PERCEIVING IMPENDING COLLISIONS

TIME-TO-COLLISION OF LOOMING SPHERICAL OBJECTS: TAU REVISITED

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ABSTRACT

As an object approaches an observer's eye, optical tau, defined as the inverse relative expansion rate of the object's image on the retina (Lee, 1976), approximates time-to-collision (TTC). Many studies have provided support that human observers use TTC, but evidence for the use of tau remains inconclusive. Here we present two studies that investigated the use of tau in object-motion and observer-motion situations. Participants were presented with a visual display of two sequentially approaching objects, and asked to compare TTC at the moment of object disappearance. In Study I, we dissociated several variables that potentially contributed to TTC perception and found that participants were most sensitive to TTC information when completing the task, and less sensitive to non-time variables such as distance-to-collision, speed and object size. Moreover, when we manipulated sources of information to specify conflicting time-of-arrivals, TTC specified by tau was weighted more than TTC derived from distance and speed.

In Study II, observers estimated TTC of a looming target that was presented in front of a stationary or simultaneously approaching background object. We compared responses to when only the target approached, when both target and background object approached, and during simulations of forward self-motion. Results demonstrated that participants overestimated TTC in situations where the surroundings of the target's contours expanded at a reduced rate. Moreover, simulated self-motion was unnecessary to induce this bias, as results were comparable in situations where this relative expansion was limited to the target's immediate surroundings. Overall, we conclude that even in presence of other monocular cues, observers showed a greater tendency to use tau information when estimating TTC. Furthermore, we demonstrated that a relative tau variable, based on the relative rate of expansion, is utilized whenever expansion beyond the object's immediate boundaries is less than the target's absolute rate of expansion.

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LIST OF ABBREVIATIONS AND SYMBOLS

In order of appearance

TTC: Time-to-collision; time-to-contact; time remaining before contact with a directly approaching object

DTC; d: Distance-to-collision

v: Speed of object approach

θ: Image size; angle subtended on retina

τ: Tau, the inverse of the incoming object's relative rate of expansion on the retina

ROE; θ': $\Delta\theta/\Delta t$ - Rate-of-expansion

SAE: Size arrival effect; phenomenon describing observer biases to perceiving larger objects as arriving earlier

TTCt: Time-to-collision specified by the object's image (i.e. tau)

TTCd: Time-to-collision specified by the object's distance (i.e. distance/speed)

S: Object's physical size

PSE: Point of subjective equality

TTP: Time-to-passage; time remaining before object passes the fronto-parallel plane containing the eyes

φ: Psi; the angle subtended on the retina representing the vertical displacement of an object

1-OA: Target-only approach condition

2-OA: Two-object approach condition

FSM: Forward self-motion condition

DECLARATION OF ACADEMIC ACHIEVEMENT

The two presented studies were collaboration projects with JJ Yan. Both JJ and I were heavily involved in designing the study, running participants, analyzing results and the writing of a recently accepted manuscript (Yan, Lorv, Li and Sun, *in press*). Credit for programming experiments and calculating parameters for our stimuli is attributed entirely to JJ. In regards to this thesis, it should be noted that Study I was derived heavily from Yan et al. (*in press*).

I. GENERAL INTRODUCTION

Humans and other animals constantly interact with a dynamic environment. These interactions can include an observer moving towards a stationary object, an object moving towards a stationary observer, or a combination of both. Over the past few decades, numerous studies have tried to elucidate which sources of visual information are used to mediate these types of interactions. Given that the time required for performing an action is biologically constrained (as a result of neural activity and sequences of muscle movements), humans and animals likely use predictive timing information specified by visual cues to guide and adjust their actions (Lee, 1976). One potentially important piece of information that the literature often focuses on is time-to-collision (alternatively time-to-contact; TTC). TTC is defined as the time remaining before contact between an observer and object, and can theoretically be derived in several ways.

For instance, as shown in Equation 1, TTC can be computed using the incoming object's distance from the observer (*d*; distance-to-collision or DTC) divided by the target's approach speed (*v*) (Lee, 1976; Cavallo and Laurent, 1988).

$$TTC = d/v \qquad (1)$$

TTC derived in this manner is often referred to as the "computational" or "inferential" approach as we compute or infer TTC from spatial or temporal cues, which by themselves do not specify time. As such, this approach necessitates that both distance and velocity information are readily available from the optic array. While it is possible that TTC is generated in this manner, studies in the past few decades have also investigated other perceptual mechanisms.

One popular alternative theory suggested by Lee (1976) argues that TTC can be extracted directly by our visual system. This "direct perception" theory, based on Gibson's ecological theory of perception (for review, see Gibson, 1966), suggests that TTC is specified by a single source of information in the optic array, specifically the optical variable tau (τ). Tau is defined as the inverse of the incoming object's relative rate of expansion on the retina (Lee, 1976; for review, see Lee, 2009), and is represented mathematically as:

$$TTC \approx \theta/(\Delta\theta/\Delta t) = \tau \qquad (2)$$

where θ, represents the projected angular size of the approaching object (image size), and $\Delta\theta/\Delta t$, the image's rate of expansion (ROE). Furthermore, tau approximates the remaining TTC given the current speed and thus neglects acceleration (see Study I: General Discussion).

Optical tau is often regarded as an invariant. It is a monocular variable that directly specifies a physical property of the environment, and is moreover, veridical and independent of other sources of information, such as the distance and velocity of the incoming object. Tau theory argues that an optical tau strategy is necessary and sufficient to perceive TTC (for review, see Hecht and Savelsbergh, 2004**)**. Compared to the time-consuming and less accurate computation of distance and speed (as demonstrated by speed estimation tasks, see Rushton and Duke, 2009), optical tau provides a quicker, more accurate and efficient estimate of TTC. The capability to perceive tau, as such, would be especially useful in situations which require immediate and accurate responses (such as playing table tennis as demonstrated by Bootsma and van Wieringen, 1990).

Evidence for tau

Prior to the conception of tau, it had already been established that the symmetrical expansion of an image (also known as looming) elicited avoidant responses in humans (see Bower et al., 1970; Ball and Tronick, 1971) and other animals (i.e. monkeys, cats, birds, frogs and fiddler crabs, see Schiff, 1965). These responses, moreover, did not occur when observers were instead presented with asymmetrically expanding or receding images. Simple expansion provides little distance or velocity information, and suggests that looming images alone could sufficiently specify an impending collision. As a result, numerous studies have attempted to validate the use of a tau strategy in a variety of timing dependent behaviour.

Earlier studies on tau focused on its use in nature, and were especially interested in tau's role in the initiation of behaviour. Early behavioural observations on humans and other animals (i.e. Lee, 1980; Lee and Reddish, 1981**;** Wagner, 1982; Lee et al., 1983) claimed that coordinating or executing certain behaviours were most consistent with the use of a tau strategy. Timing the start of an action is vital for its successful execution. For instance, in the case of the diving gannet (*Sula bassana*), streamlining of wings must occur at precise moments to avoid injury. In order to investigate whether tau could be responsible for the initiation of streamlining, Lee and Reddish (1981) filmed diving gannets and compared the observed behaviour to strategies involving tau, or strategies involving other variables such as height or velocity. The researchers argued that recorded behaviour best correlated with a tau strategy. Using comparable approaches, tau was also concluded to be involved in participants punching a falling ball (Lee et al., 1983), and athletes performing long jumps (Lee, 1991). In addition, several of these studies (Lee et al, 1983; Bootsma and van Wieringen, 1990) also demonstrated that behaviours exhibited strong action-perception coupling. It was argued that optical tau mediated the continuous adjustment of movement during the completion of an action. Meanwhile, it was also observed that a tau-like strategy involving the derivative of tau (tau dot), correlated with the initiation and adjustment of braking behaviour in virtual environments (Yilmaz and Warren, 1995; Andersen et al., 1999) real world driving (Lee, 1976; based off data obtained by Spurr, 1969), and aerial docking behaviour of hummingbirds (Lee, Reddish and Rand, 1991). Lastly, the inverse of tau from a looming shadow has also been demonstrated to correlate with neural activity in the optic tectum of pigeons, providing further evidence that animals have built in structures that are sensitive to this variable (Wang and Frost, 1992; Sun and Frost, 1998).

Taken together, these studies provide compelling evidence for the use of tau in timing dependent behaviour. However these aforementioned studies only observed how well behaviours correlated with a tau strategy (for review, see Wann, 1996). As such, we cannot ascertain whether time was drawn directly from tau or inferred from other sources such as distance/speed (for review, see Wann, 1996). Various empirical studies (i.e. Schiff and Detwiler, 1979; Todd, 1981; McLeod and Ross, 1983; Schiff and Oldak, 1990; Sun, Carey and Goodale, 1992; Wang and Frost, 1992; Kaiser and Mowafy, 1993; Regan and Hamstra, 1993; Sun and Frost, 1998) have suggested that optical tau is in fact predominantly used to perform a variety of TTC estimation tasks. For example, Schiff and Detwiler (1979) presented observers with a shadow of a looming ball, and demonstrated that a two-dimensional looming image was sufficient for accurate estimations of TTC. Moreover, it was shown that the addition of background information (such as ground or sky texture) did not significantly improve estimations. The authors concluded that the looming image itself contained sufficient information (i.e. tau) to specify TTC, implying that distance and speed information are unnecessary. Regan and Hamstra (1993) later strengthened this claim by demonstrating that tau specifically, rather than its constituents (image size and rate of expansion), was used by the observer to judge relative TTC of approaching targets (see Study I for more details). Finally, probably the strongest evidence for tau originated from a group of studies led by Savelsbergh and colleagues (Savelsbergh, Whiting and Bootsma, 1991; Savelsbergh et al., 1993) which involved the direct manipulation of the optical variable. In these studies, participants were presented with a subtly deflating ball (in subsequent studies, inflating; see van der Kamp, 1999) that led to a discrepancy between TTC specified by tau and TTC specified by distance/velocity (see Study I for more detail). Results showed that observers were reliably influenced by this manipulation, and that grasping motions made to catch deflating balls (specifically the closing velocity of the hand) were initiated later compared to balls of constant size. Responses were consistent with a tau strategy despite no differences in distance and velocity information specified by the deflating and constant-sized objects.

Multiple sources may influence TTC perception

Nonetheless, despite such evidence, many studies (i.e. Cavallo and Laurent, 1988; Judge and Bradford, 1988; DeLucia, 1991; Law, et al. 1993; Heuer, 1993; DeLucia and Warren, 1994; Kerzel, Hecht, and Kim, 1999; Rushton and Wann, 1999; Oberfeld and Hecht, 2008; for comprehensive reviews, see Wann, 1996; Tresilian, 1999; DeLucia, 2004 and DeLucia, 2008) have argued and demonstrated that other variables also significantly impact TTC perception. For instance, DeLucia (1991) showed that when viewing two approaching objects simultaneously, observers had a tendency to perceive the larger object as arriving earlier, even if the smaller object specified a sooner TTC. This phenomenon, termed the size-arrival effect (SAE), provided evidence that objects' relative sizes, a pictorial cue that does not affect tau, can bias TTC perception. The SAE, moreover, has been replicated in several subsequent studies involving absolute TTC judgment tasks (Heuer, 1993; DeLucia and Warren, 1994) and interceptive behaviours (van der Kamp, 1997; Rushton and Wann, 1999; for review, see DeLucia, 2005).

Additionally, other tau-irrelevant variables, such as approach speed (Cavallo and Laurent, 1988; Kerzel, Hecht and Kim, 1999), distance of the target (Cavallo and Laurent, 1988; Law et al., 1993), disparity (Heuer; 1993; van der Kamp; 1997; Oberfeld and Hecht, 2008) and the presence of distracters (Oberfeld and Hecht, 2008) have also been implicated to affect TTC perception. In several of these cases, the presence of multiple sources of information (i.e. looming in addition to background textures or binocular cues, such as disparity) resulted in more accurate observer responses (van der Kamp, 1997; Gray and Regan, 1998). Interestingly, Heuer (1993) also reported that the use of specific information could change depending on the present situation. In his study, participants were dichoptically presented with an array, that if overlapped would be separated by a lateral distance. Each field consisted of a circle that was perceptually fused and appeared to approach the observer via looming and disparity. This target disappeared moments prior to contact with observers, after which participants had to indicate the object's moment of arrival. In some trials, disparity and looming provided conflicting information as either the lateral distance or size of the target was held constant. Results demonstrated that participants were most influenced by looming when the target was large, but switched to using disparity information when the target was small. As Equation 2 implies, tau may be ineffectual when the image size of the approaching object (θ) is sub-threshold. Nonetheless, while these results demonstrated that tau may be used in certain situations, it revealed that other variables could also contribute to TTC perception, and may even be utilized preferentially.

In sum, the literature suggests that a variety of variables are available that may contribute to TTC perception. Multiple cues may work together and provide redundant information (for review, see DeLucia, 2004), or alternatively, observers may select for certain information depending on the present situation (Heuer, 1993; van der Kamp, 1997; for review, see Tresilian, 1999). While tau may be sufficient in judging TTC when it is the only source of information available (as demonstrated by Schiff and Detwiler, 1976; Regan and Hamstra, 1993; and argued by Tresilian, 1999), it remains uncertain whether tau is in fact still primarily used in the presence of other information. In Study I, my colleague JJ Yan and I investigated whether stationary participants under monocular conditions, utilized tau to estimate TTC of an approaching spherical object. This looming target was simultaneously presented with cues related to distance and speed. Our primary interest was to investigate whether TTC estimations were derived using tau (as the current task was performed under monocular conditions, see Study I: General Discussion) or the distance/speed ratio. The current study further manipulated optical tau and sought to quantify the contributions of these different available cues to observer judgments.

II. STUDY I: Time-to-collision during object approach: contributions of tau in the presence of multiple sources of information

To evaluate the contribution of individual sources to TTC perception, it is necessary to first dissociate different co-varying variables (e.g. TTC, distance and speed from Equation 1) that may have influenced TTC judgments. Among the studies that investigated the use of tau, two groups of studies deserve special considerations for their methods used in controlling visual information. The first group of studies, conducted by Regan and colleagues (Regan and Hamstra, 1993; Regan and Vincent, 1995; Gray and Regan, 1998; Gray and Regan, 2006), devised a novel and systematic approach to isolate tau from other related optical variables. For instance, in an attempt to dissociate tau and rate of expansion at the moment of object presentation (see Equation 2), Regan and Hamstra (1993) created a two-dimensional matrix in which the two variables were systematically varied, one along each dimension, at the start of object trajectory. Cells of the matrix then formed trials using the values of these two variables as parameters. By examining responses to relative judgments of TTC, results showed that the observer was consistent with the use of a tau strategy, and that his judgment was independent of rate of expansion. Additionally, they found that the observer was also able to specifically judge rate of expansion, which was done independently of tau. Regan and Hamstra (1993) thus concluded that separate and independent systems exist for estimating TTC and rate of expansion. This orthogonal matrix design was replicated and later used to dissociate several other optical variables which may have also influenced TTC estimations (Regan and Vincent, 1995; Gray and Regan, 1998; Gray and Regan, 2006).

Regan and colleagues, however, only applied their psychophysical manipulations in situations where image expansion was the sole cue available. It remained uncertain, therefore, whether tau would still be used if other information specifying time, such as distance over speed, was also present. In these situations, both tau, and the distance/speed ratio would have provided congruent TTC information. Given that both these sources are veridical, observers could theoretically rely on either or both to accurately estimate TTC. Although some studies have suggested that observers are poor at perceiving distance or speed of motion-in-depth (e.g. Rushton and Duke, 2009), it is unknown whether tau would still contribute to TTC judgments under conditions containing other sources of information. To resolve this issue, a second group of studies initiated by Savelsbergh and colleagues (Savelsbergh, Whiting and Bootsma, 1991;

Savelsbergh et al., 1993; van der Kamp, 1999) directly manipulated object size to create a conflict between TTC specified by tau and that of other sources. In these studies, participants had to grasp an incoming ball whose physical size was covertly manipulated through inflation or deflation during approach. Results showed that observers' responses shifted in the direction predicted by tau. Later quantitative analyses (Wann, 1996; van der Kamp, 1999), however, found that these response shifts were much smaller than predicted by a tau only strategy. A similar paradigm in an animal target-directed locomotion task also revealed comparable findings (Sun, Carey and Goodale, 1992). Altogether, these results suggested that tau is likely useful but may not be the only factor influencing TTC perception.

All told, although observers may not entirely rely on a tau only strategy (Tresilian, 1999), tau may still contribute to TTC-related tasks (Rushton and Gray, 2006) along with other sources of information. Current research questions therefore were directed to re-examine the contributions of TTC and various non-time variables during TTC estimation. In addition, if TTC was specifically used in this type of task, we wanted to determine how different TTC sources, specifically optical tau versus distance/speed, contributed. To address these questions, the present study examined participants' performance in a relative TTC judgment task. Observers were presented with two sequential simulations of a spherical object (the target) approaching head-on at eye-level. In each approach, the target would vanish en route, and the observer's task was to judge which of these two targets would arrive earlier from the moment of their disappearance.

Sensitivity to time and non-time variables

As described above, the purpose of the current study was twofold. The first was to examine whether observers were sensitive to various sources of information (time or otherwise) when making relative judgments of TTC. Regan and Hamstra (1993) showed that when only image expansion was presented, TTC specified by tau was especially informative. However, in the real world, seldom is image expansion the only available source of information. The current study therefore investigated more inclusive situations where image cues were presented alongside information that specified distance-to-collision (DTC) and speed.

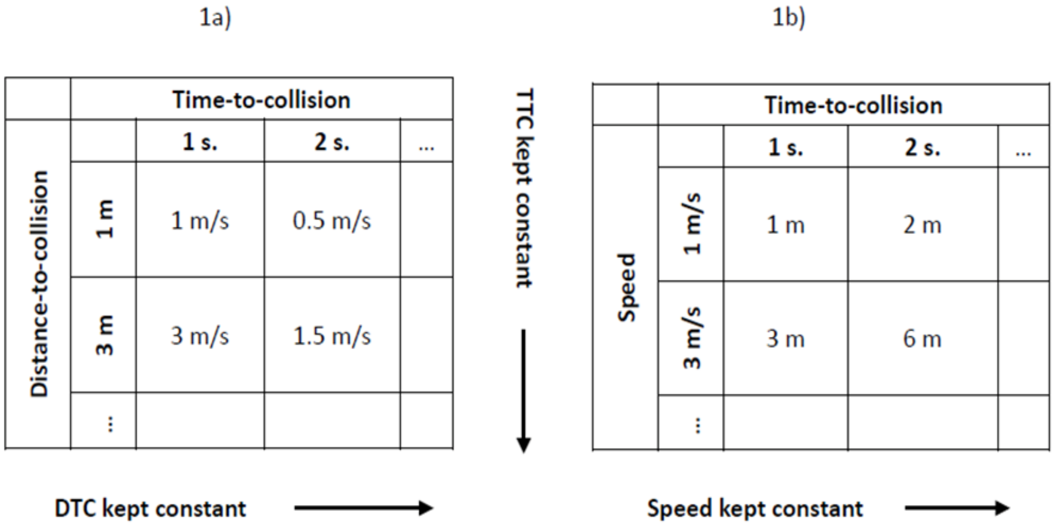
In order to dissociate different variables that may have influenced TTC judgments, we adopted the orthogonal matrix design similar to the one used by Regan and Hamstra (1993). Using this method, we manipulated vanishing TTC and vanishing DTC ("vanishing" refers to at the moment of disappearance) in an orthogonal fashion (i.e. TTC along rows and DTC along columns; see Table 1a). Even though participants were asked to perform a TTC judgment task, we could examine individual contributions of both TTC and DTC by comparing psychometric functions generated by collapsing responses from columns and rows. However, due to the mathematical relationship between TTC, DTC and speed (see Equation 1), if we varied TTC and DTC along the two dimensions of a single matrix, values for speed would unavoidably be varied along both dimensions. For instance, as shown in the rows of Table 1a, when DTC was held constant, speed co-varied with TTC. Consequently, obtained sensitivity to TTC information could have been partially contributed by this speed variation. This problem would have also occurred when evaluating the sensitivity to DTC. In both cases, the non-orthogonal speed variable was a potential confound for the analysis of TTC or DTC sensitivity. To address this issue, a second complimentary matrix was also used to dissociate sensitivity to vanishing TTC and speed (see Table 1b). All trials generated from these two matrices were then pooled and presented in a randomized sequence in the same experiment. During data analyses, re-segregating results from each trial into their respective matrices would allow the comparison of psychometric functions generated by the two arrays to examine if the third non-orthogonal variable contributed to responses.

Meanwhile, another variable that may have contributed to observer estimations is the physical size of the target. Relative size has been shown to be an important source of information for depth perception (Epstein, 1961; Bruno and Cutting, 1988; Landy et al., 1995) and TTC estimations (e.g. SAE as demonstrated by DeLucia, 1991; DeLucia and Warren, 1994; DeLucia et al., 2003). As the object's physical size potentially influences the perception of DTC, TTC and even speed, it was necessary to also dissociate object size from these other variables. We therefore varied object size along a third-dimension orthogonal to the existing two, in order to independently evaluate the effects of TTC, DTC, speed and the object's physical size on TTC perception. This three-dimensional array design was used throughout the entire experiment.

Tau versus the distance/speed ratio

While systematic variations of movement parameters provided opportunities to examine an observer's sensitivity to certain information (e.g. TTC), results would still have been inconclusive to the effects attributed to tau. It would remain uncertain how different sources of TTC information could be combined for TTC perception. As such, the second purpose of the present study was to dissociate the use of TTC information specified by the image, such as tau, from TTC information specified by the distance/speed ratio. We henceforth refer to the TTC specified by tau (Equation 2) as tau-based TTC (TTCt), and the TTC specified by distance/speed (Equation 1) as distance-based TTC (TTCd). Because both TTCt and TTCd normally co-exist and provide congruent time information, we used a method for manipulating the size of the looming object during its approach in order to provide a conflict between these two sources of TTC.

Table 1. Two matrices used to dissociate the effects of TTC and DTC (1a), or TTC and speed (1b). In Table 1a, TTC values varied along the horizontal dimension, but were keep constant along the vertical dimension. DTC values varied along the vertical dimension but were kept constant along the horizontal dimension. Speed values were determined by TTC and DTC, and as a result, varied along both dimensions. Thus, in this matrix, TTC was orthogonal to DTC, but speed remained un-confounded with both TTC and DTC. In Table 1b, TTC was orthogonal to speed, and as a result, DTC instead became the confounding variable.



1a)

		Time-to-collision		
Distance-to-collision		1 s.	2 s.	...
	1 m	1 m/s	0.5 m/s	
	3 m	3 m/s	1.5 m/s	
	⋮			

1b)

		Time-to-collision		
Speed		1 s.	2 s.	...
	1 m/s	1 m	2 m	
	3 m/s	3 m	6 m	
	⋮			

To achieve this, we used a method similar in principle to previous tau manipulation studies (Savelsbergh, et al., 1991; Savelsbergh, et al., 1993; van der Kamp, 1999) but with several improvements. In previous studies, the physical size of the looming object in tau manipulation conditions changed in a linear fashion as the object approached, either by inflating or deflating. This manipulation resulted in a different image expansion profile (of a non-constant speed) compared to that of non-manipulated objects, thus making it a less than ideal form of tau manipulation. In the present study, however, the approaching target which moved at a constant speed, was manipulated in a virtual environment so that the size of the stimulus provided a TTCt that specified a certain time sooner or later than TTCd specified by depth cues (similar to cue conflict scenarios performed by Heuer, 1993; Rushton and Wann, 1999). This method ensured that the rate of expansion for both manipulated and non-manipulated (control) targets would follow a natural course of image expansion typically experienced by objects moving at constant speed.

The present study further utilized a perceptual judgment task which asked observers to provide a single response (i.e. which stimulus arrived earlier) to the virtual stimuli. This was in contrast to motor tasks commonly used in previous studies. While utilizing motor tasks can be advantageous in many situations, they also lead to temporally variable responses resulting from the complexities of behaviour. For instance, initiation of grasping can range from the moment the approaching object is a short distance away from the hand (followed by a slower motion) to the moment that the object contacts the hand (requiring faster movement). Consequently, motor responses may not be the simplest and most direct indicator of visual perception (Tresilian, 1994). On the other hand, a relative judgment task results in simpler and more consistent responses, especially when the confounding variables are systematically controlled (as in the present study; also see Tresilian, 1995; 1999). A relative judgment task, thus, would have been a more suitable design that reflected the observer's estimation.

In summary, through systematic variations and well-controlled dissociation of movement parameters, along with the incorporation of cue conflict between the two sources of information that specify TTC; the current study aimed to quantify the relative contributions of tau and other variables such as DTC, speed and physical size of the incoming object during a TTC judgment task. In Experiment 1, the availability of distance information through the presence of ground was manipulated in order to better investigate the effects of DTC and speed. When distance information was presented, the target approached in a direction parallel to the ground surface, and projected a shadow directly underneath. In this situation, both target and its shadow provided potential depth information. However, as we varied target size between trials, DTC and speed information were most saliently provided by the contrast of the moving object and shadow along the ground, which could then be used to estimate TTCd. Responses in these conditions were then compared to when ground and shadow information were unavailable. In Experiments 2 and 3, we continued to provide ground depth information, but further manipulated the physical size of the object during some of the approaches. This TTCt manipulation led to inconsistencies between TTC specified by tau and TTC specified by the distance/speed ratio. Changes in responses due to these manipulations then allowed us to quantify the extent observers used tau.

GENERAL METHODS

Apparatus. Each experiment was conducted in a dark room. The virtual scene containing the stimulus was projected onto a film screen through a rear projection system (model: JVC projector DLA-SX21). This display measured 246x182 cm and had a resolution and frame rate of 1024x768 at 60 Hz. Participants remained stationary and viewed the screen from a distance of 133 cm resulting in a field of view spanning 85.5° x 68.8°.

Stimulus. In the virtual scene, a simulated red sphere (the target) approached at eye-level towards the stationary observer in a trajectory within the sagittal plane parallel to the horizontal. This target approached at a constant speed either in front of a uniform gray coloured background or in the presence of a black and white ground surface with random dot texture (see Figure 1). In these with-ground situations, the horizon was located directly along the mid-line of the screen. In addition, the target casted a shadow onto the ground which moved directly underneath the object as it approached. The target's height above the ground (measured from the center) was 2 m. This scenario thus simulated a shadow that was created from a light source directly above and from an infinite distance, in contrast to typical light sources that are generally specified distances away (Kersten et al.,1996; Kersten, Mamassian, and Knill, 1997; Mamassian, Knill, and Kersten, 1998). Following a brief viewing time between 1 and 2 seconds, the target vanished en route at a specified time before contact (time to contact, vanishing TTC) with the observer. It should be noted that two different types of TTC are described in the literature. The first, termed "initial TTC" (Heuer, 1993) is defined as the time duration starting from the object's initial approach until contact with the observer (Heuer, 1993; Regan and Hamstra, 1993). The other, which we refer to as "vanishing TTC" (also known as "final TTC" in Heuer, 1993; or the "extrapolation interval" in Oberfeld and Hecht, 2008), which was used in the present study, is defined as the time range between object disappearance and the moment the object would have reached the observer (Schiff and Oldak, 1990; Oberfeld and Hecht, 2008).

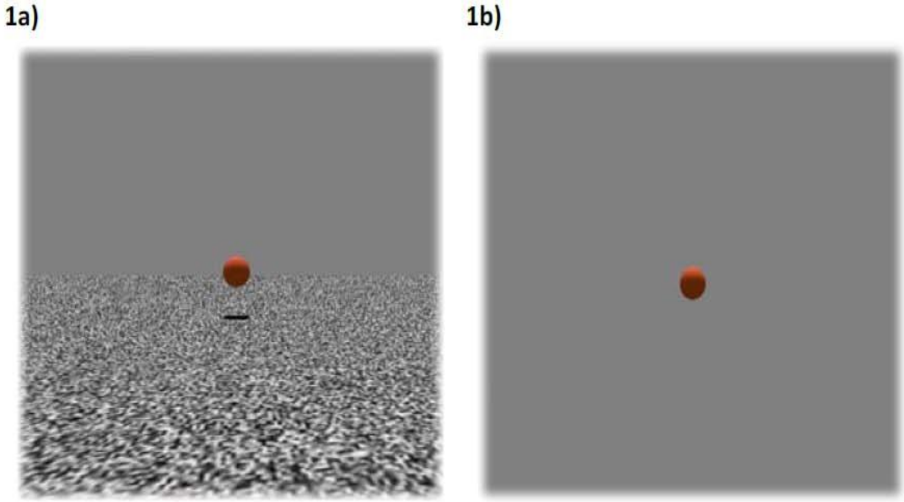


Figure 1. Snapshots of the two different ground conditions. Figure 1a depicts the with-ground condition and Figure 1b, the without-ground condition. In the with-ground condition, the target was presented simultaneously with a noise dot textured ground surface, and an artificial shadow that was casted directly underneath. The ground and shadow cues provided observers with additional distance and speed information. In the without-ground condition, only the target was visible to the observer.

Procedure. Each experiment employed a two-alternative forced choice task. Individual trial consisted of two sequential presentations of a single target approach separated by a 500 ms blank-screen interval. The participant's task was to compare from the moment of disappearance, the remaining TTC of the first and second approaches, and judge which of the two would have arrived sooner under assumption that the target remained moving at the same speed. Upon viewing the second approach, participants responded by pressing a key, after which the next trial began. Following every 72 trials, a 1-minute break was given which could be extended upon request. Prior to beginning the formal experiment, participants did 30 or more practice trials until they were comfortable with the task. Feedback was given on each practice trial to indicate whether responses were correct. No feedback, however, was provided in the formal experiment. Additionally during practice trials, participants were instructed that the physical size of the target may vary between trials and that the target and shadow, if present, were always vertically aligned. Finally, throughout each experiment, participants were instructed to wear an eye-patch covering one eye of their choice.

Experimental Design. As described, we employed a modified orthogonal matrix design similar to the one used by Regan and Hamstra (1993). To dissociate the effects of TTC, DTC and speed on estimations of target's vanishing TTC, we created two orthogonal matrices each consisting of a combination of these movement parameters (see Table 1). In addition, we varied the target's physical size along a third orthogonal dimension. Of the two resulting arrays, the first individually varied TTC, DTC and target size along the three available dimensions (TTC-DTC-size array), whereas the second varied TTC, speed and target size (TTC-speed-size array). The combination of these two arrays ensured that the effects of TTC, DTC, speed, and target size on TTC estimations could each be examined independently. Meanwhile, viewing duration was randomized between 1 and 2 seconds. As TTC and DTC were specified for the moment of target disappearance, their values at the start of the trajectory were also varied accordingly. This prevented observers from using unrelated information, such as visible target duration, to perform the present task.

In each trial, the two target approaches were each assigned as a test or a reference approach, with the presentation order randomly chosen. In the reference approach, movement and physical parameters were held constant at a TTC of 2 s (again, counting from moment of target disappearance), DTC of 20 m (virtual unit, from the position of target disappearance), target approach speed of 10 m/s and target diameter of 2 m. In the test approach, these parameters were instead chosen randomly without replacement from the stimulus pool containing all combinations from the two orthogonal arrays. An exhaustive set of these combinations composed a block of trials.

Data analysis. Responses from each participant were separated into two data sets according to the array that each trial was drawn from. In each set, responses were converted to the frequency that the test stimulus was judged to have arrived earlier. The six psychometric functions were generated by collapsing responses along each of the three orthogonal dimensions for each array, consisting of TTC, DTC and target size for the first array, and TTC, speed and target size for the second. These psychometric functions were then fitted to a logit model (Cohen et al., 2003), which was then used to calculate the relative discrimination threshold (Weber's fraction) and point of subjective equality (PSE). The relative discrimination threshold was defined as $(X_{75}-X_{25})/2$, in which X_{75} and X_{25} represented the value of the independent variable for which participants had a 75% and 25% chance, respectively, of selecting the test approach as arriving earlier.

EXPERIMENT 1

Rationale:

Using the orthogonal array design, Experiment 1 investigated whether participants were sensitive to TTC, DTC, speed or physical size when judging TTC. We were further interested in whether sensitivity to the different variables would change in the presence of a ground surface and target shadow, the inclusion of which provided salient motion-in-depth information (Kersten, et al., 1996; Kersten, et al. 1997; Mamassian, et al., 1998).

Methods:

Stimulus. Experiment 1 consisted of with-ground and without-ground conditions. As described in the general methods, the with-ground condition included a black and white ground surface with random dot texture. Additionally, a shadow was projected directly underneath the approaching target. In the without-ground condition, only the approaching target was presented (see Figure 1).

Experimental Design. For the test approaches, each of the four independent variables was varied at six levels (0.4, 0.59, 0.8, 1.25, 1.7 and 2.5) relative to values in the reference approach. As a result, each of the two arrays incorporated a 6x6x6 design, resulting in 432 (6x6x6 x 2 arrays) different trials, which contained an exhaustive combination of these movement and physical parameters. Each block of these 432 trials was repeated thrice for both with-ground and without-ground conditions. Blocks containing with-ground trials were completed prior to those containing without-ground in order to prevent participants from ignoring ground information once they became accustomed to without-ground scenarios. Each block took an hour to complete and was completed once a day for a total of six days.

Participants. Four university students participated in the study. Participants SS and SB were males, HM and TD were females. All participants had normal or corrected-to-normal visual acuity and were naïve to the purpose of the study. Each student was paid for their participation.

Results:

Figure 2 depicts the percentage of response that participant SB chose the test approach as arriving earlier than the reference. Fitted curves of the three independent variables for each array were plotted into one graph. The left and right panels represent results from the TTC-DTC-size and TTC-speed-size arrays, respectively. The top and bottom panels represent results from with-ground and without-ground conditions.

For participant SB, fitted curves based on the TTC variable were steep compared to those based on DTC, speed and size. Weber fractions for TTC ranged from 0.22 to 0.26, whereas those of non-TTC variables were ten or more times greater (between 2.8 to 28.5) and represented by the shallower curves. Furthermore, no observable difference was found between with-ground and without-ground conditions. In particular, Weber fractions for TTC in the with-ground condition (0.26 and 0.23 for TTC-DTC-size array and TTC-speed-size array, respectively) were similar to those in the without-ground condition (0.26 and 0.22 for TTC-DTC-size array and TTC-speed-size array, respectively).

Despite varied sensitivities to each variable, all four participants showed smallest discrimination thresholds for TTC information. Among observers, participant HM showed the most sensitivity to non-TTC variables. Nonetheless, even for HM, discrimination thresholds for non-TTC variables were approximately two to five times greater than those for TTC. Moreover, this greater sensitivity to non-TTC variables was largely contributed by HM’s responses from the first block of the with-ground condition (i.e. DTC was only 1.5 times less sensitive than TTC). In the subsequent two blocks, HM became mostly sensitive to time (i.e. she was more than twice as sensitive to TTC as DTC) which was similar to the other observers. Unlike HM, the other participants showed little response differences between blocks. Weber fractions for all participants are listed in Table 2.

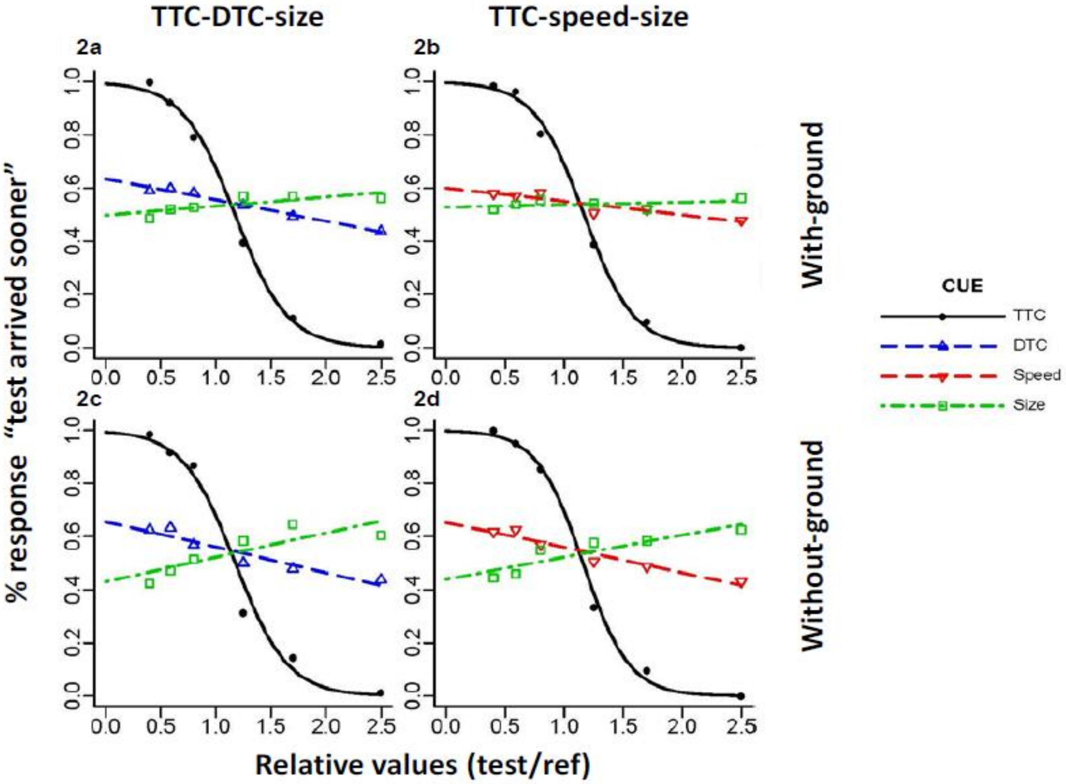
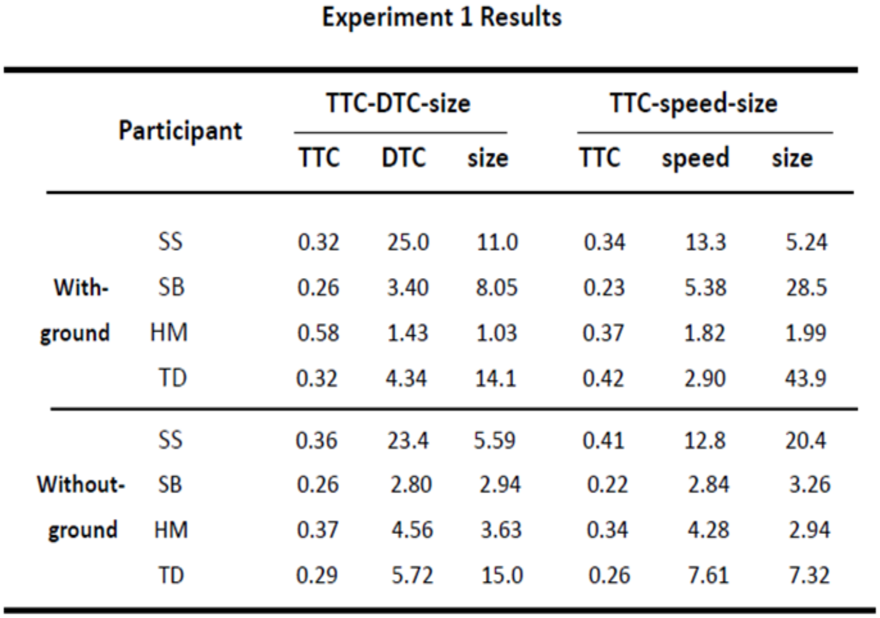


Figure 2. The fitted curves of relative TTC judgments for participant SB in Experiment 1. Each fitted curve was based on the different variables (TTC, DTC, speed and size) used in the experimental task. Results from the with-ground and without-ground conditions are presented in the top and bottom panels, respectively. Results from the TTC-DTC-size array and TTC-speed-size array are presented in the left and right panels.

Table 2. List of participants' relative discrimination thresholds (Weber fractions) for the TTC estimation task in Experiment 1, separated by independent variables.



Experiment 1 Results

Participant		TTC-DTC-size			TTC-speed-size		
		TTC	DTC	size	TTC	speed	size
With-ground	SS	0.32	25.0	11.0	0.34	13.3	5.24
	SB	0.26	3.40	8.05	0.23	5.38	28.5
	HM	0.58	1.43	1.03	0.37	1.82	1.99
	TD	0.32	4.34	14.1	0.42	2.90	43.9
Without-ground	SS	0.36	23.4	5.59	0.41	12.8	20.4
	SB	0.26	2.80	2.94	0.22	2.84	3.26
	HM	0.37	4.56	3.63	0.34	4.28	2.94
	TD	0.29	5.72	15.0	0.26	7.61	7.32

Discussion:

In Experiment 1, we investigated the contribution of four variables - TTC, DTC, target speed and physical size - during a relative TTC judgment task. Our results showed that participants could accurately discriminate trial-to-trial TTC differences based on TTC information. Discrimination thresholds revealed that TTC information was the most effective information for making TTC judgments compared to the other three variables, and that these results were consistent among all observers.

Recall that we implemented two stimulus arrays (one for TTC-DTC-size and one for TTC-speed-size) because we were concerned that the third non-orthogonal variable would confound responses for each array. As demonstrated, however, the resulting TTC psychometric functions for both arrays were almost identical. Meanwhile, DTC and speed psychometric functions (from their respective arrays) were both shallow and revealed minimal sensitivities during estimations. It was therefore unlikely that the potential confounding non-orthogonal variable played a major role in the present findings.

Moreover, there was no noticeable difference between responses in with-ground and without-ground conditions. Only participant HM showed slightly more sensitivity to non-TTC variables in with-ground conditions than without-ground. However, as described, this was due to her tendency to use non-TTC variables during the first block of the experiment. Altogether, our results suggested that depth information provided by the ground surface and target shadow, for the most part, did not influence TTC estimations. Thus, we concluded that DTC and speed information derived from ground presence affects little, if at all, the perception of TTC.

Meanwhile, observed Weber fractions for TTC ranged from 0.22 to 0.58, slightly higher than the 0.05 to 0.22 previously reported (Todd, 1981; Regan and Hamstra, 1993; Gray and Regan, 2006). Such discrepancy may be explained by the use of vanishing TTC in the present study, and also because targets disappeared much earlier - between 0.8 - 5 seconds prior to contact with the observer. This was in contrast to the smaller values of TTC (0.33-1.33 seconds) used in previous studies. As was demonstrated by Schiff and Oldak (1990), observers had a tendency to less accurately estimate approaches at longer TTCs, which would have explained the reduced sensitivity found in our results.

Furthermore, while we demonstrated that tau information was primarily used in our TTC judgment task, we also found that relative size contributed little to these estimations. This was in contrast to reports of the SAE by DeLucia and colleagues (DeLucia, 1991; DeLucia and Warren, 1994), and may have been due to several reasons. First, in the present study, instructions were provided prior to formal testing about the potential change in size between approaches. This may have directed participants to use information other than targets' relative sizes to make their estimations. Also, target size between trials varied from 0.4 to 2.5 times the reference target which ensured that participants would have noticed these differences. It is likely that when participants were aware of such variations, they abandoned a prior assumption that larger image sizes specified a closer distance and thus a shorter TTC. This would be consistent with observed SAE reductions when participants were made aware that approaching objects differed in physical size (DeLucia, 2005).

It is also important to note that the shadow of the target in our study was programmed to be positioned directly underneath the target (i.e. created from a light source infinitely far away). As a result, motion information (i.e. TTC, DTC, speed) provided by the target and its shadow were consistent. As demonstrated by DeLucia (1991), the presence of prominent ground information also weakens the SAE. This shadow may have reduced the chances that participants used the less reliable relative size cue by providing necessary ground intercept and positional information.

Lastly, it remained possible that the order of the group conditions may have also played a role in participants' judgments. Changes in target size may have been more noticeable in the with-ground condition due to distance-size scaling. As the without-ground condition was always presented after, observers may have continued to ignore target size changes due to this previous exposure. In other words, strategies used in the with-ground condition may have transferred to without-ground condition.

EXPERIMENT 2A

Rationale:

Experiment 1 found that participants were most sensitive to TTC information and less sensitive to non-time variables when judging relative TTC. However, it remained uncertain whether tau information was specifically and exclusively used for these estimations. Our results are still inconclusive as to whether participants ignored the distance/speed ratio. In principle, as the two possible means for deriving TTC (TTCt and TTCd) provided identical TTC values, the orthogonal array design cannot by itself unconfound them. In order to dissociate TTC derived from the image (TTCt) from TTC derived from distance (TTCd), we created a situation where TTCt and TTCd were incongruent. To do this, we manipulated in real-time the target's tau by changing the physical size of the approaching object. Consequently, TTCt of the target specified a time sooner or later than the TTCd, which remained unaltered.

Methods:

Stimulus. The stimulus in the with-ground condition was used for Experiment 2, along with the addition of the three different types of TTCt manipulations. In the control condition, the target's physical size was unchanged (same as in Experiment 1) and therefore provided consistent TTCt and TTCd information. In expansion and contraction conditions, however, the target's physical size was constantly manipulated (either expanded or contracted) so that tau (TTCt) specified a time 0.5 second less (expansion) or greater (contraction) than TTC specified by distance/speed (TTCd). Importantly, the distance of the target/shadow remained un-manipulated, similar to control conditions (see Figure 3).

The target's instantaneous size (S') was calculated using the equation:

$$S^{'} = S_o * d/(d - v * \Delta t) \qquad (3)$$

where d represents the target's DTC; v, its speed and S_0, its physical size at a specific time. The absolute values of Δt were 0 seconds, 0.5 second or -0.5 second for control, expansion and contraction conditions, respectively.

It should be noted that these three TTCt manipulating conditions (constant, expansion, and contraction) were only applied to the test approach, and that each trial also consisted of an un-manipulated reference approach. As the reference approach was kept at a TTC (for both TTCt and TTCd) of 2 seconds, the relative value of Δt was expressed as 0 (0 second TTCt shift/ 2 seconds TTCt), 0.25 (0.5 second TTCt shift/2 seconds TTCt), and -0.25 (-0.5 second TTCt shift/ 2 seconds TTCt).

Experimental Design. The orthogonal array design (as in Experiment 1) was again used. However, in Experiment 2a, while the levels of TTC variation remained the same, the levels of DTC, speed and target size were reduced to four. As a result, each new array contained 96 (6x4x4) combinations of parameters. These four levels corresponded to values of 0.5, 0.7, 1.4 and 2.0 relative to reference values. Each trial from the TTC-DTC-size and TTC-speed-size arrays was presented once for each TTCt manipulation condition (expansion, control and contraction). Therefore, each block contained 576 trials (6x4x4 x 2 arrays x 3 manipulations) presented in random order, which was completed thrice for a total of 1728 trials per participant.

Participants. Participants JY (the first author, male with normal visual acuity), SB, HM and TD completed Experiment 2a. SB, HM and TD each completed Experiment 1 prior.

Data analysis. Responses were first grouped according to their TTCt manipulation condition. Within each group, similar analyses as those performed in Experiment 1 were used. PSEs in the different TTCt manipulation groups were then compared to investigate the effects of tau manipulation on TTC estimations.

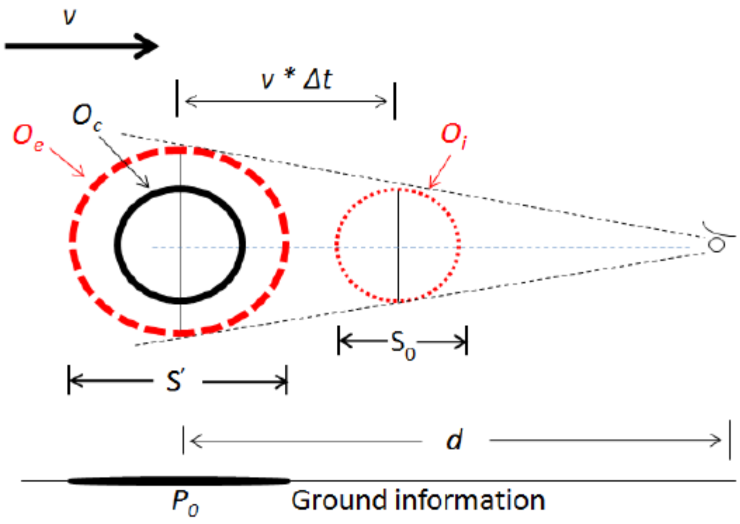


Figure 3. Illustration of the TTCt manipulation used in the control and expansion condition. This diagram illustrated the visual image of the target as it approached the observer's eye at speed *v*. For the control condition, the image of the target was depicted as O_c (black solid circle) with the physical size of the target held constant at S_0 during approach. For the expansion condition, the physical size of the target was enlarged (O_e, red dashed circle) during the approach and the magnitude of the increase was made to simulate the image of the target (O_i, red dotted circle) with constant size of S_0(same as the control), moving at a distance of $v*\Delta t$ in front of the actual object. During TTCt manipulations, the shadow of the target was made to be the same size and same position as the manipulated target (O_e).

Results:

Figure 4 depicts the percentage of responses that the same male participant SB chose the test approach as arriving sooner than the reference. To compare the effects of TTCt manipulation on each variable, fitted curves for the three different TTCt manipulation conditions were plotted in the same graph. The left and right panels represent results from the TTC-DTC-size and the TTC-speed-size arrays, respectively. Responses based on TTC, DTC, speed and size variables are presented in the top, middle-left, middle-right and bottom panels.

In general, curves based on the TTC variable for all three TTCt manipulation conditions were much steeper than those based on DTC, speed and size. For instance, as shown in Table 3, discrimination thresholds based on the TTC variable in control conditions for participant SB, were 0.21 for the TTC-DTC-size array and 0.16 for the TTC-speed-size array, similar to the corresponding 0.26 and 0.23 values obtained in Experiment 1. Also like Experiment 1, Weber fractions of the other non-time variables were nearly ten times greater than those for TTC (ranging from 3.63 to 22.6). Weber fractions for all three TTCt manipulation conditions showed similar patterns of sensitivity. See Table 3 for Weber fractions and PSEs for all participants.

For SB, PSEs for expansion, control and contraction conditions were 1.46, 1.12 and 0.97 in the TTC-DTC-size array. PSE differences from control to expansion and control to contraction conditions were 0.34 and -0.15, respectively. These values corresponded to 136% and 60% shifts, relative to the expected value of 0.25 and -0.25 had the participant relied completely on tau for his estimation. From contraction to expansion, participant SB's PSE shift was 0.49 or 98% of the expected value of 0.5. In the TTC-speed-size array, the participant's PSEs for expansion, control and contraction conditions were 1.35, 1.08 and 0.93. PSE differences from control to expansion and control to contraction conditions were 0.27 and -0.15, corresponding to relative values of 108% and 60%. From contraction to expansion, the PSE shift was 0.42, a relative value of 84%.

ANOVA analyses of mean PSE shifts for all participants indicated that there were significant PSE differences between manipulation conditions, $F(2, 6) = 114$, $p < 0.01$ for TTC-DTC-size array and $F(2, 6) = 53$, $p < 0.01$ for TTC-speed-size array. Moreover, PSE shifts were significant between TTCt manipulation conditions and control for both arrays combined, $t(7) = 7.25$, $p < 0.01$ for expansion and $t(7) = 8.01$, $p < 0.01$ for contraction. We further compared observed shifts (i.e. expansion to control, control to contraction, and expansion to contraction) with their expected shifts (0.25, 0.25, and 0.5, respectively) for all four participants; and found no significant differences except in the expansion to contraction condition for the TTC-speed-size array (expected relative shift = 0.5; $t(3) = -5.95$, $p < 0.01$). Meanwhile, there were no DTC, speed, or size differences between conditions (all $p > 0.1$). Ratios of participants' TTC shifts relative to their expected shifts are listed in Table 4.

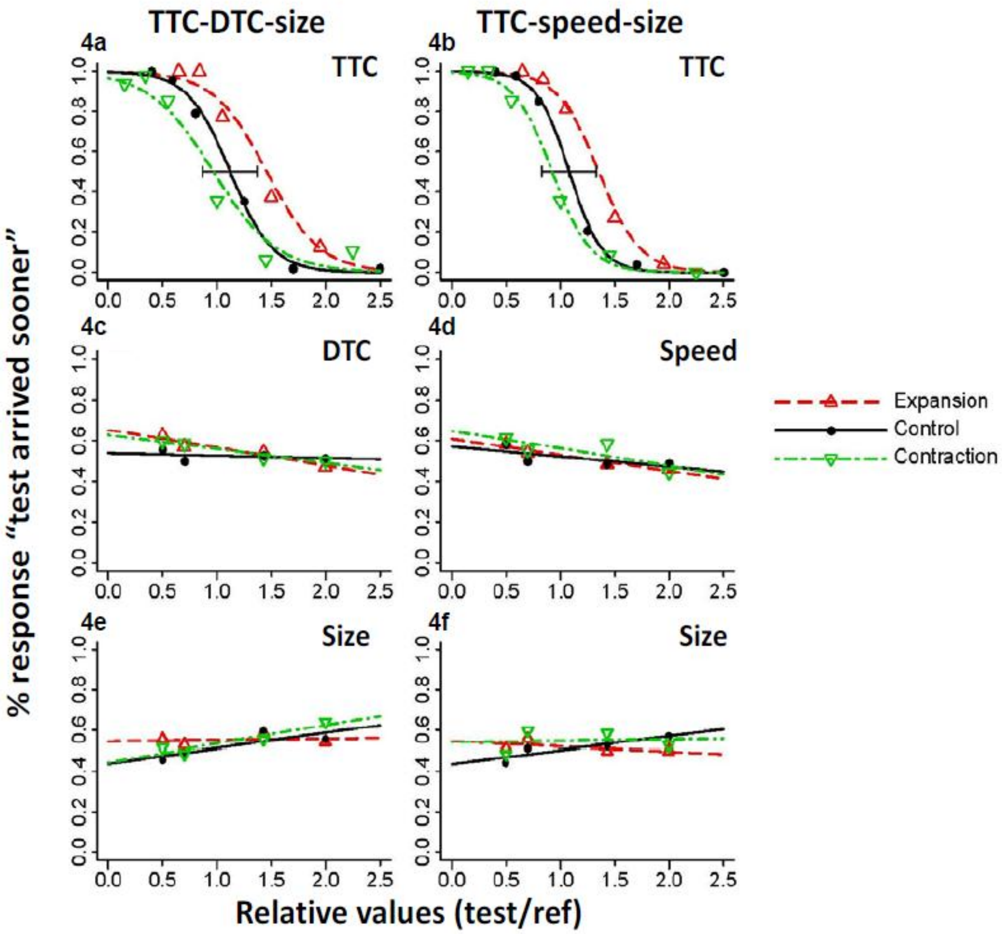
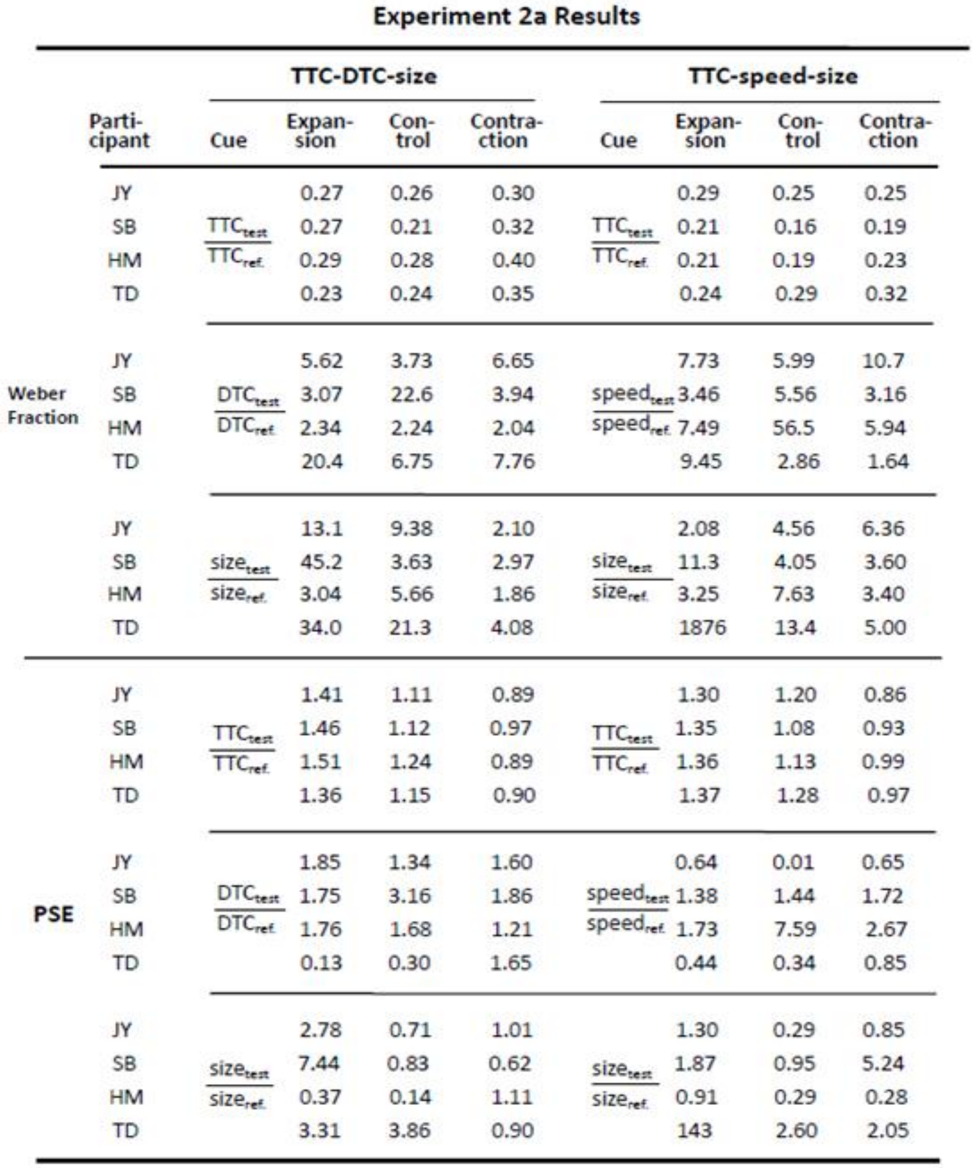


Figure 4. The fitted curves of relative TTC judgments for participant SB in Experiment 2a. Each fitted curve was based on the different variables (TTC, DTC, speed and size) used in the experimental task. To compare the effects of TTCt manipulation, responses based on each variable were further separated by manipulation conditions, and plotted into the same figure. Left and right panels depict results from the TTC-DTC-size array and the TTC-speed-size array, respectively.

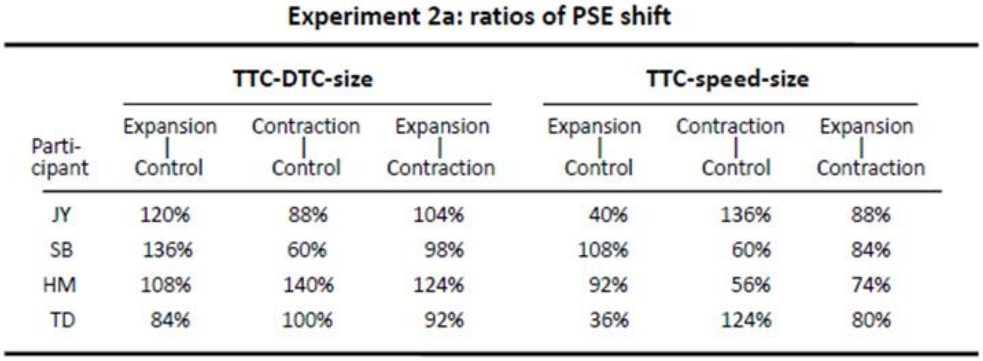
Table 3. List of participants' relative discrimination thresholds (Weber fractions) and PSEs for judging TTC in Experiment 2a, separated by each independent variable and TTCt manipulation condition.



Experiment 2a Results

		TTC-DTC-size				**TTC-speed-size**			
	Participant	**Cue**	**Expansion**	**Control**	**Contraction**	**Cue**	**Expansion**	**Control**	**Contraction**
Weber Fraction	JY	$\frac{TTC_{test}}{TTC_{ref.}}$	0.27	0.26	0.30	$\frac{TTC_{test}}{TTC_{ref.}}$	0.29	0.25	0.25
	SB		0.27	0.21	0.32		0.21	0.16	0.19
	HM		0.29	0.28	0.40		0.21	0.19	0.23
	TD		0.23	0.24	0.35		0.24	0.29	0.32
	JY	$\frac{DTC_{test}}{DTC_{ref.}}$	5.62	3.73	6.65	$\frac{speed_{test}}{speed_{ref.}}$	7.73	5.99	10.7
	SB		3.07	22.6	3.94		3.46	5.56	3.16
	HM		2.34	2.24	2.04		7.49	56.5	5.94
	TD		20.4	6.75	7.76		9.45	2.86	1.64
	JY	$\frac{size_{test}}{size_{ref.}}$	13.1	9.38	2.10	$\frac{size_{test}}{size_{ref.}}$	2.08	4.56	6.36
	SB		45.2	3.63	2.97		11.3	4.05	3.60
	HM		3.04	5.66	1.86		3.25	7.63	3.40
	TD		34.0	21.3	4.08		1876	13.4	5.00
PSE	JY	$\frac{TTC_{test}}{TTC_{ref.}}$	1.41	1.11	0.89	$\frac{TTC_{test}}{TTC_{ref.}}$	1.30	1.20	0.86
	SB		1.46	1.12	0.97		1.35	1.08	0.93
	HM		1.51	1.24	0.89		1.36	1.13	0.99
	TD		1.36	1.15	0.90		1.37	1.28	0.97
	JY	$\frac{DTC_{test}}{DTC_{ref.}}$	1.85	1.34	1.60	$\frac{speed_{test}}{speed_{ref.}}$	0.64	0.01	0.65
	SB		1.75	3.16	1.86		1.38	1.44	1.72
	HM		1.76	1.68	1.21		1.73	7.59	2.67
	TD		0.13	0.30	1.65		0.44	0.34	0.85
	JY	$\frac{size_{test}}{size_{ref.}}$	2.78	0.71	1.01	$\frac{size_{test}}{size_{ref.}}$	1.30	0.29	0.85
	SB		7.44	0.83	0.62		1.87	0.95	5.24
	HM		0.37	0.14	1.11		0.91	0.29	0.28
	TD		3.31	3.86	0.90		143	2.60	2.05

Table 4. List of participants' relative shift in point of subject equality (PSE) between different TTCt manipulation conditions in Experiment 2a. Values are expressed as percentage to the expected shift had participants relied entirely on an optical tau strategy (0.25 for both Expansion-Control and Contraction-Control conditions, 0.5 for Expansion-Contraction condition).



Experiment 2a: ratios of PSE shift

Participant	TTC-DTC-size			TTC-speed-size		
	Expansion | Control	Contraction | Control	Expansion | Contraction	Expansion | Control	Contraction | Control	Expansion | Contraction
JY	120%	88%	104%	40%	136%	88%
SB	136%	60%	98%	108%	60%	84%
HM	108%	140%	124%	92%	56%	74%
TD	84%	100%	92%	36%	124%	80%

Discussion:

Similar to Experiment 1, Experiment 2a showed that participants were most sensitive to trial-to-trial differences in TTC during a TTC estimation task, and not sensitive to variations of DTC, speed and target size. Weber fractions of curves based on TTC information were less than those produced by other variables. Additionally, we dissociated the effects of TTCt from TTCd. If observers relied on tau (TTCt) to guide their judgments, responses would have differed between the three TTCt manipulation conditions. Responses, on the other hand, would have remained unchanged if observers relied instead on TTC specified by distance (TTCd) or other non-tau sources. Our results showed that responses were mostly affected by tau, and that manipulating TTCt reliably influenced TTC judgments. Specifically, enlarging the physical size of the target during approach caused observers to perceive a sooner arriving object. In contrast, decreasing the physical size of the target during approach caused participants to view the object as arriving later. The extent that individuals utilized tau, however, remained uncertain. While the present experiment only examined four observers, it was demonstrated that at least in the TTC-speed-size array, participants did not fully shift their responses to the extent we would expect had observers only used tau.

EXPERIMENT 2B

Rationale:

It is uncertain whether the lack of sensitivity for non-TTC variables found in Experiment 2a was because participants ignored non-time variables when making relative TTC judgments, or because participants were unable to detect trial-to-trial differences in these variables. Furthermore, it was necessary to determine whether manipulation of physical size during approach also affected observers' perception of DTC and speed. We addressed these issues in Experiments 2b and 2c by testing participants' ability to make relative DTC and speed judgments during the three TTCt manipulation conditions. If participants showed high sensitivity to DTC in Experiment 2b, and to speed in Experiment 2c, it would confirm that participants simply weighted non-time variables less during TTC estimations.

Methods:

Experimental Design. Experiment 2b was similar to Experiment 2a with two exceptions. First, in Experiment 2b, the orthogonal dimensions of the two arrays were changed to DTC-TTC-size and DTC-speed-size in order to dissociate the effects of DTC from other variables during the DTC judgment task. Second, six levels of DTC were used (0.4, 0.59, 0.8, 1.25, 1.7 and 2.5 relative to reference values) along with four levels of all other orthogonal variables (relative values of 0.5, 0.7, 1.43 and 2). Due to high accuracy shown in pilot studies, participants were only required to complete one block (6x4x4 x 2 arrays x 3 TTCt manipulations = 576 trials) of trials presented in random order.

Procedure and data analysis. These were similar to the ones used in Experiment 2a. However, unlike Experiment 2a where participants were asked to judge relative TTC, they were instead instructed to judge which of the two approaches appeared closer in terms of DTC at the moment of disappearance.

Participants. Participants JY, SB and TD completed Experiment 2b. Participant JY only completed Experiment 2a prior to 2b, whereas participants SB and TD completed both Experiments 1 and 2a prior.

Results:

Figure 5 depicts the percentage of response that participant SB chose the test stimulus as disappearing closer than the reference. The left and right panels represent results from the DTC-TTC-size and DTC-speed-size arrays respectively. Responses based on DTC, TTC, speed, and size variables are shown in the top, middle-left, middle-right and bottom panels.

For participant SB, fitted curves based on DTC were steeper compared to those based on TTC, speed and size. Weber fractions of DTC ranged from 0.1 to 0.19, the smallest among all variables. These discrimination thresholds demonstrated that SB was most sensitive to DTC when making judgments of distance. For the same observer, the Weber fractions of other variables ranged from 1.67 to 107, which are represented by the shallow curves in Figure 5.

For the same participant, we also compared the effects of TTCt manipulation on DTC estimations. From control to expansion and control to contraction, the differences in PSEs between DTC curves were 0.04 and -0.04 in DTC-TTC-size array, and 0.01 and -

0.05 in DTC-speed-size array. These values were relatively small, compared to the actual manipulated target size difference (0.25). Other participants showed similar patterns of Weber fractions and PSE shifts.

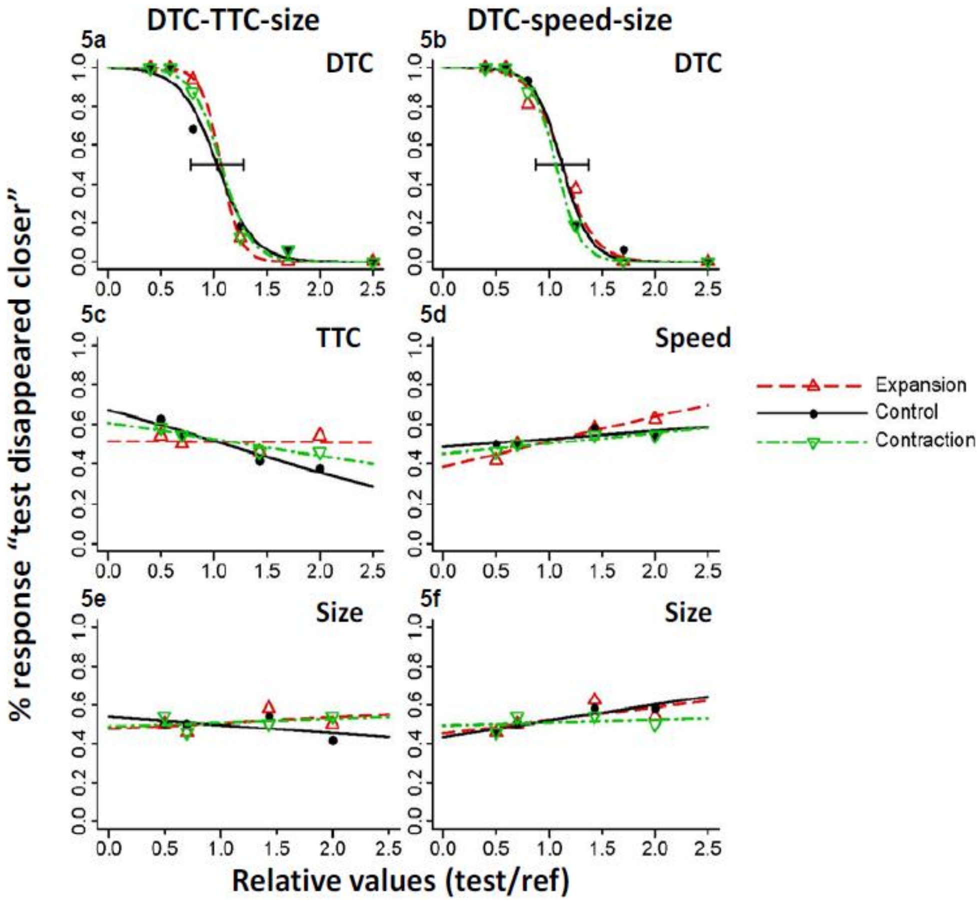


Figure 5. The fitted curves of relative DTC judgments for participant SB in Experiment 2b. Each fitted curve was based on the different variables (TTC, DTC, speed and size) used in the experimental task. To compare the effects of TTCt manipulation, responses based on each variable were further separated by manipulation conditions, and plotted into the same figure. Left and right panels depict results from the DTC-TTC-size array and the DTC-speed-size array, respectively.

EXPERIMENT 2C

Methods:

Experimental Design. Experiment 2c was similar to Experiment 2b with two exceptions. First, in Experiment 2c, the orthogonal dimensions of the two arrays were changed to speed-TTC-size and speed-DTC-size in order to dissociate the effects of speed from other variables during the speed judgment task. Second, six levels of speed were used (0.4, 0.59, 0.8, 1.25, 1.7 and 2.5 relative to reference values) along with four levels of all other orthogonal variables (relative values of 0.5, 0.7, 1.43 and 2). Each participant completed three blocks for a total of 1728 trials (6x4x4 x 2 arrays x 3 TTCt manipulations x 3 blocks). Trials from individual blocks were presented in random order.

Procedure and data analysis. These were again similar to those in Experiments 2a and 2b. This time, however, participants were asked to judge which one of the two approaches travelled faster in terms of speed.

Participants. The same participants from Experiment 2b completed Experiment 2c.

Results:

Figure 6 depicts the percentage of response that participant SB chose the test approach as travelling faster than the reference. The left and right panels represent results from the speed-TTC-size and speed-DTC-size arrays, respectively. Responses based on speed, TTC, DTC and size variables are shown in the top, middle-left, middle-right and bottom panels.

As demonstrated in Figure 6, curves based on speed were steep compared to those based on TTC, DTC and size. Weber fractions of speed ranged from 0.19 to 0.48, the lowest among all other variables. The Weber fractions for other variables ranged from 0.92 to 21.5 and were represented by the shallower curves. When we compared the effects of TTCt manipulation on target speed estimations, differences in speed PSEs from control to expansion and control to contraction were -0.02 and 0.04 in speed-TTC-size array, and -0.05 and -0.01 in speed-DTC-size array. Results from other participants showed similar patterns of Weber fractions and PSE shifts.

Discussions:

Overall, results in Experiment 2b and 2c indicated that participants could in fact discriminate trial-to-trial differences in DTC and speed. Therefore, the lack of sensitivity to DTC and speed observed in Experiment 2a was not due to inability to perceive the two variables. We also demonstrated that TTCt manipulations did not noticeably influence DTC and speed perception in the present study, thus confirming the validity of our manipulations.

EXPERIMENT 3

Rationale:

In Experiment 2, the proportion of TTCt manipulation trials (expansion and contraction) were equal to that of control (1:1:1). Given such high frequency of TTCt manipulations, it is possible that participants may have been affected by them and performed the task differently from normal. To investigate this potential issue, we returned to the TTC judgment task. This time, however, the ratio of TTCt manipulation trials to control was lowered to 1:5. Additionally, a larger sample of naïve participants was tested for a shorter duration to reduce practice effects from hours of repeated trials. Lastly, to accommodate for time and also to reduce exposure to TTCt manipulations, each participant only experienced either expansion or contraction conditions. These implementations of a larger sample size, less frequent exposure to TTCt manipulation and shorter test duration allowed us to ultimately examine more natural behaviour.

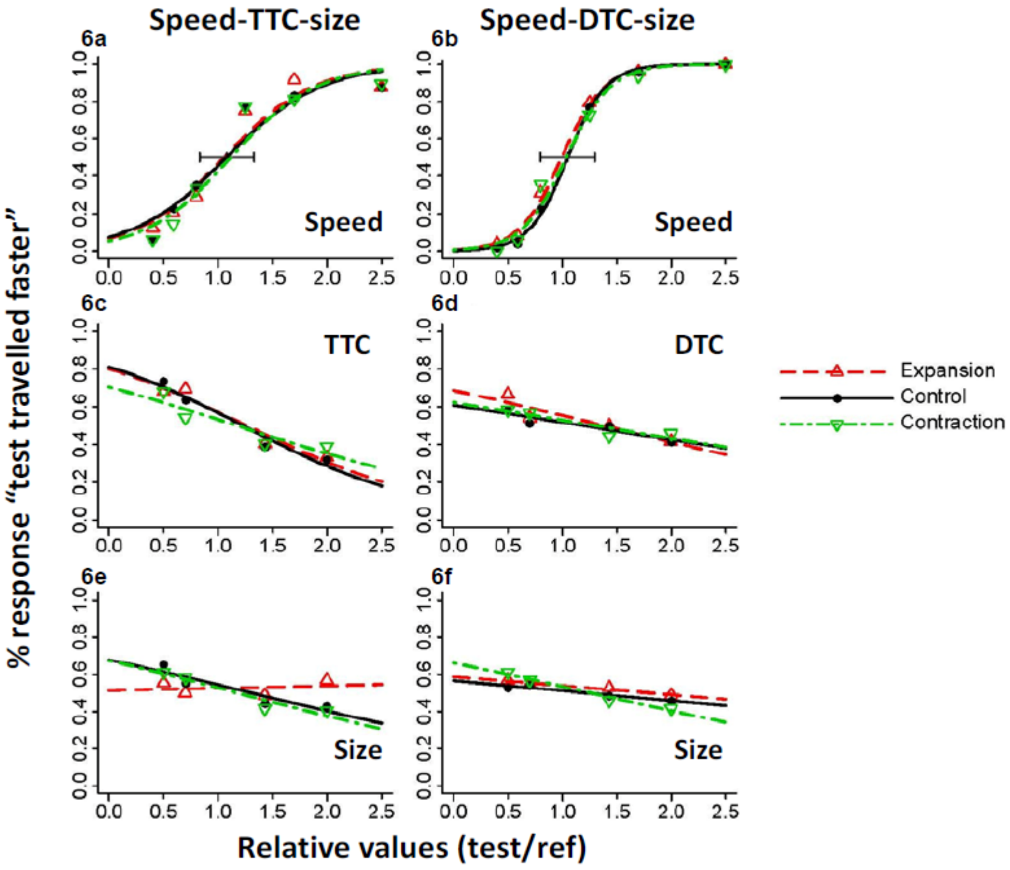


Figure 6. The fitted curves of relative speed judgments for participant SB in Experiment 2c. Each fitted curve was based on the different variables (TTC, DTC, speed and size) used in the experimental task. To compare the effects of TTCt manipulation, responses based on each variable were further separated by manipulation conditions, and plotted into the same figure. Left and right panels depict results from the speed-TTC-size array and the speed- DTC-size array, respectively.

Methods:

Experiment Design. Like Experiment 2a, two three-dimensional orthogonal arrays (TTC-DTC-size and TTC-speed-size) were used in Experiment 3. However, only four levels of TTC, DTC, speed, and target size were used. Furthermore, unlike Experiment 2a, control trials were only paired with either expansion or contraction trials for any given participant. Each participant was randomly assigned so that half of them completed the expansion and control conditions (Expansion-Control group) and the other half completed the contraction and control conditions (Contraction-Control group). For each group, trials from each array were repeated six times, once with manipulation (either expansion or contraction), and five additional times without (control condition). In total, each participant completed a single block of 768 trials (4x4x4 x 2 arrays x (1 manipulation + 5 controls)).

Procedure. The same procedures from Experiment 2a were used in Experiment 3.

Participants. Forty undergraduate students (13 male and 27 female) participated in this experiment for course credit. All participants had normal or corrected-to-normal visual acuity and were naive to the purpose of the study.

Results:

Results from individual participants were first examined to ensure observers were able to discriminate at least the largest TTC difference. Results from eight participants (one in Expansion-Control group and seven in Contraction-Control group) were consequently excluded from analyses. Figure 7 depicts, based on TTC information, the percentage of responses that the population of participants chose the test approach as arriving earlier than the reference. For the two different groups of participants, fitted curves from the expansion, contraction and their corresponding controls (total four curves) were plotted into the same graph. The left panel and right panel represent results from the TTC-DTC-size and TTC-speed-size arrays respectively.

We first examined discrimination thresholds for different psychometric functions. Results presented in Table 5 revealed that the Weber fractions for TTC information ranged from 0.52 to 0.64 for the TTC-DTC-size array and 0.42 to 0.44 for the TTC-speed-size array. Statistical analyses revealed that TTC Weber fractions were not significantly different between the Expansion-Control and Contraction-Control groups. Additionally, the Weber fractions of other non-TTC variables were greater, ranging from 1.49 to 7.54 for TTC-DTC-size array, and 2.83 to 18.6 for TTC-speed-size array. These values demonstrated that participants were at least three times more sensitive to tau than other non-tau variables.

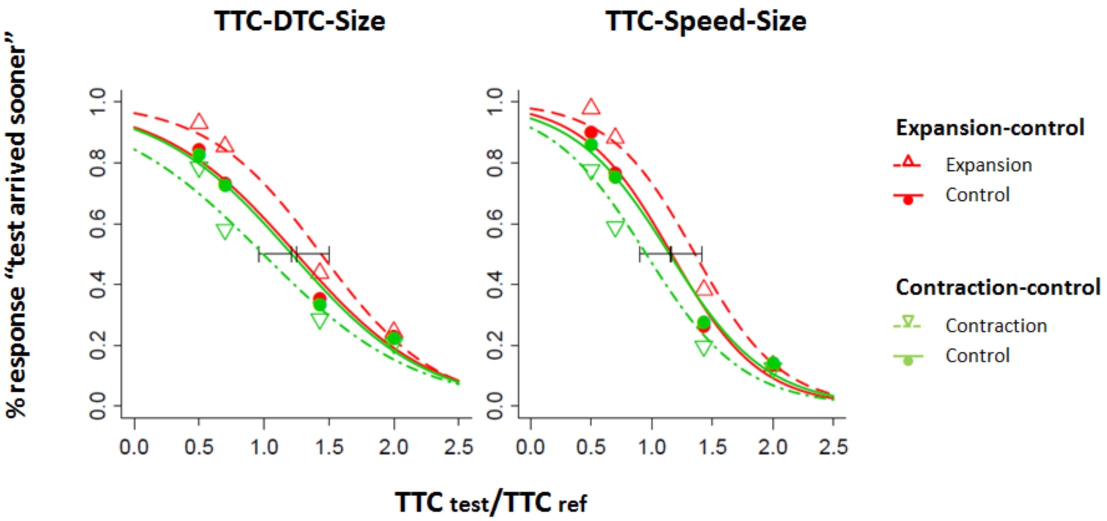
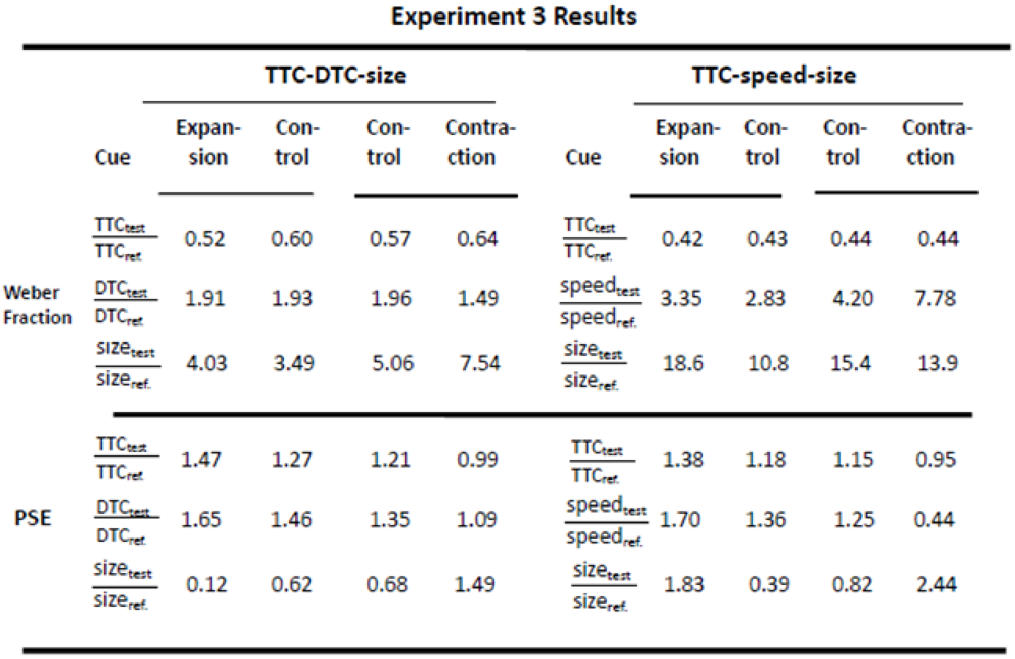


Figure 7. The fitted curves of relative TTC judgments for both Expansion-Control and Contraction-Control conditions. Only the fitted curves based on TTC information are presented. To compare the effects of TTCt manipulation, responses from two participants groups were plotted into one figure. Left and right panels depict results from the TTC-DTC-size array and the TTC-speed-size array, respectively.

Next, we compared PSEs across different conditions. In the TTC-DTC-size array, observers in the Expansion-Control group had average PSEs of 1.44 for expansion condition and 1.25 for control. Observers in the Contraction-Control group had average PSEs of 0.99 for contraction condition and 1.21 for control. PSE shifts were 0.19 (76% of the expected) and -0.22 (88% of the expected) for the two groups respectively. Results from the TTC-speed-size array showed that PSEs for tau were 1.36 and 1.16 for expansion and control conditions, and 0.95 and 1.15 for contraction and control. For both groups, these values corresponded to shifts of 0.20 (80% of expected shift). While the PSE shift, compared to no shift, was significant, $t(63) = 10.19$, $p < 0.01$ for combined arrays and groups, the observed PSE shift was marginally different from the expected (0.25) shift had observers based their estimation entirely on tau, $t(63) = -1.87$, $p < 0.07$.

Table 5. List of participants' relative discrimination thresholds (Weber fractions) and PSEs for judging TTC in Experiment 3, separated by each independent variable and TTCt manipulation condition.



Experiment 3 Results

	TTC-DTC-size					TTC-speed-size				
	Cue	Expan-sion	Con-trol	Con-trol	Contra-ction	Cue	Expan-sion	Con-trol	Con-trol	Contra-ction
Weber Fraction	$\frac{TTC_{test}}{TTC_{ref}}$	0.52	0.60	0.57	0.64	$\frac{TTC_{test}}{TTC_{ref.}}$	0.42	0.43	0.44	0.44
	$\frac{DTC_{test}}{DTC_{ref}}$	1.91	1.93	1.96	1.49	$\frac{speed_{test}}{speed_{ref.}}$	3.35	2.83	4.20	7.78
	$\frac{size_{test}}{size_{ref.}}$	4.03	3.49	5.06	7.54	$\frac{size_{test}}{size_{ref.}}$	18.6	10.8	15.4	13.9
PSE	$\frac{TTC_{test}}{TTC_{ref}}$	1.47	1.27	1.21	0.99	$\frac{TTC_{test}}{TTC_{ref.}}$	1.38	1.18	1.15	0.95
	$\frac{DTC_{test}}{DTC_{ref}}$	1.65	1.46	1.35	1.09	$\frac{speed_{test}}{speed_{ref.}}$	1.70	1.36	1.25	0.44
	$\frac{size_{test}}{size_{ref.}}$	0.12	0.62	0.68	1.49	$\frac{size_{test}}{size_{ref.}}$	1.83	0.39	0.82	2.44

Discussion:

Although no participant from Experiment 2 reported that they noticed a change in target size during approaches, it remained possible that they may have eventually sensed these changes due to the many hours of engagement and high frequency of manipulations. If so, participants may have adopted various other strategies to judge relative TTC as they may have regarded the target's physical size as unreliable. We demonstrated here, however, that this was not the case. Even for a larger sample of naïve participants, reducing the number of manipulations did not greatly change the pattern of results. Results consistently revealed that tau was the most effective and utilized source of information for judging TTC. When tau conflicted with ground-based depth information, these new participants continued to base their judgment to a large extent on tau. Tau by itself, however, could not account for the total difference in response following manipulation (approximately 80%). Statistical analyses showed that this observed shift was different, although only marginally, to the expected 100% shift we would expect if observers had based their judgments entirely on tau. This suggested that observers relied on tau primarily for TTC estimations, but also used other variables, albeit to a smaller extent.

ADDITIONAL CONSIDERATIONS: IMAGE SIZE AND RATE OF EXPANSION

In the present study, as TTC levels varied (which was approximated by tau, τ); image size (theta, θ) and rate of expansion (theta prime, θ') also simultaneously covaried. In order to investigate which of these three optical variables was used to guide observer estimates of TTC, we derived Weber fractions for the TTC judgment task as we systematically excluded the contribution of each of these three cues.

Methods:

As observers could theoretically use any combination of τ, θ or θ'·when all were available, we labeled Weber fractions for psychometric functions varying TTC as TTC_{all}. These Weber fractions which served as a baseline for comparison were the same as those reported in Experiment 1 and in control conditions of Experiments 2a and 3. The TTC-based psychometric function generated from a subset of trials where θ values at the moment of target disappearance were at the same level, represented observers' sensitivity excluding the contributions of θ. We labelled Weber fraction derived from this curve as $\text{TTC}_{\theta=\text{C}}$. Using this same principle, we also calculated the Weber fraction for the psychometric function varying θ from a subset of trials in which contributions of τ was excluded. This Weber fraction was labelled as $\theta_{\tau=\text{C}}$.

If participants exclusively used τ, but not θ, to perform the given task, then TTC_{all} and $\text{TTC}_{\theta=\text{C}}$ would be similarly low and comparable. Meanwhile, $\theta_{\tau=\text{C}}$ would be expectedly greater because the cue most useful for the task (τ) would not have differed between trials and was thus made uninformative. If, in contrast, participants used θ rather than τ in estimating TTC, then $\theta_{\tau=\text{C}}$ would be low, while $\text{TTC}_{\theta=\text{C}}$, greater. Similar analyses could also be performed comparing the usage of τ versus θ'. The values of theta and theta prime at the instant of object disappearance were calculated, respectively, using:

$$\theta(t) = 2 \times \arctan\left(\frac{S}{2 \times v \times TTC}\right) \qquad (A1)$$

$$\theta'(t) = \frac{1}{\frac{v}{S} \times TTC^2 + \frac{S}{4v}} \qquad (A2)$$

where *S* and *v* represented the physical size and approach speed of the object (also see Sun and Frost, 1998). Image cue analyses were performed for with-ground condition in Experiment 1, and control conditions for Experiments 2a and 3.

Experiment 1

In Experiment 1, the target's image size (θ) at the moment of disappearance ranged from 0.07 to 12.12 (relative to image size in the reference approach). From overall results, we chose a subset of trials in which θ values were similar (within a small range), and obtained a psychometric function and Weber fraction based on variations of TTC. We further examined five other subsets of trials with different intervals of θ values, found their thresholds to be similar, and averaged them. These six intervals were 0.5 - 0.7, 0.7 - 0.9, 0.9 - 1.1, 1.1 - 1.3, 1.3 - 1.5 and 1.5 - 1.7 in relative values, which in total included 579 trials for each participant (45% of all trials), and thus constituted a reasonable estimate of an observer's true performance. Values for θ' at the moment of target disappearance ranged from 0.03 to 18.82 (relative to the θ' in the reference approach). Again, we obtained and averaged Weber fractions from the same six intervals. These data sets totaled 465 trials for each participant (36% of all trials).

Lastly, recall that six levels of TTC were used in Experiment 1. For Weber fractions representing the exclusion of τ, we chose the subset of trials where TTC at moment of disappearance was 0.8 (close to the reference). This subset included 216 trials for each participant (17% of all trials). With τ constant, Weber fractions for both theta ($\theta_{\tau=C}$) and theta prime ($\theta'_{\tau=C}$) were obtained and compared with TTC_{all} to determine participants' sensitivity to these optical variables.

Experiment 2

Similar analyses were conducted on the control condition of Experiment 2a. However, as the levels of DTC and speed were reduced in Experiment 2, intervals we chose for analysis were changed accordingly. For subsets excluding θ ($TTC_{\theta=C}$), the intervals were 0.2 - 0.4, 0.4 - 0.6, 0.6 - 0.8, 0.8 - 1 and 1.2 - 1.4, which in total consisted of 363 trials (62% of overall data). For subsets excluding θ' ($TTC_{\theta'=C}$), the intervals were 0.3 - 0.5, 0.5 - 0.7, 0.7 - 0.9 and 1.1 - 1.3, which totaled 225 trials (39% of overall trials). Finally, for τ exclusion subsets ($\theta_{\tau=C}$ and $\theta'_{\tau=C}$), we again chose τ = 0.8, which contained 96 trials (17% of overall), for comparison.

Experiment 3

Image cue analyses for each observer were again conducted on results from control conditions. Weber fractions were derived, combined and averaged. For subsets excluding θ ($TTC_{\theta=C}$), the intervals were 0.3 - 0.5, 0.7 - 0.9, 0.9 - 1.1, 1.3 - 1.5 and 1.9 - 2.1, which in total contained a sample size of 7680 trials (75% of all trials). For subsets excluding θ' ($TTC_{\theta'=C}$), the intervals were 0.3 - 0.5, 0.5 - 0.7, 0.9 - 1.1, 1.3 - 1.5 and 1.9 - 2.1, which totaled 7360 trials (72% of all trials). Finally, for τ exclusion subsets ($\theta_{\tau=C}$ and $\theta'_{\tau=C}$), we chose τ = 1.43, which contained 2560 trials (25% overall), for comparison.

Results and Discussion:

For Experiment 1, Weber fractions for TTC containing all image cues (TTC_{all}), and for those that excluded the effects of different optical variables are depicted in Figure 8. Figure 8-A represents the comparison between τ and θ, whereas Figure 8-B, between τ and θ'. As shown**,** Weber fractions were similarly low for both TTC_{all} (all image cues available) and $TTC_{\theta=C}$ (θ excluded), but much greater for $\theta_{\tau=C}$ (τ excluded). A similar pattern between τ and θ' was also observed with exception for participant HM, suggesting that observers had a tendency to use τ over other image cues when completing the TTC judgment task. These patterns of results were similar in Experiment 2a (Figure 8-C and 8-D)**.**

In Experiment 1, participant HM had results atypical of the other three observers in that she was sensitive to θ' during the earlier blocks. In blocks 1 to 3, her ratio of $\theta'_{\tau=C}$ over TTC_{all} were 0.63, 1 and 16.1 respectively. This demonstrated that as HM progressed to block 3, the pattern of her Weber fractions became more similar to the other participants, and that specifically, her sensitivity to τ became much greater than her sensitivity to θ'. This suggested that HM switched from initially using θ' to appropriately using τ for the remainder of her participation. Results from the subsequent experiment (Experiment 2a) supported this conclusion as HM's Weber fractions were congruent to her later performance in Experiment 1, and did not change between blocks.

Figure 8-E and 8-F depicts image cue Weber fractions from the 32 participants in Experiment 3. As shown, when tau was excluded, Weber fractions for most observers increased (21 for $\theta_{\tau=C}$, and 17 for $\theta'_{\tau=C}$, represented by green lines) to at least twice that of corresponding TTC_{all}, $TTC_{\theta=C}$, or $TTC_{\theta'=C}$. When image cues for θ or θ' were excluded, three participants showed greater Weber fractions (at least twice as much) for $TTC_{\theta'=C}$ compared to TTC_{all} (represented by red lines). Meanwhile the same three participants showed low Weber fractions for $\theta'_{\tau=C}$, suggesting that they were sensitive to θ'. Sensitivities for the remaining participants (11 for θ, and 12 for θ'), however seemed to follow diverse patterns (represented by grey lines) and may have been because these individuals combined and varied the use of several variables (including non-image ones such as distance and speed) during their estimation. Overall, our results suggested that for approximately two-thirds of participants, τ rather than θ or θ' was used to guide TTC judgments.

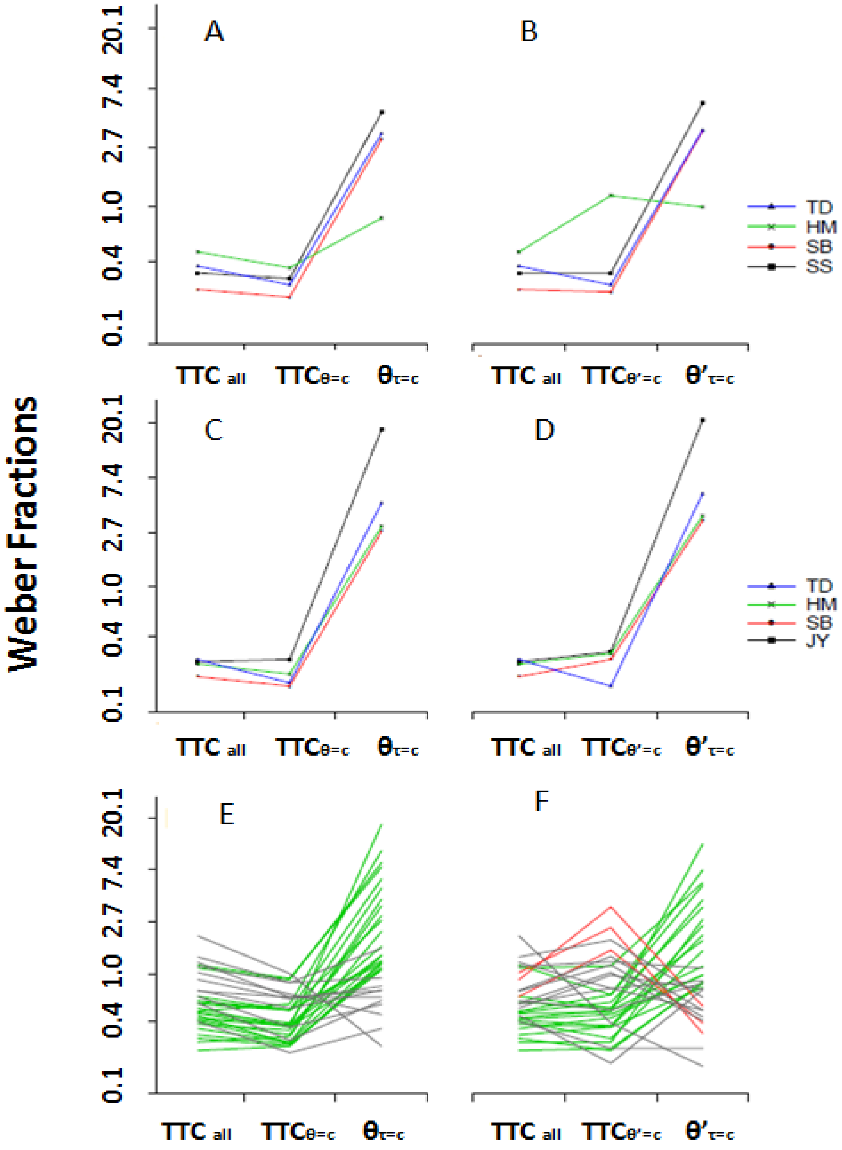


Figure 8. Comparisons of individual participant's Weber fractions for image cues in Experiment 1, 2a, and 3 (refer to text for descriptions of terms on the x-axis). The figures on the left (A, C and E) represent comparisons between the effects of tau (τ) and image size (θ). The right figures (B, D and F) represent similar comparisons between the effects of tau and rate of expansion (θ'). In bottom panels E and F, participants whose Weber fractions for non-tau variables (i.e. when tau was held constant) were twice that of TTC$_{all}$ were plotted in green. Participants whose Weber fractions for either non-theta variable (TTC $_{\theta=c}$) or non-theta-prime variable (TTC $_{\theta'=c}$) were twice that of TTC$_{all}$, were plotted in red. Remaining participants that could not be categorized under these two patterns were plotted in grey.

ADDITIONAL CONSIDERATIONS II: SHADOW-RELATED TAU

In the present study, observers, in theory, could have potentially based their TTC judgments on different parts of the image. These include TTC that is directly perceived from the looming spherical target and also the various forms of time-to-passage (TTP) information specified by the target's shadow. An illustration of the relationship between these variables is presented in Figure 9.

Optical tau generated from a looming object

As suggested by Lee (1976), TTC information is provided directly through the projected retinal image of the target. To differentiate this variable from other tau variables (i.e. those from the shadow, see below), we termed the tau generated from the target image as "object tau". The angle subtended by the looming object is represented in Figure 9 as "θ". Through equations A1, A2 and equation 2 (see Introduction), we can calculate image size, rate of expansion and optical tau, respectively. As object tau approximates the real TTC, directly perceiving this variable becomes an efficient and appealing method for generating TTC.

Features of the target shadow

Along with the target, it is possible that participants relied on the projected shadow image to directly perceive TTP. Due to the shadow's irregular shape and non-collision trajectory, several distinct features may have been useful, such as the width of the shadow, depth of the shadow and relative displacement between the shadow and target.

I) Shadow width

During target approach, image expansion of the shadow's width (through points a, and b in Figure 9) on the transverse plane is similar to the image expansion of the target's width. Tau derived from the local image expansion of the shadow's width provides a relatively accurate estimate of TTP and is a form of "local tau" as described by Tresilian (1991). According to the relationships depicted in Figure 9, we can generate equations needed to calculate the angle of the shadow width ($\vartheta(t)_{\text{width}}$) using:

$$\theta(t)_{Width} = 2 * arctan \frac{\frac{S}{2}}{\sqrt{(v * TTC)^2 + h^2}} \qquad (A3)$$

where variables *S*, *v*, *t* and *h* represent the target size (diameter), speed, TTC and target-shadow displacement (distance between center of the target and shadow), respectively.

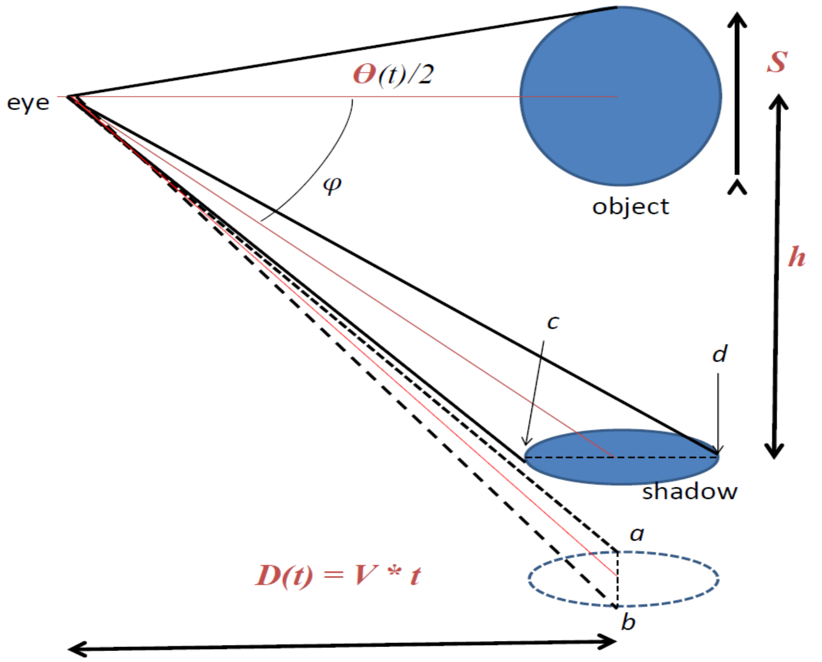


Figure 9. An illustration of the different types of information that might have contributed to the perception of TTC. At the moment of target disappearance, the object's TTC (t), speed (*V*), and DTC (*D*), are related by the equation *D* = *v***t*. The diameter of the target is represented by *S*, and the angle subtended on the observer's eye, as ϑ. The target's vertical displacement from the shadow is represented by *h*, and the image angle of this displacement as subtended on the eye as φ. The casted shadow on the ground had width *S*(a-b) and depth *S*(c-d), both equal to *S*. Note that points a, b, c and d are actually on the same plane (as they correspond to the same shadow), but were separated for illustrative purposes.

II) Shadow depth

During target motion, image expansion also occurs for the shadow's depth (through points c, and d in Figure 9) which potentially serves as an alternative "local tau" variable (Tresilian, 1991) specifying TTP. Using Equation A4, we can calculate the angle subtended by shadow depth ($\theta(t)_{\text{depth}}$), despite the projections of points c and d being asymmetrical around the center of the shadow image.

$$\theta(t)_{Depth} = \arctan\left(\frac{h}{v * TTC - \frac{S}{2}}\right) - \arctan\left(\frac{h}{v * TTC + \frac{S}{2}}\right) \qquad (A4)$$

III) Target-shadow displacement (TSD)

Given that the shadow was casted on the ground, the angle, φ (Figure 9) is subtended by the shadow's relative displacement to the center of the target, which also expands during target approach. This expansion, thus, generates a form of "global tau" as described by Tresilian (1991). We can calculate the angle of the TSD ($\varphi(\mathrm{t})_{\mathrm{height}}$) using:

$$\varphi(t)_{Height} = arctan\left(\frac{h}{v * TTC}\right) \qquad (A5)$$

Tau accuracy comparison

Theoretically, tau generated from the above described features could all have been used to estimate TTC. Using Equations A1, A3-A5, we calculated the various taus specified by the target and its shadow features, and computed relative tau values (tau for the comparison stimulus divided by the reference stimulus in the stimulus pair). Figure 10 illustrates the relative tau values of the three shadow features compared to the tau specified by the target for all trials in Experiment 1. Our results showed that with the exception of shadow-depth tau in a few trials, tau values for all shadow features were similar to the tau values specified by the target. In other words, the small and consistent errors between tau generated by the object and taus generated by the different shadow features made it impossible to identify which tau was actually used by observers during the TTC estimation task.

This problem, however, could be addressed if a large discrepancy was artificially created between information specified by these different features. Indeed when comparing object tau and TSD tau, the TTCt manipulation conditions in Experiments 2a and 3 demonstrated that participants' responses shifted to a large extent based on how object tau was manipulated. TSD tau, however, remained unaltered which suggested that object tau was more likely responsible for TTC estimates at least more so than tau specified by TSD.

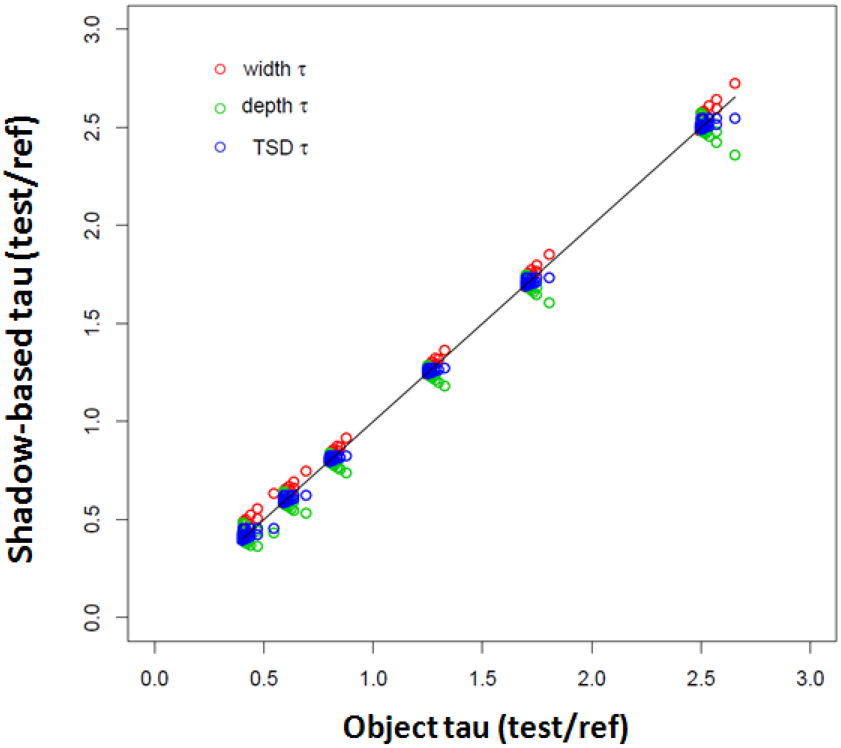


Figure 10. Scatter plot representing the accuracies of different types of tau information specified by the expansion of shadow or object. Object tau values (relative to the reference; test/ref) were plotted along the x-axis, while the 3 types of shadow-based tau were plotted along the y-axis. Shadow-width tau is represented by red points; shadow-depth tau, by green; and finally, target- shadow displacement (TSD) tau, by blue.

GENERAL DISCUSSION

In the present study, we used an orthogonal design and cue-conflict paradigm to investigate how participants made relative TTC judgments when non-time variables and different sources of TTC were available. Results from Experiment 1 showed that when judging TTC of an approaching target, participants were most sensitive to TTC and much less sensitive to variations of other non-time variables such as the approaching target's DTC, speed and physical size. Similar performances in with-ground and without-ground conditions further confirmed that participants relied mostly on TTC information during these estimations. Given that TTC information is used, we were also interested in what source of time information drove this sensitivity. Our results in Experiments 2 and 3 demonstrated that when different sources provided conflicting TTC information, observers were largely influenced by tau, and biased their judgments more towards the extent tau was manipulated. Altogether, we conclude that observers primarily used tau when making relative TTC judgments.

Optical and non-optical variables

Variables that have been previously identified to affect perception of impending collisions can be roughly considered to fall under two categories. The optical category focus on cues directly generated from the projected retinal image of the approaching object. The non-optical category, however, focuses on the approaching object's physical characteristics and its spatial relationship with the environment. Cues such as tau, angular size, rate of expansion and binocular disparity information fall under the optical category, whereas variables such as distance, speed and physical size of the object fall under the non-optical. Regan and colleagues (Regan and Hamstra, 1993; Gray and Regan, 1998) previously implemented the orthogonal matrix design in order to dissociate several of the variables within this optical classification. The present study, on the other hand, dissociated several variables from both optical and non-optical categories. Our results suggested that TTC judgments remained "tau-centric" even in the presence of depth information provided by shadow and ground. Furthermore, our findings were for the most part consistent with previous studies that demonstrated little influence of distance and speed in TTC judgment tasks (Schiff and Detwiler, 1979; McLeod and Ross, 1983; Gray and Regan, 1999).

Tau versus other optical cues during TTC perception

The present study aimed primarily to dissociate between inferring TTC via the distance/speed ratio and directly perceiving TTC from the looming image. In the latter case, however, it remained possible that image size (theta; θ) and rate of expansion (theta prime; θ') were used instead by observers. While our experimental design was not primarily intended as a means to dissociate between the different types of image-based variables (as performed by Regan and Hamstra, 1993), this was nonetheless an important issue as image size and rate of expansion would have simultaneously covaried when TTC changed. As demonstrated by several studies (Caljouw, van der Kamp, and Savelsbergh, 2004; López-Moliner, Field, and Wann, 2007; Hosking and Crassini, 2011), rate of expansion is an especially potent image variable that may strongly influence perception of TTC.

To investigate sensitivities to these optical variables, we examined, much like how TTC, DTC and speed were dissociated, Weber fractions for the TTC judgment task as the contribution of each variable was systematically excluded (see Additional Considerations I). This was performed by analyzing subset of trials in Experiments 1, 2a and 3, in which values of individual image-based variables were within a small range. Analyses on Experiment 1 revealed that observers were more sensitive to the tau variable, and less sensitive to variations of image size and rate of expansion when completing the task. Specifically, removing cues provided by image size ($TTC_{\vartheta=C}$) or rate of expansion ($TTC_{\vartheta'=C}$) did not significantly affect observer performance (Figure 8, Additional Considerations I). On the other hand, when variations of tau were excluded (i.e. $\theta_{\tau=C}$ and $\theta'_{\tau=C}$), most observers performed much worse. These findings were consistent with similar analyses conducted on results from Experiment 2a.

In Experiment 3, at least two-thirds observers clearly relied on tau for their estimations. Three of the 32 observers, however, used rate of expansion instead of tau, while the remaining participants had comparable sensitivities to both tau and rate of expansion. As was demonstrated in Experiments 1 and 2, testing duration may explain why individuals did not preferentially use tau for their estimates. Experiments 1 and 2a each involved four observers who individually completed more than six hours of testing. Experiment 3, on the other hand, tested a larger subject pool (n = 32) for a shorter duration (two hours for each participant). Like HM in Experiment 1, prolonged exposure to the stimulus may eventually bias observers' responses more towards tau. Nonetheless, results overall suggested that for many individuals, tau was the most useful optical variable for judging TTC, and was used much more than image size and rate of expansion.

The role of shadow in the stimulus

It is important to note that in the present study, the projected target image was used primarily as a source of tau (thus TTC) information. The assumptions of tau, along with target size manipulation within and between-trials, required that the center of the target be at eye-height level to ensure targets always approached at the same trajectory. Meanwhile, characteristics of the shadow on the ground were used to provide salient distance and speed information for the target. During each trial, however, images of both target and shadow expanded simultaneously. Therefore, it may have been possible that observers perceived different types of tau information (e.g. "local tau" and "global tau"; Tresilian, 1991) from either or both the looming target and expanding shadow. In Additional Considerations II, we compared the accuracy of the various time information specified by both target and shadow. Results demonstrated that tau specified by the target or various parts of the shadow provided similar accuracy (at least for the purposes of our relative judgment task). Thus, it would be difficult to ascertain which source of tau was used by observers to generate TTC information. Nevertheless, the use of either object tau or shadow "taus" would have validated tau theory, as the purpose of the current study was to dissociate the use of tau-based TTC from distance/speed based TTC.

Observers may not only use tau to guide their estimations

While responses to TTCt manipulations demonstrated the use of tau, it does not, however, imply that observers fully and only used tau when performing TTC-related tasks. As mentioned, one observer (HM) among the four in Experiment 1, showed a tendency to use rate of expansion in earlier trials (see Additional Considerations I). Moreover, in Experiment 3, approximately one-third of participants showed some sensitivity to other optical variables. Quantitative analyses on TTCt manipulation conditions in Experiment 3 further showed that observed mean PSE shifts were only about 80% of the expected shift (though only marginally significant) had observers fully used tau to guide their estimations. Analysis of a data subset demonstrated that this partial shift even existed (significant difference between observed and expected shift) for observers that primarily used tau. As Additional Considerations I illustrated, these observers were not sensitive to image size or rate of expansion, and thus non-tau optical variables likely did not contribute to their estimates. Instead, these observers may have potentially relied on, although to a smaller extent, derived scene variables such as distance or speed when making their judgments.

Multiple sources of information and the perception of TTC

In the presence of only image-based monocular information, tau may be the most reliable source available for perceiving TTC. Thus, it should be expected that observer responses are influenced entirely by this optical variable (Regan and Hamstra, 1993). In our study, we showed that this was indeed the case, as demonstrated by observers' sensitivity to TTC information in the without-ground condition of Experiment 1. In natural situations, however, observers are presented with many cues that could potentially influence TTC perception.

Although considerable studies have addressed the question about what sorts of information are detected and used by observers, only a few studies have examined how multiple sources of information are actually utilized to perceive TTC (e.g. Gray and Regan, 1998; Rushton and Wann, 1999; DeLucia, et al., 2003). Additionally, these results have been inconsistent in terms of how different variables contribute to TTC perception. Some studies (Gray and Regan, 1998; DeLucia, et al. 2003) have suggested that perceiving TTC may be to some extent similar to perceiving depth, in that different available cues are averaged together for perception (Bruno and Cutting, 1988; Landy, et al., 1995). Others, however, argued that the variety of information involved in TTC perception render a simple average rule unlikely under many situations.

The present study along with several others (Landy et al., 1995; Tresilian, 1999) provided evidence that observers may have largely based their responses on the most effective variable, either because of accessibility, reliability, efficiency or usefulness. For instance, previous demonstrations of the SAE may have been indicative that observers used the most readily accessible (and therefore efficient and useful) variable, namely size differences, to estimate TTC. When the present study, and others (DeLucia, 2005), removed the usefulness of this cue (via changes in target size between trials), effects of relative size were reduced.

Furthermore, several studies have also demonstrated that depending on the circumstances, observers could change their use of information during TTC-related tasks.

For instance, Heuer (1993) investigated the effects of target-vergence and size of an approaching object, and found that their relative use was dependent on the size of the approaching stimulus. His results showed that for larger objects, changes in image size resulting from object motion were more influential in affecting observer responses. For smaller objects, however, vergence was much more salient. This change in strategy was interpreted to be because larger objects provided higher quality information (Heuer, 1993; Tresilian, 1994). Therefore, the larger the object, the more image size became a reliable source of TTC information. In contrast, smaller objects provided lower quality image information, and thus, target vergence would have instead served as a better source for TTC. In these situations, it seemed observers directed their response to be more aligned with the higher quality (and thus more reliable) source of information.

Similarly, Rushton and Wann (1999) reported a switch in cue weighting between an object's optical looming and binocular information. Their findings suggested that the relative effectiveness of optical looming and binocular disparity cues was determined not only by the object's physical size, but by whichever information specified the earliest arrival. This would certainly be a reasonable feature as any cue that would have indicated a shorter TTC must necessarily be attended to in order to avoid a potentially harmful situation. In this case, it seems that the use of information was dependent on the urgency (and thus efficiency and usefulness) of available information.

Our results demonstrated that observers used multiple variables when making TTC estimations. These non-tau variables, however, were used to a much smaller extent than tau. This suggested that tau may have been the most efficient source of information in the present task, likely due to its reliability (as distance information was often limited), accessibility (as it was directly available) or efficiency (obviating the perception of distance and speed). Overall, collective evidence suggest that observers use multiple sources of information in a given situation by changing cue weighting during perception, and biasing their response based on the most effective source available.

Consequently, caution should be taken when generalizing our results. As mentioned, the use of tau is likely dependent on the presence and quality of other sources of information, many of which were made unavailable in the present study. For instance, one such powerful and missing cue was binocular disparity. Research, has demonstrated that binocular cues are important sources of TTC information (Heuer, 1993; Gray and Regan, 1998; Rushton and Wann, 1999; Gray and Regan, 2004), the presence of which has been shown to increase accuracy during TTC judgment tasks (Cavallo and Laurent, 1988) and affect perception of depth. Additionally, familiar size, a potent cue in natural situations, was also made absent and thus prevented prior information from influencing TTC perception. Therefore, it is uncertain whether the demonstrated primary use of tau would remain, had binocular disparity or any other powerful cue also been present. Nonetheless, the present study demonstrated that even when provided with distance, speed and size information, observers to a large extent preferentially used tau to guide their estimates of TTC.

In summary, our study performed systematic and quantitative examinations on whether observers were sensitive to optical and non-optical variables when judging relative TTC. It was shown that under the current paradigm, human observers were highly sensitive to TTC and mainly used tau when performing a relative TTC judgment task. However, while our results showed a strong capacity to use tau, we acknowledge that the actual weighting of variables in more natural situations remains to be tested. Finally, the hypothesis that multiple sources of information redistribute their weighting in different tasks and situations warrants further investigation, especially in regards to how they integrate and change when observers interact with the physical environment (Tresilian, 1999; Warren, 2006).

III. STUDY II: Time-to-collision in optic flow: is tau obtained using the absolute or relative rate of expansion?

When moving or interacting with objects in an environment, various visual patterns can occur in the optic array. Each pattern can specify different types of events (see Frost and Sun, 2003). For instance, motion within a small area of the retina relative to other parts of the image usually indicates object movement within the environment. On the other hand, visual flow patterns across the entire retina generally signify observer self-motion. Many real-world situations involve a combination of both object and observer motion. In all cases, looming images within the optic array represent objects of interest, whether they are items to avoid, or to interact with. Tau theory postulates that the time-to-collision (TTC) of any directly approaching object within the environment (if continuously travelling at the same speed) can be specified using the optical variable tau, which is derived independent of other sources of information such as distance and velocity of the approaching object (Lee, 1976). It is generally assumed that tau is veridical regardless of the type of visual motion. As such, use of optical tau should result in identical estimates of TTC in both situations when an object is moving towards an observer, and when an observer is moving towards an object. Recent studies, however, cast doubt on the generality of using tau. As demonstrated in Study I, tau is primarily used by observers to estimate TTC in situations where a stationary observer is approached by an incoming object. In this study, we investigated whether tau is also used in situations of observer self-motion.

From an ecological perspective, looming images resulting from object motion should be distinguished from looming resulting from self-motion. While both are necessary for survival, the two oftentimes serve distinct ecological roles (see Frost and Sun, 2003) and should intuitively influence the way TTC is perceived. It is likely that the processes used to detect and avoid aversive stimuli (oftentimes derived from looming images resulting from object motion) are distinct from processes used to trigger pursuit and interactive behaviour with incoming objects (usually from looming images obtained via self-motion). A number of studies have suggested that looming images resulting from object motion are indeed processed differently than looming images resulting from self-motion. For instance, Sun and Frost (Frost and Sun, 1997; Sun and Frost, 1998) demonstrated that looming sensitive neurons (those that specifically responded to tau) fired when stationary observers (pigeons) were presented with simulated approaching objects. These neurons, however, did not fire when the same looming image was presented alongside an expanding background that simulated self-motion.

In a subsequent study, Gray and Regan (2000) provided behavioural evidence that a simulated optic flow-field imitating self-motion, reliably influenced TTC estimations in human participants. Using a two-alternative forced-choice task, Gray and Regan (2000) had participants judge whether a simulated approaching and disappearing target would arrive earlier or later than a presented auditory signal. This target was surrounded by many peripheral squares that either moved outwards and expanded, or moved inwards and contracted. Peripheral squares could freely move off screen or behind the approaching target, thereby simulating forward and backward self-motion respectively. The researchers showed that participants underestimated TTC in the forward self-motion condition more so than in a control condition consisting of static moving squares. Moreover, these same participants overestimated TTC in the backward self-motion condition. Interestingly, the researchers also found that under- and overestimation errors vanished when the peripheral squares, while still moving outwards or inwards, remained a constant size; dispelling the illusion of motion-in-depth. Gray and Regan (2000) argued that these estimations errors in the presence of "self-motion" served ecological roles, providing heuristics for initiating actions (i.e. readying muscle sequences during a chase) while accounting for body acceleration. In a follow-up study, Gray, Macuga and Regan (2004) found that similar manipulations of self-motion also influenced speed judgments, reliably increasing perceived speed during a forward motion task, and decreasing it during backward motion.

Lastly, a recent study by Geri, Gray and Grutzmacher (2010) demonstrated that observers show biases to self-motion when simultaneously presented with object motion. Participants were shown a spherical target that approached mid-air over a textured ground surface (similar to with-ground conditions used in our first study), and were asked to indicate (by pressing a button) when the approaching object, which disappeared some time before contact, would have reached them. Object motion conditions were typical looming scenarios and as such, only the target appeared to approach the observer. Simulated self-motion conditions, on the other hand, coupled increases in target size with terrain expansion. Like previous findings, Geri and colleagues demonstrated that observers underestimated TTC more so in situations involving self-motion. However, when both types of motion were presented simultaneously, it was the proportion of object-motion/self-motion that determined observer responses. Specifically, a higher ratio resulted in reduced underestimations to match responses to object-only motion conditions. Collectively, these studies suggest that a simple tau strategy alone may be insufficient to explain TTC perception in both situations involving object- and self-only motion. Furthermore, they allude that the optic array contains features that are unique to self-motion, which may have caused the observed underestimations. One such feature may be the radial pattern of expansion from the observer's direction of heading (the focus of expansion), known as optic flow (Gibson, 1966; for review, see Lappe, Bremmer and van der Berg, 1999)

Optic Flow

Optic flow is an important source of depth and kinaesthetic information. Manipulation of optic flow has been reliably demonstrated to influence perceived self-motion (see Lee, 1980; Lappe, Bremmer and van den Berg, 1999). For instance, Lishman and Lee (1973) found that the presentation of optic flow to stationary observers was sufficient to induce feelings of self- movement. This visual information, moreover, biased observers more so than simultaneously presented conflicting mechanical kinaesthetic information (such as vestibular or proprioceptive cues). Prokop, Schubert and Berger (1997), additionally, demonstrated that walking velocity on a self-moving treadmill could be reliably influenced by an artificially generated optic flow pattern (via a spherical screen). It seemed participants, when asked to keep a constant walking velocity, modified their movement speeds and increased it in the presence of forward optic flow (simulating slower propulsion) and decreased it during patterns of backward flow (simulating faster propulsion). The use of optic flow, moreover, has also been implicated in the control of body sway (Lee and Lishman, 1975) and distance estimation (Bremmer and Lappe, 1999); further supporting the importance of optic flow for perceiving depth and self-movement through an environment.

Typically when approaching an object during self-motion, background objects and textures behind the object also approach on the retina, but appear to do so at a slower rate. Images of the object and background expand on the retina, but the closer object expands to a greater and thus faster extent than images from the farther background (Gibson, 1950). Therefore, the local expansion immediately outside the contours of the object exhibits a different rate of expansion (ROE) from the approaching object itself.

Recall that tau is derived using the image size (θ) of the incoming object divided by the image's ROE (Δθ/Δt; alternatively θ′).

$$TTC \approx \theta/(\Delta\theta/\Delta t) = \tau \qquad (2)$$

During looming motion of only one object, ROE of the approaching target could be used to generate a veridical estimate of its TTC. In optic flow conditions (i.e. forward self-motion), however, ROE of the approaching target is potentially influenced by the surrounding visual flow. Specifically, we proposed that during forward visual flow, the difference in ROE between the approaching target and its surroundings can result in reduced "relative" expansion rates, consequently leading to overestimations of tau and a larger "relative tau" value.

Interestingly, this overestimated response predicted by relative tau during simulated forward self-motion is opposite of the underestimated response demonstrated by Gray and colleagues (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010). Gray and Regan (2000) argued that observers parse retinal flow information from self-motion using higher-level image processing which can lead to TTC underestimations. The authors suggested that converging activations of changing size receptors activate neurons that generate motion-in-depth signals. These signals then potentially influence local receptors, such as those based on tau to specify underestimations. Various other studies (Rushton and Warren, 2005; Rushton, Bradshaw and Warren, 2007; Royden and Connors, 2010) have also suggested that observers do dissociate object motion and self-motion using global, rather than local image processes. However, the possibility remains that local image cues, such as relative tau, still contribute to TTC perception in scenarios containing optic flow. As such, the present study offered an opportunity to investigate the direction of biases during simulated forward self-motion. Overestimated responses would suggest that observers relied on the local portion of the image for TTC perception, while underestimations would suggest higher-order processing and control.

Meanwhile, there are several scenarios that result in similar expansion patterns as those produced by forward self-motion. For instance, one such situation is when a stationary observer is approached by two objects in sequence. As long as the image of the closer object does not fully occlude the image contour of the second object, local relative expansion of the closer object will be smaller than that of object expansion alone. Comparing TTC estimations in simulated self-motion and this two-object approach scenario, therefore, offers an additional opportunity to investigate the processing of unique properties in self-motion during TTC perception. Overall, we believe that despite the observed differences between TTC estimation during object and self-motion (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010), tau may still play an important role in processing TTC during forward visual flow. Furthermore, it may be relative tau that is used instead of absolute tau.

The Current Study

The present study was primarily interested in determining whether relative or absolute tau is involved in the perception of TTC when in self-motion. We were interested in investigating whether tau, if used during forward visual flow, is dependent on the relative ROE between the object's image boundary and its surroundings; and whether relative tau could account for TTC perception during simulated self-motion. To address these questions, Study II also utilized a relative TTC judgment task similar in design to Study I. Participants were asked to compare the time-of-arrival of two sequentially presented approaching targets (a test and reference approach) that vanished prior to contact with observers. In all scenarios the approaching target (again, a red sphere) was presented in front of a non-textured background object (green sphere) that either remained stationary or moved forward along with the target. Meanwhile, instead of a ground surface, the current study delivered the approaching target within a textured tunnel (with its longer axis aligned with the z-axis of the target's displacement), which was used to provide background visual information in all directions around the two objects and evoke a stronger sense of depth (comparable to the optical tunnel introduced by Gibson, Purdy and Lois, 1955). Sources of information present in the virtual scene include distance and speed cues provided by perspective (convergence towards the end of the tunnel), changes in texture gradient of the tunnel, and edge rate of the target during motion.

Three conditions were used to evaluate the use of tau. These three conditions provided visual simulations of either a target-only approach (referred to as 1-OA); a two-object approach (target and background object; 2-OA) or simulated forward self-motion (FSM) where both target and background remained stationary but the observer approached the target. In the 1-OA condition, the background object and background tunnel remained stationary, and thus did not expand on the retina during target approach (relative ROE was equal to absolute ROE). Participants, thus, perceived the approaching target's absolute ROE without interference from surrounding visual flow. In the 2-OA condition, the background object was manipulated to move towards observers at the same speed as the target, but expanded at only half the target's ROE (relative ROE was half of absolute ROE). This setup, thus, enabled us to investigate to what extent observers were capable (or incapable) of using the target's relative ROE in the presence of background expansion. Meanwhile, the background tunnel remained stationary which caused this manipulated expansion pattern to be localized to the boundaries of the target and background object. Lastly, in the FSM condition, target and background object remained stationary as the observer (specifically the camera) moved towards the target. This movement caused optic expansion of all features in the environment, providing a forward motion experience. Importantly, the presence of the background object led to a smaller relative expansion rate near the immediate boundaries of the target in the same way as the 2-OA condition. This manipulation, therefore, allowed us to examine whether self motion specifically influences TTC perception. A summary of retinal expansion presence for different features of the scene (target, background object and background tunnel) is presented in Table 6.

Table 6. A summary of the retinal expansion pattern for different features of the environment in all three conditions used in the present study.

		Retinal Expansion		
		Target	Background object	Background tunnel
Conditions	1-OA	✓		
	2-OA	✓	✓	
	FSM	✓	✓	✓

Like our previous study, we adopted the method of constant stimuli. Moreover, an orthogonal matrix design, similar to the orthogonal array used in Study I, was again used to generate the combination of parameter values for the test approach in each trial. This time however, TTC and ROE were varied along the two dimensions (see Regan and Hamstra, 1993) in order to investigate whether observers relied on TTC cues (specifically tau, as argued in Study I) or ROE information for their TTC estimates.

In Experiment 1, we first examined observer sensitivities to TTC and ROE in order to investigate the influence of tau in TTC perception. 1-OA and 2-OA conditions were compared to determine whether TTC perception is mediated by absolute or relative tau (assuming tau was used). If participants utilized absolute tau, we would expect no difference between 1-OA and 2-OA, as absolute ROE between conditions would have remained unaltered. If, however, observers used relative tau we would expect overestimations of TTC in the 2-OA condition. The extent of any response shift could then be quantified and compared to the expected shift had participants fully based their estimation on relative tau (similar in principle to cue conflict manipulations performed in Study I). In Experiment 2, we additionally included a simulated FSM condition to investigate whether self-motion specifically influenced TTC estimations. If relative tau was primarily used to guide TTC perception in the presence of forward visual flow, we would expect no difference between 2-OA and FSM conditions as local expansion patterns were matched in both scenarios. Meanwhile, we would continue to expect observers to overestimate responses in both 2-OA and FSM conditions. If self-motion specifically influenced TTC perception independent of this local expansion; we would expect observers to respond differently to the two conditions, perhaps underestimate TTC in FSM conditions (as suggested by Gray and colleagues).

EXPERIMENT 1

Rationale:

In order to evaluate whether observers utilized absolute or relative tau when estimating TTC, we compared observer responses in target-only (1-OA) and two-object approach (2-OA) conditions. We expect that observers would overestimate TTC in the 2-OA condition if they relied on tau generated from the relative rather than absolute ROE. Any shifts in estimation could then be quantified and compared to the expected shift had participants based their entire estimation on absolute (no shift) or relative tau (see *Data Analysis*).

Methods:

Apparatus. The experiment was conducted in a similar manner using the same setup and equipment as Study I. Again, the display measured 246 x 182 cm with a resolution and frame rate of 1024 x 768 at 60 Hz. Participants remained stationary and viewed the screen from a distance of 133 cm resulting in a field of view spanning 85.5° x 68.8°.

Participants. Four individuals, 3 females and 1 male between the ages of 22-32 participated in this study for course credit or monetary compensation. Participants had normal or corrected-to-normal acuity and were naive to the purpose of the experiment.

Stimulus and Procedure. The target was a simulated non-textured red sphere that approached the observer in a direct trajectory within the sagittal plane parallel to the horizontal. This target approached at a constant speed in front of a non-textured green sphere (background object) that either remained stationary or approached at the same speed as the target. Both the target and background object had shading information (illuminated from above) that create a sense of 3D volume despite no discrete texture elements on the surface of either sphere. Consequently the most distinct expansion would occur at the boundaries of the object.

The entire scene vanished at moments prior to contact between target and observer (specified by the TTC variable, see *Target Characteristics*), with total stimulus viewing duration randomly generated between 0.75 and 1.25 seconds. During target approach, both target and background object were presented and centered at eye-level along the long axis of the cylindrical tunnel. This tunnel, which was intended to evoke a sense of 3D depth, was textured with black converging rectangular patterns that ran along the length of its side (see Figure 11).

In each trial, observers were presented with two sequential presentations of a target approach separated by a 250 ms blank screen interval. The participant's task was to compare from the moment of disappearance, the remaining TTC (thus vanishing TTC) of the first and second approach, and judge which of the two would have arrived earlier under assumption that the targets remained moving at the same speed following disappearance. After each response, the next trial began following a 500 ms blank-screen interval.

Movement Parameters of the Target:

In each trial, the two approaches were each assigned as a reference or a test approach, with the presentation order randomly chosen. For the reference approach, the target's TTC (at the moment of disappearance) was kept constant at 1.5 seconds (s), ROE at 2.54 degrees/s, speed at 10 m/s (virtual unit), and diameter at 1 m (virtual unit). For the test approach, however, the target's motion characteristics were either controlled by an orthogonal matrix (similar to the array used in Study I) or randomized (i.e. viewing display duration and size). The orthogonal matrix varied TTC and ROE along the horizontal and vertical axes respectively (similar to Regan and Hamstra, 1993). Each cell of this matrix, which consisted of a combination of a TTC and ROE value, was then used to specify parameter values for the approach (see introduction in Study I for more details on the orthogonal array design). Six levels of TTC (0.6, 0.8, 1, 1.3, 1.5 and 1.8 relative to TTC of the reference approach) and 4 levels of (absolute) ROE (0.6, 0.9, 1.4 and 1.7 relative to reference ROE) were used in the orthogonal matrix, resulting in 24 unique combinations of approaches. On the other hand, target speed, which was kept constant during each approach, was adjusted depending on the TTC and ROE of the incoming target. Meanwhile, target size was varied randomly between 4 fixed values (0.6, 0.9, 1.4 and 1.7 relative to reference size). Lastly, as viewing duration was randomized between 0.75 and 1.25 seconds, TTC and ROE of the target at the start of the trajectory changed accordingly. The random display duration prevented observers from using other unrelated information, such as initial angular size and visible target duration, to perform the present task (see Regan and Hamstra, 1993).

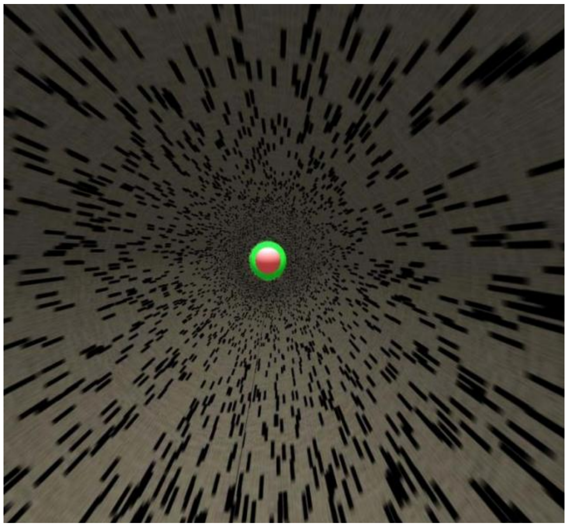


Figure 11. A snapshot of the stimulus used in the present study. The approaching red target was symmetrically aligned and presented in front of the green background object. Both objects were delivered within a textured cylindrical background which provided depth information.

Movement Parameters of the Background Object:

In reference approaches, the background object was always kept stationary. In test approaches for the 1-OA condition, the background object remained static (similar to the reference approach), and thus exhibited no image expansion. In the 2-OA condition, however, the background object approached observers at the same speed as the target, but always at half the target's ROE at the moment of scene disappearance. In other words, as we varied (across four levels) the absolute ROE of the target, the ROE of the background object also varied accordingly, so that its value was always half the target's ROE.

For both conditions, the background object always projected a larger retinal image size than the target (initial size determined by target parameter and background object ROE), and consistently ended 1.25 times the target's image size at the moment of scene disappearance. This ensured that relative size of the visual angle between the target and background object would be constant at the end of every approach; and only relative ROE of the target in reference to that of the background object would vary among 1-OA (identical to the absolute ROE) and 2-OA conditions (half of the absolute ROE). Consequently, relative tau in the 2-OA condition is twice that in the 1-OA condition.

Figure 12 illustrates sample relationships between image size and ROE for 1-OA (left) and 2-OA condition (2-OA) during the course of target approach.

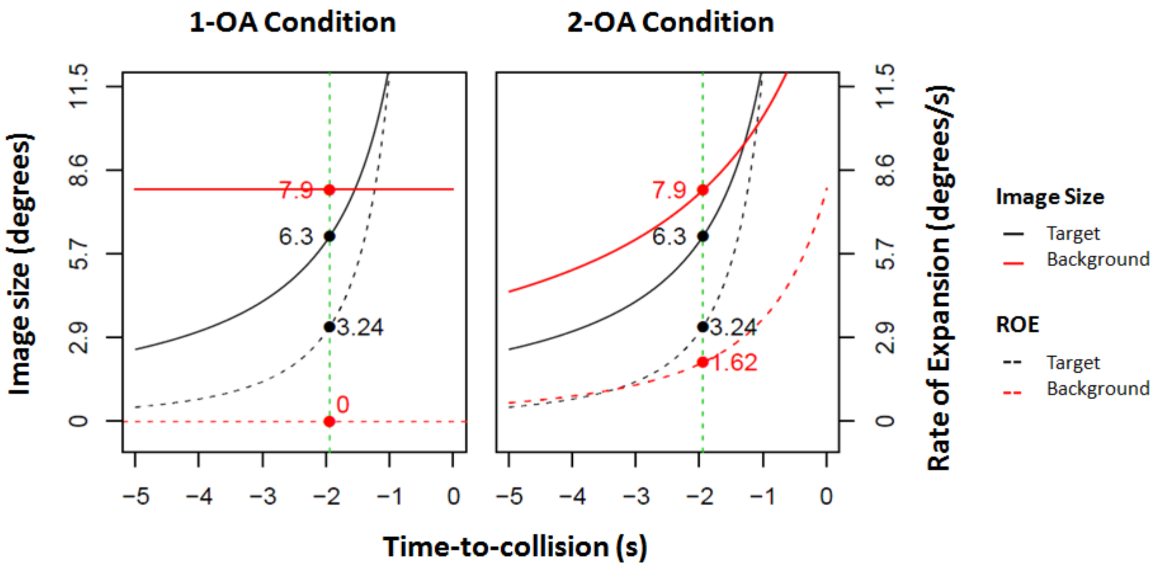


Figure 12. Sample image size and rate-of-expansion (ROE) profile during course of approach for target-only (1-OA; left panel) and two-object approach (2-OA; right panel) conditions. The abscissa represented the time-before-contact with observers. In both conditions, the image size of the background object was always fixed at the moment of disappearance to be 1.25 times the size of the target. In the 1-OA condition, image size and ROE of the background object were kept constant, the latter being 0. In the 2-OA condition, however, the ROE of the background object was made to be ½ the target's ROE during the entire approach. Note that the graph illustrates the time course for 5 seconds of movement, but the actual image presentation only lasted for a duration randomly chosen between 0.75 and 1.25 s until the moment of scene disappearance, indicated by the vertical green-dashed line.

For approaching objects, the angular subtense projected on to the retina is represented by Equation 4 (See Sun and Frost, 1998).

$$\tan\left(\frac{\theta(t)}{2}\right) = \frac{\frac{S}{2}}{d(t)} = \frac{S}{2 \times v \times TTC(t)} \tag{4}$$

In this equation, *d* represented the distance-to-collision from the observer; *v*, the object's approach speed; and *S*, its diameter. From Equation 4, Equations 5 and 6 were derived and used to generate appropriate image size (θ) and ROE (θ') for both target and background object.

$$\theta(t) = 2 \times \arctan\left(\frac{1}{2 \times TTC(t)} \times \frac{S}{v}\right) \tag{5}$$

$$\theta'(t) = \frac{1}{TTC(t)^2 \times \frac{v}{S} + \frac{S}{4v}} \tag{6}$$

Given that values for TTC, DTC and speed are pre-determined for each target at the moment of scene disappearance (from the orthogonal matrix), we can calculate the object's image size and ROE. Further, recall that the background object was always specified to be 1.25 times the image size of the target, and half its ROE. As a result, we can determine the appropriate values of TTC, DTC and size for the background object at the moments of initial approach and disappearance.

In this experiment, a block of trial was composed of an exhaustive combination of target parameters and the two background manipulations (therefore 48 trials in total). Parameters for test approaches were chosen randomly and without replacement from each block. Each participant completed 12 blocks, for a total of 576 trials (approximately one hour). Every 72 trials (approximately 10 minutes), a 1-minute break was provided, which could be extended upon request. Additionally, prior to beginning the formal experiment, participants were given practice trials in 1-OA conditions until they were comfortable with the estimation task. Feedback was given on each practice trial to indicate whether responses were correct. No feedback, however, was provided in the formal experiment. Finally, in all experiments, participants were instructed to wear an eye-patch covering an eye of their choice.

Data analysis. Responses were analyzed similarly to Study I. Responses for each participant were converted to the frequency that the test stimulus was judged to have arrived earlier. This frequency was generated by collapsing responses along each of the two orthogonal dimensions. These responses were further separated into their respective conditions, resulting in 4 psychometric functions, two varying TTC and 2 varying ROE along the abscissa. These psychometric functions were then fitted to a logit model (Cohen, Cohen, West, and Aiken, 2003), which was then used to calculate the relative discrimination threshold (Weber's fraction) and point of subjective equality (PSE). The relative discrimination threshold was defined as $(X_{75}-X_{25})/2$, in which X_{75} and X_{25} represented the value of the independent variable for which participants had a 75% and 25% chance, respectively, of selecting the test approach as arriving earlier.

Next, PSE differences between conditions were compared and converted to a relative shift value. Relative shift was defined as the ratio of the observed shift over the predicted shift had observers fully used relative ROE to generate tau. As expansion rate of the background object was always half the target's ROE at the moment of scene disappearance, the predicted shift was expected to be -0.5.

Results:

Figure 10 depicts the percentage of responses that participant BH selected the test approach as arriving earlier than the reference based on TTC or ROE. Responses in 1-OA (black line) and 2-OA (green line) conditions were plotted in the same graph. Left and right panels represent fitted curves based on TTC and ROE, respectively.

For participant BH, fitted curves based on the TTC variable (left panel) were much steeper compared to those based on ROE (right panel). Weber fractions for TTC were -0.22 to -0.23 for 1-OA and 2-OA conditions, whereas thresholds for ROE were -2.08 and -1.12 respectively, and approximately 4-10 times greater, precluding the need for further investigation.

Interestingly, as shown in Figure 13, fitted curves for the TTC variable were shifted to the left for the two-object approach condition. This demonstrated that the presence of a moving background object caused BH to consistently overestimate her responses. PSEs for 1-OA and 2-OA scenarios, in the units of test value/reference value, were 1.07 and 0.80, respectively, which equated to an observed shift of -0.27. This shift corresponded to a 54% shift relative to predicted had participant solely utilized relative ROE and consequently relative tau. More importantly, direction of response bias between participants was consistent. While no statistical tests were performed due to the small sample size, the average PSE shift between 1-OA and 2-OA condition was 0.30, and thus 62% of the predicted shift. This was again not quite the full extent expected had relative tau fully guided TTC estimations. Relevant Weber fractions and PSE comparisons for all 4 participants are presented in Table 7.

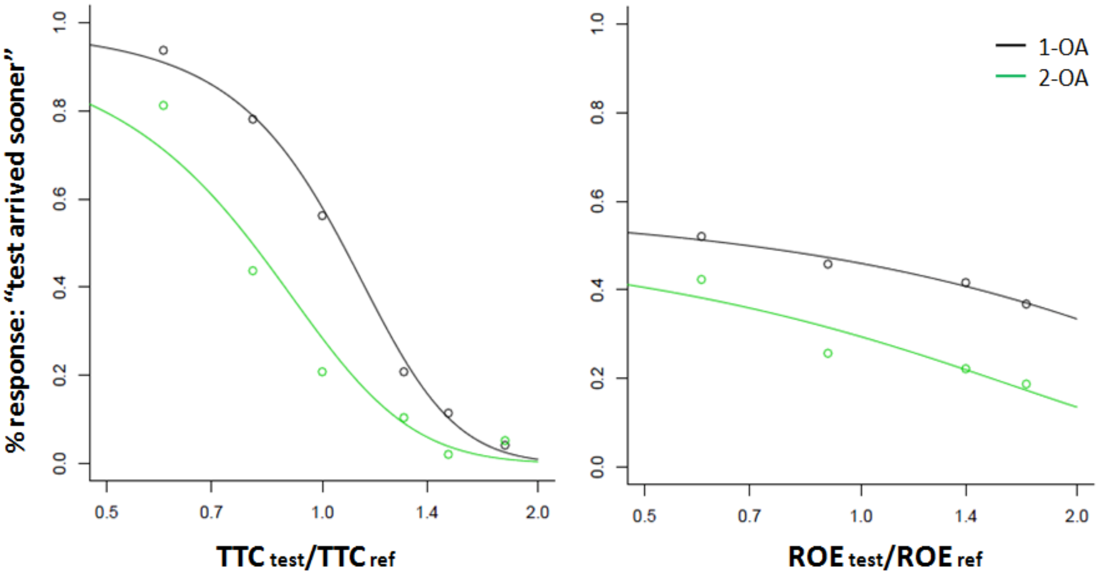


Figure 13. The fitted curves of relative TTC judgments for participant BH in Experiment 1. The left curve was based on the TTC variable, while the right was based on ROE. To compare the effects of 1-OA (black line) and 2-OA (green line) conditions, responses were further separated by the background manipulation conditions, and plotted into the same figure.

Table 7. Relevant Weber fractions and PSEs of all 4 participants used in Experiment 1.

		Weber Fraction (absolute and average)		**PSE (TTC test/TTC ref)**	
		TTC	ROE	1-OA	2-OA
Participants	BH	0.23	1.60	1.07	0.80
	AB	0.43	6.46	1.10	0.40
	BC	0.22	1.33	1.00	0.92
	YW	0.26	2.25	1.10	0.92

Discussion:

Overall, results from Experiment 1 suggested that tau may still be the primary source of TTC information even in the presence of local forward flow. Similar to findings from Study I and those obtained by Regan and Hamstra (1993), participants seemed to have relied mostly on tau information when performing the present TTC estimation task. This was true, moreover, in both 1-OA and 2-OA scenarios. In addition, it was demonstrated that the presence of background object motion caused overestimations of TTC in all participants. As absolute ROE was unaltered in both scenarios, observed responses were inconsistent with a tau strategy that relied on the absolute ROE of the incoming target (as suggested by Lee, 1976). Instead, the present results suggested that observers may have used a relative tau strategy that involved relative ROE information.

Additionally, the present results were opposite to those obtained by Gray and colleagues (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010) which showed that simulated self-motion led to underestimations in perceived TTC. This suggested that observers chose to rely on the local expansion pattern to complete the TTC estimation task. However, as the present study only localized relative motion patterns to the immediate surroundings of the target, the effects of optic flow remains to be tested. As such, tau specified by the local image may still have served as the optimal source of TTC information. It remained uncertain, therefore, whether simulated self-motion especially with the presence of peripheral optic flow could further influence perception of TTC.

EXPERIMENT 2

Rationale:

Given that TTC was overestimated most likely due to the relative expansion of the approaching target and its surroundings; the present experiment wanted to investigate whether simulated forward self-motion (FSM) would have the same effect on TTC perception. FSM was generated by having observers (specifically, the camera projecting the scene) approach a stationary target and background object. In this case as in Experiment 1, the presence of the background object provided background expansion outside the contour of the approaching target. Importantly, we made the self- motion speed in FSM conditions the same as the target speed in the 2-OA condition so that the local expansion rates in areas surrounding the target could be made to match expansion patterns in the 2-OA condition. As such, comparing FSM and 2-OA conditions allowed us to investigate whether self-motion provided any unique influence on TTC perception. We predict that estimations would not differ between FSM and 2-OA conditions if TTC perception during forward self-motion was entirely dependent on relative tau.

Methods:

Participants. Nine individuals, 5 males and 4 females between the ages of 19-32, participated in this study for course credit or monetary compensation. Participants had normal or corrected-to-normal acuity and were naive to the purpose of the experiment.

Stimulus, Procedure and Experimental Design. The present experiment essentially incorporated the FSM condition to Experiment 1. Stimuli and procedures otherwise remained unchanged. In the FSM condition, the target and background object remained stationary as the observer approached. This, therefore, enabled us to investigate the effects of self-motion while keeping target parameters identical to those used in the previous experiment. The same six levels of TTC (0.6, 0.8, 1, 1.3, 1.5 and 1.8 relative to TTC of the reference approach) and 4 levels of ROE (0.6, 0.9, 1.4 and 1.7 relative to reference ROE) were used to specify test approaches in the present study. Moreover, target size was again randomized from the same 4 values (0.6, 0.9, 1.4 and 1.7 relative to reference size). Distance and size of the background object in FSM conditions were determined by the target's combination of parameter values to ensure that the background at moment of disappearance was 125% of the target size. Due to the presence of the background object, the relative expansion rate of the borders surrounding the target was ½ the target's ROE; and thus produced similar local flow pattern in parameter matched 2-OA conditions. In total, with all 3 conditions, 72 different combinations of parameters were possible (24 target parameter combinations x 3 conditions), which were randomized and presented as a block of trials. Participants in total completed 8 blocks (576 trials) and were again provided with breaks and a practice session (with feedback) prior to the formal experiment.

Results:

Figure 14 depicts the percentage of responses that participant YW chose the test approach as arriving earlier than the reference based on tau or ROE. Responses in 1-OA (black line), 2-OA (green line) and FSM (red line) conditions were plotted in each graph. Left and right panels represent fitted curves based on tau and ROE, respectively.

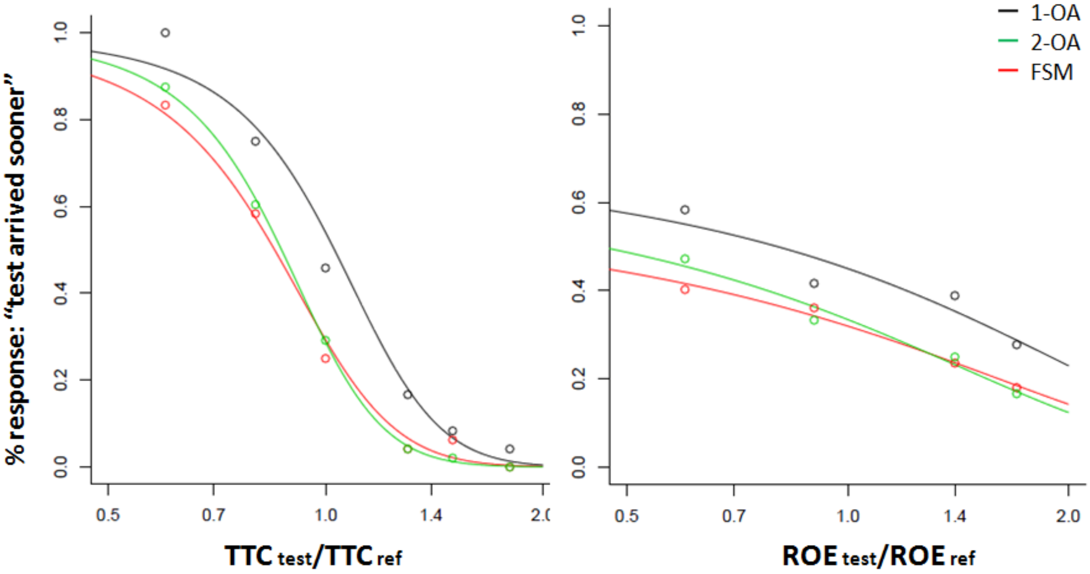


Figure 14. The fitted curves of relative TTC judgments for participant YW in Experiment 2. The left curve was based on the TTC variable, while the right was based on ROE. To compare the effects of 1-OA (black line), 2-OA (green line) and FSM (red line) conditions, responses were further separated by the background manipulation/self motion conditions, and plotted into the same figure.

For participant YW, fitted curves based on the TTC variable (left panel) were again much steeper compared to those based on ROE (right panel). Weber fractions for TTC were -0.2, -0.16 and -0.19, for 1-OA, 2-OA and FSM conditions respectively. Thresholds for ROE were again approximately 4-5 times greater, ranging from -0.87 to -1.09.

As shown in Figure 14, fitted curves for the TTC variable were shifted to the left for both 2-OA and FSM conditions. This suggested that presence of a moving background object or simulated self-motion caused YW to consistently overestimate TTC of the stimuli. Furthermore, fitted curves for 2-OA and FSM appeared to overlap, demonstrating that observers responded similarly to these two conditions. PSEs for 1-OA, 2-OA and FSM scenarios, in the units of test value/reference value, were 1.03, 0.87 and 0.85 respectively. These PSE shifts corresponded to relative shift values of approximately 32% (observed shift of -0.16, divided by the predicted shift of 0.5; see Data Analysis of Experiment 1) for between 1-OA and 2-OA conditions, and 38% (-0.19) for between 1-OA and FSM.

Among participants, TTC estimations for 2-OA and FSM conditions were consistently overestimated from the 1-OA condition. Results, however, demonstrated individual variations in the magnitude of this overestimation. Figure 15 depicts a comparison of PSE shifts from 1-OA scenarios in 2-OA and FSM conditions.

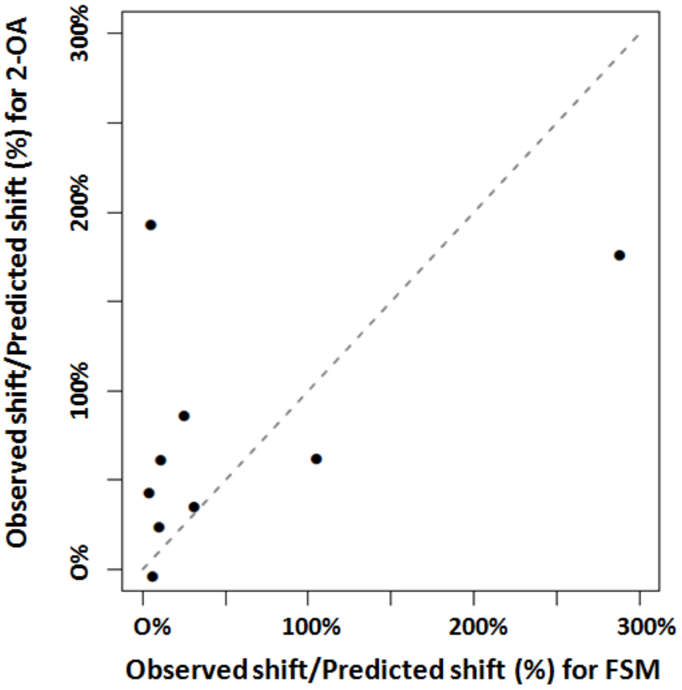


Figure 15. A scatter plot comparing the relative shift in PSE (observed shift/predicted shift) in two-object approach (2-OA) and forward self-motion (FSM) conditions, for all participants. Results demonstrated that participants generally overestimated TTC compared to the baseline 1-OA condition, and did so to a similar extent for both 2-OA and FSM conditions.

Statistical analyses revealed that there was an overall PSE difference between conditions (F(2,8) = 4.39, $p < 0.05$). While post-hoc analyses revealed that the average PSE shift between 1-OA and 2-OA conditions was insignificant (pair-wise difference = -0.29, $p \approx 0.15$); examination of Figure 15, nonetheless showed that most individuals overestimated their TTC response. Meanwhile, PSE shift was found to be significant between 1-OA and FSM conditions (pair-wise difference = -0.44, $p < 0.05$). Finally, there appeared to be no significant difference between the 2-OA and FSM condition (pair-wise difference = -0.14, $p \approx 0.64$), although there appeared to be slightly greater overestimations in FSM (as most points were positioned above the diagonal line).

Additionally, as demonstrated in Figure 15, two individuals (with shift around or greater than 200%) performed very differently from the other participants, which may have biased results. Upon removing these outliers, statistical analyses still revealed that there was an overall PSE difference between conditions ($F(2,6) = 5.3558$, $p < 0.05$). Again, post-hoc analyses revealed significant PSE differences between 1-OA and FSM conditions, but not between 1-OA and 2-OA, or between 2-OA and FSM.

Discussion:

Overall, our results seemed to indicate that observers overestimated TTC in both 2-OA and FSM conditions. We found that TTC estimations in simulated FSM were in the opposite direction as previous demonstrated (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010), and that responses were similar to those obtained during 2-OA scenarios. It appeared therefore, that the relative ROE between the boundaries of the approaching target and surrounding background was sufficient to explain results from both 2-OA and FSM conditions. It seemed, however, that observers did not fully shift their responses to the expected extent had they relied entirely on relative tau. This suggested that observers may not have always or fully integrated relative ROE into their estimates. Nonetheless, we conclude that observers relied on the relative local expansion in the image to perceive TTC in situations of simulated self motion, which further supports the use of a modified relative tau variable.

GENERAL DISCUSSION

In summary, our results demonstrated that observers used the local image expansion to base their estimates of TTC. This was demonstrated by the performance contrast between target-only motion (1-OA condition), and both local background motion (2-OA) and simulated self-motion (FSM). It appeared that the presence of forward visual expansion surrounding the target in 2-OA and FSM conditions caused observers to overestimate TTC, and did so to the same extent. This suggested that the relative ROE derived from the difference between the ROE of the target and background object, rather than absolute ROE of the approaching target, was used for TTC perception. As expected, the reduced ROE caused an overestimation of tau, and ultimately TTC. These results indicated that the local motion signal surrounding the contours of the approaching object was sufficient to affect estimations of TTC. Subsequently, the similarities between 2-OA and FSM conditions demonstrated that TTC perception during self-motion may also be attributed to this relative local visual motion.

Overall, our findings suggest that a modification to tau theory is necessary. As observer responses were unequal in situations of object-only motion versus simulated two-object motion and self-motion, it is therefore unlikely that absolute ROE is used to generate TTC estimates. Therefore, we propose that the tau variable is modified to take into account the relative ROE of the incoming object and its immediate surroundings. Specifically, we propose that the denominator of the tau equation is replaced with the relative ROE (Equation 2). This would not alter TTC perception in object-only motion conditions, but would be relevant in self-motion and other situations, where object motion is presented against background motion.

Discrepancy with previous findings

Our findings that participants overestimated TTC during simulated self-motion situations was opposite to previously demonstrated underestimations of TTC (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010). Our results thus emphasize an important issue between observer reliance on local properties of the image versus higher-order processes. As suggested by Gray and Regan (2000), information about self-motion is produced at global levels where motion-in-depth signals are generated to influence TTC specified by more local receptors. Several subsequent studies (Rushton and Warren, 2005; Rushton, Bradshaw and Warren, 2007; Royden and Connors, 2011) indeed demonstrated that a global higher-order process is in fact used to dissociate visual expansion resulting from object- and self-motion. These researchers argued that when presented with scenes containing optic flow, observers cancelled retinal flow information from self-motion, and utilized the local expansion of the approaching object to determine TTC. These cancelled signals then potentially influence local receptors such as those that respond to tau in order to specify sooner time-of-arrivals. From an ecological perspective, underestimation of responses during forward self-motion would provide the necessary extra time to account for body acceleration. It is therefore reasonable to expect that humans and other animals have developed means to utilize optic flow as a heuristic for self-motion, which could then be used to influence perception and behaviour.

Our results, however, demonstrated that participants had a tendency to rely on expansion patterns in the local image to base their perceptions of TTC. Observed responses were shown to be overestimated even in the presence of simulated self-motion. This is interesting as even reliance on other local-based non-tau cues such as ROE (as suggested by Caljouw, van der Kamp, and Savelsbergh, 2004; Hosking and Crassini, 2011; López-Moliner, Field, and Wann, 2007), would have led to overall overestimated responses. Combined findings between ours and those obtained by Gray and colleagues suggest that there may be at least two factors that contribute to perception of TTC in self-motion. These are 1), the local property of the image, and 2), higher-order processing which parses away retinal flow from self-motion. Our observed increased reliance on local image expansion along with the lack of such an observation in other studies can potentially be attributed to the various methodological differences between ours and previous investigations.

Limitations of previous investigations

Two issues may have affected the generalizability of results obtained by Gray and colleagues (specifically Gray and Regan, 2000; Gray, Macuga and Regan, 2004). First, recall that these previous studies presented simulated "self-motion" (i.e. size expansion of many square textures along with radial direction of texture movement) devoid of other sources of information such as depth. Our study remedied this short-coming by delivering stimuli within a textured cylinder, and generated forward self-motion through movement of the observer's point of view. Secondly, in these studies, the target of interest expanded within an opaque window in front of the surface containing peripheral textures; thus creating an empty gap around the looming object. In real-life situations, however, peripheral optic flow is continuous with the surrounding local expansion of the target. In fact, Gray and Regan (2000) demonstrated that increasing the size of this artificial gap reduced the effects of their self-motion simulations. This gap, therefore, may have removed crucial information that prevented a veridical optic flow pattern specifying self-motion. In our stimulus, the immediate surroundings of the target boundary importantly provided local expansion information, potentially influencing relative ROE and perceived TTC of the approaching object.

Interestingly, Geri and colleagues (2010) utilized a 3D scenario containing a ground surface that addressed some of these issues, but still found that observers underestimated TTC during forward self-motion. This may be because the use of local relative motion requires that the expansion of the approaching target contour is compared against expansion in the visual field immediately surrounding the target. For simulations including a ground surface with no above-ground textures (i.e. Geri, Gray and Grutzmacher, 2010), motion signal from the visual elements immediately beyond the target's boundary would have only been available for lower regions of the object (and may have even been small). Consequently, relative and absolute ROE of the target may have been alike.

In the present study, local relative expansions were salient and specifically set to half the ROE of the approaching target. As mentioned, this is in contrast to previous studies where this local relative expansion was either absent (Gray and Regan, 2000; Gray, Macuga and Regan, 2004) or less prevalent due to the lack of surrounding textures (Geri, Gray and Grutzmacher, 2010). As a result, this may have reduced observer capability to use relative expansion information, and overall reduced dependency on local properties of the image. The recent findings by Geri and colleagues (2010) showed that simply providing a ground surface resulted in a noticeable reduction in underestimations. While this potentially suggested greater utility of the local image, these observations also illustrated that other features such as higher-order processing may have also been integrated into TTC perception.

One issue with the current study that warrants further investigation is the inclusion of the background object behind the target. Admittedly, this background object may have appeared artificial, as rarely in the real-world are observers approaching or directly approached by (either via object motion or self motion) two symmetrically aligned, closely positioned targets. The presence of the background object, therefore, may have appeared unfamiliar to participants and subsequently influenced responses (i.e. alternative interpretations of the scene). At the moment, observers' TTC estimations in both 2-OA and FSM conditions were similar and in the direction predicted by a relative tau strategy. However, both 2-OA and FSM conditions incorporated this background object. As such, it is uncertain whether observed results are truthful or are unintended consequences of this specific stimulus configuration. To address this concern, future studies could remove this background object and investigate the direction of responses in conditions analogous to 1-OA and FSM scenarios. If these results showed smaller overestimated or even underestimated responses, it would suggest that results from our current paradigm are purely the results of amplified relative local expansion. This would demonstrate that humans are capable of processing the relative image expansion, but may do so less in real-life situations due to general absence of strong background signals. On the other hand, if results again showed the same overestimated response during FSM, it would strongly suggest that there are other methodological differences mediating the discrepancy between present and previous results.

Absolute versus relative judgment tasks

An alternative explanation for the observed discrepancy may have been because the present study utilized a relative judgment task rather than one based on absolute judgments (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010). Although an absolute estimation task may appear to be more veridical as it necessitates full estimation of the actual TTC, using such a task also raises important issues. For instance, in cases where the stimulus is presented on a screen at a distance away from the observer, participants may choose to dissociate themselves from their physical location in order to successfully respond. As observers have to imagine that the target reaches them after some moment in time, participants are required to extrapolate the TTC either to their own physical location, which is difficult without knowing the proper scaling factor of the scene, or extrapolate the stimulus from a virtual location (which further requires converting virtual units to real ones). Therefore, computer-based absolute TTC tasks, while may appear to be simpler and more ecologically valid, potentially hinder the use of a tau strategy. Bootsma (1989) additionally demonstrated that compared to hitting a ball, or pressing a button to allow a mechanical arm to do so; pressing a button to indicate the moment of contact (an absolute judgment task) led to more temporally variable and inaccurate responses. A relative judgment task, however, by-passes this issue as it only requires observers to estimate TTC prior to contact. As long as participants are required to only compare aspects of the presented stimuli, it is irrelevant where the observer is physically situated. Therefore, a relative judgment task may provide a better, more accurate opportunity to test a tau strategy, potentially explaining the present results. While admittedly relative judgment tasks have their own faults (i.e. artificiality, memory constraints in storing TTC estimates between approaches), we believe they nonetheless serve as better indicators of perceptual processes.

Incomplete integration of relative tau

As previously mentioned, in our study observers did not always or fully utilized relative tau during TTC estimation. Specifically, the extent that participants shifted their responses in the presence of forward visual expansion was not to the predicted magnitude had relative ROE completely influenced tau perception. As discussed, this may have been due to integration of both relative and absolute tau during TTC perception. This latter explanation would follow the same logic in interpretation as the study by Geri, Gray and Grutzmacher (2010) who argued that observers had a tendency to integrate both object and self-motion.

Interestingly, an earlier pilot study done in our lab using a similar design as Experiment 1, demonstrated that the magnitude of overestimations increased when the image of the background object was made to converge on the target at the moment of disappearance (target's image size/background object's image size = 1). Such a manipulation, thus, reduced the distance between the image boundary of the approaching target and background object. This suggested that perhaps in the present study, participants could not fully or always use the relative expansion pattern present in the immediate surroundings of the target. Recall that in the present manipulation, the image of the background object was always made to be 125% of the target's image at the moment of disappearance. Especially in situations where the image size of the object was large, the gap between contours may have made it more difficult to fully integrate relative expansion percept. Nevertheless, the current design in Experiments 1 and 2 was preferentially chosen to replace this background object convergence to reduce ambiguity in the scene so that observers clearly perceived the approach of two objects. Especially since viewing duration was short (0.75-1.5 seconds), having the background object initially present and then occluded by the target may have made the task more puzzling, less natural, and ultimately negatively affect results.

In conclusion, the present study provided compelling evidence that tau derived from relative expansion in the local image can be used to perceive TTC in both object and self-motion conditions. Importantly, tau based on the absolute ROE of the target was insufficient to explain current findings. Because local relative expansion patterns in the immediate surroundings of the object appeared to have caused observed TTC overestimations, we propose that the tau variable is modified to incorporate this relative rate of expansion.

IV. GENERAL CONCLUSIONS

Even despite mounting evidence against a tau-only strategy, the two presented studies demonstrate that optical tau may still strongly contribute to TTC perception. In Study I, we demonstrated that observers, in the presence of depth information such as distance, speed or relative size, still relied on a tau strategy to estimate TTC of a looming object. Moreover, when we manipulated sources of information to provide conflicting TTC information, TTC specified by tau was weighted much more than TTC derived from distance and speed. In Study II, we investigated the use of tau in situations containing motion contrast to the background, and showed that observers relied on the local relative motion to base their estimations. It appeared that participants overestimated TTC when presented with situations where the immediate surroundings of the target's contours expanded at a reduced rate. As such, observers likely utilized a TTC strategy in accordance with a relative tau variable that incorporated the relative rate of expansion. Additionally, results were comparable in both situations when this relative local image expansion was created by the approach of two symmetrically aligned, closely positioned objects, and during simulated forward self-motion. This suggested that during situations containing optic flow (such as self-motion), relative tau is potentially used to perceive TTC.

While our results suggest that tau is a powerful cue that influences TTC perception, we do not believe that the optical variable is used primarily in every situation. As previously mentioned, many strong cues exist in the environment (such as familiar size and binocular disparity) that can aid or even supplant tau as the primary source of TTC information (for review, see Tresilian, 1999; DeLucia, 2004). For instance, previous results on the effects of simulated self-motion on TTC (Gray and Regan, 2000; Gray, Macuga and Regan, 2004; Geri, Gray and Grutzmacher, 2010) suggested that global image processing can influence TTC perception. We, therefore, argue that use of tau likely depends on the strength and reliability of available cues in the environment. In Study I, we demonstrated strong dependency on tau in situations containing unfamiliar object sizes but strong depth information. In these experiments, tau was the most accurate and salient source of TTC information available. As such, it is unsurprising that observers would utilize tau to complete their estimations. Similarly in Study II, the prominence of relative local expansion may have influenced participants to utilize relative tau information. Nonetheless, it remains uncertain whether tau is truly used in more veridical situations such as during initiation of action and in the presence of binocular information. Based on our own findings, we suspect that tau usage may be surprisingly more prevalent than previously thought (i.e. Tresilian, 1999). Collectively, the literature appears to suggest that a wide variety of information sources, likely including tau, are used simultaneously to provide accurate TTC perception.

Lastly, our studies revealed great individual differences in TTC perception. As demonstrated by approximately a quarter of participants in Study I, observers may have based their TTC estimates on other available cues in the environment (i.e. rate of expansion). Interestingly, it can be argued that the tendency to utilize tau may increase over time. As demonstrated by van der Kamp (1997), prolonged exposure to a grasping task increased accuracy of performance even in monocular conditions. So while other less efficient sources of TTC information, such as image size (argued by van der Kamp, 1997) or rate of expansion (i.e. Hosking and Crassini, 2011) may be utilized preferentially at first. Perhaps like HM from Study I, observers eventually learned to switch to using the more efficient and accurate tau variable. Therefore, an interesting follow-up study could compare the usage of different sources of information over time. In summary, the present findings strongly recommend re-evaluation of optical tau. While, future studies would need to evaluate the importance of tau in more veridical situations, optical tau nevertheless, remains a powerful source of TTC information that potentially influences our everyday interactions with objects in the environment.

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