$ lie below that line. This implies that a background patch moving toward the observer results in a value of τ_R that overestimates the true t_c, while a background patch that moves away from the observer results in an underestimate of t_c. As noted previously, smaller values of δ (in absolute value) result in larger errors in estimating t_c.

Figure 4 about here

An alternative way to view the errors introduced by using τ_R as a measure of t_c (Equation 3) is shown in Figure 5. (This is similar to Lee's method for plotting errors introduced by taking tau as a measure of t_c in the case of non zero acceleration (Lee & Young, 1985).) Suppose that two objects, A and B, simultaneously begin to move toward a stationary observer at a constant velocity. Suppose that object A moves with no noticeable environmental effects, while object B moves together with a noticeable background patch such that the difference in times to contact of the background patch and the object is δ. Figure 5 plots the positions of objects A and B for different starting distances from the observer and for different values of δ. The number to the left of the top line in each graph is the actual value of t_c if the object is assumed to approach at 1 m/sec, while the number to the right is the predicted value of t_c using τ_R. As discussed above, the errors are greater for lower values of δ. In addition, τ_R gives an overestimate of the distance of the object from the observer for $\delta > 0$ and an underestimate for $\delta < 0$.

Figure 5 about here

As an object approaches a stationary observer, background information can be used in two different ways. One possibility is that the background forms a large, continuous, noticeable surface that completely fills the area between the closed contour of the object and the limit of the visual field on the retina during the approach of the object (Figure 3). In this case, the τ_R estimate for t_c is provided by the appropriate δ curve (Figure 4). At some point, the approaching object will fill the entire visual field, and environmental information will no longer be available. At that time, τ_A will be used to predict t_c.

The other way in which the environment can provide information about t_c involves multiple occlusions of several background patches. Occlusions are not accounted for in the equation for τ_R (Equation (3)), since τ_R includes only time to contact information about the object and the background patch, while occlusion also involves the relative sizes of the object and background patch. Occlusion of a background patch occurs when $A_{obj}(t)=A_{bg}(t)$ (given that the closed contour corresponding to the background patch surrounds that of the object). Assuming constant velocity, once occlusion has occurred, the background patch remains occluded, so the information it provided is no longer available during the approach of the object. The time at which occlusion occurs can be calculated from the geometry of the approach in terms of δ, the relative velocities and the relative environmental heights (maximal radii) of the background patch and the object. To simplify the math, we will assume the closed contours corresponding to the background patch and the object form concentric circles on the retina. (The general case can be calculated similarly.) At occlusion, these circles coincide, so the radii on the retina are equal (Figure 6). From similar triangles, it follows that

$$\frac{h_{obj}}{Z} = \frac{h_{bg}}{Z+D} \quad .$$

Since $Z = V_{obj} * t_c$ and $Z+D = V_{bg}(t_c + \delta)$,

$$\frac{h_{obj}}{V_{obj} t_c} = \frac{h_{bg}}{V_{bg}(t_c + \delta)} \quad .$$

Rearranging and solving for t_c yields:

$$t_c = \frac{\delta}{h\frac{V_{obj}}{V_{bg}} - 1} \qquad (4)$$

where $h=h_{bg}/h_{obj}$, the relative environmental heights of the background patch and the object.

Figure 6 about here

The predictions made by the relative tau model can now be explained. Suppose an object approaches a stationary observer on a collision course at constant velocity. Suppose that some piece of background information is also perceived by the observer. This background patch may be stationary, forward moving, or backward moving relative to the observer, but it is assumed to be moving at constant velocity on a positive or negative collision course with the observer. It is also assumed to surround and be directly adjacent to the object. τ_{bg} and τ_{obj} are optically perceived by the observer and, because of the model assumptions, they yield true values of times to contact of the background patch and the object with the observer. Their difference, δ, defines a curve of approach to the observer (Figure 4) that provides τ_R estimates of time to contact of the object with the observer using the information provided by the background patch. This particular δ curve is followed until the background patch is occluded. (The time of occlusion is provided by Equation (4).) At that time, another background patch is perceived by the observer and is used to provide relative information about t_c. A new δ corresponding to the new background information is optically computed and the new δ curve is used. As explained above, at some point before the object contacts the observer, the entire retinal field is filled with the closed contour of the object. At this point, τ_R reduces to τ_A, so the line $\tau_A = t_c$ is used to provide t_c information.

As noted above, our proposed relative tau model appears to provide a generalization of the adjacency principle. Is the model consistent with previous work on reference mark density as reviewed in an earlier section of this paper (Gogel & McNulty, 1983)? For this to be the case, the model should predict that an object moving against a background with a high reference mark density should appear to be moving faster than an object moving against a background with a low reference mark density. This implies that if two experiments are conducted, identical in all respects except for the reference mark density of the backgrounds, τ_R should be less for the experiment with the higher reference mark density (since in that case, the object should appear to be moving faster and hence reach the observer sooner). One possible way for this to occur would be for the increased background reference mark density to provide an alternative perception of the boundary of the image of the background patch on the retina in such a way as to reduce the corresponding value of τ_R. The degree to which the relative tau model can distinguish among different background textures is not entirely clear since experimental work has not yet been done. The issue of the effect of the background texture on time to contact judgements is raised again later in this paper.

Visuomotor Delay

As mentioned earlier, Lee's τ strategy includes a visuomotor delay, a relatively constant initiation time before an action can begin after a critical value of τ has been reached. Lee computes this delay, Δt, by computing the value that minimizes the variance in the value of τ at the Δt before initiation of the action. In his study involving subjects attempting to punch an accelerating ball falling towards them (Lee et al., 1983), Lee computed visuomotor delays ranging from 50 to 135 ms. Visuomotor delays of 60 ms were computed for diving gannets in another study (Lee & Reddish, 1981). However, in their study of muscle preactivation in preparation for landing, Sidaway et al. (1989) found visuomotor delays of 0 ms across all subjects. An explanation for this absence of visuomotor delay may be that Sidaway et al. used EMG traces to compute τ, while Lee et al. used potentiometers to monitor limb movements. EMG traces allowed responses of the motor system to τ to be recorded considerably earlier. We may conclude from this that the visuomotor delay is not a constant but rather a variable, that potentially depends on a number of factors such as the method of measurement or the particular task being performed.

Summary of Predictions

Assuming that both the object and the background patch are moving at constant velocity on a direct collision course with the observer and that the background patch surrounds and is directly adjacent to the object, the major predictions of the relative tau model can be summarized as follows:

1) A forward moving background patch results in an underestimate of t_c. A backward moving patch results in an overestimate of t_c. A stationary background patch results in an accurate estimate of t_c.

2) The errors induced by the above effects reduce as t_c approaches zero, i.e., as the object approaches the observer.

3) Larger errors occur when δ, the separation in times to contact between the object and background patch, is small.

All of these predictions are easily verified using Equation (3), and can be explained in terms of a generalization of the adjacency principle as described earlier in this paper.

Discussion

Lee's τ theory (Lee et al., 1983) of t_c is based solely on changes in local tau associated with the approaching object. In this theory for t_c, Lee did not include the potential information in global tau that he and others have demonstrated to be important in the maintenance of upright stance (Lee & Aronson, 1974; Lee & Lishman, 1975; Lishman & Lee, 1973). As we have shown, this omission does not theoretically alter t_c predictions when the surrounding optical array is stationary relative to the approaching object. However, when the surrounding optical array does change relative to that associated with the approaching object, our model predicts either over or underestimates of t_c depending on the direction of this change. But why is it necessary to consider the surrounding optical array in the perception of an object in the environment relative to the observer? The extensive research on the so-called adjacency principle and induced movement effect (Duncker, 1929; Gogel, 1974,1979; Gogel & McNulty, 1983; Gogel & Mershon, 1969;

Wallach, 1959) provide a strong rationale for doing so. In the spirit of the much earlier Gestalt tradition in psychology, this research indicates that perception of objects is made in relation to the environmental surround. Under most circumstances this surround cannot be ignored since it contributes to the perception of the object's distance from the observer. Our attempt at taking the environmental surround into account in t_c judgements with an approaching object is in the form of a new construct that we term τ_{bg}. The present approach incorporates the information contained in τ_{bg} that is in close proximity to the object within the visual field. Our view is that the information contained in local tau of the associated object (τ_{obj}) is always perceived relative to the information contained in τ_{bg}. In this way, the relative τ model provides a fundamentally different view of how the visual system works in formulating t_c perceptual judgements compared to Lee's τ theory.

In the present relative τ model, there is no fixed closed contour on the retina corresponding to τ_{bg}. The only constraints are that its boundaries lie within the total visual field and surround those associated with the approaching object. One factor that could determine the retinal closed contour of τ_{bg} is the texture of the surrounding optical array. As an illustration, take the case of a luminous ball approaching the observer in a uniformly dark background (Savelsburgh et al., 1991). Under these conditions it may be difficult for the visual system to define a relatively fixed τ_{bg}. As the object approaches, the visual system's attempt at formulating a fixed τ_{bg} may undergo fluctuation, and this fluctuation could result in an increase in variability of t_c judgements. If sufficient texture is placed in the environmental surround, this may provide the visual system with enough information to stabilize the retinal boundary of τ_{bg} and reduce fluctuations in judgement of t_c. We should point out that in a strict interpretation of Lee's τ theory, environmental texture should not influence t_c judgements because perception is solely based on changes in local tau associated with the approaching object. In the present model, texture provides a way for the visual system to formulate τ_{bg}; however, at this time we offer no specific recommendations as to the relationship between the type of texture in the environmental surround and the closed contour on the retina corresponding to τ_{bg}. This issue would seem to be an important topic of future work, perhaps best studied in the laboratory where systematic manipulations of background textures could be done.

The nonlinear relationship between t_c and τ_R under conditions of forward motion (i.e. towards the observer) of the environmental surround (see Figure 4) bears a striking resemblance to similar curves formulated by Lee et al. (1983) under different accelerations of an approaching object. In accelerative conditions (with a stationary environmental surround), Lee showed that subjects would tend to overestimate the arrival of the object for $t_c > 300$ ms with the overestimates increasing as t_c increases. However, the relationships converge to the constant velocity situation at around 300 ms, allowing the observer to compensate for earlier overestimates of t_c. In the case of forward motion of the environmental surround, overestimates of t_c are also predicted in our model with the overestimate increasing as a function of the differences in times to contact of the object and the environmental surround with the observer. In addition, our model predicts underestimates of t_c when the optic array associated with τ_{bg} moves in a direction away from the observer. However, in the case of constant velocity approaches of the object directly towards the observer, these over and underestimates of t_c continue to reduce as t_c decreases. As under Lee's accelerative conditions (Lee et al., 1983), the relationships between τ_R and t_c converge to the constant velocity, no background motion curve for $t_c <$ 300 ms or so. If subjects are sensitive in changes in τ_R as the present model predicts, we expect that motor actions will be geared to τ_R and **not** τ_A (or τ_{obj}). Specifically, this would mean that actions of longer duration would be affected to a greater extent (over or underestimated) compared to conditions under which the environmental surround is stationary. However, subjects should be able to compensate in time as t_c approaches 300 ms in order to successfully complete the action, such as the catching of an approaching object. Therefore, to completely test these predictions, both kinematic analyses of the evolving motor act as well as a measure of final goal achievement is required. In addition, it would be necessary to examine motor acts of sufficient duration in order to determine whether the components of the movement are indeed geared to τ_R as the motion evolves over time. How might the predictions in the relative τ model be tested empirically? The critical manipulation would be for the experimenter to have independent control of both the velocity of the object and the environmental surround within the subject's visual field. One method would be to use one of Lee's famous experimental paradigms: the moving room (Lee & Aronson, 1974; Lee & Lishman, 1975; Lishman & Lee, 1973). Subjects could be required to catch a ball while the room moves either towards or away from the subject. In addition to the well known postural sway effects that are induced by this manipulation we would also make the above predictions with respect to changes of τ_R and its influence on the grasping pattern itself. The effects of different background textures under these conditions could also be explored.

The primary objective of the present approach is to develop a model of t_c judgements that takes into account known influences of the environmental surround on the perception of objects. While the present mathematical model is theoretical, we are hopeful that it will not only stimulate experimental interest in pursuing the various hypotheses but also cause us to think about alternative ways the visual system works in contributing to perceptual judgements. The major question to be answered along these lines is: what environmental information is the visual system sensitive to in making t_c judgements? We believe the original Lee τ model is incomplete in this regard because it does not address the potential contribution of the environmental surround. To a first approximation, the proposed relative τ model, in our opinion, brings us one step closer to answering this question. The present model suggests that movement of an approaching object either through a stationary or a moving environmental surround induces interactions between their respective optical flow fields. And, it is these interactions that the visual system is sensitive to. In the present formulation, the resulting 'illusory' perceptual effects induced by background motion relative to the approaching object are proportionately greater for large values of t_c and gradually dissipate as t_c decreases. It may be, however, that the visual system is not sensitive to all possible interactions between τ_{obj} and τ_{bg} but that illusory effects will be found only within certain ranges of the parameter space of the interactions. This type of result is what would be expected in a nonlinear dynamical system whose major characteristic is self-organization among its individual components (eg. Haken, 1983; Nicholis & Prigogine, 1977; Prigogine & Stengers, 1984). A remarkable feature of self-organization is the formation of 'attractors' which are preferred states of the system as it is influenced or imposed upon by outside variables called 'control parameters'. A possibility along these lines is that the visual system is sensitive to only a few of the many possible interactions between τ_{obj} and τ_{bg} and the pattern of curves relating τ_R and t_c would look much different. The mathematical modeling for these effects would require a different approach, perhaps similar to the nonlinear dynamical modeling used in describing other perceptual and motor behavior (eg. Haken, 1989; Haken, Kelso & Bunz, 1985; Kelso, Buchanan & Wallace, 1991). In the meantime, experimental investigations are needed to verify or refute the predictions generated by the present theoretical approach.

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Figure Captions

Figure 1. Relationship between optical and environmental variables. Dilation tau is defined as r/r' and is equal to t_c when the object approaches directly at constant velocity.

Figure 2. Underlying geometry for spherical tau. Spherical tau is defined as 2A(t)/A'(t) and is equal to t_c under conditions of constant velocity and direct approach.

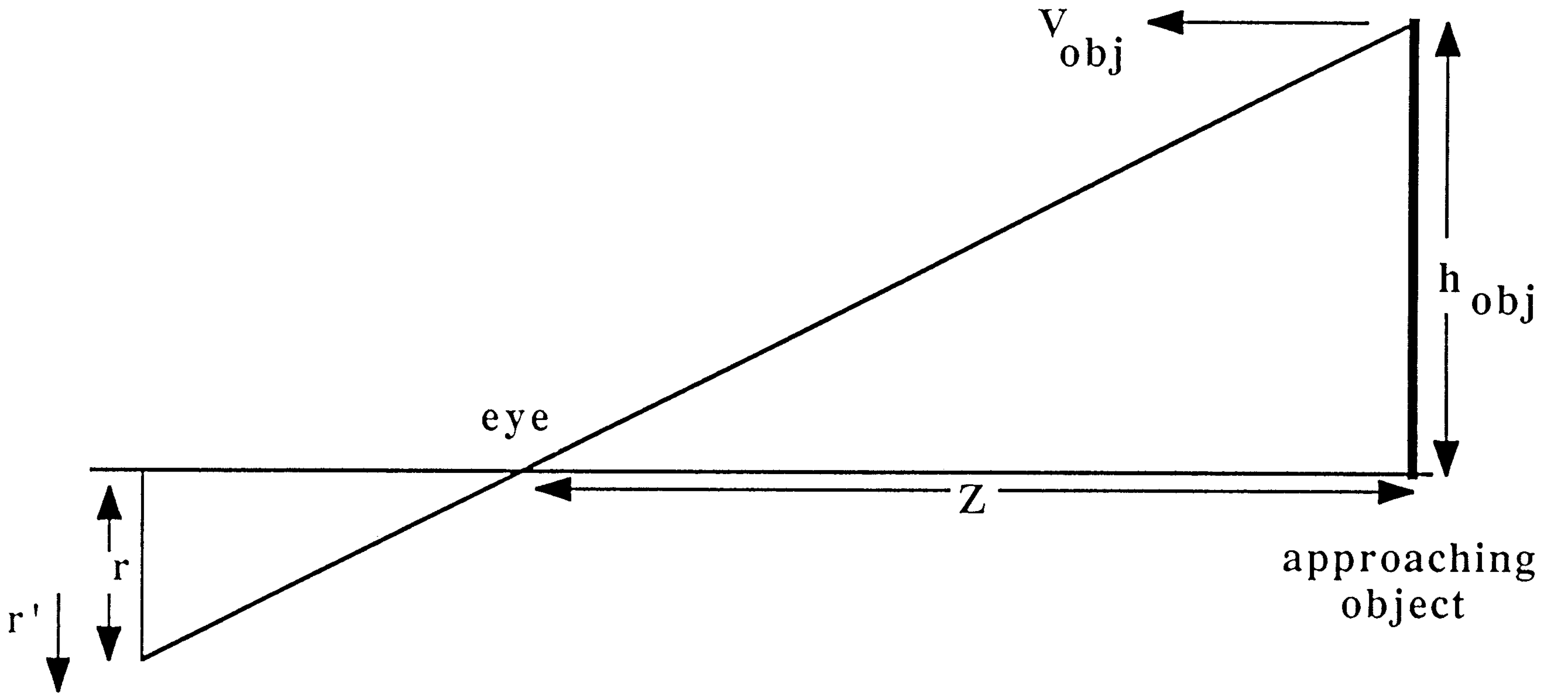
Figure 3. Closed contours on the retina corresponding to the approaching object and an adjacent, surrounding background patch. This figure represents the contours as concentric circles but any closed contours can occur provided that the contour corresponding to the background patch completely surrounds that corresponding to the object.

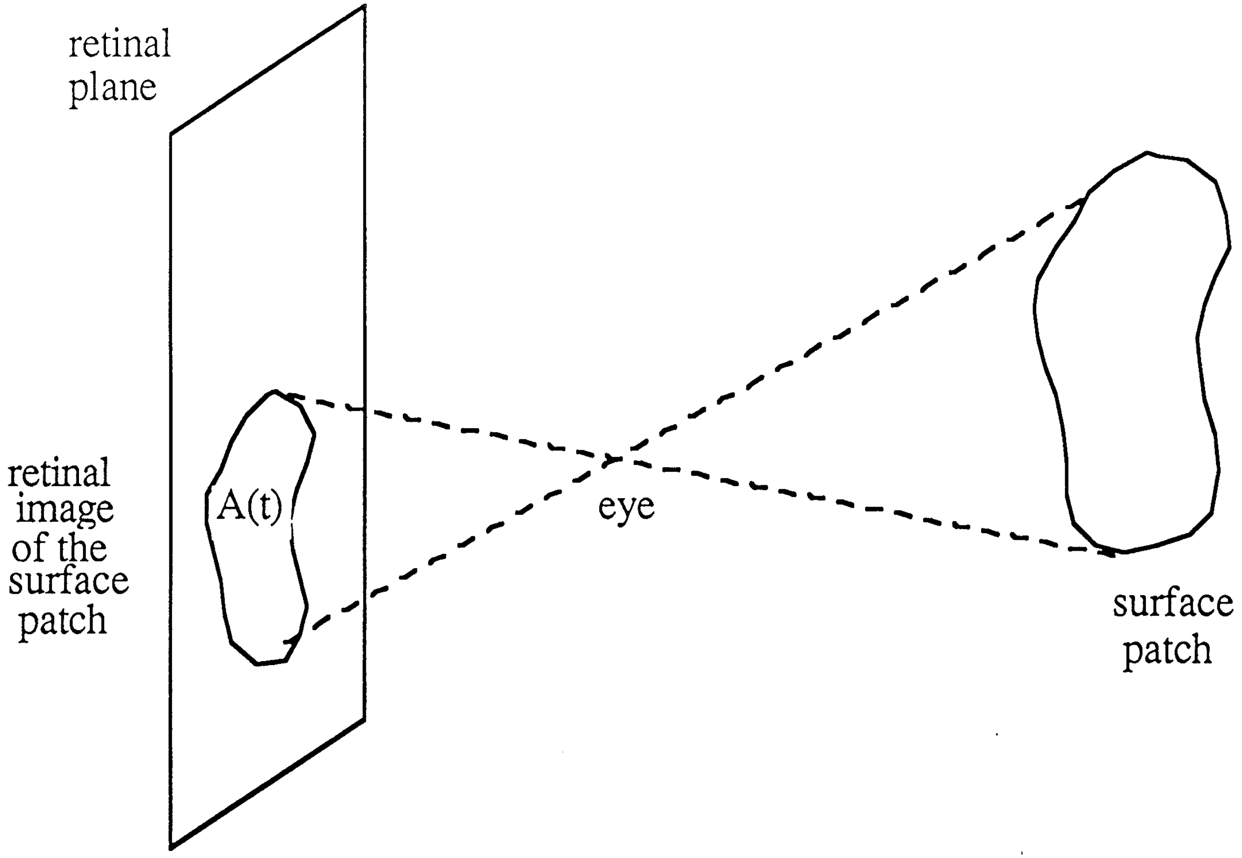
Figure 4. Relative tau (τ_R) as a function of t_c. Each of the δ curves pictured corresponds to a different separation (δ) of the times to contact of the object and surrounding, adjacent background patch. The straight line ($\tau_R = t_c$) corresponds to the case of a stationary background patch, which represents Lee's absolute τ. The δ curves for $\delta > 0$ correspond to a forward moving background patch (towards the observer) and provide overestimates of t_c ($\tau_R > t_c$). The δ curves for $\delta < 0$ correspond to a backward moving background patch (away from the observer) and provide underestimates of t_c ($\tau_R < t_c$).

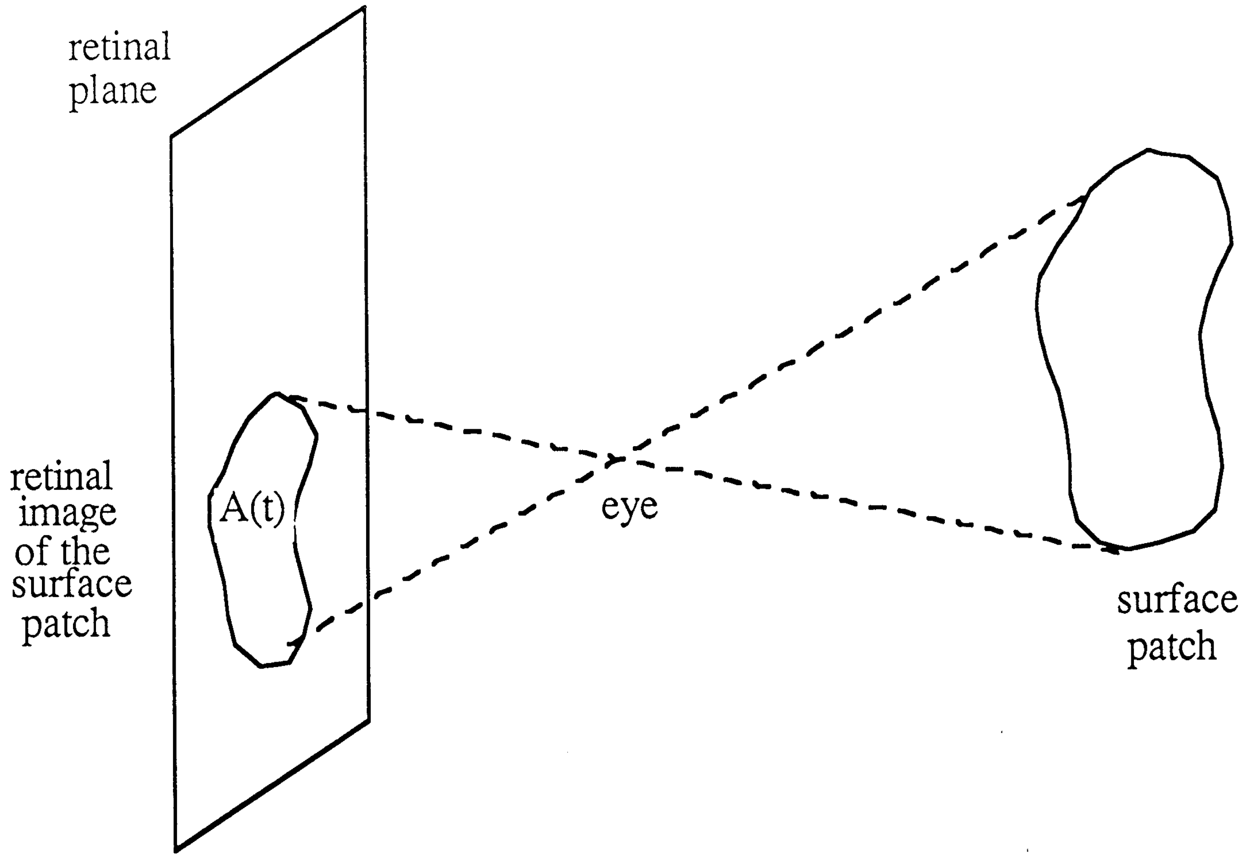
Figure 5. Error introduced by taking τ_R as a measure of t_c under conditions of constant velocity and direct approach. The two sides of each graph correspond to two different objects, A and B, that simultaneously begin to move toward a stationary observer. Object A, on the left side of each graph, represents an object that moves with no noticeable environmental effects, as predicted by Lee's t model. Object B, on the right side of each graph, represents an object that moves together with a background patch such that the separation in times to contact is δ (given at the top of each graph). The top line of each graph represents the starting distance of the two objects. Each successive line represents a comparison of the predicted distance to contact of the objects A and B. The number to the left of the top line in each graph is the actual value of t_c if the object is assumed to approach at 1 m/s, while the number to the right is the predicted value of t_c using τ_R. Graphs (a) -

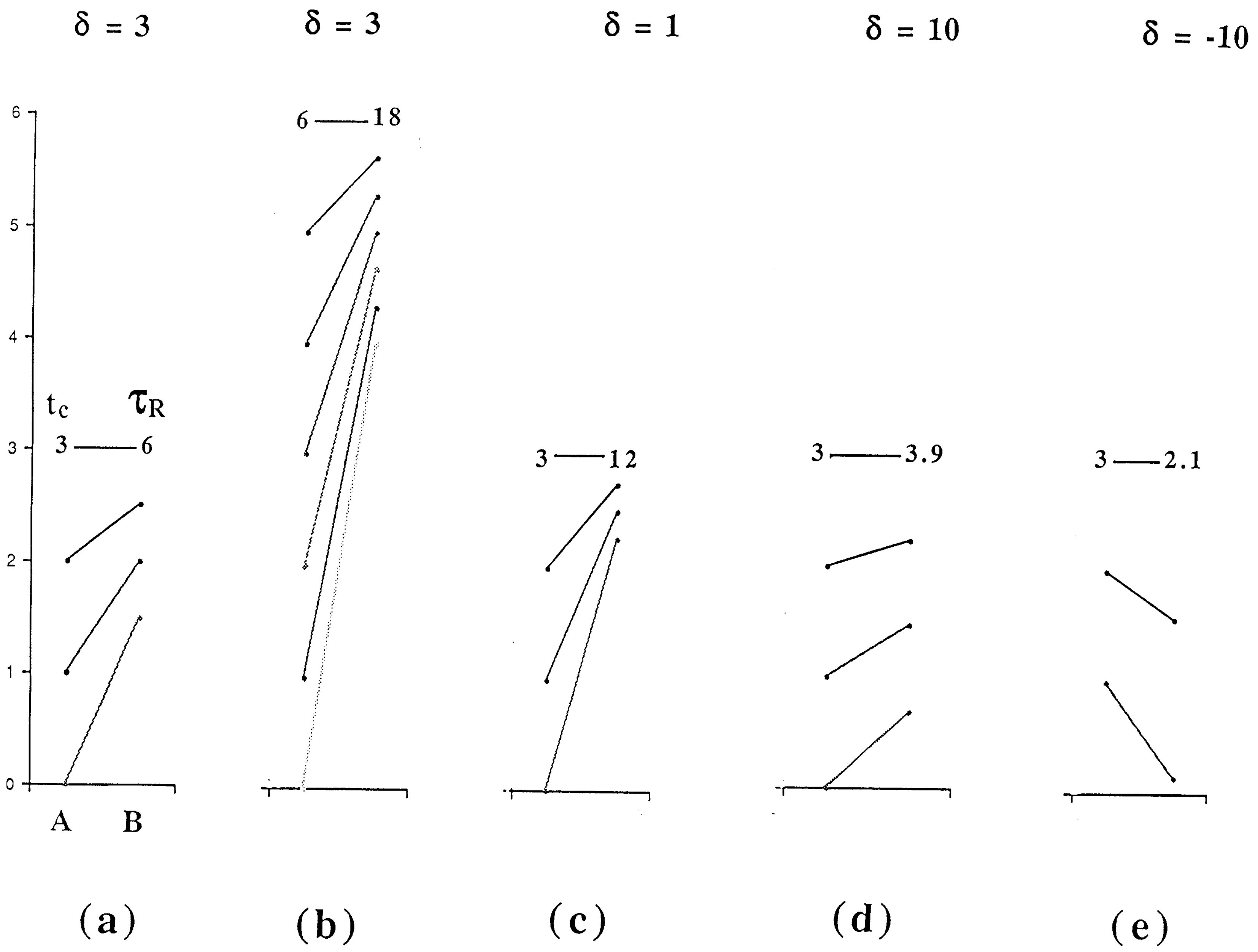
(d) represent a forward moving background patch, which graph (e) represents a backward moving background patch.

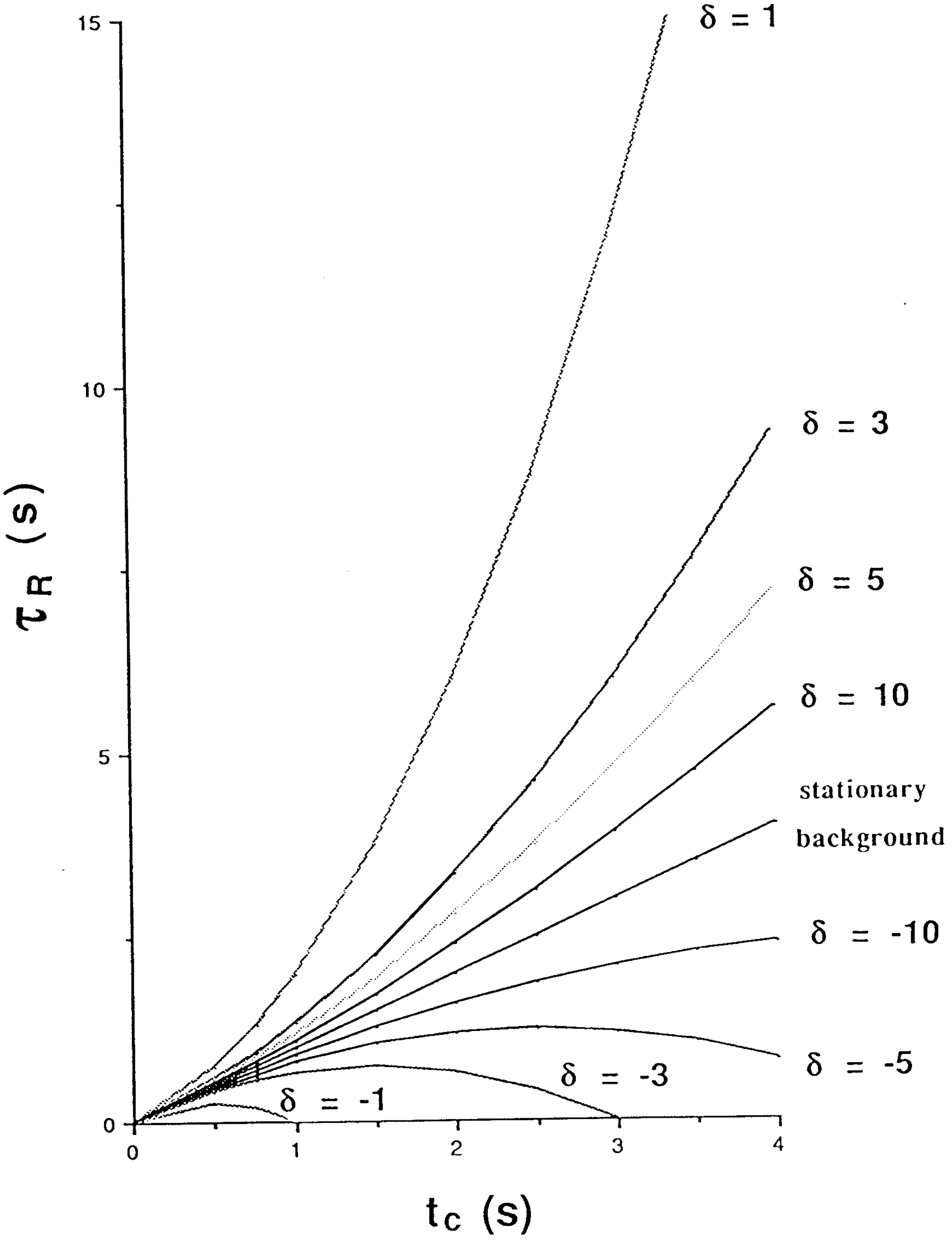
Figure 6. Geometry of occlusion of the background patch by the approaching object. V_{obj} denotes the velocity of the approaching object and V_{bg} is the velocity of the background patch which can be either positive (+) or negative (-). h_{obj} denotes the environmental height of the object and h_{bg} and is the height of the background patch. D represents the physical distance between the object and background patch at occlusion, while Z is the distance of the object from the observer at occlusion. r denotes the retinal height of both the object and background patch at occlusion.


V_{obj}
h_{obj}
eye
Z
approaching
object
r
r'

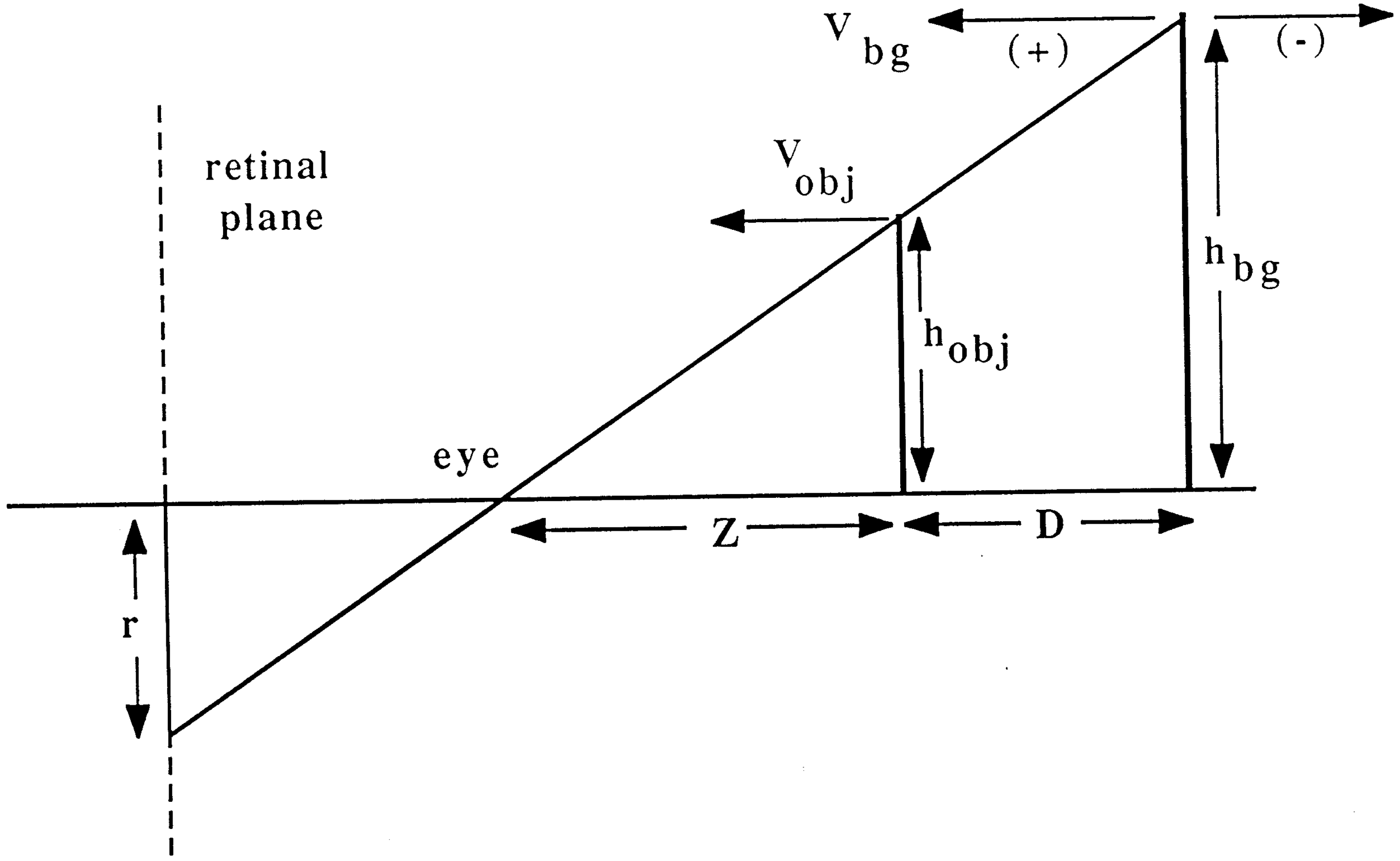

retinal
plane
retinal
image
of the
surface
patch
A(t)
eye
surface
patch


retinal plane
retinal image of the surface patch
A(t)
eye
surface patch


δ = 3
δ = 3
δ = 1
δ = 10
δ = -10
6
5
4
3
2
1
0
t_c
τ_R
3 —— 6
6 —— 18
3 —— 12
3 —— 3.9
3 —— 2.1
A
B
(a)
(b)
(c)
(d)
(e)



δ = 1
δ = 3
δ = 5
δ = 10
stationary background
δ = -10
δ = -5
δ = -3
δ = -1
15
10
5
0
0
1
2
3
4
τR (s)
tc (s)


V_{bg}
(+)
(-)
V_{obj}
retinal plane
h_{bg}
h_{obj}
eye
Z
D
r