

**INVESTIGATION OF THE VISUO-MOTOR TIMING
MECHANISMS EMPLOYED IN INTERCEPTIVE
PREHENSION MOVEMENTS**

by

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Abstract

The question of how the human visual system processes information from moving objects, making possible precise eye-to-limb coordination, has long been one which has perplexed scientists (e.g., Gibson, 1950; Regan, Beverley, & Cynader, 1979). Numerous studies (e.g., Lee & Reddish, 1981; Wagner, 1982) have indicated that across changes in the approach velocity of objects or surfaces, the initiation of interceptive movements or coincidence timing skills seems to be most consistently geared to the remaining time-to-contact (t_c). It is how one perceives this t_c information however is where question arises. One body of theorists believing that t_c estimation is obtained from cognitive computation, the other suggests that its estimation is a direct process arising from interpretation of an optical image displayed on the retina. This has led to the emergence of two differing perspectives about the specific visual information used in the perception of, and in the regulation of action towards moving objects. The primary objective of this study was to determine exactly what perceptual information sources may be used to initiate and regulate coincidence timing tasks. Specifically, whether t_c estimation is obtained through direct processes via the optic variable tau or from independently obtained distance and velocity information. Additionally, the effect of task constraints upon the control strategy adopted were investigated. Two experiments were conducted. The first experiment was to determine both the effect of varying the object approach velocity and the influence of constraining the task by predefining the point at which the object must be intercepted. The second to examine the effects of constraining viewing time, thus limiting the amount of optical expansion. Experiment 1 yielded little evidence to support the use of a constant tau strategy, although selected movement kinematics did provide some indication that optical expansion information was the perceptual source of information best utilized by subjects. Experiment 2 produced support for the use of a constant tau strategy, but only in conditions of severe task constraint such as that provided by a diminished viewing period and relatively fast object approach velocity. Movement kinematics provided inconclusive evidence as to the type of perceptual information utilized by subjects.

"Perception and action are interwoven and we are likely to
lose perspective if we attend to one and neglect the other;
for it is in the manner of this union that properties of each are
rationalized. After all, there would be no point in perceiving
if one could not act, and one could hardly act if one could not
perceive".

Turvey, (1977), p. 211

To my parents Angela and David,

Thanks for everything.

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Chapter 1

Introduction

It is now well established that all organisms whether bacteria, oak trees or whales, must adapt to their environments if they are to survive and reproduce (Bruce & Green, 1985). Indeed the behaviour of living organisms is continually altered throughout life, so as to "fine tune" them to their environments. One of the ways this is achieved is through the movement of the body and limbs by contraction of the muscles. This however, necessitates regulation or guidance in accordance with one's environment.

In order for movement to be regulated (by the environment) and for organisms to successfully interact within the environment, an animal must be able to detect both structures and events in its surround. This ability of extraneous stimulus detection has been widely termed perception. Indeed, it has been argued (e.g., Chennakesaven & Pampapath, 1964) that the ultimate goal of perception may be to achieve clarity of the percept stimulus, with stimuli taking on new and improved meanings as they become repeatedly accepted.

The most commonplace successes of an animal in behaving and in consistently producing coordinated, goal directed movements gives witness to the vastness and accuracy of its perception of the environment. For example, a visually unimpaired human negotiating a busy street performs an impressive feat of visual judgement, not only in walking, (usually) without stumbling, but also in the avoidance of approaching vehicles, pedestrians, and the like. Other equally impressive, but no less complex tasks, include the ability to accurately intercept and grasp both moving and stationary objects, and the uncanny ability to recognize a friend, or well-known

face, even after decades of change (Michaels & Carello, 1981; Regan, Beverley, & Cynader, 1979).

From the above examples it may be seen that the control of actions in the environment clearly requires multifarious perceptual information about the complex, and dynamic (spatial and temporal) relationship of the organism to its environment. Indeed it is not a simple problem to determine how physical stimulus energies (e.g., light, sound, mechanical pressure) reach our sense organs and are somehow transduced into neural impulses to provide our brain with encoded information about the world and our relation to, and within it. As such, many aspects of how we extract, interact and exploit information from the environment still remains, largely unanswered.

Of the five perceptual systems traditionally attributed to humans and other higher order animals, it is vision and its concordance with movement and limb orientation which is considered to be of primary importance in the utilization of information and subsequent guidance of movement. The primary importance of vision is further exemplified by a number of studies on vision and its role, in particular to posture and the stability, which is in essence the antithesis of movement, (e.g., Lee & Aronson, 1974; Lee, Lishman, & Thomson, 1982).

One of the most cited of these works has been that conducted by Lee and Aronson (1974) in their study involving a "moving room". Essentially the study involved moving the (suspended) walls of an artificially constructed room without any corresponding movement of the floor. In adult subjects, postural sway was observed in phase with the direction of the wall movement, which in infants, led them to fall or stumble. These findings indicate the overriding importance of vision in the maintenance of balance. Perturbations to the visual information resulted in subjects apparently ignoring all other proprioceptive information, and correcting their posture in relation to the visual information source only.

In the pursuit of a greater understanding of the human visual system and its interaction with the movement process, two major paradigms encapsulating differing perspectives have emerged. Traditionally, the theory of information processing, developed initially from Structuralism of the late nineteenth century, asserted that perception was achieved by summing individual meaningless sensations. These theorists conceived perception as being mediated, hence the terminology, indirect (e.g., Helmholtz "the unconscious interference"), and until recently enjoyed almost unanimous support among contemporary psychologists (e.g., Forgas & Melamed, 1976; Koffka, 1935; Lindsay & Norman, 1977). These theorists have implied the intervention of memories and representations (to the visual image) due to the senses being provided with an impoverished insufficient input. This view can be well encapsulated in a quote by Neisser (1967).

"These patterns of light at the retina are... one sided in their perspective, shifting radically several times each second, unique and novel at every moment. [They] bear little resemblance to either the real object that gave rise to them or to the object of experience that the perceiver will construct.... Visual cognition, then deals with the processes by which a perceived, remembered, and thought-about world is brought into being from as unpromising a beginning as the retinal patterns".

Neisser, (1967, p.7-8)

Conversely, an opposing body of theorizing exists, stemming essentially from the postulations of Gibson (1966), who proposed vision as producing a far richer source of information than is implicitly implied by simple passive observation. These theorists (e.g., Lee 1976, 1980a; Michaels & Carello, 1981; Turvey, 1977),

have proposed a functional approach to sensory perceptual sensitivity, stressing the dimensions of sensitivity, with perception being seen more as a process in an animal-environment system.

Of the major proponents of this direct perception, or ecological theory of motor control, David Lee has provided an insightful enhancement to the way in which we view our surrounding environment, in regard to both object, and observer movement. In 1976, he first proposed a mathematically based theory of how an expanding optical image on the retina of an observer could accurately predict the time-to-contact of an approaching object with the observer. Through the usage of this retinal image it was proposed that an organism could accurately initiate and regulate actions without regard to any specific cognitive processes. Numerous studies, both by Lee and others, in activities as varied as braking in driving (Lee, 1976), long jumping (Lee, Lishman, & Thomson, 1982), and ball catching and hitting in humans (Hubbard & Seng, 1954; Savelsbergh, Whiting, & Bootsma, 1991), to wing folding in diving birds (Lee & Reddish, 1981) and leg projection in landing flies (Wagner, 1982) substantiate these claims. Exact visual sources of information have not however been identified, with timing components of movement initiation being primarily investigated. This has led to the concept of time-to-contact as an important variable. Time-to-contact is defined as the ratio of the distance-to-contact to the object velocity at any instant in time. However, no unequivocal evidence has emerged as to whether time-to-contact is empirically derived, or obtained directly from optical expansion information, as initially postulated by Lee (1976). The present study attempted to address some of these problems, in the hope of elucidating both some of the mechanisms of visual control employed in interactive actions and how our interaction with the environment is affected by the presence of various constraints.

Chapter 2

Review of Literature

An introduction

Much progress has been made in our understanding of the nature of perception since the theorizing of the early philosophers and scientists. Between the sixteenth century and the early part of the present century some individuals conceived perception as activistic, while others conceived it as wholly determined by learning. The former group usually stated that the entire stimulus pattern was capable of being perceived at birth, while the latter believed that it had to be built up gradually through experience.

As well as defining the nature of the input for vision, a theory of perception must also make inferences as to how it is that the structured light reaching a perceiver gives rise to perceptual experience and subsequently to visually guided action (Bruce & Green, 1985). The hypothesized mechanisms provided by traditional theories contrast sharply with those of more recent theories. The roots of these differences are found in the history of James J. Gibson and his theory of direct perception. This has led to the emergence of two quite different perspectives with regard to the specific visual information used in the perception and regulation of action towards moving objects. One of the more pertinent of these questions is how we perceive, monitor, and react to impending collision of an approaching object or environment. Consideration of these factors leads us to a discussion of time-to-contact information.

Evidence of utilization of time-to-contact information

Numerous studies (e.g., Lee & Reddish, 1981; Wagner, 1982) have indicated that across changes in the approach velocity of objects or surfaces, the initiation of interceptive movements or coincidence timing skills seems to be most consistently geared to the remaining time-to-contact (t_c), rather than to any other potential source of optical information, such as the reaching of some critical distance or velocity. These studies propose that actions are initiated when the projected t_c with the surface (or object) reaches a specific fixed value. The gearing of action to t_c theoretically allows precise coincidence timing to be achieved across a wide range of approach velocities without the necessity to adjust the duration of movement(s).

It is the derivation of this t_c information however, where question of interpretation arises. One body of theorists believe that t_c estimation is obtained from cognitive computation, the other suggest that its estimation is a direct process arising from interpretation of an optical image displayed on the retina.

Probably the most cited example lending support to the notion of actions being initiated at some constant t_c value, regardless of approach velocity, is that provided by Lee and Reddish (1981) in their diving gannets study. The researchers observed gannets plummeting into the sea, and through cine-film analyses determined the moment at which the folding of the birds wings commenced. It was found that, when taking velocity into account (and allowing for slight variations in acceleration), the time at which wing folding commenced occurred at a constant time prior to contact with the water.

This now classic finding was essentially replicated one year later by Wagner in an examination of the commencement of deceleration coupled with the extension of the legs in preparation for landing in houseflies. The findings of these much cited natural studies¹, were again more recently reproduced, using similar, though more advanced

techniques, by Lee, Reddish and Rand (1992) in examination of ariel docking by hummingbirds.

These researchers noted that hummingbirds were able to, in one tenth of a second, accelerate, then brake to gently dock on a flower with pinpoint accuracy. Whilst seeming to require rapid calculation of distance, velocity and acceleration information, Lee and his colleagues, through high speed (300 fps) film analysis noted that the control of braking was consistent with keeping the rate of change (constant optical image expansion) of the retinal image constant, a derivative Lee termed tau dot. The researchers subsequently proposed that the control of deceleration was via this optical image, rather than through any cognitive computation of displacement changes, or derivatives thereof, rendering the necessity for information about distance, speed and deceleration unnecessary (Cavello & Laurent 1988; Schiff & Detwiler, 1979). These findings led the researchers to propose that the usage of tau dot provided a more evolutionary sound method of time-to-contact estimation. That is, less variables are required for its usage, and the specific value is independent of the magnitude and type of input (for example acoustic input variables whose tau functions may be used by echo-locating bats).

The initiation of movement, and invariant movement times corresponding to a fixed t_c value have also been demonstrated in numerous human activities. The most favoured for study have been catching and hitting tasks or movements pertaining to walking, running and jumping activities. While not examining time-to-contact per se, Hubbard and Seng (1954) produced one of the first of these studies in their reporting of the timing of the swing phase of baseball batting. They found that variations in ball velocity were compensated for by alteration of leg swing and stance, rather than the changing swing time of the bat. Similar findings were also reported by Tyldesley and Whiting (1975) and Bootsma and van Wieringen (1988) in table tennis, and Franks, Weiker and Robertson (1985) in field hockey, all of which involved the striking of a

moving ball, and in which invariant movement times were observed. Additionally, a series of studies by Savelsbergh and Whiting (1988), Savelsbergh, Whiting, and Bootsma (1991), Savelsbergh, Whiting, Burden, and Bartlett (1992) and Savelsbergh, Whiting, and Pijpers (1992) have indicated that t_c information is used both in the initiation of movement and in the initiation of the grasping action in various ball catching activities.

In Savelsbergh et al.'s (1991, 1993) innovative studies, the researchers cleverly manipulated the approaching object (luminescent ball) characteristics, by controlling the deflation of the ball during its approach, thus manipulating the amount of optical expansion perceived from the contour of the ball, and decoupling this information with information regarding instantaneous position and velocity. As control conditions, a ball of constant size, equal to the size of the 'deflated' ball at the start of its trajectory, and a ball of constant size, equal to the size of the 'deflated' ball at the end of its trajectory, were used. It was observed that subjects adjusted their grasping action to the deflating ball, initiating the closing action of their catching hand later in the deflating, than the control ball condition, whilst maintaining fairly consistent movement times (Savelsbergh et al., 1993). This follows the prediction made if they were able to use t_c information (pertained via optical expansion information), as the deflating condition would specify a longer t_c time. The researchers additionally proposed that these findings lend significant support to a finely tuned perception-action coupling, as subjects in all cases were unaware of the ball deflating during its approach, as determined from verbal questioning post hoc.

Previous research efforts have also concentrated on the timing components of walking, running and jumping, stemming again primarily from a study by Lee and his colleagues (Lee et al., 1982). These researchers demonstrated that the flight times of the final few (three) strides of female long jumpers were directly modulated in response to t_c with the take-off board, with a greatly increased variability being observed in these

final stages. This study was again replicated in 1988 by Hay, using fourteen elite male and fourteen elite female athletes, who again found evidence for visually-based adjustments in accordance with the t_c in the final preparatory stages prior to the execution of the jumping action. In concordance with the above two studies, Meeusven and Magill (1987) observed similar findings in the variability of foot placement in the final two strides for female gymnasts approaching a vaulting horse. They also proposed that the control of stride length and foot placement were modulated in accordance with t_c information (via adjusting vertical force impulse).

Similar conclusions have also been drawn by other researchers, though in notably different activities. Both Lee and Young (1985) and von Hofsten and Lee (1982) have found that the leg extension phase of the jumping action found in the take-off of ski-jumpers is geared to a constant t_c parameter, with the point of collision or contact being the lip of the ski jump. Moreover, Laurent, Dinh, Phung, and Ripoll (1989) in a study of gait regulation in horse jumping demonstrated that the gait of horses approaching a jump is adjusted so that the take-off position occurs at a constant t_c value.

Others have taken a rather different tact in their examination of t_c estimation as a possible indicator or mechanism for movement initiation (e.g., Dietz & Noth, 1978; Liebermann, 1988; Savelsbergh, Whiting, Burden, & Bartlett, 1992; Sidaway, McNitt, & Davis, 1989). These researchers have examined the onset of muscle activity (through EMG activity recording) in a number of different activities. Dietz and Noth (1978) in a study in which human subjects were required to fall forward, from a vertical starting position, through a range of 50 - 80 degrees, to a padded platform braking their fall with their hands, observed that the onset of EMG activation (in the triceps brancii) always occurred at a constant t_c value. Moreover, this coupling of EMG activity to t_c disappeared when subjects were blindfolded, highlighting the importance of vision to this process. Sidaway et al. (1989) and Liebermann (1988) examined a whole body free-fall, with EMG measures being taken from the rectus

femoris and gastrocnemius muscles respectively. Sidaway and colleagues had subjects step off three different height platforms (72, 104, 159 cm) onto a force plate that acted as a landing surface, whilst Liebermann had subjects suspended from an overhead bar, releasing their grip to freefall, again to a force platform, from heights of 5, 20, 60, and 90 cm. In both cases the findings produced by Dietz and Noth were generally replicated, in that a coupling was found between EMG onset and t_c in full vision conditions.

A discrepancy however was also observed between the data of Liebermann (1988) and Dietz and Noth (1978). In Liebermann's study results from both vision and no-vision conditions were found to be quite similar. This is in direct contrast to the data found by Dietz and Noth, who observed quite substantial differences between comparable sets of data. Liebermann concluded that while a cognitive based computational strategy seemed not to be used, the adoption of a landing strategy based solely on time-to-contact obtained through tau appears unlikely. Indeed, Sidaway's conclusion that "the evidence contradicts the hypotheses that subjects could compute t_c , and therefore, initiate preactivity of some constant t_c for all heights" (Sidaway et al., 1989, p.260), was also supported by Liebermann.

In a slightly different vein, Savelsbergh et al. (1992) examined the preactivation of muscles used in the grasping (catching) of an approaching ball, projected from a ball machine at speeds of 11.9, 13.9 and 16.2 m/s. Tau-margins (t_c) were calculated at the time of the initiation of the grasp movement for each subject at each speed. Muscle activation onset was found to be independent of ball speed, again lending support to the contention that movement initiation was controlled by the optical variable tau, rather than by some distance or velocity computation.

The emergence of two contrasting theories

Over the past two decades there has been considerable interest in exactly what perceptual (visual) information enables such veridical estimation of time-to-contact (e.g., Bootsma, 1988; Rosengren, Pick, & von Hofsten, 1988; Sharp & Whiting, 1974; Tresilian, 1991; Whiting, 1986), with its importance as a control variable being argued cogently by Lee (1976, 1980a) and others (e.g., Turvey & Carello, 1986). In theory there are at least two distinct ways in which time-to-contact may be obtained; derivatively from low order information, known as the cognitive method, or directly from the changing optic array, often termed the ecological approach (McLeod & Ross, 1983).

These two major theoretical positions differ in their conception of the organization of the visual system and how it functions. What follows is a brief synopsis of the two viewpoints, and some of the major work in the area. More detailed accounts of the cognitive perspective can be found in the works of Marr (1982), Ullman (1980), and Fodor and Pylyshyn (1981). For reviews and views of perception from a direct viewpoint see Gibson (1979), Michaels and Carello (1981), Turvey (1977), and Turvey, Shaw, Reed and Mace (1981).

Cognitive theories of perception

Traditional theories of visual perception have evolved around the notion of some higher executive detecting and cognitively processing input information in rather the same vein as much of the work pertaining to an information processing approach to human behaviour. These imply that the information perceived from the external environment is, in some way impoverished requiring enhancement in order to produce an accurate representation of the outside world.

This view has stemmed from the physical observation that retinal anatomy, made up of various photoreceptors, cannot represent the world in an accurate manner, as their

mapping onto optic nerve fibres is not a simple one-to-one ratio. Direct detail needed to specify objects in the visual field is therefore believed to be lacking, requiring cognitive reconstruction to provide meaningfulness and usefulness and to be able to invoke appropriate action or response. In order for this reconstruction some comparative process is believed to occur invoking the need for some central representation, an essential feature of an indirect theory of perception.

Due to its very nature and underlying assumptions, cognitive or indirect perceptionists tend to focus their research orientation towards the computation stages of perception, an issue which has become a central point of contention. This is especially true with regard to coincidence timing interceptive skills. The most heavily stressed of these points and one which opponents of a cognitive based theory propose its dismissal, remains that of the computational complexity and timing associated with both normal vision and time limited accounts of human behaviour. Most recent advocates of the cognitive approach to visual perception have proposed more general algorithms to approximate the computational power of the human visual system. Regardless, there remains a great deal of contention over the suitability of these theories to human visual perception. As regards the timing of interceptive actions, two major paradigms have emerged from this cognitive theory as being the most dominant; that of distance-velocity computation, and that of distance-change computation. Both of these are briefly outlined below.

(i) The distance-velocity paradigm

It has been proposed that an observer can obtain time-to-contact information from perceived distance and velocity information (Tresilian, 1991). This cognitive method can be best described as, if at some instant of time the distance of the moving object from the interception point (a point on the future path of the object) is d and the relative

speed of the object at the interception point is v (which will be considered to be constant), then the t_c at this instant of time may be given by

$$t_c = \frac{\text{observer to object distance}}{\text{object approach velocity}}$$

or, more simply,

$$t_c = d/v.$$

The assumption is made that velocity information is obtained via some sort of distance/time computation.

Vision researchers have also investigated the psychophysics of distance estimation (Ross, 1967; Ross, Dickenson, & Jupp, 1970; Teghtsoonian & Teghtsoonian, 1969, 1970), and time and velocity estimation (Evens, 1970a, 1970b; Ross & Rejman, 1972). Results indicated that humans appear capable of estimating these low-order parameters for the derivation of t_c . However, what needs to be specified precisely is what perceptual information about real-world distances and velocities might be used to compute t_c (Tresilian, 1990). Indeed, there seems to be evidence that t_c can be calculated when no absolute distance and velocity information is available (Schiff & Detwiler, 1979; Todd, 1981). This is based on experimentation on monocular vision or in computer video 'ball' games, which are presumably two-dimensional. Nevertheless, this does not rule out the use of distance and velocity information when it is available, nor does it exclude the possibility that circumstances dictate whether this or other strategies are used in the determination of t_c (Schiff & Oldak, 1990).

(ii) The distance-change paradigm

A slightly modified version of the distance-velocity theory was proposed by Cavello and Laurent (1988). Here reliance is placed upon distance change information, as opposed to distance and velocity information. This is expressed as

$$t_c = \frac{d_1}{(d_1-d_2)/(t_1-t_2)}$$

where d_1 and d_2 are the distances between the observer and the object at times t_1 and t_2 respectively. Note that (d_1-d_2) represents the distance change relative to the observation interval (t_1-t_2) . This is in contrast to the distance and velocity strategy which uses distance from the object to the perceiver.

Ecological theories of perception

In 1958, Gibson, dissatisfied with current theories of perception, proposed a drastically different theory which has come to be known as an ecological theory of perception. Noting that the light reflected by surfaces makes visual perception possible he suggested that this reflected light at a precise location of the environment forms what is termed a densely structured "optic array". Moreover, each observation point specifies a unique optic array (Gibson, 1958). Therefore, as an object moving at a constant speed approaches an observer, the image of the object coming towards the observer in the optic array dilates. Gibson also applied this conception of motion perception to the case of a moving observer, that is the perception and control of self-motion. This perception always has a subjective component as well as an objective component (i.e., it specifies the observer's position, movement, and direction as much as it specifies the location, slant, and shape of the surface, Gibson, Olum, & Rosenblatt, 1955). These conjectures of Gibson gave rise to the so called direct perceptionist view of perception. In contrast with a cognitive based theory no elaboration of the retinal image is required by the observer to accurately perceive and interact.

Gibson (1979) termed his theory a "direct perception" approach, based on the ontology of an intrinsic relationship between an individual (actor) and the environment. His genesis is the ambient optic array (previously termed the retinal image) that is

sampled by the observer, with the theory being based solely on the ecological approach to the problems of perception. The theory rejected the stimulus-response formula to perception, proposing that the world need not be internally represented because it is already presented in the structure of light, with geometric space being seen as "a pure abstraction". Gibson proposed that perception is a direct active process of picking up the properties, or affordances, of the environment, rather than a constructive process, thereby supposing that perception can give a lawful account of behaviour (Gibson, 1979).

Some advocates of an ecological (direct) theory have further suggested (e.g., Warren, 1988) that the laws of physics which underlie and describe motion of all types give rise to ecological optics (for the perception of motion), and these in turn give direct rise to its laws of control (specifying the observers/actors response). As with other ecological theories, these views deny the necessity of any memory system or cognitive representation of any type. Indeed it is this failure of recognition of any memory system with which opponents of direct theories of perception have cogently used in argument against the possible existence and utilization of direct perception.

As regards the perception of change or the perception of motion, ecological theorists have searched for invariants within the optic flow field which are able to specify directly those structural properties which remain constant and are characteristic of events under such conditions. This optical information has more recently been described as the relative rate of dilation of two or more discriminable areas, contours, or points on a surface of a directly approaching object by Schiff (1965) and Tresilian (1990). Modifications for objects approaching on a near miss path have been similarly specified geometrically by Young (1985). Alternate explanations of this phenomenon have been given in work by Lee (1976, 1980a, 1980b).

Direct perception and time-to-contact

Based on the above notion of ecological optics, Gibson (1966) proposed that t_c information is directly available through the changing optic array at the eye of an observer, with t_c being specified by the relative rate of expansion of the retinal image over time. This is given by

$$t_c = \frac{q_1}{(q_2 - q_1)/(t_2 - t_1)}$$

with q_1 and q_2 being the angular separation of any two points, (of an object), at times t_1 and t_2 respectively.

Lee (1976) developed the concept formally, in proposing a theory of the visual information used in the perception of t_c based on the earlier work of Hoyle (1961), Gibson, Olum, and Rosenblatt (1955), and Purdy (1958). In this theory, t_c is optically specified by a single optical variable, which Lee called tau (τ). Tau has been presented as a first order source of information that is able to directly specify t_c (Lee, 1976), unperturbed by eye movements or up and down head movements. That is, the value of the optic variable tau on the retina is independent of how the eye is moving (Lee 1976, et al., 1983). This theory is presented within the conceptual framework given by Gibson (1979) and thus has often been presented as the paradigm example of Gibson's "direct perception" (e.g., Michaels & Carello, 1981; Turvey & Kugler, 1984). The optical variable tau may be defined as the inverse of the relative rate of dilation of the image of the approaching object on the retina (see Figure 1). If P and Z are points on an object which is heading directly towards the eye, at a certain instant, P and Z are distance $Z(t)$ from the schematic eye and moving with velocity V in the direction shown. While P', the projected image of P is distance $r(t)$ from O the centre of the schematic retina, onto which Z is imaged. Because of P's motion P' is moving radially outward from O with velocity $v(t)$. From similar triangles $Z/R = 1/r$. Differentiating with respect to time $V/R = v/R^2$. Eliminating R: $Z/V = r/v = \tau$. Thus the time-to-

contact, if V remains constant, is specified by the optic variable τ . As v/r is the rate of dilation of the image on the retina, τ is simply the inverse of this rate and thus directly available.

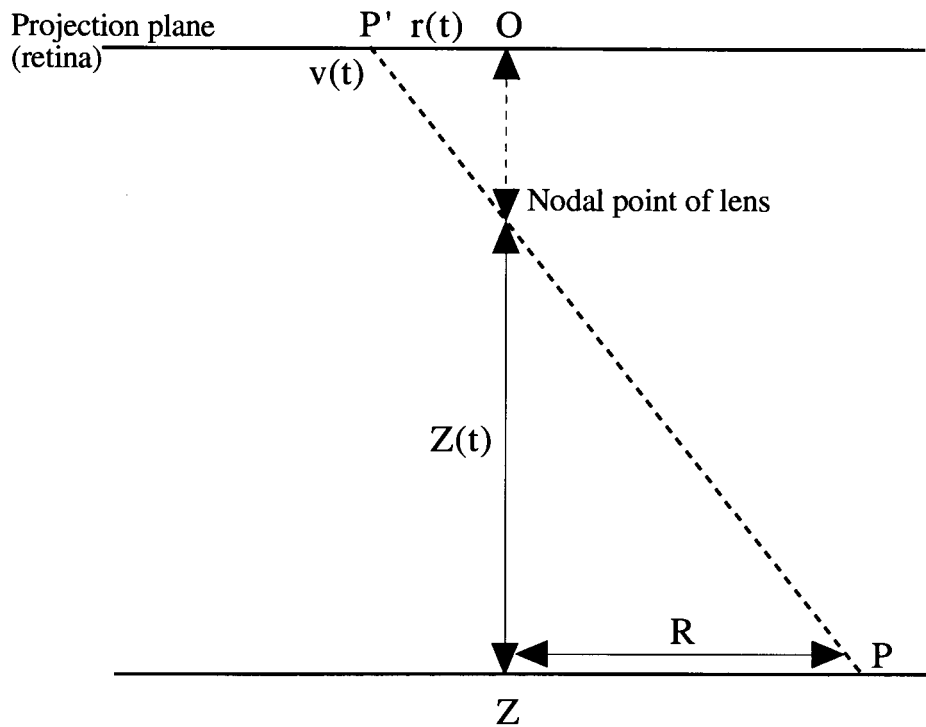


Figure 1. How time-to-contact is specified in the optic flow field. Light reflected from an object (P) passes through the nodal point of the lens and projects an expanding optic flow pattern onto the retina of the eye (P'), (adapted from Lee & Reddish, 1981).

The magnitude of the angle subtended by the object at the point of observation increases symmetrically when an object directly approaches an observer. Importantly this increase is not a linear function (see Figure 2), because the magnitude of the angle is inversely related to the distance from the point of observation. While the angle increases only slowly during the initial part of the approach, the latter part shows a sudden explosion in the expansion of the retinal image. This explosion has been termed "looming" (Schiff, 1965).

The visual stimulus for an individual in using τ to compute t_c is what Lee termed an 'optic flow field', a continuously changing optic array (Lee, 1976), with some properties of the optic flow field specifying aspects of the environment, and others which specify aspects of the observer's movement (Lee, 1974, 1976). An organism therefore does not need information about the position, orientation and movements of the body in absolute terms. Rather, it needs information about the changing environment-body relationships (Lee, 1976). The optic flow pattern was proposed as a means to access predictive information, enabling an individual to control their locomotion or movement through a cluttered environment, to avoid obstacles, and adopt action specifically attuned to the environment (Mestre, 1992).

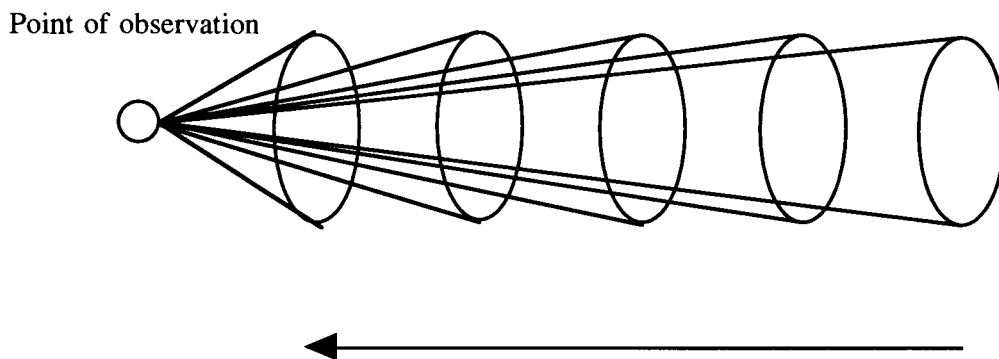


Figure 2. Geometrical representation of the non-linear increase in the angle subtended by an approaching ball at the point of observation, (adapted from Bootsma & Peper, 1992).

Lee (1976) proposed that the inverse of the dilation rate² ($1/\tau$) of an image will equate t_c , suggesting that its calculation results from automatic information-processing provided by radial expansion or dilation of the retinal image (which Lee, 1980a also termed the optic array). Thus, when an object approaches under constant velocity, specific information of distance and velocity are not required in order to compute t_c

(Lee, 1980b; Lee et al., 1983). In experimental studies using object simulation of two-dimensional images where no information about distance or velocity is available (e.g. Schiff & Detwiler, 1979; Todd, 1981), this has been shown to be the case. Time-to-contact could be estimated from the monocular two-dimensional information available, which was presumably the variable tau.

The theory of tau

Tau has been defined by Lee in three ways since its conception in 1976. Global tau³ $\tau_g(\tau)$ refers to the focus of expansion of a locomotor optic-velocity field (Lee, 1980b), occurring when an animal is moving through a rigid environment. A flow field containing a central focus of expansion is imaged onto the retina, corresponding to what Gibson called the 'optic-flow field' (Gibson, Olum, & Rosenblatt, 1955).

The second and third definitions of tau may be collectively termed local tau (τ_l) although they lend themselves to two separate instances. One refers to the relative rate of separation of two points on the image of a moving object (Lee, 1976), and the other refers to the rate of dilation of the image of a moving object or surface patch (Lee & Young, 1985). It is this local tau which is the quantity that is relevant to interceptive acts like catching and hitting in which the individual interacts with an object moving in relation to the environment. Note that it is this violation of the global-rigidity constraint of global tau that necessitated postulation of a local tau. For local tau to give t_c , the condition of constant velocity of approach and direct collision course with the observer must be met. However, it is possible that even if these conditions are not strictly met local tau may still play a useful role in interceptive timing (Tresilian, 1991).

(i) **Local tau and changing velocity**

Lee (1980b) proposed the notion that even in the presence of changing velocity or acceleration, tau could be used to time interceptive action with acceleration to be

registered implicitly and t_c to be derived from the optic variable τ and its time derivative $\dot{\tau}$ (Lee et al., 1983). This process was termed the 'tau-strategy' (Lee & Reddish, 1981; Lee et al., 1983), as this was the strategy which would be followed if an animal were to use τ to time interactions with moving objects. Stated formally,

"the tau-strategy hypothesis assumes that, in controlling the sequential timing of actions, so that the body is in the appropriate dynamic state at the moment of contact, the value of time of an action variable $D(t)$ will be geared to, and be a function of, $\tau(t-Dt)$, the latest available value of τ ."

Lee et al. (1983, p. 335)

This later became termed the tau-margin (Lee & Young, 1985), with the optic variable τ always specifying the tau-margin, only equalling the t_c if the speed of approach is constant. In accelerative conditions therefore τ will always be seen to overestimate t_c (Lee & Reddish, 1981; Lee et al., 1983; Lee & Young, 1988).

From experimentation Lee and Reddish (1981) and Lee et al., (1983) reported results which they concluded would be expected if actions were geared to τ (i.e., not what would be expected from a preprogrammed ballistic act simply triggered when a specific order parameter reached a certain value). The timing of actions became notably more precise as the moment of contact approached (i.e., < 300 ms), a phenomena which again would not be expected if a preprogrammed ballistic act were 'blindly' being carried out. For if subjects were simply performing some ballistic action, no "on-line" error corrections would be made, as was observed in Lee's studies. To examine what the consequences would be of following this tau-strategy in timing actions during a constant accelerative approach, (see also appendix A), as in

intercepting a falling ball or diving into water, [Figure 3 has been developed] (from Lee et al., 1983, p.335).

Lee (1983) further developed how τ varies with time-to-contact and how the relationship between τ and t_c depends upon the total dropping time. Note that functions for dropping time all lie above the straight line $\tau = t_c$; thus τ may be seen to always overestimate t_c in accelerative conditions. This is due to the fact that $\tau = (\text{current distance/current velocity}) = t_c$ in instances where velocity remains constant. As velocity is increasing, the actual t_c is shorter. The three curves all lie very close to the straight line $\tau = t_c$ for time-to-contact values of less than around 0.3 s. Thus, the closer t_c is, the more accurate the prediction of t_c given by τ becomes. Additionally, for any value of τ the corresponding value of t_c is greater the longer the dropping time, allowing greater margin for error (Lee et al., 1983).

From this work it was concluded that visually guided actions were geared to τ as opposed to their being geared specifically to t_c (Lee et al., 1983). This prompted the suggestion that the visual mechanism may not have evolved beyond the first order in that it has proved adequate to control the timing of action simply on the basis of the variable τ (Lee et al., 1983).

(ii) Tau and non-collision course trajectories

In addition to the assumption of constant velocity and object rigidity, tau also assumes a direct collision course between object and its point of observation (i.e., the eye). As Lee and Young (1985) recognize however, this condition is one which is rarely met in real world situations. In their brief discussion however, Lee and Young (1985) in a non-rigorous manner define tau (or tau-margin as they utilize it) to be the time to the nearest approach of the object to the point of observation, (given the relative velocity of the two objects remain constant). This is however a rather inaccurate description as is made evident by Tresilian (1991). As indicated in Figure 4 the

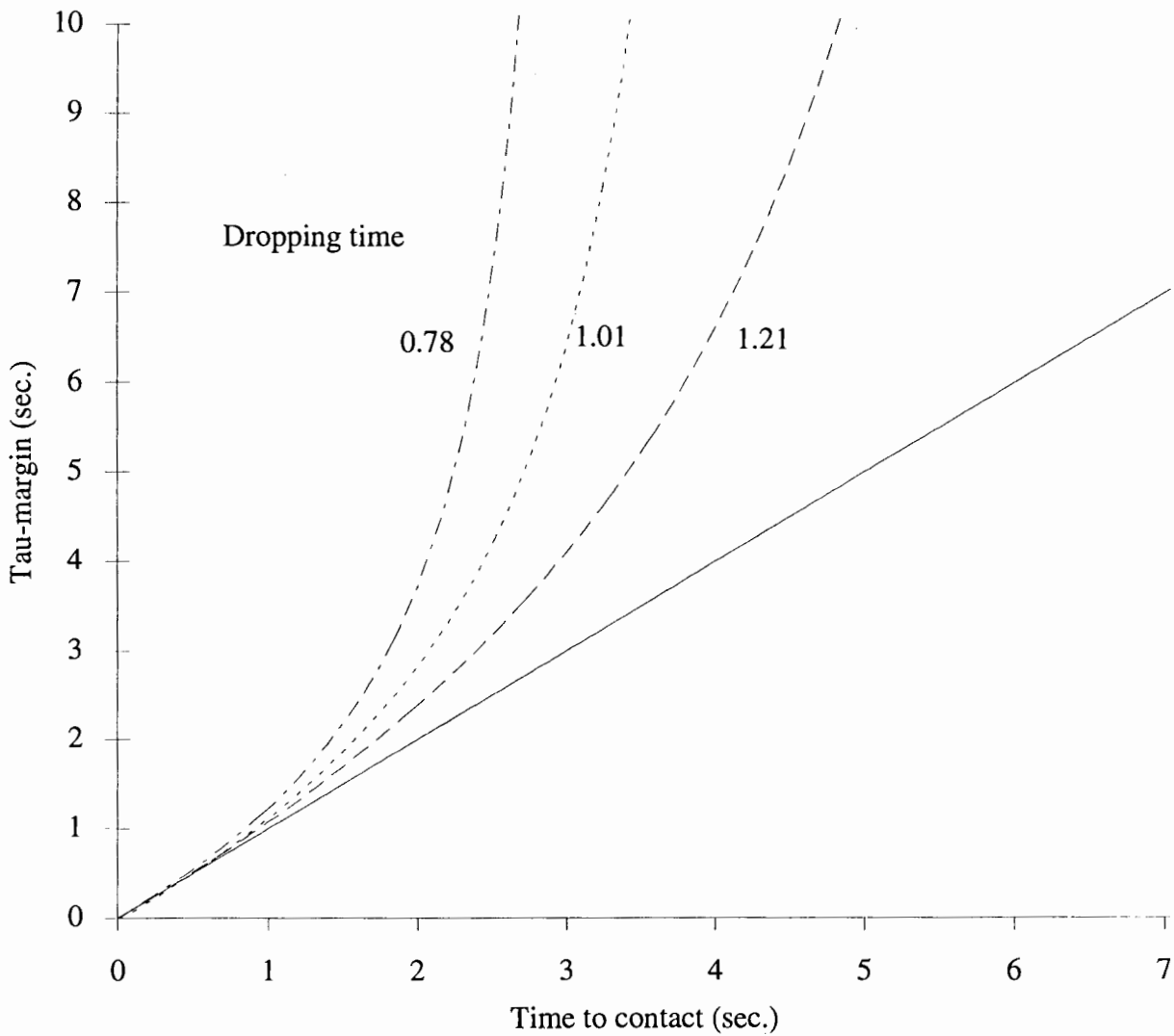


Figure 3. Showing how tau the optical variable specifying current distance away divided by current approach velocity, varies with time-to-contact, during accelerative approaches under gravity. The values of t_d for the curves are .78, 1.01, 1.21 s, which are the dropping times from the heights of 3, 5 and 7.2m used in the experiment. The straight line $\tau = t$, corresponds to constant velocity approach (adapted from Lee et al., 1983, p. 335).

relationship between tau (time-to-contact, τ_L) and the illustrated environmental quantities (initially derived by von Hofsten & Lee, 1982) is

$$\tau_L = T_N + S^2 / ZV$$

where T_N is the time to contact with the point of nearest approach, Z the distance from the object to its point of interception at movement initiation, V the object velocity, and S the displacement of the eye from the point of interception, given the observer wishes to intercept the object at point N .

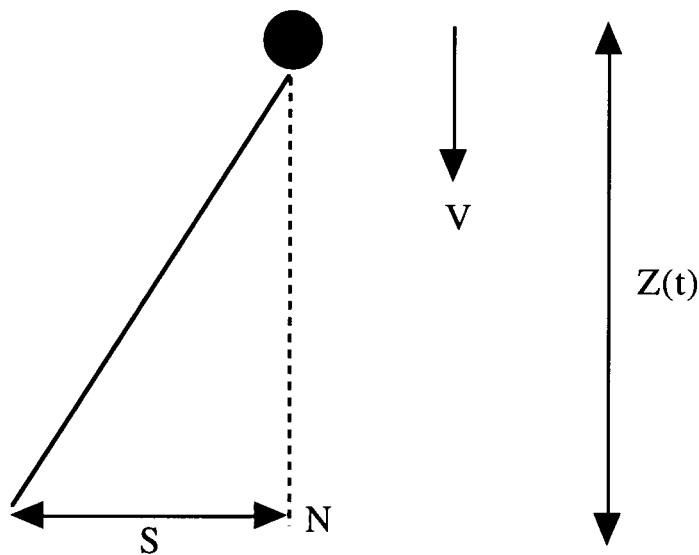


Figure 4. An object moving in the plane of the page is approaching an observation point o on a near miss path (dotted line), with constant velocity. The ball is instantaneously a distance $Z(t)$ from the point N , on its projected path nearest the point of observation. The time-to-contact of the ball with N is equal to $Z(t)/V$, (adapted from Tresilian, 1991).

The error introduced in using τ_L as an approximation of t_C is of magnitude S^2 / ZV . If S is small or V very large this error may be acceptable, if not, the error may be unsatisfactory. For example, if a ball travelling at 20 m/s passes on a trajectory 50 cm from an observer, and if information perceived 300 ms prior to contact is adequate for reasonably effective catching (Sharp & Whiting, 1974, Tyldesley & Whiting, 1975) the

error in taking t_c as an estimate of T_N is approximately 2 ms. If a temporal accuracy of 5-10 ms is taken to be required to catch effectively (Lee & Young, 1985), it can be seen that the τ approximation offers very precise information about the t_c . If the object speed is decreased to 6 m/s, the error increases to 23 ms, and at 1 m/s rises to 800 ms (Tresilian, 1991). These data are more clearly shown in Figure 5. Tresilian therefore concludes that the tau approximation strategy for non-collision course trajectories, for ball catching, is only useful at relatively fast object approach speeds.

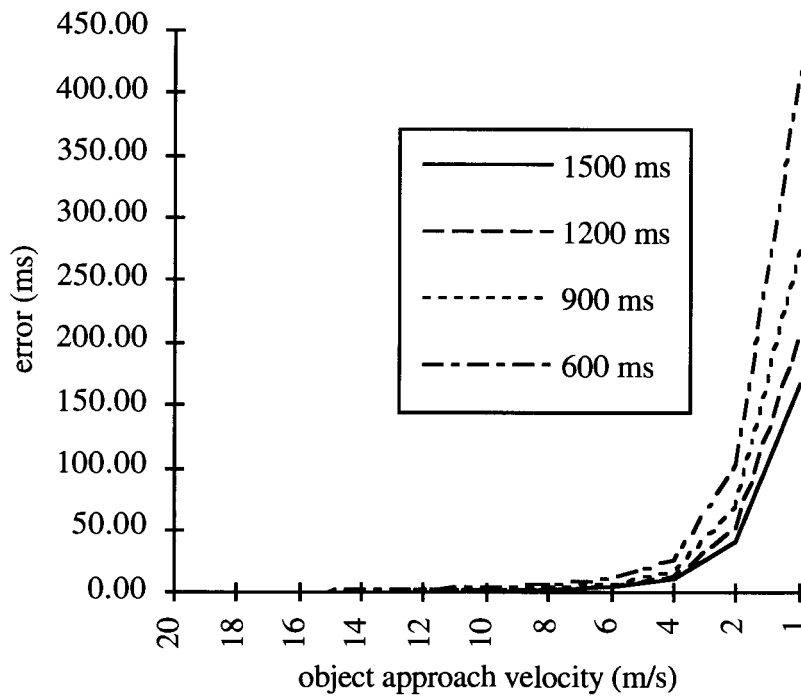


Figure 5. Error in using tau as an indicator of time-to-contact when significant (50 cm) hand-eye separation is present across differing object approach velocities.

However, the above calculations are based on the assumption that information obtained 300 ms before contact provides adequate information for the effective catching of an approaching object. It therefore assumes catching to be a temporal

problem only, with no spatial relocation of the catching limb being required.

Extending the time over which information is perceived from 300 ms to 1 second, the error introduced by using τ_L as an estimator of T_N decreases to less than 1ms at an approach velocity of 6 m/s, and to 2.5 ms at a velocity of 1 m/s. Errors of this magnitude have little effect on catching behaviour.

A further examination of the problem of non-collision course trajectories was made in 1992 by Wallace, Stevenson, Weeks, and Kelso (1992). These authors recognized that time-to-contact of an object with an observer, as specified by the optical variable tau, is derived specifically for the case of direct approach with the eye. In many interactive situations this is not the case. As indicated in Figure 6 tau provides time-to-contact of the object with the eye rather than the hand of the subjects (assuming a catching experiment). Thus a slightly different derivation is required, which follows:

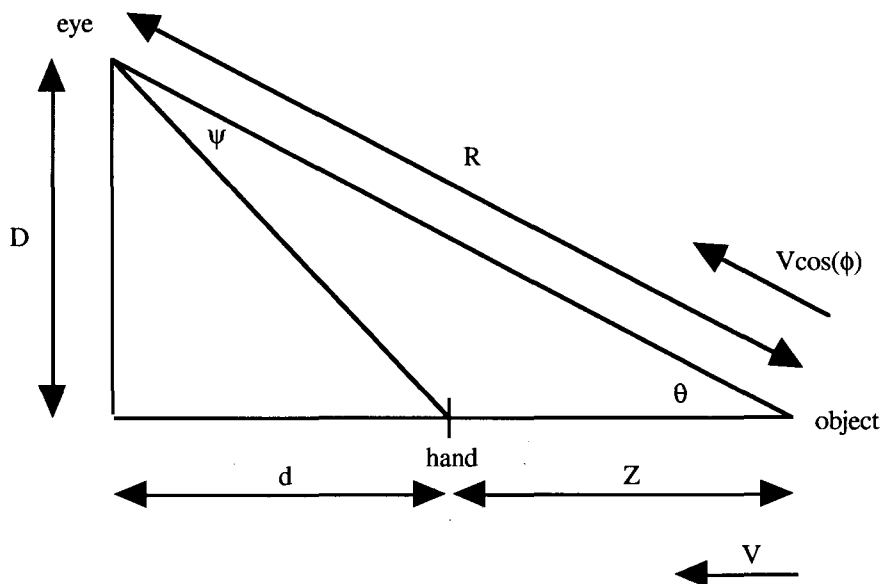


Figure 6. The geometry of the hand and object. D and d donate the vertical and horizontal components of the hand-eye separation respectively, τ , the time-to-contact of the object with the eye is represented by the ratio $R/V \cos(\theta)$, while the time-to-contact of the object with the hand is given by Z/V (adapted from Wallace et al., 1992).

Let d denote the horizontal component and D the vertical component of the distance between the hand and the eye. Let R denote the distance between the object and the eye of the observer at time t , V the object velocity, and ϕ the angle defined by the eye, object, and hand. It is $R/V \cos(\theta)$ which most accurately donates tau as defined, as opposed to Z/V which describes time-to-contact with the hand only.

(iii) Critical tau strategy or functional tau ratio?

Whilst it is recognized that most actions are far more complex than the simple motor acts which are often studied in motor control investigations, such complexity is often overlooked or ignored in many experimental investigations. The examination of visual timing strategies is no exception to this oversight, with simple answers often being sought for complex problems which may require more indepth examination and explanation.

Wallace et al. (1992) attempted to address just such an issue in their investigation into the possible perceptual mechanisms employed in an interactive motor task. They postulated that due to the fact that interceptive tasks require an action or sequence of actions on the part of the observer, the manner in which tau is used may depend on the motion of the observer (e.g., motion of a limb). They proposed a functional relationship existing between tau and the motion of the observer, such that changes in one affect changes in the other. Indeed evidence for such a relationship had already been provided by Bootsma and van Wieringen (1990) in their investigation of skilled table tennis players, and has also been proposed by De Vries (1992). Such a strategy implies that movement is not initiated at a critical tau value, as proposed by previous studies, (e.g., Lee & Reddish, 1981; Wagner, 1982), but rather that a more flexible usage of tau is made. In a study incorporating table tennis, Bootsma and van Wieringen found evidence for a negative correlation existing between the magnitude of the tau value at

movement initiation and the mean acceleration during the stroke, a phenomena they termed 'compensatory variability'. An additional facet to this observation was the implication that skilled table tennis players (as used in the study) do not necessarily learn to identify a precise value of tau, but rather that they can learn a relationship between tau (and some other variable) and the manner in which a particular motion may be produced.

In synthesis

Various visual factors have been proposed as potential regulators of movement towards both stationary and moving objects, including both tau (time-to-contact) and distance and velocity. Accurate measurement of these variables however, is difficult due to their complex interactions and the difficulty in distinguishing between them, making the task of identifying the possible effecting mechanisms of visual movement perception and regulation a difficult and perplexing one. It has been suggested that at very fast object speeds (e.g., Savelsbergh et al., 1992), a tau based approximation strategy is used to initiate and regulate action (Alderson et al., 1974; Cavello & Laurent, 1988; Sharp & Whiting, 1974), but is used less so for slow and moderate object approach speeds. At slower speeds it is suggested that some other, more precise, information is required (Tresilian, 1991).

It has also been noted (De Vries, 1992) that much of the work pertaining to tau and its use as a movement regulator has been conducted in studies in which movement times were required to remain at a near minimum (i.e., movements made as fast as possible). However, this is not able to account fully for the problem as many other studies have been conducted in which fine control of non-maximal movement has also been shown to be, at least in part, to be possibly regulated by tau (e.g., Lee et al., 1992; Wagner, 1982). Further investigation into these phenomena is therefore needed to help elucidate some of the mechanisms of visual

perception, and how they might interact with the regulation and control of human movement. Specifically, how is visual information used in interceptive/interactive tasks to precisely coordinate motor actions?

It has been well documented that appropriate and successful behaviour in coordinated interception activities is likely based on visual perception of time-to-contact with an object or surface. For without veridical perception of time-to-contact it would essentially be impossible to successfully accomplish any interactive motor tasks. The question remains however as to the exact nature of our perception of such time-to-contact information; is time-to-contact visually perceived (i.e., directly) or is it determined by the observer (i.e., derived computationally)? Indeed, it is to this problem that this thesis is directed.

Chapter 3

Experiment 1

Introduction

Many questions regarding vision in coincidence timing tasks remain. One of the more interesting of these, concerns the influence of object velocity upon the timing mechanisms employed at movement initiation. That is, in situations where one has to act very rapidly, are different mechanisms involved than in situations without critical timing demands? Another effect, that of predefining the point at which the object must be intercepted has received little attention. This is notable in that in real life situations in contrast to laboratory studies, very rarely are we subjected to specific constraints on our movements with respect to the 'interception point'. Rather, constraints are usually less stringently imposed, by such factors as for instance, the peripheral field in which we are able to interact with an approaching object. For example, in the catching of a ball we are restricted to the area in which we may catch it only by biological limitations such as that imposed by the length of either of our arms. Similarly, in the hitting of a baseball, we are free (within limits imposed by the rules of the game) to strike the ball at any point in its trajectory, once it enters an area in which we are physically able to reach it. It is to the above, to which the first experiment is directed.

Two conditions (predefined interception point, no predefined interception point), and three differing object approach velocities were used in experiment one. An index of the type of strategy used will be based on the examination of a number of dependent measures which are of fundamentally two types. The first relates to the timing components of movement initiation, the other concerns the selected movement kinematics displayed. Of the timing variables either measured or derived

(tau-margin and distance-to-contact at both movement and grasp initiation), only that of tau is expected to be constant across all conditions if a direct perception tau-based timing strategy is used. Regarding the kinematic measures (total movement time from initial hand lift to final ball lift, percent time after peak deceleration, maximal grip aperture, percent time to maximal grip aperture) it is expected that only movement time will be constant given that a tau-based strategy is being employed. Moreover, should optical expansion information be used, then it is expected the kinematics will reveal that the proportional time spent in the deceleration phase will decrease with increasing object velocity. The percent time taken to reach maximal grip aperture is also expected to increase with an increasing object velocity giving a decreased deceleration phase on the grasping motion in increased velocity conditions. The maximal grip aperture is expected to increase with decreasing object velocity.

Methodology

(i) Subjects

Ten subjects were used in this study. All subjects were right handed (as determined from the Edinburgh handedness inventory, Oldfield, 1971), students (21-27 years) from the university population, and had normal or corrected to normal vision. All subjects were naive with respect to the purpose of the experimentation.

(ii) Apparatus

A linear aluminium trackway (3 m long, triangular in cross section of 7 cm diameter), was positioned at 11° to the horizontal, on a standard laboratory table. The track was supported at the elevated end (farthest from the subject) by a metal frame, and at the other (nearest to the subject) by a clamped metal plate. An

aluminium trolley containing a platform (adjustable to the horizontal) was designed to ride smoothly down the track, with minimal frictional resistance (see Figure 7). Projected from the platform, by a miniature tripod structure (consisting of a suspended reed switch and supporting pins) was the object to be grasped (a golf ball). Embedded within this ball was a small magnet, which when placed upon the tripod would cause the reed switch to close. Output from the reed switch was connected to a data acquisition unit (see later for further explanation) enabling an accurate detection of time of ball lift. The point at which subjects were instructed to interact with the approaching object was specified by means of a small wooden structure placed by the side of the track.

Velocity of the trolley down the track (towards the subject) was controlled by adjusting weights on a weighted pulley system. A three dimensional, motion analysis system (OPTOTRAK 3010, Northern Digital Inc., Waterloo, Ontario) was used to monitor and record both trolley displacement and all movement kinematics, in conjunction with an associated data acquisition unit (ODAU). The OPTOTRAK system was internally precalibrated with a static error < 1 mm, and dynamic error < 2 mm.

Liquid crystal display (LCD) goggles (Plato, model s-2, T.T.I., see Milgram 1987) were also used throughout the experiment. These controlled the exact time duration for which the subjects were able to view the approaching object. The goggles had a clear to opaque transformation of < 4 ms. An accompanying ODAU unit, used for the collection of temporal signals, provided both continuous (e.g., physical variables) signal acquisition, and discrete (e.g., digital data) input/output. This allowed for the computerized control of trolley release and goggles opening, as well as time of movement initiation and ball lift. All measurements synchronized with the three dimensional measurement data.

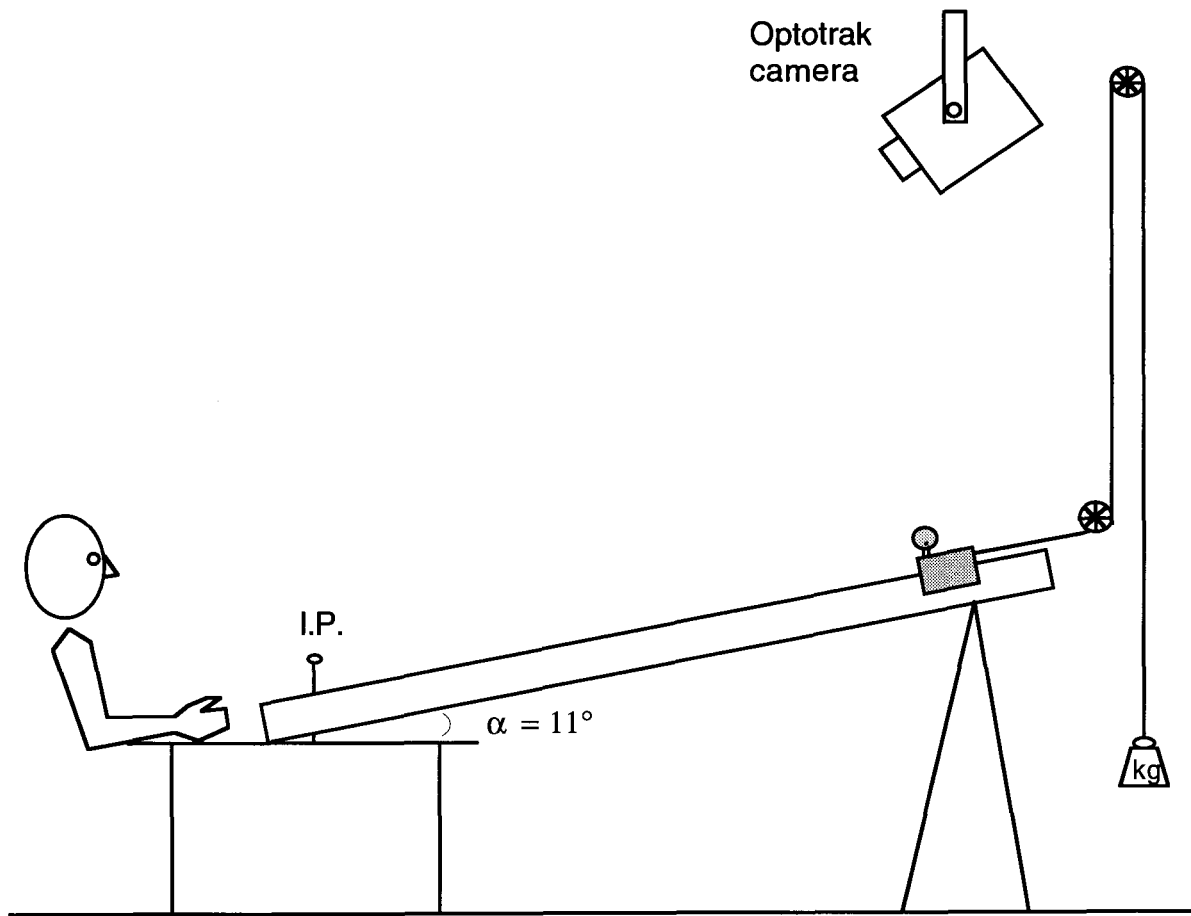


Figure 7. The experimental apparatus and design.
Note. I.P. = interception point

(iii) Procedure

Subjects were seated orthogonal to the track with their midline approximately in line with the centre of the track. Infra-red emitting diodes (ireds) were placed on the tips of the thumb and index finger, and on the styloid process of the wrist of the right hand (raised slightly so as not to be obscured from the sensors during the movement). The forearm flexion was approximately 90° , the hand in line with the forearm. In addition a small metal 'contact' plate was attached to the base of the

hand (in line with the little finger) so as to connect with a metal 'base/home' switch when rested on the table top. This allowed accurate time of hand lift to be obtained. Subjects began each trial with the contact plate resting on the base switch, with the distal pads of the index finger and thumb placed together in a loose grasping position. The contact plate was positioned 5 cm from the end of the track and 10 cm to the right (5 cm from the edge of the table).

A subject's task in the experiments was to move towards and grasp the ball from the approaching trolley, making a single smooth continuous motion of the right limb only. No other speed constraint was imposed upon the task. Trolley release occurred at a random interval (2-3 s) after data collection was initiated (by the experimenter), followed by opening of the LCD goggles (from opaque to clear) and hand lift of the subject (determined as movement initiation). The LCD goggles remained opaque at the initial time of trolley release. Movement (task) completion was defined as the time at which ball lift occurred. In order to control for any possible acoustic influence of noise from the trolley, all subjects were required to wear earplugs and were exposed to white noise via headphones.

Prior to all experimental trials subjects were allowed to make the reaching and grasping (prehension) movement in all three velocity conditions under which they were to be tested. Neither headphones or goggles were worn during these practice trials, so as to enable subjects to completely familiarize themselves with the experimental task. Four practice trials per velocity condition were administered for all subjects tested.

(iv) Experimental protocol

A three (velocity) by two (condition) experimental design was used. The two conditions were either with or without a predefined interception point. Vision of the trolley and apparatus was available for approximately 1.5 seconds in each

condition prior to the trolley reaching the interception point (or the point at which it would have reached it, in the case of the no interception point condition). Thus, for the three velocity conditions, whilst viewing time remained constant, the distance over which the trolley and ball were seen to travel during that time increased as approach velocity increased (see Figure 8).

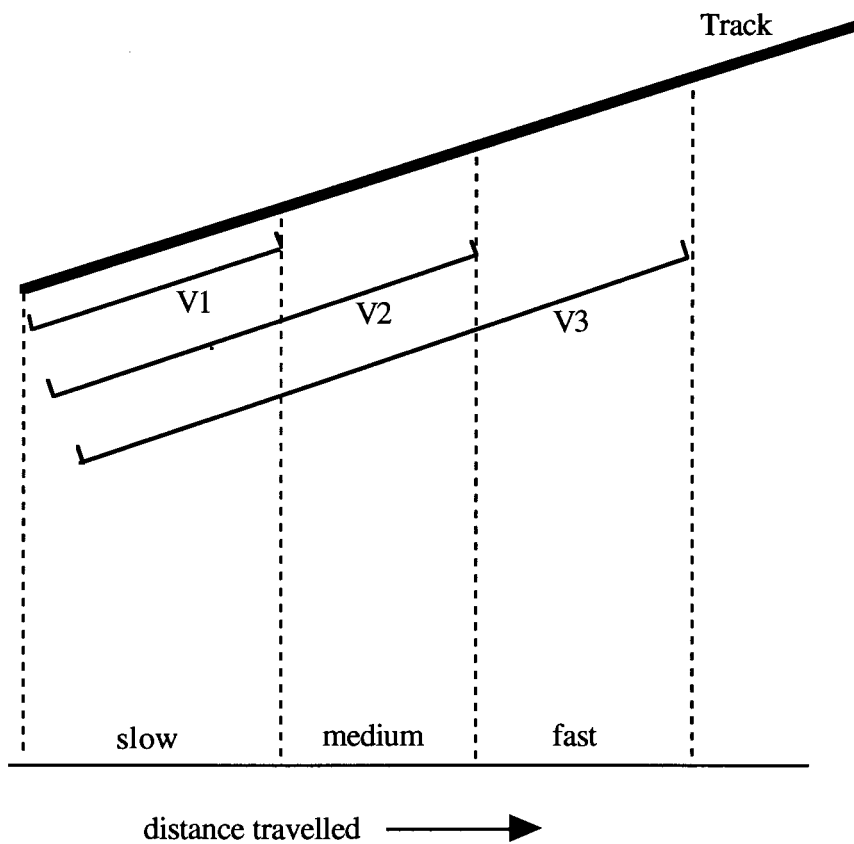


Figure 8. Diagrammatic representation of the varying optical expansion patterns perceived over differing object approach velocities given a constant viewing time of approximately 1.5 seconds.

In one set of velocity conditions, subjects were instructed to grasp the ball as near as possible to the interception point, thus providing a spatial constraint on the

task performed. In the other set of velocity conditions subjects were instructed to grasp the ball at whatever point they felt most comfortable (prior to the trolley reaching the end of the track), thus being limited by only biomechanical constraints. Trials for each subjects were blocked for condition, (counterbalanced between subjects), while approach velocity conditions were presented randomly both within and between subjects. Object (trolley and ball) approach velocities (at the interception point) were maintained at approximately 1.6 m/s (fast), 1.2 m/s (medium), and 0.8 m/s (slow), in the three velocity conditions⁴. Fifteen trials at each velocity were given. Prior to each trial subjects were permitted full vision so as to allow them to reorientate themselves. Goggles were returned to opaque three seconds prior to each trial.

(v) Data collection

Each trial was initiated by the experimenter, under computer control with both temporal and kinematic data being collected over a 7 second period. Kinematic (ired) data were sampled at 200Hz, with temporal data also being sampled at 200Hz collected via the ODAU (channels 1 to 4). The trolley delay (2-3 sec. randomly selected) and the goggles opening delay were directly controlled via a Macintosh computer through an inhouse (labVIEW 2, National Instruments Corporation) program allowing monitoring as well as control of experimental parameters as velocity conditions changed.

(vi) Data processing

Raw kinematic data (from three 1-dimensional sensors) were converted to 3 dimensional data via an OPTOTRAK program (using a non-linear, least squares algorithm) and then transferred with the temporal data (from the ODAU unit), via ethernet, to a UNIX system, where all data analyses were performed.

a) Temporal data

Temporal data of interest were determined by means of specific algorithms implemented as part of the OPTOTRAK system software⁵. Times of hand lift and ball lift were tabled, as were times for trolley release and opening of the LCD goggles.

b) Kinematic data

Kinematic (displacement) data were first processed according to procedures consistent with treatment of OPTOTRAK data (e.g., Marteniuk, Leavitt, MacKenzie, & Athenes, 1990). This consisted of rotating coordinates to a known frame of reference prior to clipping and filtering. All kinematic data (other than that pertaining to the ired placed on the trolley) were subject to interpolation (@ 4 frames), and then low pass filtered using a 2nd order Butterworth dual pass filter with a cut off frequency of 3Hz. Data were viewed after interpolation, with those files still containing glitches eliminated from further analyses⁶.

Data from the trolley ired (used to calculate tau-margin values) were treated only by filtering (@ 3Hz) before determining the displacement at hand lift and ball lift as well as total movement distances (in cm). The displacement files were then differentiated (to obtain velocity data), with instantaneous velocity of the trolley/ball being determined at the moment of movement initiation (hand lift). Tau-margin values were then obtained using methods previously described.

Kinematic data pertaining to movement profiles was further processed to produce grip aperture profiles. This was determined by finding the differences between the two ireds placed on the thumb and index finger, throughout movement execution. Transport profiles were determined from processing the wrist ired data.

(vii) Data analyses

Whilst the main crux of this research was concerned with an investigation into the visuo-motor timing mechanisms employed in coincidence timing tasks (i.e., the usage of tau or employment of some cognitive strategy), supporting evidence is provided from selected kinematic procedures. Dependent variables of interest were therefore selected as pertaining to one of either two categories, relating either to differences in movement (transport and grasp) kinematics due to manipulations in either condition or velocity, or to the temporal components of movement initiation (both for grasp and initial movement initiation).

Independent analyses of variance for all dependent variables were performed for all data, using a 2 condition (interception and no interception point) by 3 velocity (fast, medium, slow) design. When post hoc analyses was required Tukey's HSD ($p < .05$) test was used.

Results

(i) Initial analyses

The first dependent measures to be considered were those directly related to the temporal components of movement and grasp initiation. Table 1 provides a summary of these initial data as a function of condition and velocity. It should be noted that whilst 10 subjects were tested for the purpose of experimentation, data from only 9 subjects were used in the analyses, due to data loss from equipment malfunction⁷.

Table 1 Mean values for initial analyses as a function of both
condition and approach velocity

Dependent measure	<u>Interception point</u>			<u>No interception point</u>		
	Fast	Medium	Slow	Fast	Medium	Slow
Initiation distance (eye) in cm	90.5	82.3	76.7	85.8	81.1	73.0
Grasp distance (eye) in cm	24.2	21.3	16.1	18.6	18.9	15.9
Tau - initiation	.969	1.15	1.42	.913	1.07	1.29
Tau - grasp	.199	.222	.222	.151	.184	.218

Distance values (i.e., the distance from the object to the eye at the moment of hand lift) were first calculated for movement initiation (distance R in Figure 6), and then grasp initiation (distance Z in Figure 6). Significant differences across velocity of object approach in distance-to-contact were found for both movement initiation,

$F(2,16) = 26.091, p < .001$, and for grasp initiation, $F(2,12) = 14.023, p < .001$. This indicates that a constant distance-to-contact strategy was not used in either case. Post hoc analyses indicated each distance-to-contact to be significantly different ($p < .01$) for differing object approach velocity. For grasp distance only the distance-to-contact in the slowest and the faster two velocities were significantly different from each other ($p < .01$) (see Figure 10). No differences were found in the distance-to-contact between the medium and fastest approach velocities. In addition, for grasp distance an interaction between condition and velocity was found $F(2,12) = 5.474, p < .05$ (see Figure 10), with distance-to-contact increasing to a greater extent with increasing approach velocity in the interception point condition than in the no interception point condition.

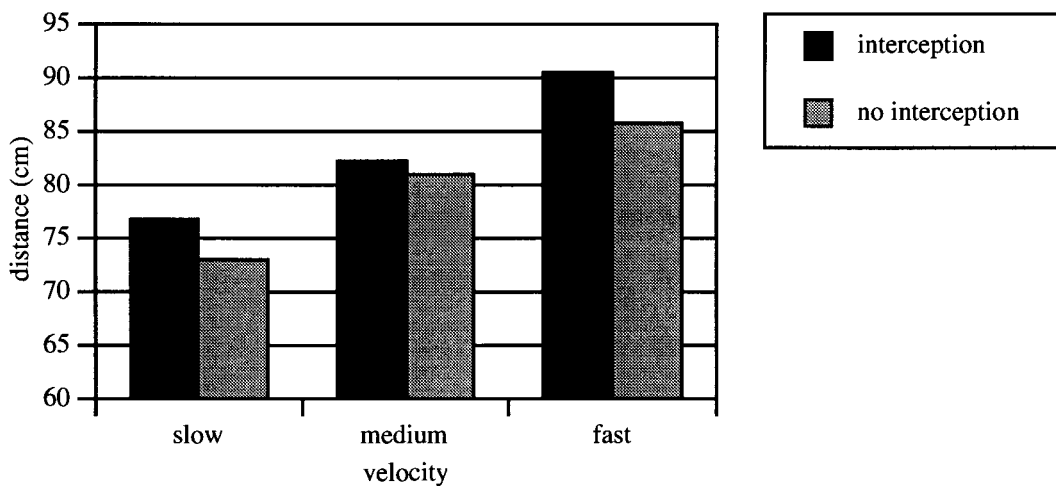


Figure 9. Mean initiation distance for all subjects.

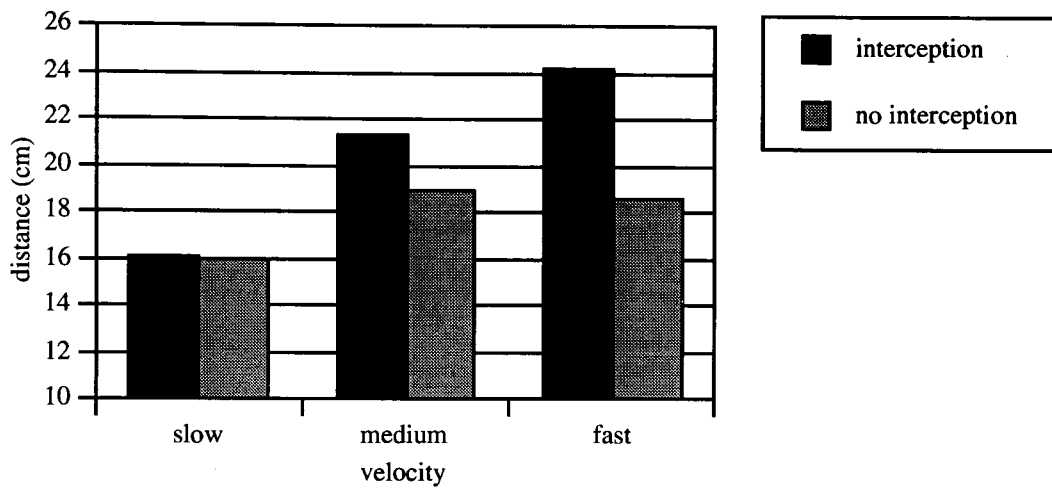


Figure 10. Mean grasp distance for all subjects.

(ii) Tau-margin determination

Given that there was no support for a constant distance-to-contact strategy, it appears that a strictly cognitive based strategy was not used. In order to examine the evidence for a constant tau strategy, tau-margin values were calculated (for object collision with the eye, as opposed to time-to-contact values with the hand). Significant differences in tau-margin values across the three object approach velocities were found, $F(2,16) = 82.347, p < .001$. Post hoc analyses indicated all differences to be significant ($p < .01$). Significant effects were also found for condition, $F(1,8) = 11.904, p < .01$, with the interception point condition producing greater tau-margin values than the no interception point condition (see figure 11).

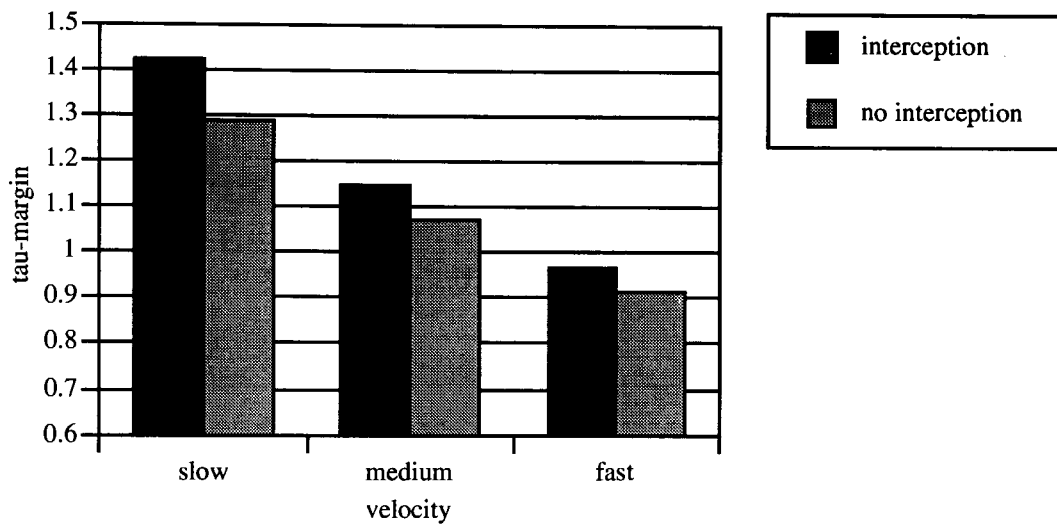


Figure 11. Mean tau-margin values for all subjects at movement initiation.

For grasp initiation, tau-margin values were found to be significantly different across approach velocity, $F(2,12) = 53.348$, $p < .0001$. Post hoc analyses again indicated significant differences between all velocity conditions ($p < .01$). No statistically significant differences for interception point condition were found (see Figure 12).

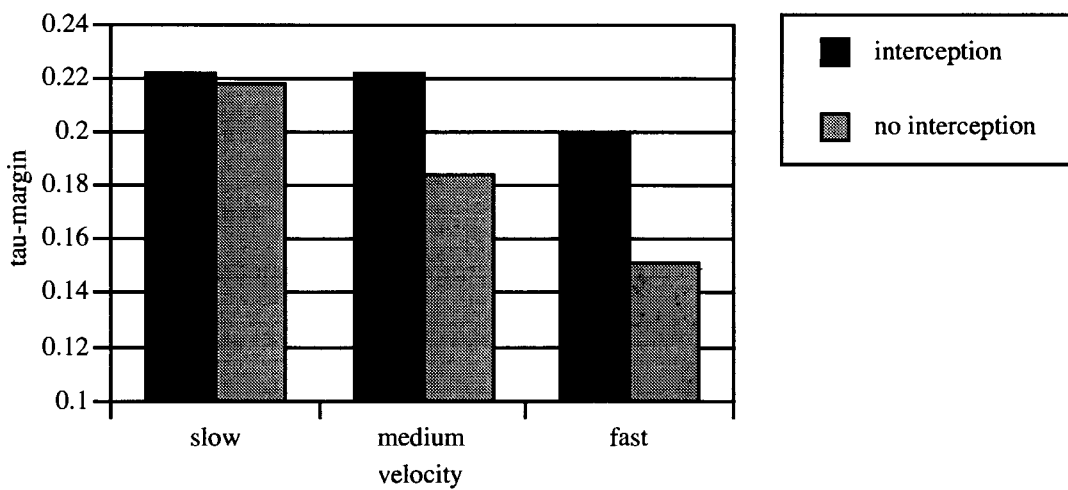


Figure 12. Mean tau-margin values for all subjects at grasp initiation.

Kinematic data

Selected kinematic measures were used in an attempt to more completely describe the movements under the various conditions. Table 2 contains a summary of these selected kinematic data.

Table 2 Mean values for selected kinematic analyses as a function of both condition and approach velocity

<u>Dependent measure</u>	<u>Interception point</u>			<u>No interception point</u>		
	<u>Fast</u>	<u>Medium</u>	<u>Slow</u>	<u>Fast</u>	<u>Medium</u>	<u>Slow</u>
Movement time (ms)	639	702	753	596	650	670
Time after peak deceleration (%)	28	27	33	24	23	24
Maximum grip aperture (mm)	95	93	89	105	98	96
Time to maximal aperture (%)	66.7	65.3	67.6	74.7	71.5	72.3

(i) Movement time

As with the temporal data a significant main effect was found for object approach velocity, $F(2,16) = 9.837, p < .001$. Post hoc analyses indicated that the fastest velocity resulted in a movement time significantly shorter ($\bar{x} = 618$ ms) than both the slowest ($\bar{x} = 712$ ms) and medium ($\bar{x} = 675$ ms) object approach velocities ($p < .01$). No differences between the medium and slowest velocity conditions were

found (see Figure 13). No statistically significant difference was found between the interception point conditions.

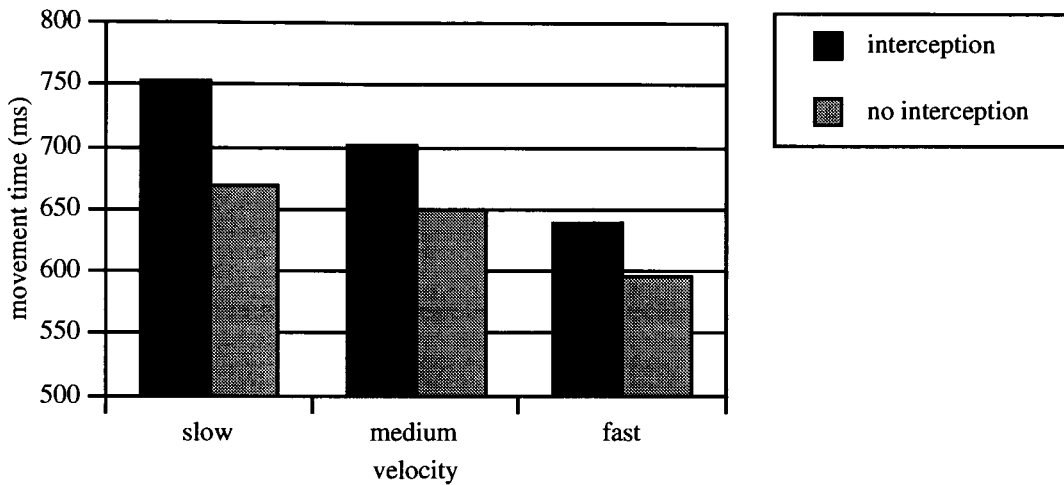


Figure 13. Mean movement time for all subjects.

(ii) Percent time after peak deceleration

Across object approach velocity a significant difference was found in the amount of time spent after peak deceleration when viewed as a percentage of total movement time, $F(2,14) = 4.443$, $p < .05$. Relatively less time was spent after peak deceleration in the slow ($\bar{x} = 28\%$) velocity condition than in the medium ($\bar{x} = 25\%$) approach velocity ($p < .05$) (see figure 14). No differences were found between the medium and fast ($\bar{x} = 26\%$) velocity conditions. These data indicate that (although an overall greater time is spent after peak deceleration in slower approach velocities) as a percentage of overall movement time, less time is spent after peak deceleration in slow than in fast velocities.

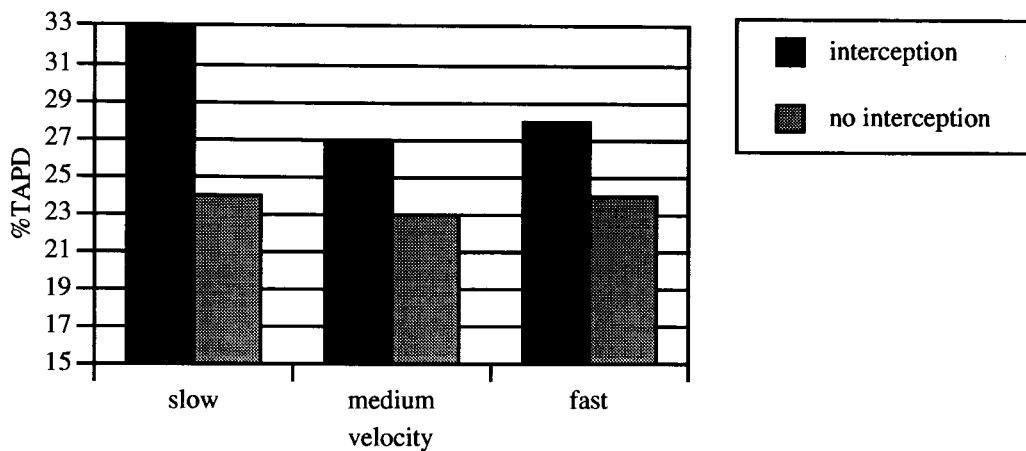


Figure 14. Mean percent time spent after peak deceleration.

(iii) Grasp component

The maximum grip aperture showed significant main effects for both interception point condition, $F(1,5) = 117.35, p < .001$, and object velocity, $F(2,10) = 34.661, p < .001$. In the fastest velocity condition the grasp aperture ($\bar{x} = 100$ mm) was different from that in both the medium ($\bar{x} = 96$ mm) and slowest ($\bar{x} = 92$ mm) velocities ($p < .01$), and the medium velocity was significantly different from the slowest velocity condition ($p < .05$). When the data were normalized and the moment of maximum grasp aperture observed as a percentage of total movement time, significant differences were noted for the interception point condition, $F(1,5) = 9.670, p < .05$. Post hoc analyses indicating that maximal aperture occurred relatively later in the movement trajectory in the interception point condition than in the no interception point condition. No effect of velocity was found. These data are shown in Figures 15 and 16.

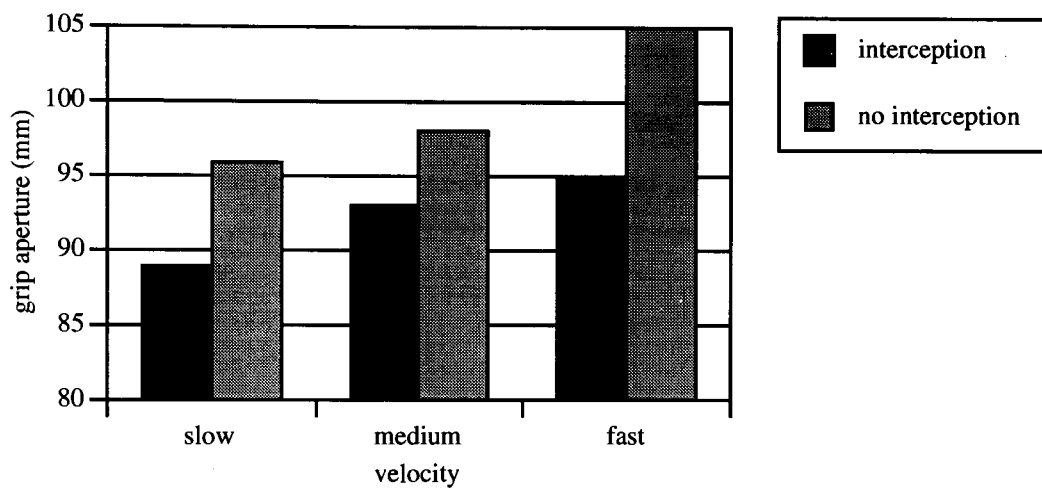


Figure 15. Mean maximal grip aperture for all subjects.

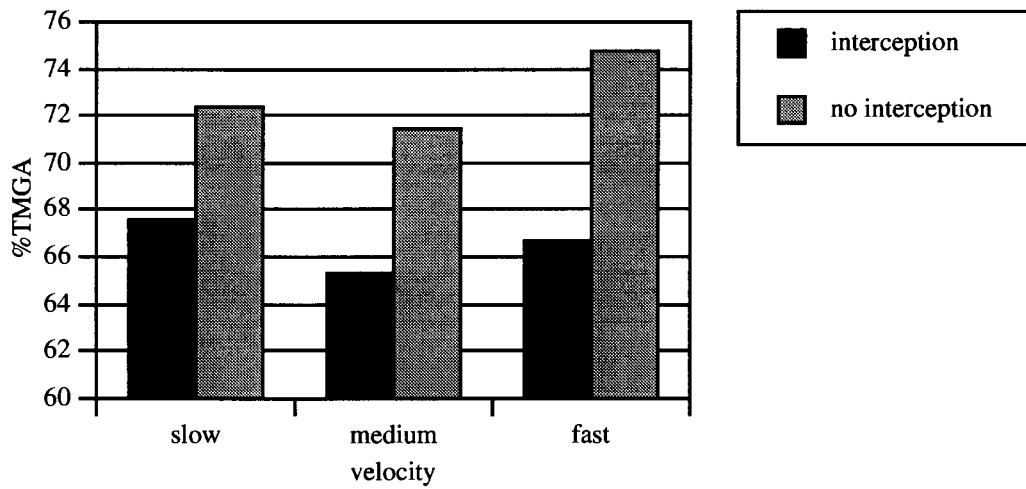


Figure 16. Mean percent time to maximal grip aperture for all subjects.

A summary of these selected kinematic measures and their implication as far as their support or opposition for the usage of optical expansion information as the perceptual source of information used to initiate and guide interceptive movements is provided in table 3.

Table 3. The kinematic measures across the three velocity conditions in providing support or no support for optical expansion

Kinematic measure	Support	No support
Movement time	✓	
% Time after peak deceleration	✓	
Maximal grip aperture		✓
% Time to maximal grip aperture	no effect	no effect

Discussion

(i) Temporal component

Some prominent researchers have suggested that a cognitive computation of distance or velocity information, or some derivation of the two, is the most likely method of time-to-contact estimation in interceptive actions (e.g., McLeod & Ross, 1983; Todd, 1981). Others however have argued that this method would introduce too great a source of error to be able to accurately account for the very replicable, precise and coordinated actions that are performed by humans (e.g., Lee et al., 1983; Tresilian, 1990). The present experimentation was undertaken in an attempt to determine whether some method of cognitive computation, or a more direct measure of time-to-contact estimation is likely to be employed in interceptive prehension motions. In this initial experiment, distance-to-contact at movement and grasp initiation were examined. As Figures 9 and 10 illustrate, support for the use of a constant strategy was not found. Rather, as the velocity of the approaching object increased, so did the distance-to-contact at both movement and grasp initiation. These results are consistent with those found by both Wallace et al. (1992) and Chieffi et al. (1992, exp. 1), in which although finding a decreased movement amplitude at increased object velocities, they found an increased distance-to-contact at movement initiation with an increasing approach velocity.

In addition to investigation of the effects of varying object velocity, this experiment aimed to establish whether the temporal and kinematic components of interceptive actions are influenced by object velocity once the location in space at which the object has to be intercepted is fixed. Again as illustrated in Figures 9 and 10 this was not found to be the case. It may also be noted that although an interaction effect was found for distance-to-contact at grasp initiation, a constant distance-to-contact strategy was not employed in either case.

The above findings fail to support for a constant distance-to-contact cognitive strategy being employed to initiate interceptive movements. Attention was therefore turned towards use of a direct estimation of time-to-contact along the lines proposed by Lee (1976, 1980a). The tau theory originally advanced by Lee (1976) advocated that time-to-contact estimation arose as the direct result of perception of optical expansion information, provided by an approaching object. Although initially presented for the case of constant object approach velocity and direct collision course with the eye, tau has since been shown to adequately specify time-to-contact even when these initial conditions are not met.

As has recently been noted by Wallace et al. (1992), in most real world situations the angle of object approach to the observer usually deviates from direct collision with the eye. They proceed to demonstrate mathematically that when significant hand-eye separation is present, tau will lead to a significant overestimation of time-to-contact (in constant velocity conditions). However, even when using these corrected tau values Wallace et al. (1992) were unable to find support for a constant (or critical) tau strategy being used across different object approach velocity conditions. Results from this first experiment were consistent with those of Wallace et al. (1992) in that across changing velocity conditions for both movement and grasp initiation, tau-margin values were found to decrease with an increase in object approach velocity.

In searching for an (ecological) explanation of time-to-contact estimation it is evident from Figures 11 and 12 that constant tau-margin values (as would be expected if a critical tau strategy were being used) were not found. As is clearly demonstrated in Figure 11, the time-to-contact values specified by tau were found to decrease with an increasing object approach velocity. For movement initiation, significant differences were additionally found between conditions. The presence of a predefined interception point requiring a different movement initiation strategy.

(ii) Kinematic component

As is shown by Figure 13, mean movement time was found to increase with a decreasing object approach velocity (despite movement distances decreasing in the same conditions). It is suggested that that this indicates object velocity has a direct influence on the transport component of interceptive prehensile motions, a postulation consistent with that of Chieffi et al. (1992).

The inclusion of a fixed point at which the subjects must interact with the approaching object did seem to affect the temporal relationship between the time taken to reach maximal grip aperture and the transport component of movement. The relative time taken to reach maximal grip aperture was significantly less in the presence of an interception point. The relative time spent after maximal grip aperture (i.e., between maximal grip aperture and the closure of the hand around the object) was greater when the point of interaction was defined prior to movement initiation. This derived measure is comparable with that of percent time after peak deceleration, in that it gives a measure of a selected division of the acceleration phase of a movement component. Additionally, unlike the percent time after peak deceleration which may have associated inaccuracies in that subjects may not have decelerated to the same extent in differing velocity conditions, the percent time to maximal grip aperture profiles does not seem to have these problems. In order to successfully complete the grasping action subjects must close their fingers to the same extent in all velocity conditions, since the size of the object to be grasped did not change. The velocity at which subjects completed their grasping action however, did not have to remain constant, allowing subjects to complete the required action relatively earlier in their movement cycle, without decelerating to the same extent in all conditions.

Associated with the time of occurrence of maximal grip aperture, the maximal size of grip aperture has been postulated as being an indicator of task difficulty

(Wing et al., 1986). A greater maximal grip aperture permits a greater tolerance for positioning errors just prior to contact, and therefore is postulated as being employed in more difficult or precise tasks. As is indicated in Figure 14, an increased maximal grip aperture occurs with an increased object velocity. Additionally, this coincides with a decreased movement time, a result consistent with those found by Wing et al. (1986). It appears then that the grasping of the ball in the faster object approach condition is a more difficult task for the subjects to perform.

Noting that in the present study the amount of optical expansion information available to the subjects was constrained, the above results are not what is expected if an increased amount of perceived optical expansion information results in an easier task to perform. With the same time duration (1.5 s) a greater amount of optical expansion is perceived in a faster object approach velocity, as the object is seen to travel over a greater distance. This increased optical expansion information however does not seem to result in decreased task difficulty indicated by maximal grip aperture.

When looking at the percent time after peak deceleration (Figure 14) another kinematic measure often taken as being an indicator of task difficulty, a decrease in time is seen to correspond to an increased object approach velocity. As indicated in table 3, it seems feasible to postulate from these profiles that optical expansion information may possibly be the most readily available perceptual source of information that allows us to accurately initiate and guide our actions. However, as has been previously noted this may not be the case, with subjects failing to decelerate to the same extent in faster object approach velocity conditions, and therefore completing the task (intercepting the object) relatively earlier in the overall movement cycle (see appendix B).

The results of experiment 1 failed to provide any conclusive evidence either in support of, or to aid in the dismissal of a tau based account of movement regulation. The question of exactly what perceptual information is afforded by the environment allowing humans to make such precise, coordinated and replicable movements remains. Data from from the selected kinematic measures do however seem to lend some support for the use of optical expansion information as the perceptual source of information best utilized by subjects in coincidence timing tasks.

To further examine the movement control strategies employed under differing task constraints, a second experiment was conducted in which viewing time was progressively reduced to a minimum. This leads us to the second question of how does a diminished viewing time affect selected prehension kinematics in interceptive actions?

Experiment 2

Introduction

If time-to-contact estimation is derived through cognitive computation of either distance or velocity information then it may be hypothesized that restricting viewing time below some critical threshold will cause a decrement in performance. The underlying rationale to this hypothesis is that if computational processes are undertaken they must take some finite time to perform. If this finite time (of computation) is less than or equal to viewing time, then determination of t_c will be inaccurate or impossible to perform, leading to a decrement in performance. One of the only reported studies to date in which viewing time has been experimentally manipulated is that by McLeod and Ross (1983), in which they imposed a minimum viewing time of two seconds. No decrement in time-to-contact estimation was observed, leading them to suggest that a computational derivation of its estimation was not used, or that the critical minimum viewing time had not been reached.

The second experiment was designed specifically to address this problem of diminished viewing time using an identical experimental configuration as in experiment 1. Two velocity conditions, fast (1.6 m/s) and slow (0.8 m/s), and three viewing periods were used (1200 ms, 900 ms, 600 ms). The shortest viewing period was determined through preliminary pilot testing as being the shortest possible period in which subjects were still able to perform the task successfully.

Encompassing the findings from experiment one, it is proposed by this author that whilst the usage of tau as a movement timing initiator does undoubtedly seem to be used in a wide variety of situations, its universal application does not provide

a definitive answer to the timing of interactive or interceptive actions as used herein. Rather, it is proposed that a less stringent usage of tau may be employed in many situations in which time is not a limited entity. The second experiment, using similar dependent measures to those of experiment one, was designed specifically to evaluate the effects of restricted viewing time on movement and grasp initiation. It is expected that a diminishing viewing time would have similar effects in experiment two, as that initially expected of a decreasing object velocity in experiment one. That is, constant tau-margin values would be observed across all different viewing time conditions. Conversely if some cognitive method of time-to-contact estimation is used, varying tau-margin values will be observed.

Methodology

(i) Subjects

Ten subjects were used in the second experiment. All subjects were right handed (as determined from the Edinburgh handedness inventory, Oldfield, 1971), students (21-27 years) from the university population, and had normal or corrected to normal vision. All subjects were naive to the purpose of the experimentation and had not participated in experiment one.

(ii) Protocol

Experiment 2 consisted of a three (viewing period) by two (velocity) experimental design, with no specified point of object interception (see Figure 17). The viewing periods were manipulated so as to produce an equal amount of viewing time prior to the object reaching the observer in both velocity conditions. [Note that while the viewing periods for the two velocity conditions remained identical, the amount of optical expansion perceived by the subjects was greater in

the faster velocity condition in all cases due to the object being seen to travel over a slightly greater distance].

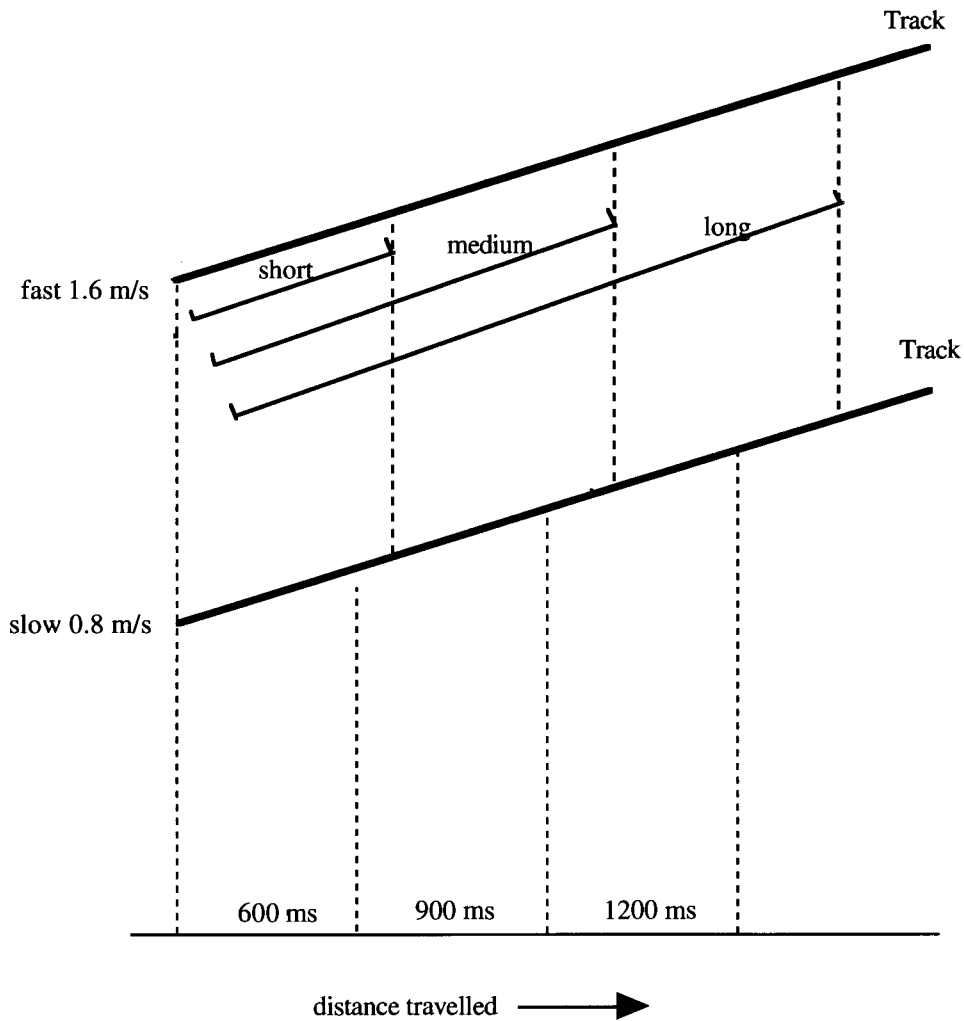


Figure 17. Diagrammatic representation of the varying optical expansion patterns perceived over differing object approach velocities, with differing viewing periods.

Subjects were instructed to grasp the ball (prior to it reaching the end of the track) at whatever point they felt most comfortable, while making a single smooth continuous movement. Trials were presented randomly for both velocity and viewing period, within and between subjects. Fifteen trials for each condition were

given. All other apparatus, procedures and data processing remained as for experiment 1.

(iii) Data Analyses

As with experiment 1, the dependent variables deemed to be of interest were determined to be either kinematic or temporally related, and influenced by either approach velocity, viewing time, or a combination of the two. Two (velocity) by three (viewing periods) independent analyses of variance were performed upon all dependent measures, with significant effects being further explored using Tukey's HSD ($p < .05$) post hoc analyses.

Results

(i) Initial analyses

As in experiment 1, the first measures to be considered were those related temporally to the movement and grasp initiating components of the interceptive motion⁸. Table 4 provides a summary of these initial data.

Table 4 Mean values for initial analyses as a function of both
approach velocity and viewing period

<u>Dependent</u> <u>measure</u>	<u>fast approach velocity</u>			<u>slow approach velocity</u>		
	<u>long</u>	<u>Medium</u>	<u>Short</u>	<u>long</u>	<u>Medium</u>	<u>Short</u>
Initiation distance (eye) in cm	67.1	62.8	55.4	58.6	54.7	52.5
Grasp distance in cm	23	19.7	14.7	17.7	17.5	14.5
Tau - initiation	.643	.646	.693	1.08	1.26	1.45
Tau - grasp	.100	.144	.217	.121	.144	.220

Statistically significant differences were found for both object approach velocity and viewing time when distance-to-contact values were examined at movement initiation, $F(1,7) = 36.861$, $p < .001$, $F(2,14) = 27.461$, $p < .001$, respectively. Post hoc analyses revealed the longest viewing period to be significantly different from both the medium and shortest viewing periods ($p < .01$), and the medium viewing time being significantly different from the shortest viewing period ($p < .05$) (see Figure 18).

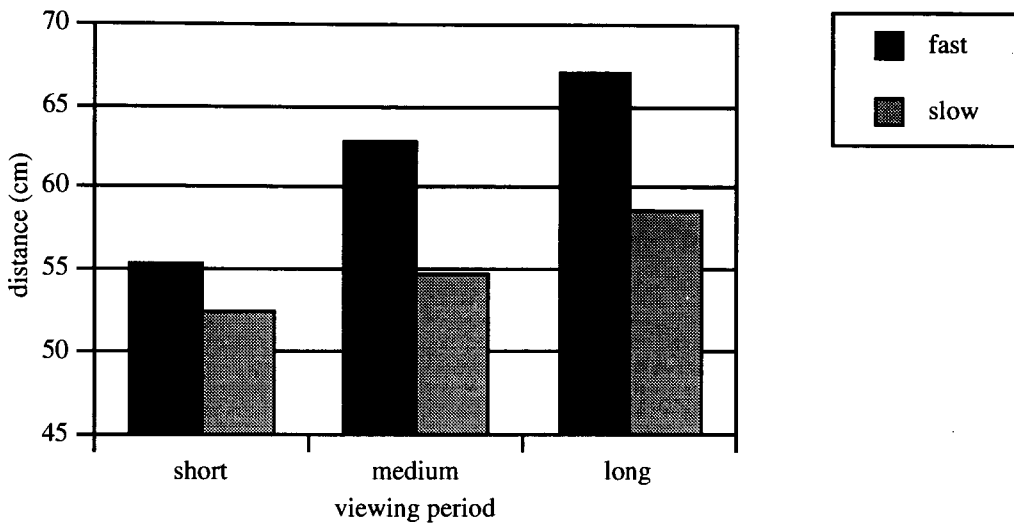


Figure 18. Mean initiation distance for all subjects.

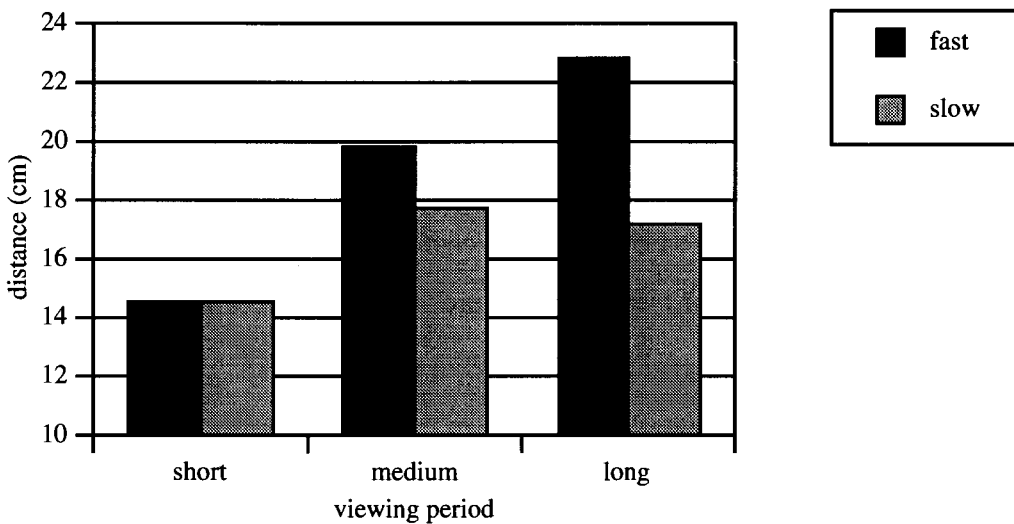


Figure 19. Mean grasp distance for all subjects.

Significant differences were also found for distance-to-contact at the initiation of the grasp movement for both viewing time, $F(2,12) = 28.011$, $p < .001$, and velocity of object approach, $F(1,6) = 7.087$, $p < .05$. Post hoc analyses indicated differences between the longest and medium, and longest and shortest viewing periods to be

significant ($p < .01$). Additionally an interaction effect was found between viewing period and approach velocity, $F(2,12) = 42.4$, $p < .01$. Distance-to-contact differences increased more with an increasing viewing period with a faster object approach velocity. These data are shown in Figure 19.

(ii) Tau-margin determination

When tau-margin values were calculated significant differences were found for both viewing time, $F(2,12) = 11.474$, $p < .01$, and for object approach velocity, $F(1,6) = 54.970$, $p < .001$. Post hoc analyses indicated statistically significant differences to be between the shortest and longest viewing periods ($p < .01$), and between the shortest and medium viewing period ($p < .05$). An interaction effect was also observed, $F(2,12) = 14.859$, $p < .001$, with values decreasing in a slow approach velocity with an increasing viewing time, while remaining constant with a faster object approach velocity (see Figure 20).

At grasp initiation, no significant effects for object velocity were found, although a significant effect was found to be present for viewing period, $F(2,12) = 47.683$, $p < .001$. Tukey analyses indicated these differences to be identical to those found for the tau-margin values at movement initiation (see Figure 21), with significant differences found between both the shortest and medium, and shortest and longest viewing periods, but not between the medium and longest viewing periods.

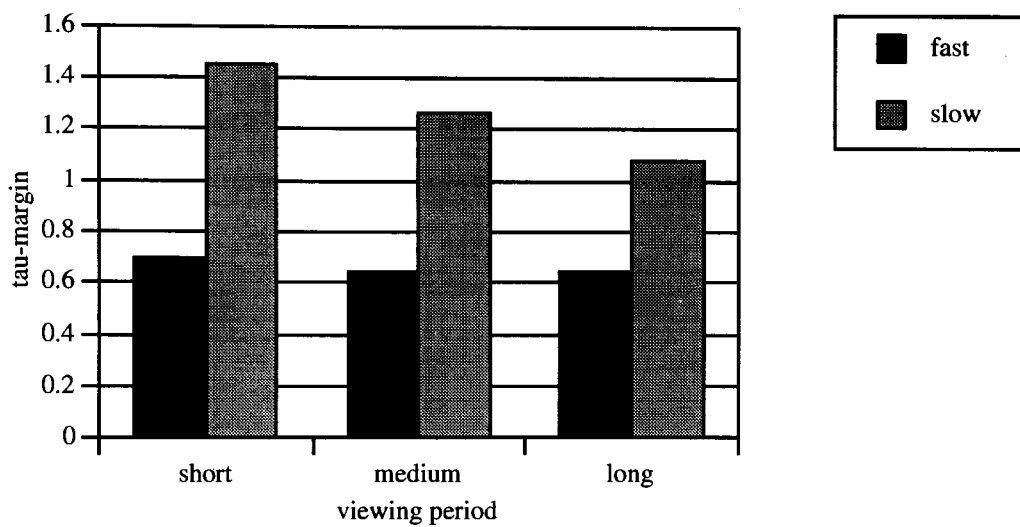


Figure 20. Mean tau-margin values at movement initiation for all subjects.

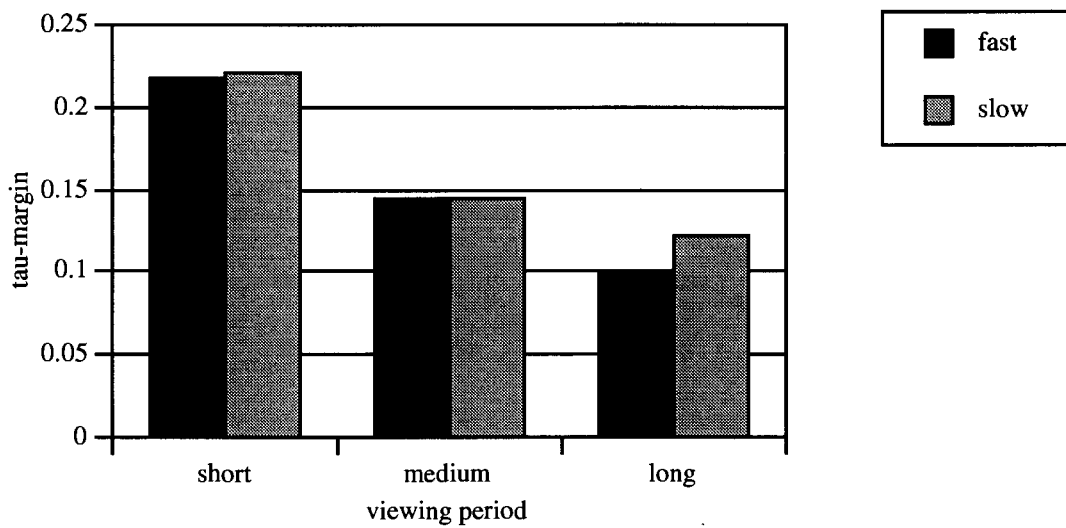


Figure 21. Mean tau-margin values at grasp initiation for all subjects.

Kinematic data

As with experiment 1, selected kinematic measures were used to aid in the determination of task difficulty, to help provide an indication of the type of perceptual information utilized by subjects. Table 5 contains a summary of these selected kinematic data.

Table 5 Mean values for selected kinematic analyses as a function of both approach velocity and viewing time

Dependent measure	<u>fast approach velocity</u>			<u>slow approach velocity</u>		
	Long	Medium	Short	Long	Medium	Short
Movement time (ms)	577	525	442	648	600	545
Time after peak deceleration (%)	27.6	26.8	24.5	29.5	27.3	24.3
Maximum grip aperture (mm)	86	95	104	87	93	95
Time to maximal aperture (%)	75.1	74.2	76.6	74.3	70.1	80.7

(i) Movement time

Significant main effects for both object approach velocity, $F(1,7) = 88.023$, $p < .001$ and for viewing time, $F(2,14) = 53.825$, $p < .001$ were found. Post hoc analyses indicated a decreased movement time with a increase in object approach velocity ($p < .01$). A decreased viewing time also resulted in a corresponding

decreased movement time ($p < .01$) between the longest ($\bar{x} = 613$ ms), medium ($\bar{x} = 562$ ms), and shortest ($\bar{x} = 497$ ms) viewing periods, as may be seen in Figure 22.

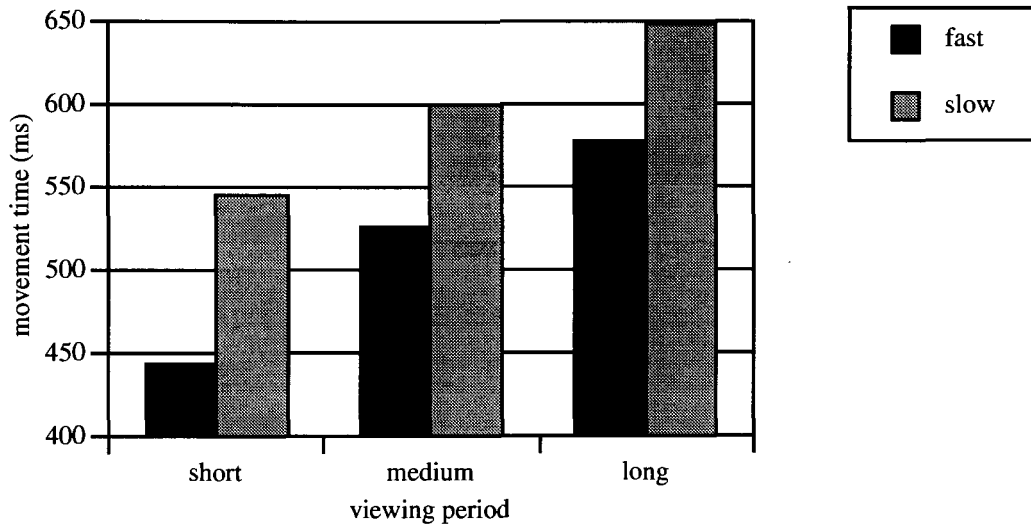


Figure 22. Mean movement time for all subjects.

(ii) Percent time after peak deceleration

Statistically significant differences in the time spent after peak deceleration were found for viewing time only, $F(2,14) = 4.232$, $p < .05$. Post hoc analyses indicating the shortest viewing period to correspond with less time being spent after peak deceleration (24.5%) when compared to the medium ($\bar{x} = 27\%$) and longest ($\bar{x} = 28.4\%$) viewing periods ($p < .05$). No differences between the medium and longest viewing periods were shown (see Figure 23).

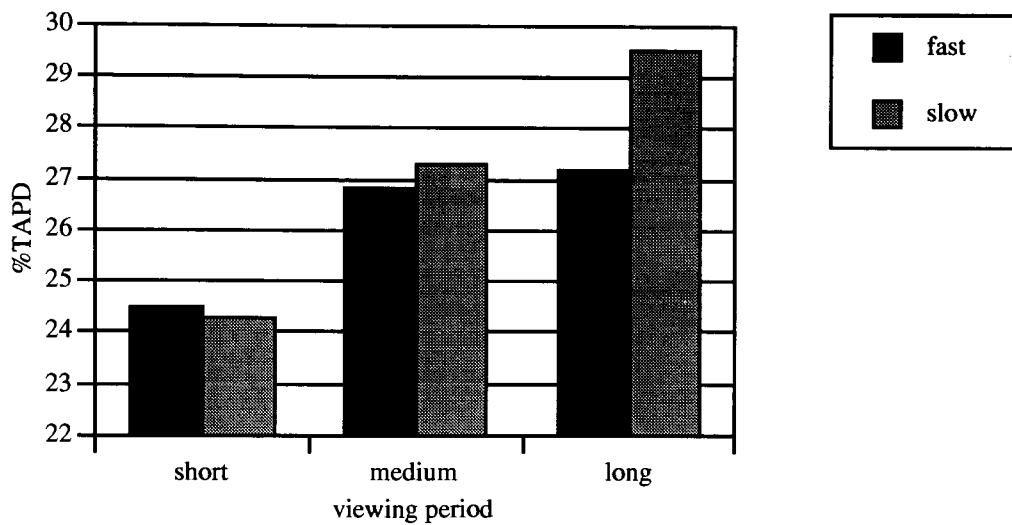


Figure 23. Mean percent time after peak deceleration.

(iii) Grasp component

Maximum grip aperture showed significant main effects for viewing time only, $F(2,14) = 31.916$, $p < .001$, with no differences for velocity being observed. In light of the significant interaction, ($F(2,14) = 5.343$, $p < .05$) a post hoc analyses was carried out. For both velocities, as viewing time decreased, there was an increase in maximal grip aperture. In addition, in the shortest viewing time the fast approach velocity lead to a greater grip aperture from the slow object approach velocity condition. This effect was evident in the other viewing time conditions

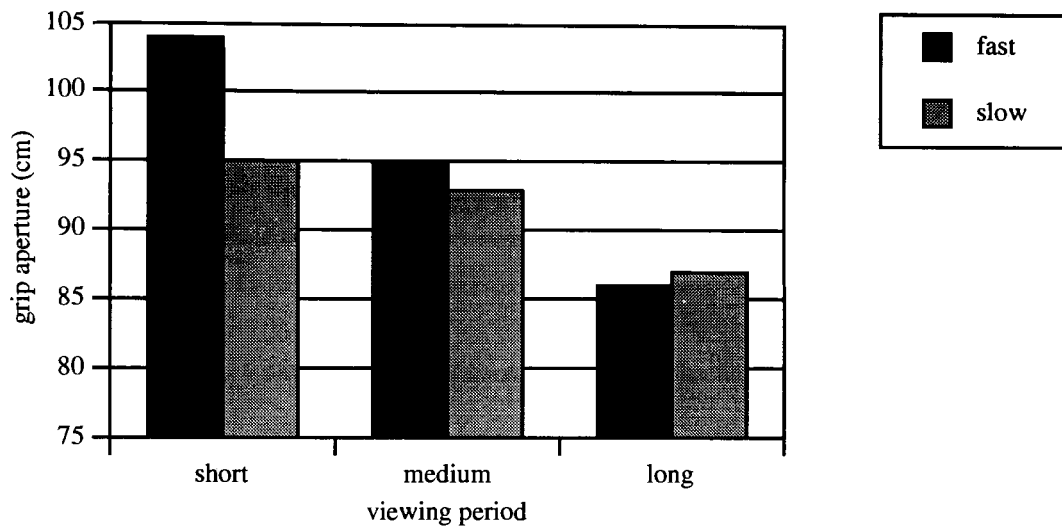


Figure 24. Mean maximal grip aperture for all subjects.

When examined as a percentage of total movement time, differences between object approach velocity disappeared with maximal aperture occurring at around 75% of total movement time. Differences were however found for viewing time, $F(2,14) = 4.404, p < .05$, with maximal aperture occurring relatively later in movement with a shorter viewing period (see Figure 25).

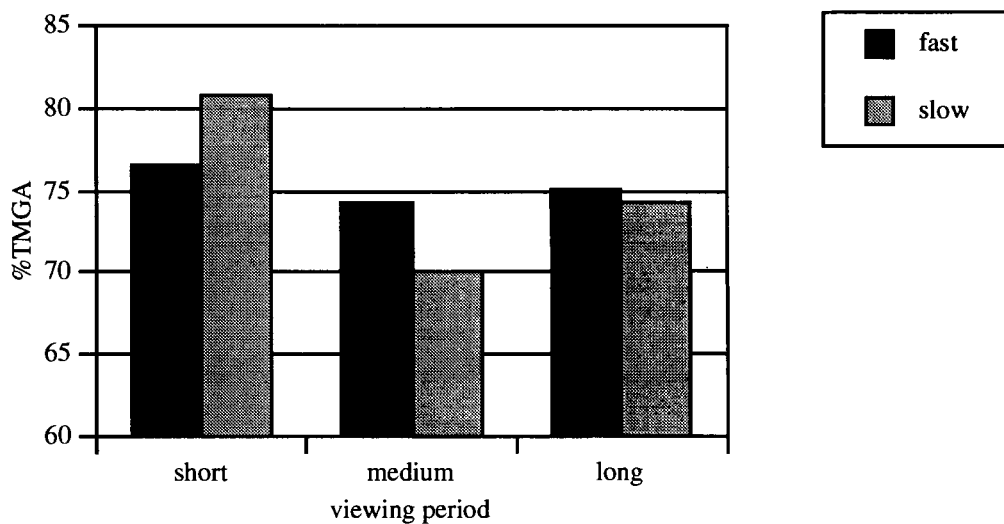


Figure 25. Mean percent time taken to reach maximal grip aperture for all subjects.

Again, a summary of these data and their implications as pertains to the type of perceptual information used by subjects to initiate interceptive movements is provided in table 6.

Table 6. The kinematic measures across both velocity and viewing time in providing support or no support for the usage of optical expansion

Kinematic measure	Velocity		Viewing period	
	Support	No support	Support	No support
Movement time	✓			✓
% Time after peak decel'n	✓			✓
Maximal grip aperture		✓	✓	
% Time to maximal grip aperture	no effect	no effect		✓

Discussion

(i) Temporal component

The main aim of the second experiment was to determine whether under severe environmental constraints such as those imposed by severely restricting viewing time, subjects would use a constant tau-strategy, as opposed to any cognitive method of time-to-contact estimation.

Consistent with experiment 1, results again indicated that a constant distance-to-contact strategy was not used for either movement or grasp initiation. Differences were found between different object approach velocities, a faster approach velocity resulting in a significantly greater distance-to-contact being present at movement initiation, a finding mirroring those found by Chieffi et al. (1992). This increased distance-to-contact at movement initiation with a faster object approach velocity, was again found to be associated with an overall decreased movement time (comparison of Figures 18 and 22). Indeed, if comparable results from experiment 1 (Figures 9 and 13, no interception point, fast and slow velocity, 1.5 sec viewing period) are combined with those from Figures 18 and 22, Figures 26 and 27 may be developed. These latter two figures clearly indicate the increase in movement time as velocity decreases, and the associated decrease in movement time as viewing period decreases, suggesting possibly some sort of functional trade-off or relationship between these variables.

Finding no support for a cognitive distance-to-contact strategy being used to initiate arm movement or hand closure, attention was turned towards the use of a more direct process of time-to-contact estimation, such as that postulated by the employment of tau. Tau-margin values were determined as previously, for direct collision with the eye, rather than for collision with the subjects' hand. As in experiment 1, tau-margin values were not found to be consistent across approach velocity for either movement or grasp initiation with increased values observed with

decreasing object approach velocities. However, an interaction was found with data indicating that a constant tau margin was indeed employed, but only in the case of a relatively fast object approach velocity and a diminished viewing time. This lends strong support to the hypothesis that employment of the optic variable tau is only made in conditions of severe task constraint.

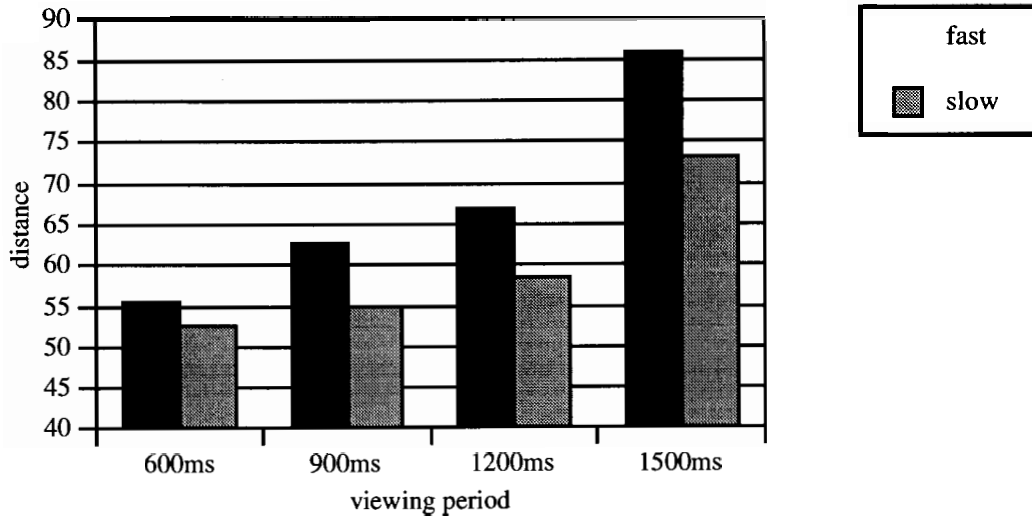


Figure 26. Combined movement initiation distance from experiments 1 and 2.

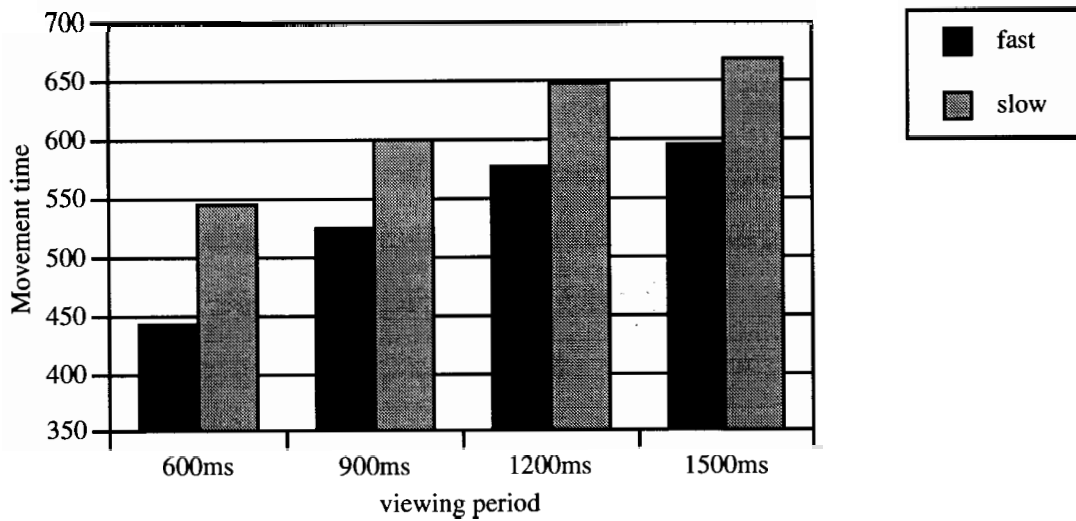


Figure 27. Combined mean movement times from experiments 1 and 2.

(ii) Kinematic component

Movement time and distance-to-contact seemed to follow the same pattern as in the first experiment under differing object approach velocity conditions. An increased movement time was observed with a decreased distance-to-contact at both movement and grasp initiation. In addition to this increase of mean movement time with decreasing object approach velocity, it was also observed (see Figure 27) that movement time increased with an increased duration of time available to view the approaching object. This may be an indication of a less difficult task demand in conditions in which viewing time is severely restricted, or may be a result of the experimental design.

An examination of the percent time after peak deceleration profiles (Figure 27) provides contradictory evidence. It may be noted that a proportionally longer time is spent after peak deceleration in conditions in which viewing time is not so severely restricted. The problem of associating too much importance to the percent time after peak deceleration profiles in the present research however is one which has already been addressed in the discussion of experiment 1. The same problems of subjects intercepting the object with differing limb velocities in different conditions remain in this second experiment. It may therefore be postulated that rather than percent time after peak deceleration profiles in the present experiment providing an indication of task difficulty (in terms of perceptual/optical expansion information received), their providing somewhat erroneous information. As movement time was constrained to a near minimum, with restricted viewing time, as a result of the experimental task (rather than as a direct result of the amount of visual information available) the associated percent time after peak deceleration profiles were similarly affected as in experiment 1 with increased object approach velocity (see appendix B). For it may be that with such short movement times the subjects had insufficient time available to controllably decelerate their movements

towards the object, rather intercepting the object with higher end point velocity of the limb than in other conditions.

Although no measure of movement end point variability was taken in the present experiment, it may be seen in both experiments 1 and 2 that with a decrease in movement time, maximal grip aperture always increases. Wallace and Weeks (1988) and more recently Jeannerod and Marteniuk (1992) have noted that maximal grip aperture increases with a decrease in movement time. It has been suggested that an increased maximal grip aperture reflects the increased probability of making a grasping error, the aperture size being increased to preserve the overall goal of prehension. It has also been suggested that this increase in maximal grip aperture, with a decrease in movement time, occurs to compensate for the increased movement variability in decreased movement time conditions, with some sort of speed/accuracy trade-off, or functional relationship existing. Thus, it may be hypothesized that this "error-compensatory adjustment" is being employed in the present study, to preserve the overall goal of the movement. It may also be noted that for a diminished viewing period the maximal grip aperture profiles provide support for the use of optical expansion information by subjects in the guidance of their actions.

In regard to the time taken to reach maximal grip aperture, it has been suggested that it is reached earlier in more difficult tasks, giving a greater proportion of time to be spent in the deceleration phase of the grasp (Jeannerod & Marteniuk, 1992; Marteniuk et al., 1990). As is seen in experiment 2 this is indeed found to be the case, with maximal grip aperture being reached earlier in conditions of increased viewing time.

The results of experiment 2 fail to provide conclusive evidence for a universal tau-based time-to-contact strategy being employed in the regulation of interceptive movement initiation. However support for the use of a constant tau strategy was

found in conditions of severe task constraint, such as that imposed by a diminished viewing period and a relatively fast object approach velocity. Selected movement kinematics similarly proved to be inconclusive. As table 6 testifies, evidence was found in support of the use of optical expansion information in conditions of increasing object approach velocity, although in conditions of a diminished viewing period only the kinematics relating to maximal grip aperture were found in its support.

General Discussion

General discussion

The main aim of this study was to investigate the visuo-motor timing mechanisms employed in interceptive prehensile motions. In particular, the attempt to determine whether evidence could be found in support of using a constant tau-based strategy, suggesting that these movements are controlled using information derived from the environment via the optical expansion of an approaching object's image on the retina.

Two experiments were conducted. The first examined both the effects of varying the velocity of the approaching object, and of predefining the point at which its interception must be made. The second examined the effects of severe environmental constraints, imposed by constraining the time available to view the approaching object. Selected movement kinematics were used in conjunction with temporal and distance measures to aid in the determination of whether optical expansion information was the information source utilized for the initiation and guidance of interceptive prehension actions. This aided in the determination of whether cognitive or direct perception methods are used in the extraction and usage of environmental information.

Constant viewing periods and differing approach velocities were used in the first experiment, with the underlying rationale being that with a faster object approach velocity subjects would see the object travel over a greater distance than they would with a slower velocity. A greater amount of optical expansion of the object's image on the retina would therefore be available in this faster velocity condition. If optical expansion information is the perceptual source of information

used by individuals to initiate and guide interceptive actions, then the faster velocity condition should be an easier task to perform, as indicated by the selected movement kinematics. The same basic premise, rationale and hypothesizing was applied to the second experiment in examining the the effects of selectively diminishing viewing time. A greater amount of optical expansion information being available with an increased time to view the approaching object.

No support of a constant distance-to-contact strategy used to regulate movement (and grasp) initiation was found in either experiment one or two. The fact that there were significant differences in the distance-to-contact at both movement and grasp initiation for different object velocities suggests that subjects did not use a constant distance-to-contact strategy in timing their actions.

Time-to-contact as specified by the optical variable tau varied inversely with object velocity in both experiments one and two, indicating that at high object approach velocity the subjects initiated both their movement and grasp closure when the object was closer in time, but further in distance, than at slower object velocities. This decrease in time-to-contact with increasing object velocity also corresponded to a decreased movement time, a finding consistent with those of Wing et al. (1986). Similarly, Bairstow (1988) found subjects average movement time decreased as object target speed was increased. In the present experiment these findings hold true for all conditions except with a fast (1.6 m/s) object approach velocity and diminishing viewing period (<1200 ms), where a constant tau-value was observed. These data seem to indicate that subjects did not use a constant or consistent time-to-contact strategy to determine either movement or grasp initiation across all object velocities, except under conditions of severe task constraint, such as that imposed by a diminished viewing time and increasing object approach velocity.

Similar results and conclusions have been obtained in other catching experiments (e.g., Savelsbergh et al., 1992; von Hofsten, 1983; Wallace et al., 1992), in which (as in the present experiment) a significant hand-eye separation relative to the object has existed. Interpretation of these findings however have differed considerably. Von Hofsten (1983) concluded that subjects (infants), initiated their actions in accordance with a coordinate system fixed to the approaching object, rather than to the static background. Lacquaniti and Maioli (1989) however, suggested that no single sensory-perceptual process could be identified as the sole source of information in estimating time-to-contact. They proposed rather that subjects made use of Gibson's affordances to estimate time-to-contact. Wallace et al. (1992) put forward yet another explanation. Whilst agreeing with Savelsbergh and colleagues in that a constant tau-strategy is used when the object is on a near direct collision course with the eye, they postulated that when this trajectory deviates significantly, a pure tau-strategy is not used. They argue rather that tau appears to depend on the velocity of approach (an increasing value for tau being found with a decreasing object velocity, indicating that at a high object velocity the subject's began movement when the object was closer in time but further in distance), as indeed was the case in the present study. It was therefore proposed that subjects based their time-to-contact estimation on something other than tau, or that the information obtained via tau was used to estimate time-to-contact (as opposed to being directly specified by tau).

In support of these above studies Wallace et al. (1992) have gone so far as to provide an indication, in mathematical terms, that when a significant hand-eye separation is present, tau leads to a significant overestimation of time-to-contact with the catching hand. They indicate this overestimation of time-to-contact by tau, to be proportional to the distance between the eye and the hand, and inversely proportional to the objects velocity. This postulation results in small errors being

made (by tau) in higher object velocity conditions relative to the hand-eye separation (see Figure 5, p.24).

Wallace et al. (1992) further propose that a possible alternative to a constant or critical tau-strategy may be that subjects initiate the closure of their grasping action at some value of tau relative to tau at the start of the object movement. This method however has numerous failings. First, it fails to provide any indication as to the method of initial movement preparation or execution, in that no constant ratio is specified. Second, and possibly more pertinent from a direct perception viewpoint, is that it requires not only that subjects keep track of two values of tau, but also that it requires some sort of computation to take place.

The present study does however provide an indication that there may exist some type of perceptual-motor coupling between tau and the time taken to complete the prehension movements. In both experiments one and two, average movement time is seen to increase with a decreasing approach velocity. Additionally, in experiment two, average movement time is seen to increase with an increasing length of time available to view the approaching object. If these data are interpreted as to give an indication as to the type of perceptual information possibly used by subjects to guide their actions, the data are somewhat contradictory. If the data are examined for velocity alone, they seem to indicate that the slower object approach velocity is more difficult than a faster velocity, due to the increase in overall movement time, a result expected if optical expansion information is the perceptual source of information utilized by subjects. If examined for viewing time however, the data seem to indicate that the longer the subjects are able to view the object, the harder the task becomes. This increase in movement time with a longer viewing period is not what is expected if optical expansion information were being used by subjects. These contradictory data however, are most likely the result of an artifact of the experimental design, especially in the case of diminishing viewing time. The

fact that subjects were able to view the approaching object for decreasing periods of time meant that in order to successfully interact with the object, their movements had no choice but to be performed faster. It seems reasonable therefore to largely ignore the movement time data for viewing period in experiment 2, but to consider its changes for velocity only.

In examination of the movement time data for experiment one only, a very high correlation (within subject) was found between the magnitude of tau at both movement and grasp initiation and their corresponding overall movement times ($r = .94$ for movement initiation, $r = .97$ for grasp initiation). This high correlation indicates that whilst successful movements were made, there was a substantial amount of variability in these movements. If an alternative strategy had been used, such as that proposed by a constant tau strategy, the corresponding movement times would have also been constant, and the correlation between tau and movement time would have been much lower.

The question therefore arises as to how might the relationship between tau and movement time have been established. The fact that only a very few catching errors occurred across the whole experiment attests to the notion that even though the subjects were presented with a novel task, they had enough experience in intercepting and catching approaching objects to perform successfully. It may be postulated, as was by Wallace et al. (1992), that this degree of experience may have been sufficient to develop some type of perceptual-motor coupling via a relationship between tau and the manner in which movements were made.

A functional synergy, such as that proposed by Kelso and Tuller (1984) would indicate that changes in one element affect changes in the other. For example, an individual performing an action at a faster speed than normal would choose to initiate their actions at a different value of tau than would be chosen if performing at normal speed. Alternatively, tau may be the indicator as to when movements are

initiated, with the subsequent movement times corresponding accordingly. Whether tau dictates or is dictated to makes no difference in this case to the success of the action, for if the perceptuo-motor coupling is functionally related, the resulting movement execution will always be successful. For the present experimentation, it seems that the nature of this coupling is fairly robust, for it remained intact across a range of randomly presented velocity and interception point conditions ($r = .98$ for movement initiation, $r = .88$ for grasp initiation, with a predefined interception point). It remains however that individuals may not use tau or other deviations of optically specified information in their estimation of time-to-contact information when significant hand-eye separation is present. The final analyses of this thesis attempted to address this problem through the examination of certain selected movement kinematics.

In examination of the percent time after peak deceleration in both experiments one and two, it is evident that in both cases the deceleration phase appears to be directly affected by object velocity. A significant increase in time was observed with a decrease in object approach velocity. However these data may be due to a modified version of the task being performed in which subjects did not decelerate their limb to the same extent in all conditions.

Unlike the deceleration profiles of prehension movements, the implications of maximal grip aperture and its associated time to (or after) are less subject to discussion. It is generally accepted that the size of the maximal grip aperture reached during a prehensile motion may be used to give some indication as to the task difficulty in that a larger maximal grip aperture gives an indication of increased task difficulty or constraint. In the present experimentation, the purpose of the examination of grip aperture may be seen to be twofold. Primarily, its examination would aid in the determination of task difficulty, and could therefore be related to whether optical expansion information was likely to have been the perceptual source

of information utilized by subjects to initiate and guide their actions. Secondly, was the purpose of dismissing the contention that intrinsic object properties only (i.e., size, shape, texture) affect the shaping of the grip aperture. It has been proposed that whilst this contention may hold true for static prehensile motions made with constant movement times towards stationary objects, a far more versatile usage of maximal grip aperture is made when variations of movement time or object location (i.e., its velocity) are made.

As has been documented earlier, maximal grip aperture was found to increase with increasing object velocity in both experiments. This is a finding consistent with neither the belief that intrinsic object properties only affect grip aperture profiles, or the data obtained by Chieffi and colleagues, who found maximal grip aperture to be formed independently of object approach velocity and sensitive only to changes in object size.

One possible explanation for this discrepancy in findings between the present study and that by Chieffi et al. (1992) may be related to the velocity of the approaching object and the subsequent alterations in subjects movement times. In the Chieffi et al. (1992) study, object velocity was varied from only .25 m/s to .64 m/s, with corresponding changes in movement times having a range of only 55 ms. In the present study, end-point object velocity ranged from .80 m/s to 1.6 m/s, with corresponding movement time changes of up to 135 ms. It seems therefore that whilst in prehensile motions made towards stationary or slowly moving objects, the shaping of the hand is governed primarily by intrinsic object properties, in moving towards faster moving objects, when significant changes in movement time are also affected, the object velocity has a direct influence on the grasp aperture.

In so far as implications as to the type of perceptual information utilized by subjects are concerned, the data from the present study do not seem to lend support to the usage of optical expansion information. For, with an increased maximal grip

aperture being found with a faster object approach velocity, the implication made is that this is a more difficult task to perform. This is not what would be expected if optical expansion information were being used. However, when data from experiment two are looked at, it may be seen that an increased aperture is found in conditions of decreased viewing time. This is a result which would be expected if perceptual information were being derived from the expanding objects image on the retina. It may then be argued that the data pertaining to maximal grip aperture are somewhat contradictory in terms of support or dismissal for the usage of optical expansion information to initiate and guide subjects actions. It may be proposed that the grip aperture data relating to changes in object velocity are influenced by more than merely the conditions of object approach . It has been suggested (Wing et al., 1986) that a decrease in movement time (albeit to stationary objects) will affect changes in maximal grip aperture, due to an increased movement end-point variability being observed in movements performed at a faster speed than normal. They postulate that with a decrease in movement time, the failure to decrease movement variability as the target was approached, are because there was less time after maximal grip aperture in which to affect corrections based on visually guided feedback.

If these same data are examined from the present study, it is evident that in neither experiment one or two were significant effects for velocity found in the percent time to maximal grip aperture profiles. It therefore becomes difficult for any explanation to be made as to the exact nature of the increased maximal grip aperture found with a decreased movement time, other than to say that it exists. This "error compensatory-adjustment", as termed by Wing et al. (1986) does however seem to be a very feasible explanation for alterations in grip aperture, with a wider aperture giving a greater tolerance for positioning errors just prior to contact. It is therefore proposed that whilst object velocity alone does not seem to

suffice any alterations in maximal grip aperture, the associated changes in movement time do facilitate changes, providing an indication that some sort of functional relationship exists between movement time and maximal grip aperture.

In so far as to the effects of predefining the point at which the object is required to be intercepted, it seems that adding this constraint makes for a more difficult task, as reflected both by maximal grip aperture and its associated relative time to. The effect of a diminishing viewing period seem, from the percent time to maximal grip aperture profiles, to suggest that optical expansion information is not the perceptual source of information used to initiate and guide subjects actions.

Summary and Conclusions

Summary and Conclusions

This thesis set out to explore the possible mechanisms which humans may employ in the timing of interceptive actions. Previous investigations concerning this problem had directed themselves primarily with the notion of how whole body actions are regulated, such as the timing of braking behaviour in driving (Lee, 1976), and stride regulation in long jumping (Lee, Lishman, & Thomson, 1982), with little work being conducted towards ball catching and hitting activities. However as interest in the notion of how coincidence timing tasks are carried out grew, so did the body of research concerning the problem. This led not only to an increased interest in the area, but also to an increased variety of tasks and species studied leading ultimately to the study of coincidence/interceptive timing in tasks as varied as flies leg projection in landing (Wagner, 1982) to examination of aerial docking by hummingbirds (Lee, Reddish, & Rand, 1992).

However, the question of exactly what perceptual information allows such coordinated and precise movements to be made repeatedly with very little, or no, performance error has remained one which is as yet incompletely understood. Although it is generally regarded that the extraction of this multifarious perceptual information is complex, requiring information about the dynamic (spatial and temporal) relationship of the organism to its environment, the exact nature of how we extract, interact and exploit information from the environment, still remains largely unanswered.

While being in general agreement that the initiation of interceptive movements or coincidence timing skills seems to be most consistently geared to the remaining

time-to-contact (t_c), rather than any other potential source of optical information, (such as the reaching of some critical distance or velocity), researchers have questioned the exact nature of the extraction and utilization of this information. This has led to the emergence of two major paradigms, encapsulating differing perspectives on how such actions are regulated. One encompasses the traditional views of cognitive science, in which some cognitive computation and calculation of distance and velocity information has been proposed. The other, a more radical view, stems from the direct perceptionist views of J.J. Gibson (1966).

One of the major proponents of this so called direct perception, or ecological theory of movement regulation, has been David Lee. Through his works, he proposed that the critical time at which an object would reach either its point of interception, or its point of collision, could be directly specified by the expanding optical image of the object projected onto the retina of an observer's eye. Through the usage of this retinal image, it was proposed that an organism could accurately initiate and regulate actions without regard to any specific cognitive processes. However, the exact visual sources of information have, as yet, not been identified, with no unequivocal evidence emerging as to whether time-to-contact is empirically derived, or obtained directly from optical expansion information, as initially postulated by Lee (1976).

The present study attempted to address some of these problems, in the hope of elucidating both some of the mechanisms of visual control employed in interactive actions and how our interaction with the environment is affected by the presence of various constraints. In particular, it attempted to specify precisely what perceptual information about real world distances and velocities might be used to estimate time-to-contact of limb and a moving body, and how variation of this visual information may influence our movements.

The first experiment was conducted in an attempt to determine the influence of differing object approach velocity, and of having a predefined point at which subjects had to intercept an approaching object. This attempted to determine whether a direct (tau based) process is used in all natural situations, or whether it is only employed in carefully controlled situations. Results from this first experiment provided no conclusive evidence in support of either a cognitive or a tau-based strategy being used. Kinematic information however seemed to provide an indication that the type of perceptual information which is used to guide our actions may be obtained from that of optical (retinal) expansion.

To further examine the movement control strategies employed under differing task constraints, a second experiment was conducted which attempted to push the visuo-motor system to its limits, by restricting the amount of visual information available by constraining of viewing time. This second experiment similarly provided no support for the employment of a cognitive based strategy being used. It did however indicate that under severe environmental constraints velocity, a constant tau strategy may be employed. The kinematic data remained inconclusive as to the type of perceptual information best utilized by subjects, although some evidence for the use of optical expansion information was found.

In regard to movement initiation and regulation in coincidence timing tasks, it seems that when significant hand-eye separation is present, as was the case in the present experimentation, the tau-margin seems to depend on the velocity of object approach. Subjects based their time-to-contact estimation on something other than a constant tau-margin, or used the information obtained via tau to estimate time-to-contact (as opposed to being directly specified by tau). Under conditions of severe constraint however evidence for a constant tau-strategy was found. The existence of some sort of functional synergy between the value of tau and movement time

seems to be a more feasible explanation, with (in both experiments one and two) a high correlation between these variables existing.

In concluding, it must be stated that whilst it is possible that subjects did not consistently use a constant tau-strategy or other forms of optically specified information in their estimates of time-to-contact, they may have utilized it in conjunction with some other temporal measure as has been suggested by Bootsma and van Wieringen (1990). While it has been argued by Tresilian (1991) that a tau based strategy cannot be distinguished from a distance divided by velocity strategy based on information that is not optically specified, it was hoped that through the additional usage of selected movement kinematics, this would not be the case. However, the tau information obtained in the present study has again shown that severe limitations exist in the use of a critical or constant tau strategy being employed when significant hand-eye separation is present, except it seems under conditions of severe environmental constraint.

It is nevertheless suggested that subjects are able to use the information contained within tau to help estimate time-to-contact, with the value of tau being dependent on the velocity of object approach. Significant movement alterations are also affected by these non-constant movement times resulting from the use of a constant tau strategy. Most notably, the very strong coupling of movement time with maximal grip aperture establishing a functional relationship to ensure successful movement execution. Finally, it may be added that whilst intrinsic and extrinsic object properties and their effects upon the various components of prehension may be well established when regarding stationary objects, the robustness of these properties must come into question when interacting with approaching or moving objects.

Footnotes

¹We note that the studies were observational only. Animals were observed in ecologically valid, or natural activities under changing conditions.

²The dilation rate equals the rate of separation of the images of two points on a (spherical) projection surface centered on the point of observation.

³So termed as it refers to the velocity field as a whole.

⁴Object velocities were determined from trial runs. Sample profiles are provided in Appendix B. After an initial acceleration, velocities remained fairly constant through the range of viewing time due to an approximate balance between acceleration forces (gravity) and deceleration forces (friction of pulleys for weight system, and frictional resistance of the trolley).

⁵I thank Dr. Marteniuk for the provision of this software, and Mrs L. Kalbfleish for her help in learning to use the software.

⁶Occurrences in data collection in which no data is recorded in a frame due to ireds "missing" from the camera lenses. This was rectified by interpolation, a process of joining frame values prior to, and immediately following a glitch.

⁷In addition to data from only 9 subjects being used, in many cases data from certain subjects had to be discarded for the purpose of analyses due to various insufficiencies.

⁸As with experiment 1 some data had to be discarded for the purpose of analyses due to insufficiencies.

Appendix A

Tau as a time-to-contact estimator for accelerative approaches

The standard formula for distance travelled under constant acceleration to give t_c (during a linear approach) is

$$Z = Vt_c + 1/2 At_c^2 \quad (1)$$

where:

$A(t)$ = signed magnitude of relative acceleration (assumed to be constant).

$V(t)$ = relative speed.

$Z(t)$ = distance between object and point of observation.

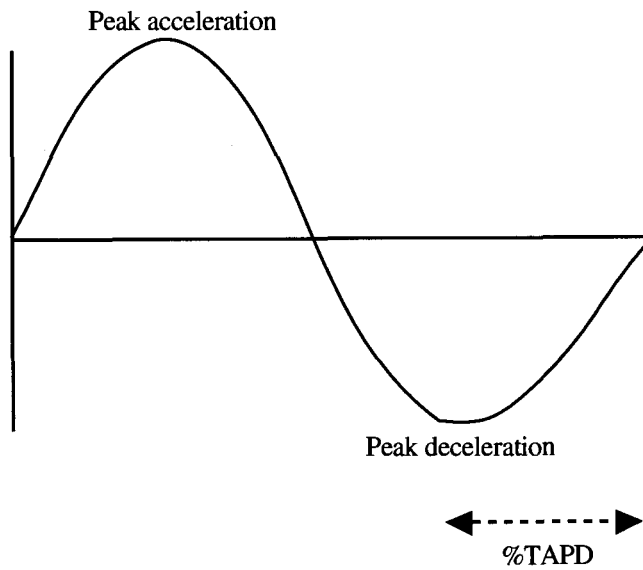
By treating equation 1 as a quadratic in t_c and taking the positive root, the expression [derived by Lee et al., 1983] for the time-to-contact of the moving object under the conditions described above, is

$$t_c = \frac{\tau_1 [1 - \sqrt{(-2t_1 - 1)}]}{(1 + t_1)} \quad (2)$$

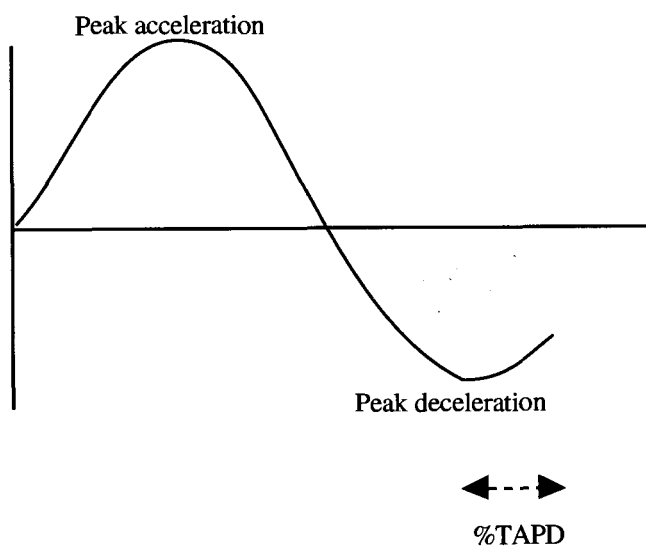
Equation 2 demonstrates that for accelerative approaches, t_c is specified by a far more complicated expression than τ_1 alone (which specifies t_c in the same circumstances but with constant velocity).

Appendix B

Schematic acceleration profiles for prehension actions



Typical acceleration profile for prehensile actions when object is reached with zero end point velocity.



Typical acceleration profile when zero end point velocity is not reached.

Appendix C

Anova tables for experiment 1

Initiation distance

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	134.964	1.538	
Error	8	87.744		.250
v	2	796.334	26.091	
Error	16	30.522		.001
cv	2	14.367	1.798	
Error	16	7.986		.197

Grasp distance

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	6955.205	4.204	
Error	6	1654.326		.086
v	2	1076.731	14.023	
Error	12	767.839		.001
cv	2	2314.734	5.474	
Error	12	422.875		.024

Tau (initiation)

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	.108	11.904	
Error	8	.073		.008
v	2	1.557	82.347	
Error	16	.151		.001
cv	2	.016	1.836	
Error	16	.069		.191

Tau (grasp)

Source	D.F.	Mean Square	F	P
c	1	.008	5.594	
Error	6	.001		.055
v	2	.009	53.348	
Error	12	.000		.001
cv	2	.001	2.941	
Error	12	.000		.091

Movement time

Source	D.F.	Mean Square	F	P
c	1	.048	4.043	
Error	8	.012		.079
v	2	.040	9.837	
Error	16	.004		.001
cv	2	.002	.723	
Error	16	.003		.506

%time after peak deceleration

Source	D.F.	Mean Square	F	P
c	1	379.688	3.534	
Error	7	107.438		.102
v	2	50.021	4.443	
Error	14	11.259		.032
cv	2	31.688	3.588	
Error	14	8.830		.055

Maximal grip aperture

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	490.623	117.355	
Error	5	4.181		.001
v	2	175.696	34.661	
Error	10	5.069		.001
cv	2	17.939	1.230	
Error	10	14.590		.333

%time to maximal grip aperture

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	360.610	9.670	
Error	5	37.252		.026
v	2	16.860	1.806	
Error	10	9.337		.214
cv	2	7.587	1.226	
Error	10	6.190		.334

Appendix D

Anova tables for experiment 2

Initiation distance

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	503.820	36.861	
Error	7	13.668		.001
v	2	316.438	27.461	
Error	14	11.523		.001
cv	2	38.130	10.896	
Error	14	3.449		.001

Grasp distance

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	66.881	7.087	
Error	6	9.437		.037
v	2	120.381	28.011	
Error	12	4.298		.001
cv	2	23.524	9.424	
Error	12	2.496		.003

Tau (initiation)

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	3.858	54.970	
Error	6	.070		.001
v	2	.155	11.474	
Error	12	.013		.001
cv	2	.089	14.859	
Error	12	.006		.001

Tau (grasp)

Source	D.F.	Mean Square	F	P
c	1	.001	.486	
Error	6	.001		.511
v	2	.043	47.683	
Error	12	.001		.001
cv	2	.000	1.883	
Error	12	.000		.194

Movement time

Source	D.F.	Mean Square	F	P
c	1	.048	4.043	
Error	8	.012		.079
v	2	.040	9.837	
Error	16	.004		.001
cv	2	.002	.723	
Error	16	.003		.506

%time after peak deceleration

Source	D.F.	Mean Square	F	P
c	1	379.688	3.534	
Error	7	107.438		.102
v	2	50.021	4.443	
Error	14	11.259		.032
cv	2	31.688	3.588	
Error	14	8.830		.055

Maximal grip aperture

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	490.623	117.355	
Error	5	4.181		.001
v	2	175.696	34.661	
Error	10	5.069		.001
cv	2	17.939	1.230	
Error	10	14.590		.333

%time to maximal grip aperture

<u>Source</u>	<u>D.F.</u>	<u>Mean Square</u>	<u>F</u>	<u>P</u>
c	1	.750	.023	
Error	7	32.560		.884
v	2	171.521	4.404	
Error	14	38.949		.032
cv	2	68.813	3.753	
Error	14	18.336		.049

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