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Visually timed action: time-out for 'tau'?

James R. Tresilian

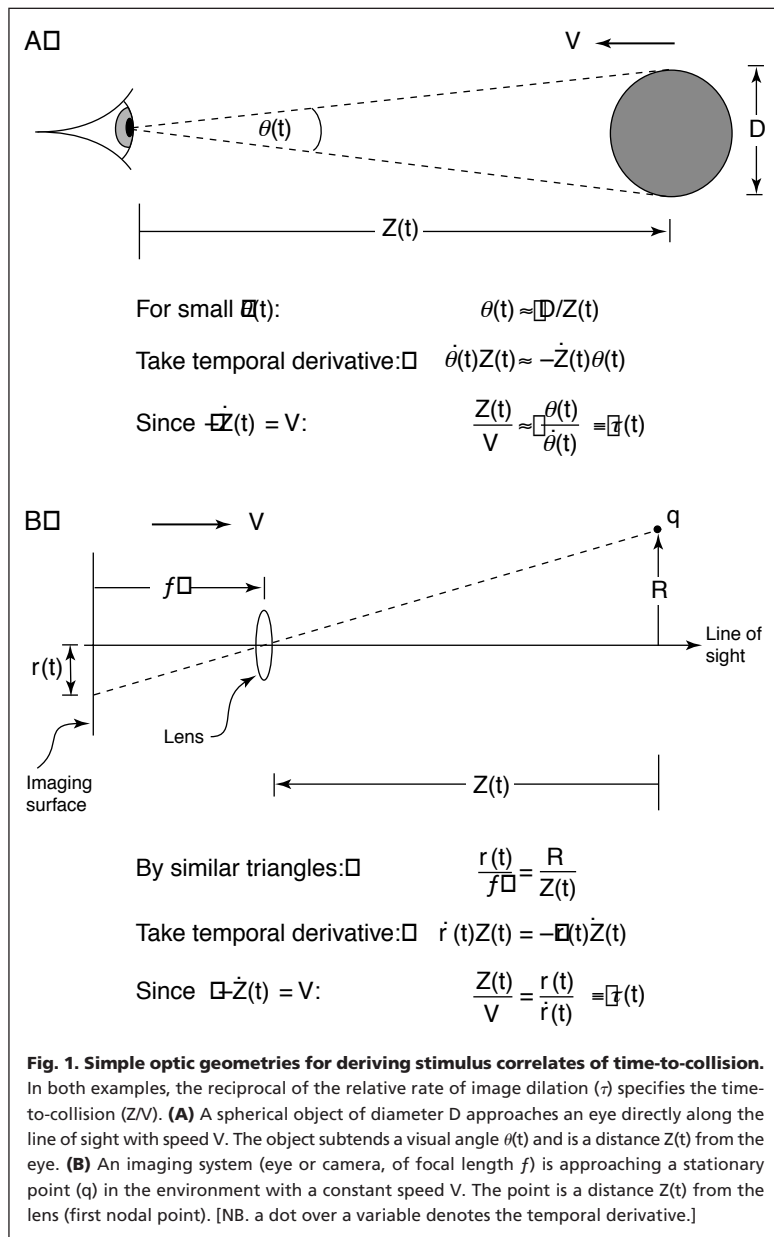
Bringing about desirable collisions (making interceptions) and avoiding unwanted collisions are critically important sensorimotor skills, which appear to require us to estimate the time remaining before collision occurs (time-to-collision). Until recently the theoretical approach to understanding time-to-collision estimation has been dominated by the tau-hypothesis, which has its origins in J.J. Gibson's ecological approach to perception. The hypothesis proposes that a quantity (τ), present in the visual stimulus, provides the necessary time-to-collision information. Empirical results and formal analyses have now accumulated to demonstrate conclusively that the tau-hypothesis is false. This article describes an alternative approach that is based on recent data showing that the information used in judging time-to-collision is task- and situation-dependent, is of many different origins (of which τ is just one) and is influenced by the information-processing constraints of the nervous system.

In his science fiction novel *The Black Cloud*¹, Sir Fred Hoyle created a disaster scenario in which the eponymous cloud is on a collision course with the solar system. Faced with the impending doom, the question on everyone's lips was 'How long have we got?' The answer was not immediately apparent

when nobody knew how far away the cloud was or how fast it was moving. In his novel, Hoyle provided a simple method for determining the time remaining. This method was subsequently introduced into the psychological literature as an hypothesis for how activities involving interactions with

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moving objects – such as catching or hitting a ball – could be timed^{2,3}. The method is presented in Fig. 1 and shows that an object's time-to-arrival or time-to-collision (TTC) can be obtained from the ratio of the object's image size to the rate of change of size. Lee² gave this ratio the special name tau (τ).

When hitting or catching a ball, your movements usually need to be timed very precisely so that you get to the right place *at the right time* to make the hit or catch. In games like baseball or cricket the temporal precision required to hit a home run or a six is about ± 2 ms (Ref. 4). Temporally co-ordinating your movements with external events to this level of precision requires accurate and reliable anticipatory timing information and τ might do the job^{2,5}: it is visually available and does not involve prior measurement of speeds, distances or accelerations. Because τ requires no complex computations, it became a paradigm example of J.J. Gibson's ecological approach⁵⁻⁷. This approach supposes that the information required for accurate perception of the world is entirely present in the stimulus: hypothesis testing, logical inference, the addition of information from memory or other constructive

processes are unnecessary for understanding perception^{5,7} (see Box 1). Gibson emphasised the identification of stimulus variables that specify perceived aspects of the world ('invariants'). Tau has been used as a concrete example of such a variable and to illustrate how non-constructivist perception is possible⁵.

The use of τ for timing interceptive actions is claimed to be supported by a body of empirical data. Lee provided evidence that τ is the basis for the timing of wing retraction in diving gannets⁶, as well as for ball-punching⁸ and leaping humans³. It has also been implicated in the timing of leg extension in landing house flies⁹ and hawks¹⁰ and in the timing of ball hitting¹¹ and catching^{12,13}. Psychophysical experiments have established that human observers are sensitive to tau^{14,15} and electrophysiological studies have found neurons sensitive to $1/\tau$ in the optic tectum of pigeons^{16,17}. These data have been interpreted as suggesting a particularly simple account of how interceptions are made^{2,5,12}. This account will be called the ' τ -hypothesis' and can be stated as follows:

The information provided by τ is used to make estimates of TTC which determine the timing of interceptive actions, avoidance manoeuvres and psychophysical judgments of TTC.

This hypothesis is a general account of interceptive timing skill. It applies to gannets⁶, flies⁹, pigeons¹⁶ and hawks¹⁰ as well as to people because the information upon which timing is based (τ) is present within the optic array⁷ – the visual stimulus medium described independently of any imaging system (e.g. eye). However, recent work has established that this τ -hypothesis is false¹⁸⁻²², and the wealth of data that has been marshalled in its support does not, on close examination, support it at all^{20,22}. It is vitally important to note that the falsity of the τ -hypothesis does not entail rejecting the idea that τ is involved in TTC estimation – indeed, the empirical evidence suggests that τ is involved, at least in some tasks¹⁵, but is not the only source of information for TTC estimation.

Why the τ -hypothesis is false

Reasons for rejecting the τ -hypothesis derive from direct experimental tests and logical arguments based on empirical observations. To address the latter first: τ is limited as a source of TTC information by four factors: (1) it neglects accelerations; (2) it provides information about TTC with the eye; (3) it requires that an object be spherically symmetric; (4) it requires that the object's image size and expansion rate be supra-threshold^{23,24}. These factors seriously restrict the utility of τ as a source of TTC information^{18-21,24,25}. On its own, τ cannot account for how people time interceptions for short falls under gravity^{18,20}; for how people time interceptions when the point of interception is far from the eye^{20,21,25} (bypass approaches); or for how people intercept very small objects^{23,24}. It also has difficulty accounting for precisely timed interceptions of irregularly shaped objects that are rotating relatively slowly (e.g. rugby balls or juggling clubs). Only a very small subset of interceptive tasks that people perform routinely can be successfully timed using tau^{20,22}. These are not arguments against the use of τ per se, but they clearly refute the τ -hypothesis described earlier – τ cannot provide a general account of timing skill.

Perhaps there are tasks in which τ could, in principle, provide sufficient timing information. However, the only studies that have shown that τ on its own can be used to make

Box 1. Perception and information

It is a logical fact that the visual stimulus (either retinal image or optic array) does not contain sufficient information to support veridical perception (Refs a,b). Rather, perception appears to require that information be added to that obtained from the stimulus. Gibson realized that what is *logically* true is not necessarily *ecologically* true (Ref. c). Although there is an indefinitely large number of logically possible environments that could give rise to a particular stimulus, many of these will not be ecologically possible – owing to the physical laws and regularities that constrain the structure and behaviour of the ecological world (Ref. d) – thus, they are irrelevant for understanding perception. Gibson hypothesized that in normal (ecological) conditions the information available in the stimulus is sufficient for adequate perception of the environment (Ref. c).

Gibson's rethinking of the informational basis for perception required a rethinking of what the perceptual processes are doing: if something is there (the information is present in the stimulus) then you do not have to construct or compute it. Perception, Gibson suggested, is more like the process by which radio receivers pick up radio transmissions: the information is 'out there' ready to be received – your radio receiver does not compute it. In order for this analogy to make sense there must be stimulus analogues of radio transmissions – sources of information in the stimulus to which the perceptual systems are tuned. Gibson referred to these as 'invariants'. In general terms, invariants are conceived to be complex, spatiotemporally distributed, 'higher order' structures (Refs c–e). In effect, therefore, Gibson proposed three hypotheses:

- (A) that the stimulus is informationally sufficient in ecological conditions;
- (B) that information is carried by invariants, which specify environmental properties and states of affairs;

(C) that invariants are detected directly: they are not computed or constructed from simpler or lower-order stimulus variables.

Note that it is possible for the stimulus to be informationally sufficient but for perceptual processing to be indirect and for invariants to be non-existent. Indeed, the account of TTC perception described in the main text of this article assumes exactly this: it accepts (A) but rejects (B) and (C). A similar position has been adopted by Cutting (Ref. f), who accepts hypothesis (A), rejects (C) and presents a version of (B) rather different from that proposed by Gibson. Cutting's version allows for multiple invariants specific to a perceivable aspect of the environment, where Gibson allowed only one. The position adopted here differs from that of both Gibson and Cutting by rejecting the usefulness of Gibson's concept of invariants. Instead there are proposed to be individually ambiguous and partial sources of information, traditionally known as cues. A given cue might be sufficient for one task but not another. In the latter case, several cues combined together might provide the necessary information.

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TTC judgments are a very few carefully controlled psychophysical experiments¹⁵. Many experimental tests of whether τ could be the basis of general timing performance have accumulated and the result is clear: with the exception of those psychophysical studies in which τ is the only source of TTC information, other information is always used in addition to or instead of τ ^{18,21,24–32}. Here I will briefly mention two such studies that used interceptive tasks (TTC judgment tasks will be discussed in subsequent sections). First, Lacquaniti and colleagues¹⁸ showed conclusively that the timing accuracy observed when experimental participants caught balls dropped from heights of less than about 1.5 m could not have been timed using τ . It was demonstrated that an estimate of the ball's acceleration was contributing to the estimates of TTC used to make the catch. Second, Tresilian²¹ showed that even when the only *visual* information about TTC available to observers was that provided by τ (or its equivalent), performance in an interceptive task was far too accurate to have been based on τ . Indeed, performance was often better in those conditions in which τ was least accurate than when τ more closely approximated the TTC. It was also demonstrated that other perceptual variables, which could involve the use of articular proprioceptive information, were critical for achieving the observed temporal precision. The results from these and other empirical tests again support the conclusion that τ cannot provide a general account of timing performance.

What has been learned?

The theoretical problems with τ prompted a search for other sources of TTC information that could avoid them: this search was undertaken by Lee³⁴ and others^{19,20,24,26}. The first systematic attempt to solve the problems with τ was made

by Tresilian¹⁹ who showed that accurate TTC information was available for use in bypass approaches (see Box 2); that methods are available for overcoming the problem with irregularly shaped rotating objects (if the object is rotating sufficiently fast, temporal filtering or averaging of the image could be used^{20,34}); and that binocular information about TTC was available that obviated the need to measure image size or expansion, and could thus cope with the small objects problem^{19,20,24,28} (Box 2). This and related work^{26,34} showed that there are several potential sources of information about TTC, and evidence for their use has subsequently been reported^{21,24,26,28,35}.

Most of the theoretical work just described was guided by two considerations: Gibson's idea that stimulus information is specific to perceived aspects of the world (see Box 1), and Lee's hypothesis^{6,8} that perceived TTC ignores accelerations. The latter derives some support from published data on interceptive timing^{6,8,11} and is consistent with the finding that the human visual system is very insensitive to image accelerations^{36,37}, particularly so over short viewing periods³⁷ (<100–200 ms). Thus, perceived acceleration is unlikely to make a significant contribution to perceived TTC during rapid interceptive actions where the target is viewed for a short period. It has been fairly well established that accurate timing in rapid actions like catching, hitting a baseball and playing strokes in table tennis can be achieved using a first-order estimate of TTC that ignores acceleration^{8,19,21,26,34}. Nevertheless, as discussed earlier, a first-order estimate is not always sufficient^{18,21}.

From Gibson's notion of specificational information it follows that TTC information should specify the TTC and should, therefore, be measured in units of time (as is τ). This

Box 2. Some alternatives to tau

An example of a binocular information source that can be used as an alternative to τ can be derived from the geometry shown in Fig. 1A, which represents the simplest case (Refs a,b). The point M is moving with speed V directly towards the midpoint between the eyes; point F is fixed. Simple trigonometry establishes that,

$$\alpha + 2(\varphi + \delta/2) = \gamma + 2\varphi \Rightarrow \alpha + \delta = \gamma \quad (1)$$

By definition [and incorporating (1)], we can write,

$$\tan \frac{\gamma}{2} = \tan \left(\frac{\alpha + \delta}{2} \right) = \frac{1}{2X} \quad (2)$$

If point F is at effective optical infinity (>6 m distant), then its binocular

parallax (α) is zero. Thus, for sufficiently distant points F, equation (2) becomes,

$$\tan \left(\frac{\delta}{2} \right) = \frac{1}{2X} \quad (3)$$

Following differentiation with respect to time, and some rearrangement, equation (3) yields the relationship,

$$\frac{X}{V} = \frac{\sin \delta}{\dot{\delta}} \quad (4)$$

where δ is the horizontal binocular disparity of M relative to a distant point F, $\dot{\delta}$ is the rate of change of disparity and X/V is the time remaining before M reaches the mid-point between the eyes.

In Fig. 1B an object is shown moving with constant velocity V towards an interception point, p. From this geometry a source of TTC information can be derived (Refs c,d), which informs about the moving object's TTC with any perceptually specifiable point p. The sine rule establishes that,

$$\frac{\sin \beta}{B} = \frac{\sin \psi}{X} \quad (5)$$

Differentiating this with respect to time and noting that β is constant, yields, after some rearrangement,

$$\frac{\dot{X}}{X} = \frac{\dot{B}}{B} + \psi \cot \psi \quad (6)$$

Noting that $\dot{X} = -V$ and that $-B/\dot{B} = \tau$, we can rewrite equation (6) as follows:

$$\frac{X}{V} = \frac{\tau}{1 - \tau \psi \cot \psi} \quad (7)$$

Where X/V is the time remaining before the moving object reaches point p, and the right-hand side contains only variables that can, in principle, be measured by the visual system. These sources of information [equations (4) and (7)] are both accurate only when the object (or observer) is not accelerating.

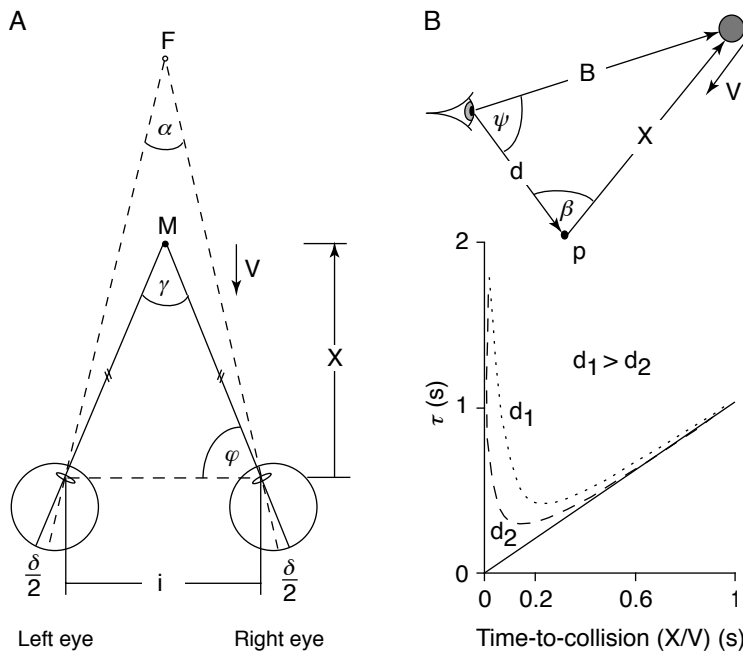


Fig. 1. Geometry of sources of TTC information. (A) Geometry of binocularly viewed approach of a small object (M) moving with constant speed (V) directly towards the midpoint between the two eyes. At least one visible fixed point (F) is present and has binocular parallax α . In this symmetrical case, the horizontal binocular disparity of point M relative to point F is δ . The binocular parallax of M at the instant of time shown is γ and it is an instantaneous distance X from the observer whose interpupillary distance is i . **(B)** When an object is not approaching the eye but some other point (p) with constant speed (V) as shown, $\tau (=B/\dot{B})$ is not equal to the time remaining before the object reaches p ($=X/V$). The relationship between τ and X/V is shown in the graph below. This shows that the approximation to X/V provided by τ becomes less accurate for larger values of d and smaller values of V, i.e. the further away the point of interception and the lower the speed.

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raises two questions: first, are time units appropriate ones for the nervous system to use for measurement and representation of timing information? Second, does the information people use to make TTC estimates specify TTC? The answer to both these questions seems to be no. In answer to the first question, it seems more likely that timing information is represented in units of reciprocal time (as explained in Box 3): as noted earlier, the neurons studied by Frost and colleagues^{16,17} responded to $1/\tau$.

In answer to the second question, not only do people often use approximate sources of TTC information (such as the first-order approximation) but TTC judgments have been

found to be influenced or determined by variables that are only correlated with TTC^{15,27,29,30,32,38}. These variables (which include image size^{27,32} and rate of expansion^{15,29}) are not measured in units of time or reciprocal time. Studies reporting these effects have often (but not always; see Refs 29,32,39) employed psychophysical tasks that do not involve an interception of a moving target. Instead, judgments are made about whether or not a particular stimulus object will arrive at a designated location before or after a simultaneously presented stimulus^{14,27,30,40}, or an internalized standard¹⁵ (relative judgment tasks, Fig. 2). Alternatively, a real or simulated moving object disappears from view and the observer attempts

Box 3. Measurement and representation of tau

It has been proposed that measurement of τ from the retinal image involves the prior measurement of image size and rate of image expansion (Ref. a) with τ being derived in a subsequent processing stage. This could be done simply by dividing image size by expansion rate (Ref. a) or by using size-expansion rate opponency.

An opponent mechanism could compute the difference between size (θ) and expansion rate ($\dot{\theta}$). If $\dot{\theta}/\theta (=1/\tau)$ is equal to 1 then the difference, $\dot{\theta}-\theta$, is zero. A mechanism that responds when $\dot{\theta}-\theta>0$ will have a threshold of 1 unit and will respond when $1/\tau>1$. More generally, if $\dot{\theta}/\theta=w$, then $\dot{\theta}-w\theta=0$ and a mechanism that responds when $\dot{\theta}-w\theta>0$ has threshold w . Neurons that behave in this fashion have been discovered by Frost and colleagues in the accessory optic system of the pigeon brain (Refs b,c). These neurons start to fire when $1/\tau$ reaches a threshold value and continue to fire (at a constant rate) when this threshold is exceeded. The value of $1/\tau$ is thus directly related to the total number of these neurons that are active. A possible model of a detector based on these results and ideas is shown in Fig. 1.

Frost and colleagues' finding that the neurons were sensitive to $1/\tau$ rather than τ is significant. It is not obvious that the nervous system should represent TTC information in units of time. By definition, TTC is large when collision is a long way off but small when collision is imminent: a signal that carries TTC will be 'small' close to collision. This is the opposite of what is likely to be most useful; that is, a large 'urgent' signal when collision is imminent and a small signal when it is distant.

An alternative is to use the reciprocal of TTC (e.g. $1/\tau$), a quantity Koenderink has referred to as 'nearness in time' or 'immediacy' (Ref. d): as an impending collision gets nearer in time, the immediacy gets larger. However, accurate estimates of a perceptual variable require that small differences be discriminable. An information channel in which noise is proportional to signal magnitude will have a reduced ability to discriminate small differences when signals are large (this follows from Weber's law). Thus, there is a dilemma in TTC measurement: a signal should be more salient as collision approaches (immediacy is better) but greater sensitivity is required as collision approaches (TTC is better). The detector in Fig. 1 could help resolve this dilemma if there are multiple summing units. Suppose there are N threshold units which can be ordered in immediacy-threshold magnitude from that with the smallest threshold (u_1) to that with the largest (u_N): $u_1 < u_2 < \dots < u_N$. Suppose that these units are divided into m groups of q units ($m=N/q$): thus, the first group is made up of units $u_1, u_2, \dots, u_q$, the second of units $u_{q+1}, u_{q+2}, \dots, u_{2q}$, and so on. Each of the m summing units can receive

its inputs from one of the m groups of threshold units. Each summing unit then has the same immediacy resolution and responds when the immediacy is in the range determined by the group of units from which it receives inputs. This means that the measurement resolution for immediacy will be relatively independent of the magnitude of the immediacy.

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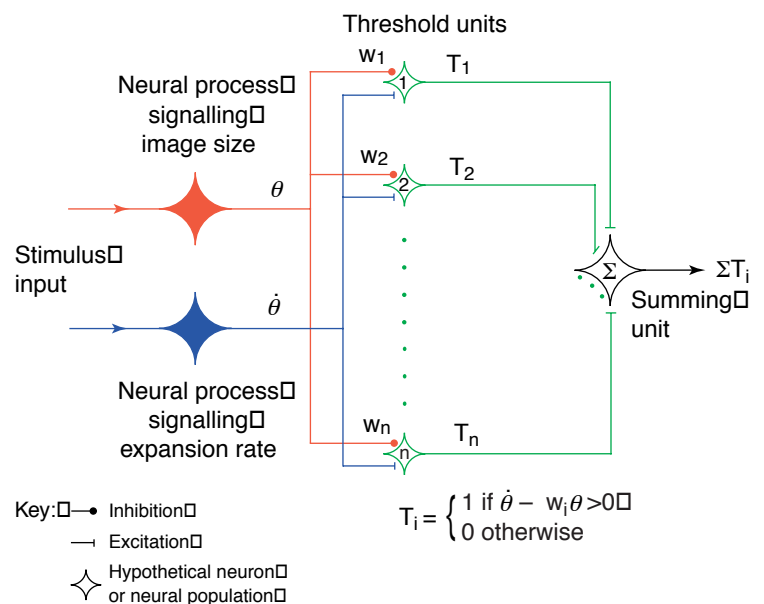


Fig. 1. Hypothetical model for computing immediacy (reciprocal of TTC). Immediacy is calculated from independent image size (θ) and expansion rate ($\dot{\theta}$) channels based on known properties of neurons in the nucleus rotundus of the pigeon brain (Refs b,c). The size and expansion channels feed into a population of threshold neurons whose outputs ($T_i=0,1$) depend upon their inputs ($\theta, \dot{\theta}$) according to the rule shown. The output of the summing unit is proportional to the number of threshold units that are firing at a given time (ΣT_i).

to make a button-press response which coincides in time with the object's arrival at a designated location^{41–43} (prediction-motion tasks). Some of the perceptual variables that have been implicated in interceptive timing and relative TTC judgments are given in Table 1.

The finding that many different variables, sensory systems and sources of information can contribute to estimates of TTC is what might be expected of a biological system. Biological perception is the achievement of an adaptive, neural dynamic system, which is in a continuous state of adjusting itself to the informational demands of behaviour by exploiting regularities in the stimulus input^{44,45}. Performance of any given class of perceptual tasks, such as timing tasks, is likely to involve a patchwork of approximate and opportunistic computations and cues⁴⁵ – perceptual systems 'never miss a good trick'⁴⁶. Under this conception, the system will

never or almost never converge on a single source of information for a class of tasks. This is only likely to happen when the task constraints and stimulus conditions are always similar and one information source is the only source available capable of providing sufficient information⁴⁷.

Replacing the τ -hypothesis

The picture of TTC perception that emerges from the work reviewed in the previous section is a complex one. A variety of perceptual variables can influence TTC perception and the influence of a given variable is task dependent: one task might use one set of variables and another task a completely different set. A theory like the τ -hypothesis, which attempts to account for all TTC judgments in the same way is untenable. At the opposite extreme is the view that no theory is possible, merely a taxonomy of timing tasks where each

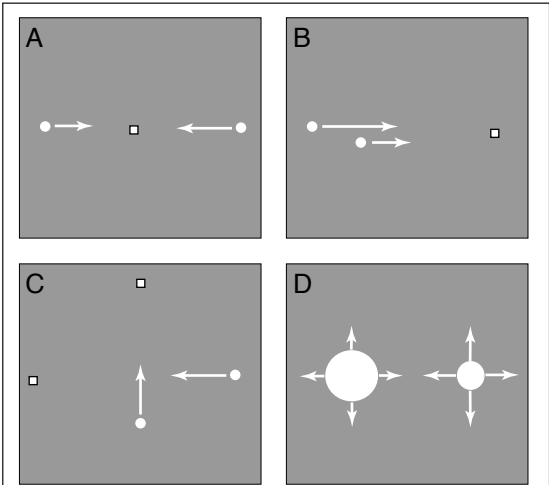


Fig. 2. Stimulus configurations used in relative TTC judgment tasks. The grey background indicates the total display (computer screen). In (A), (B) and (C), two moving ‘objects’ (circles) are approaching a target (square) or targets (C). Arrows indicate the magnitude (length) and direction of the moving objects’ velocity. In (D) two objects (circles) expand on the screen (as indicated by arrows) simulating approach to the observer. In all configurations, the moving objects (circles) vanish at some point and the observer must indicate which of them would have reached the target first (in A–C) or would have reached him/her first (D). Displays of types (A), (B) and (C) were used in experiments by Law and colleagues^{55,56}. Displays of type (A) were also used by Bootsma and Oudejans²⁶ and display type (D) by, for example, DeLucia²⁷ and Todd⁴⁰.

task is associated with a particular set of variables. However, the currently available data do not force us to accept this second, rather unparsimonious option; it is possible to identify principles and constraints that allow a more theoretically motivated account to be formulated. A recent approach to an integrated understanding of TTC perception^{38,47,48} that emphasizes the importance of identifying these principles and constraints is described below. Note, however, that

aspects of this approach are based on research in other areas of perception and remain largely untested in the context of TTC estimation.

To account for the empirical observations already reviewed it is necessary: (1) to adopt a broader concept of information than Gibson’s narrow, specificational sense; (2) to explain how interceptive tasks are timed when the information provided by τ is insufficient; (3) to explain how multiple perceptual variables and sources of information can contribute to TTC estimation; (4) to account for the task dependency of information usage.

Cutting⁴⁹ has broadened Gibson’s specificational concept of information to deal with situations in which there is a multiplicity of information sources that specify a single state of affairs in the world (see Box 1). Cutting’s approach, however, is not sufficiently general to account for the results described above. These results appear to require that Gibson’s specificational concept be abandoned and replaced with a ‘correlational’ conception. Any stimulus variable (e.g. image expansion) that co-varies with a physical variable describing an external state of affairs (e.g. TTC) provides some information about that state of affairs. In general, a stimulus correlate of an environmental quantity will not uniquely determine (specify) that quantity; the information it provides will, therefore, be partial, ambiguous or probabilistic rather than complete and specific. Clearly, some stimulus correlates of TTC provide more precise (less ambiguous) information than others – τ provides better TTC information than image expansion for example. However, no stimulus correlate of TTC yet identified is completely specific – it would be misleading to call any of them ‘invariants’. They are more properly described by the traditional term ‘cue’.

Given the potentially large number of stimulus variables that could provide some information about TTC, the nervous system is faced with the problem of how to use these variables to obtain an estimate of TTC sufficient for the requirements of the task in hand. This includes the problem of information selection (which variables to include and which to exclude) and the problem of information integration^{50,51} or fusion⁵². The latter can be broken down into two aspects: first, the construction of more specific, ‘higher-order’ cues from relatively primitive perceptual variables – for example, the construction of τ from image size and rate of expansion (Box 3), or calculation of first-order TTC from τ , the optical gap and the rate of gap constriction (Box 2); second, the combination of multiple cues. The best understood example of cue combination is that of depth perception: many visual depth (relative distance) cues can be identified, including image size, motion parallax, height in the visual field, occlusion, texture gradients, blur, linear perspective and binocular disparity^{50,53,54}. A body of empirical work supports the idea that in some situations at least, these cues are simply averaged together to obtain an overall depth estimate^{53,54}. Recent evidence suggests that similar processes are involved in TTC perception, notably for the combination of monocular and binocular cues^{24,35}. The question of how the integration process is organized is a new and important question for research in TTC perception and existing theoretical ideas can be usefully applied to it⁴⁸.

The problem of cue selection emerges most noticeably in the context of relative judgment tasks (Fig. 2). These tasks are not actually timing tasks – the observer does not necessarily

Table 1. Some of the perceptual variables that have been implicated in TTC estimation

Perceptual variable	References
τ	Kaiser and Mowafy ¹⁴ , Regan and Hamstra ¹⁵ , Rushton and Wann ³⁵ , Todd ⁴⁰
Binocular analogue of τ (B_r) (see Box 2)	Gray and Regan ²⁴ , Heuer ²⁸ , Rushton and Wann ³⁵
Image size (θ)	DeLucia ²⁷ , DeLucia and Warren ³²
Rate of change of image size ($\dot{\theta}$)	Regan and Hamstra ¹⁵ , Stanard <i>et al.</i> ²⁹
Optical gap (ψ) (see Box 2)	Bootsma and Oudejans ²⁶ , Law <i>et al.</i> ⁵⁵ , Tresilian ²¹
Optical speed ($\dot{\psi}$) (see Box 2)	Kaiser and Mowafy ¹⁴ , Kerzel, Hecht and Kim ³⁰ , Law <i>et al.</i> ⁵⁵ , Smeets <i>et al.</i> ³¹ , Smeets and Brenner ³⁹ , Tresilian ²¹
Combination of perceptual variables	Bootsma and Oudejans ²⁶ [τ , ψ , $\dot{\psi}$], Gray and Regan ²⁴ [τ , B_r], Regan and Hamstra ¹⁵ [τ , $\dot{\theta}$], Rushton and Wann ³⁵ [τ , B_r], Tresilian ²¹ [τ , ψ , $\dot{\psi}$]

need to determine the TTC of the target stimulus; he simply needs to determine whether or not it will arrive earlier than the comparison stimulus. An observer could use anything that enabled such a judgment to be made, or which he thought would enable such a judgment. This expectation has been repeatedly confirmed³⁸. For example, in a study reported by Law and colleagues⁵⁵, observers were asked to judge which of two moving objects would reach a particular location first (see Fig. 2A,B,C). In the absence of performance feedback, observers frequently applied a 'closer-first' rule to make their decision: the target closer in space to the designated location at the time of display termination was judged to be closer in time. Provision of performance feedback was found⁵⁶ to reduce the prevalence of the closer-first rule, as it was not in fact a reliable predictor of which target arrived first. Therefore, it appears that one role for learning in these tasks is to deselect those sources of information that interfere with satisfactory performance³⁸.

The task-dependency of information usage is likely to be best understood from an analysis of the temporal accuracy requirements of different tasks. For interceptive actions it is often possible to define a time-window during which successful interception is possible and which can therefore quantify the timing requirements imposed on performance^{4,21,57}. Definition of such a window requires a rather precise description of how the interceptive task is executed. This is relatively straightforward for laboratory-based tasks whose execution can be controlled by appropriate design of apparatus^{21,57} (Fig. 3) and is possible to calculate for some of the more constrained sporting tasks such as batting in cricket and baseball⁴. It is much more difficult to define in unconstrained real-world tasks such as catching. Catching can be performed in a variety of different ways and the time-window can vary quite considerably. For example, when catching a ball it is temporally much more demanding to reach out perpendicularly to the ball's path and snatch it out of its trajectory than it is to move your hand in the plane of the ball's path allowing the ball to fall into it.

So far little empirical effort has been directed at establishing the time-windows for real-world interceptive actions. Nevertheless, it is possible to provide a coarse taxonomy of such tasks and to use existing data to develop hypotheses about the type of information used^{38,47}.

First, actions that involve the actual interception of a moving target, and which define a proper time-window for successful performance (Fig. 3), should be distinguished from those tasks (such as avoidance^{32,58} and braking tasks^{2,59}) that do not define a proper time-window (they define a late temporal boundary but not an early one; the latter may be defined by the observer according to internally imposed criteria which presumably vary). The initiation of braking to a stop is an example of the latter type of task: theoretically, braking could be initiated at a particular TTC with the stopping location², but a recent study found that it was actually initiated at a particular distance^{22,59}. If the task does not impose the requirement of precise timing the available data indicate that TTC is either not used, or if it is used, it is in conjunction with other information as well⁴⁷.

Second, it is possible to identify a class of interceptive actions with time-windows that range from about ± 2 ms to ± 25 ms – these include one-handed catching⁶⁰, playing a

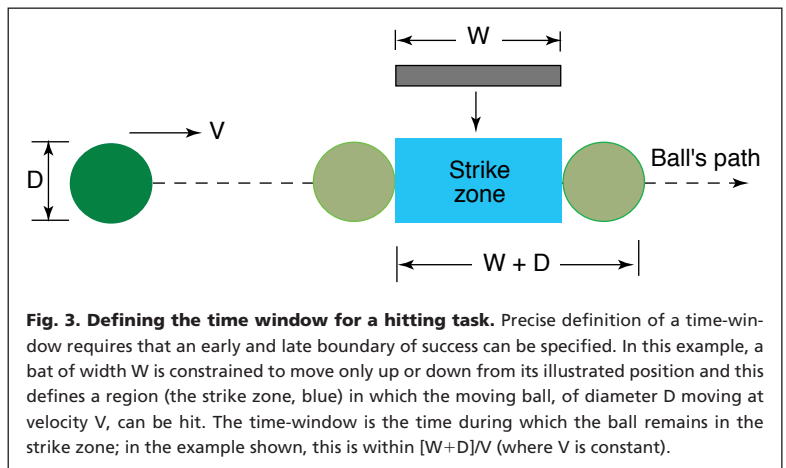


Fig. 3. Defining the time window for a hitting task. Precise definition of a time-window requires that an early and late boundary of success can be specified. In this example, a bat of width W is constrained to move only up or down from its illustrated position and this defines a region (the strike zone, blue) in which the moving ball, of diameter D moving at velocity V , can be hit. The time-window is the time during which the ball remains in the strike zone; in the example shown, this is within $[W+D]/V$ (where V is constant).

tennis or table-tennis stroke¹¹, hitting the ball in cricket or baseball⁴, and various laboratory tasks^{21,57}. These interceptive actions are executed rapidly with movement times of less than 500 ms, sometimes as little as 100–200 ms (Refs 11,12,60), and the time for which the object is seen prior to movement initiation is often only a few hundred milliseconds^{11,21,57,60}. Successful timing of these fast interceptive actions requires that accurate and reliable TTC information be obtained within a relatively short period of time.

Within the class of fast interceptive actions two subclasses should be distinguished: those that involve short falls under gravitational acceleration and those that do not. It is impossible to time precisely the interception of an object that falls a short distance (< 3 m) from rest without taking acceleration into account^{18,47}. Assuming that acceleration is not measured from the retina^{36,37}, such interceptions must involve the use of acceleration information obtained from elsewhere. Because the acceleration due to gravity is a terrestrial constant (g), it is possible to determine its value and use it to obtain an estimate of TTC from a perceptual estimate of drop height (H): they are related by the equation $H = g(\text{TTC})^2/2$, where air-resistance is neglected²⁰. Table 2 presents a rough taxonomy of timing tasks and the types of information that they are likely to involve, based upon currently available knowledge.

Using information to control a response

Not only do different tasks involve different sources of information but the way in which the information is used in the control of the response is likely to differ between tasks and to change with experience and practice. A body of evidence – behavioural^{61,62}, neurological⁶² and neuroanatomical^{62,63} – supports the idea that there are at least two functional streams of visual information processing within primate (including human) neocortex^{62,63}. These streams appear to support different functions: the dorsal stream is involved with visual processing for the control of skilled motor action (motor stream); the ventral stream is involved with processing that supports conscious visual perception and cognitive judgments (cognitive stream)⁶². The operation of the motor stream proceeds largely automatically and without awareness^{57,61}. Although it is not yet completely clear whether the functional distinction between motor control and perceptual judgment corresponds with the anatomically defined streams³⁹,

Table 2. Time-to-collision estimation: tasks and variables

Task	Defined time window?	Approx. window size (ms)	Timed response?	Short MT?	Control of MT possible?	Short viewing time?	Online control possible?	TTC available at initiation?	First-order TTC suffice?
Catch/hit a rapidly approaching object ^{4,11–13,21,60,67}	✓	2–30	✓	✓	✓	✓	✓(?)	✓	✓(?)
Hit/catch a falling object ^{8,25,57}	✓	2–30+	✓	✓	✓(?)	✓(?)	✓(?)	✓	✗
Hit/catch a slowly approaching or passing object ^{25,39}	✓(?)	20–100+	✓	✗(?)	✓	✗(?)	✓	✓	✓(?)
Avoid object on collision course ^{32,58}	✗(?)	to 3000+	✓	✓	✓	✗(?)	✓(?)	✓	✓
Brake to a stop ^{2,59}	✗(?)	–	✓	✗(?)	✓	✗(?)	✓(?)	✓	✓(?)
Prediction-motion tasks ^{41,42,43}	✓(?)	(?)	✓	✓	✗	✗(?)	✗	✗	✗(?)
Relative judgment tasks ^{14,15,27,31,40,55}	✗	–	✗	✓	✗	✓(?)	✗	✗(?)	(?)

The different tasks place different demands and constraints upon the performer, as indicated by ticks and crosses, and are thus likely to exploit different sources of information. The distinction between tasks is not hard and fast but somewhat 'fuzzy', hence the question marks (?) which are used to indicate that there are likely to be conditions under which the opposite to the marked symbol might be the case. (MT = movement time; First-order TTC = time to collision estimate that ignores acceleration.)

it is clear that visuo-motor control can proceed without awareness^{61,64}, which is probably the normal state of affairs for fast interceptive actions^{38,57}. Thus, even if it turns out that conscious visual perception and cognitive visual operations are supported by the same stream of information processing as skilled visuo-motor control, it is likely that the latter taps this stream at an early, pre-cognitive stage or level⁶⁵. In either case, skilled execution of interceptive actions appears to bypass cognitive operations⁵⁷, whereas laboratory-based tasks may involve cognitive operations^{38,42}. This is particularly likely in

prediction-motion tasks: performance in these tasks is highly variable, with systematic biases^{38,41,42} uncharacteristic of other timing tasks, and cognitive modelling processes^{38,43} and mental imagery⁴² have been implicated in their execution. Thus, control of response is likely to be mediated by different processes in laboratory tasks and interceptive actions³⁸. As I have argued in detail elsewhere^{20,38}, it is not possible to make generalizations about the information used to estimate TTC, or about how this information guides behaviour, from results obtained in any particular task.

Even within the class of skilled, fast interceptive actions a number of possibilities exist for using TTC information for controlling movement timing⁴⁷. An early proposal was that TTC information is used to trigger an action of constant duration^{3,66}. Thus, control of timing would simply reduce to initiating the movement at the correct moment: when TTC reaches a particular value determined by the movement duration (constant) and sensorimotor delays (also constant), an initiation command is issued. It is now known that this strategy is not generally used, movement duration typically being quite variable, even in stereotyped actions of very short duration such as table-tennis smashes¹¹ and grasping movements in catching¹². Thus, it now appears that the nervous system uses a more flexible strategy that allows movement time to be controlled by TTC information^{47,48,67}.

Conclusions

This article has reviewed recent work that shows conclusively that the hypothesis which proposes the variable τ as the informational basis for TTC estimation is false. Instead, it is clear that τ is a component of a more complex picture and it may or may not contribute to performance in a particular

Outstanding questions

- How do the requirements for temporal accuracy vary between tasks and what perceptual quantities are available to provide the timing information necessary to explain observed levels of performance? How do these requirements constrain the selection and integration of TTC related information? What other factors affect selection and integration?
- Exactly what sources of TTC information in addition to τ can the nervous system detect and how are they detected? Some suggestions have been proposed and there are empirical data to support some of these, but a clear and complete picture has yet to appear. How, for example, is an interception timed when there is no direct perceptual information about the location of the interception point?
- How do factors intrinsic to the central nervous system (thresholds, attention, time delays) and the musculo-skeletal system (muscle and limb dynamics) affect the use of perceptual information in timing control?
- How does the nervous system learn to eliminate irrelevant or compromising sources of information and how is the transition to a rapid, automatic processing mode achieved?
- How is TTC information used to control movement? Are there tasks that involve a triggering mode of control? What other modes of control are used?

task. A new framework for understanding TTC perception, very different from the Gibsonian τ -hypothesis, is outlined here. This framework is based, firstly, upon results that demonstrate that many different cues are used to estimate TTC and that their use is task dependent, and secondly, on the idea that biological perceptual systems are continuously adapting, opportunistic learning machines, constrained by task requirements, stimulus conditions and neural information-processing limitations. This framework is capable of integrating all the theoretical and empirical work on TTC estimation that has been published. It emphasizes the critical importance of task constraints in determining the perceptual cues used in the performance of visually timed behaviours and raises many challenges and questions for future research into TTC perception.

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Speechreading: illusion or window into pattern recognition

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In the Fuzzy Logical Model of Perception (FLMP) perceivers are conceptualized as forming perceptual judgments by evaluating and integrating multiple ambiguous sources of information, in an optimal manner based on relative goodness of match. This model has been tested favorably against a variety of competing theories and models. Recent extensions of the FLMP are described in this article along with empirical applications and verification, and progress in the study of speech perception by ear and eye is reviewed within this general theoretical framework. The model illuminates the differences that are observed across different languages in terms of information as opposed to information-processing. Pattern recognition of bimodal speech is representative of pattern recognition in a variety of other domains, such as emotion perception, and there are several domain-dependent reasons why multimodal presentation of audible and visible speech is particularly conducive to accurate pattern recognition. We believe that the positive outcome of this research provides a framework for the development of computer-animated agents, which can serve as language tutors and as conversational characters in other domains, easing the interaction of humans and machines.

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It has been well over two decades since the publication of an article entitled 'Hearing lips and seeing voices' by the late Harry McGurk and his colleague John McDonald¹. The so-called McGurk effect has obtained widespread attention in many circles of psychological inquiry and cognitive science. The classic McGurk effect involves the situation in which an

auditory /aba/ is paired with a visible /aga/ and the perceiver reports hearing /ada/. This outcome is dubbed a so-called fusion response because two different segments are fused into a third. The reverse pairing, an auditory /aga/ and visual /aba/, tends to produce a perceptual judgment of /abga/, a so-called combination response. The McGurk effect had such an