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Visual discrimination thresholds for time to arrival

Klaus Landwehr · Robin Baurès · Daniel Oberfeld · Heiko Hecht

Abstract In a seminal article, Todd (Journal of Experimental Psychology: Human Perception and Performance 7:795-810, 1981) reported a difference threshold of about 50 ms to discriminate the times of arrival of two differently sized objects that simultaneously approached head-on at constant but different velocities. Subsequent investigators, however, have often found much higher thresholds. We did one complete replication of Todd's experiment, and then modified his stimuli and experimental regime, which we hypothesized may have been responsible for some of the discrepancies reported in the literature. Unlike Todd and most other researchers, we exclusively used untrained observers. Several of our participants performed almost as well as the trained observers used by Todd and others, but the performance of most of our participants fell short of this standard. Furthermore, thresholds were affected by the experimental regimes, with large differences between objects' sizes and speeds compromising performance. Analyses of the response patterns revealed that the responses were driven mainly by the objects' relative apparent sizes.

Keywords Visual perception · Optic flow · Time to collision · Difference thresholds

Time to arrival (t_A) is the time remaining before an object or an observer, moving toward a goal, will actually arrive there (Schiff & Oldak, 1990). Here, we shall be concerned with the ability of human observers to visually discriminate between different t_As. Three decades ago, Todd (1981) reported that the discrimination threshold for the times of arrival of two objects, which simultaneously approached head-on toward a stationary observer, amounted to a mere 50 ms.[1] Most subsequent work, however, has obtained values seven to ten times higher than this (Table 1). We think that it is important to identify the causes of these apparent discrepancies, because otherwise our estimates of human proficiency with regard to t_A encounters might possibly be too optimistic. In this article, we shall focus on three ingredients of t_A experiments that might explain the observed discrepancies: (a) the use of different stimuli, (b) the use of different experimental regimes, and (c) the use of differently qualified observers.

Stimuli

Most research on visual discrimination of arrival times makes reference to the geometrical–optical variable τ, defined as the ratio of a given visual angle and its instantaneous first temporal derivative (Lee, 1974, 1976). For comparatively small visual angles, head-centered straight trajectories, and constant velocity, τ specifies t_A. As was explained by Lee and Young (1985), there are three possibilities to define visual angles that may be entered into the τ formula: Reference is to two points on a plane surface, or to an object's outer contour, or to the so-called *focus of expansion* of an optic flow field considered in its entirety (cf. Gibson, 1950). The three types of τ that ensue were dubbed *local τ type 1* ($\tau_L^{(1)}$), *local τ type 2* ($\tau_L^{(2)}$), and *global τ* (τ_G), respectively, by Tresilian (1991). For head-

K. Landwehr · R. Baurès · D. Oberfeld · H. Hecht
Psychologisches Institut, Universität Mainz, Mainz, Germany

K. Landwehr (✉)
Psychologisches Institut, Universität Mainz, 55099 Mainz, Germany
e-mail: landweh@uni-mainz.de

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[1] As has also been noted by others (e.g., Bootsma & Craig, 2002, p. 918, note 6), in Todd's (1981) experiment, approach was not head-on in the sense of the two objects' midpoints traveling on converging trajectories toward the observer (cf. Kebeck & Landwehr, 1992, for such a scenario); rather, the two objects were set side by side, so that the two abutting lateral edges traveled on a collision course along the observer's cyclopean line of gaze.

Table 1 Authors, parameters, and results of previous t_A discrimination threshold studies

Authors	Paradigm	Stimuli	Observers	Thresholds (ms)	Weber Fractions
Todd, 1981	2AFC	Dotted-outline squares	Trained	50	0.016
Simpson, 1988	2AFC-Stc	Crosses	Trained/naïve	$195 \sim 443_{\mathrm{r}}$	0.15~0.34
Bootsma & Oudejans, 1993	2AFC	Outline squares	Trained	50_{f}	0.02
Kaiser & Mowafy, 1993	2AFC	Dots	Informed	500_{g}	0.125
Regan & Hamstra, 1993	1I-2AFC	Filled squares	Trained	32~85	0.049~0.129
Bootsma & Craig, 2002	2AFC	Spheres/dots	Naïve	$250_{\mathrm{g}} \sim 500$	0.083~0.125
Kim & Grocki, 2006	2AFC	Hexahedrons	Naïve	500	0.25

2AFC = Two-alternative forced choice. Stc = Staircase. 1I = One interval. Unmarked thresholds refer to approach events, those indexed with an "f" to frontoparallel motion, those indexed with an "r" to recession events, and those indexed with a "g" to τ_G-defined events. Weber fractions were computed by dividing the thresholds by mean t_A—or by mean viewing time (t_{view}), if $t_A >> t_{\mathrm{view}}$. The threshold reported by Todd (1981) was read off his Fig. 3, the one reported by Kaiser and Mowafy (1993) from their Fig. 4, the ones reported by Bootsma and Craig (2002) from their Figs. 4–6, and the one reported by Kim and Grocki (2006) from their Fig. 3, all in accordance with a 75 %-correct criterion. The thresholds reported by Regan and Hamstra (1993) were independent from t_A.

centered, straight trajectories, the optic flow field's focus of expansion coincides with the object's or the observer's direction of travel and gaze (Warren, 1998), and global τ, at this point, is undefined (or zero). It is only with off-center passages that τ_G comes into play (cf. Kaiser & Mowafy, 1993, who isolated this variable by using dot-like objects). Geometrically, $\tau_L^{(1)}$ cannot be deconfounded from $\tau_L^{(2)}$ (Beverley & Regan, 1980, p. 158: Fig. 5), but visual systems may respond differently to continuous contours than to discrete dots. If so, $\tau_L^{(1)}$ can be isolated by means of two dots, and $\tau_L^{(2)}$, by means of a closed contour—the circle, in particular, because it does not exhibit singular points.

Most of the objects that have been used in t_A research (e.g., filled or outline squares, hexahedrons; Table 1) did not perfectly deconfound $\tau_L^{(1)}$ and $\tau_L^{(2)}$, in the sense just explained, but emphasized $\tau_L^{(2)}$; only Simpson's (1988) crosses nearly isolated $\tau_L^{(1)}$—although the four corners of a square or the maximally visible six or seven corners of an hexahedron pairwise provide obvious $\tau_L^{(1)}$ information, and, conversely, the four outermost points of a cross constitute a virtual square, hence, $\tau_L^{(2)}$ information. Todd's (1981) dotted-outline squares (cf. the first paragraph of the Prestudies section for a precise characterization) occupy an intermediate territory: For one thing, a dense sequence of dots strongly suggests the presence of a line (Westheimer & Li, 1996); for another, four virtual, orthogonal lines strongly suggest a square (Kanizsa, 1979).[2] Todd's (1981) stimuli thus provide both types of local τ information simultaneously. With regard to stimuli, we reasoned that if the superior performance of Todd's observers had been due to the available stimulus information, then random arrays of dots with the same number of flow vectors as were present in Todd's squares would constitute an appropriate control stimulus: Such "dot clouds," as we shall call them, would compromise $\tau_L^{(2)}$, emphasize $\tau_L^{(1)}$, but retain dense optic flow (Fig. 1). Thence, on the assumption that $\tau_L^{(2)}$ information can be dispensed with in favor of $\tau_L^{(1)}$, the cloud stimuli should support t_A performance as well as Todd's original stimuli did.

It is important to note that our cloud stimuli differ from those that have typically been used to study effects of surface texture on t_A judgments (cf. Landwehr, 2004, for a review; Hosking & Crassini, 2011; Jacobs & Díaz, 2010; López-Moliner, Brenner, & Smeets, 2007; Oberfeld, Hecht, & Landwehr, 2011, for more recent research). In the respective experiments, "texture" has usually been materialized by checkerboard tilings. Although, geometrically speaking, in any such display an infinity of pairs of points define plane visual angles, dedicated response mechanisms are more likely to be activated by points that stand out optically (Beverley & Regan, 1979, 1980). The observed effects of texture have most often been weak, even when dot patterns have been used (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003). Harris and Giachritsis (2000; Giachritsis & Harris, 2005), who also used random-dot kinematograms, found that, with regard to t_A judgments, global image expansion dominated over local, dot-related size changes. However, in these experiments, levels of information were pitted against one another, and in terms of τ variables, the comparison was between τ_G and $\tau_L^{(2)}$, or between τ_G and a mix of $\tau_L^{(1)}$ and $\tau_L^{(2)}$. We therefore think that a comparison of stimuli that emphasized either $\tau_L^{(1)}$ and $\tau_L^{(2)}$, or $\tau_L^{(1)}$ alone (with τ_G constant), would still be informative.

Experimental regimes

Inspection of Table 1 does not reveal any obvious differences between the experimental paradigms that have been used by

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[2] Our reasoning may be reminiscent of phenomenological Gestalt theory here, but we note that there is neurophysiological evidence that our visual system under specific conditions responds according to "laws of grouping," or even principles of "amodal completion" (Roelfsema, 2006; Sasaki, 2007).

Fig. 1 Screenshot of our dot-cloud stimulus

individual researchers or research groups: All took advantage of a variant of the two-alternative forced choice paradigm (2AFC; Jones, 1971). Regan and Hamstra (1993), however, used a one-interval stimulus presentation procedure and an implicit standard (the arithmetic mean of a series of t_A values, to be discovered "online" by observers themselves; cf. McKee, 1981),[3] and Simpson (1988) combined the basic paradigm with a maximum-likelihood staircase procedure (Pentland, 1980). Such modifications of the 2AFC paradigm may affect performance (see Macmillan & Creelman, 2005, pp. 175–176), although, with regard to the use of an implicit standard, Morgan, Watamaniuk, and McKee (2000) have shown an explicit standard to be superfluous (see also Norman et al., 2008).

A systematic comparison of possible variants of 2AFC was beyond our present endeavor. Instead, we concentrated on the stimulus variants described in the preceding section, and on observer variables (to be discussed subsequently), and modeled our experimental setup strictly after Todd's (1981). However, a number of observations that accrued during prestudies (cf. the Prestudies section of this article) prompted us to consider various modifications of Todd's original experimental regime. Table 2 provides a contrasting juxtaposition of Todd's regime and the one that we used, for purposes of comparison in our main experiment. The most important differences between the regimes concern the presence versus absence of a fixed standard, partial versus complete randomization of the sequence of trials, and different ranges of object sizes and velocities. As we shall see from the results of our main experiment, some of these modifications can be held responsible for the observed differences in participants' performance.

Observers

With regard to the observers' status, most of the authors cited in Table 1 had recruited trained observers, including themselves (e.g., Regan & Hamstra, 1993; Todd, 1981). This raises concerns about population validity. In fact, Simpson (1988) reported differences between his own data and those of a group of naïve observers, as well as deviating results for another, individual untrained observer (related to symmetric vs. asymmetric sensitivity to approach vs. recession). Not surprisingly, expert observers generally outperform the others. The use of trained observers is meaningful if one's aim is "testing the limits," and indeed there are remarkable achievements of timely responses in a variety of sports (cf., e.g., Bootsma & van Wieringen, 1990; Regan, 2012). However, the use of naïve observers is called for if one is interested in the average performance of lay persons. We invited undergraduate students, and only accepted those who had not participated in a t_A experiment before.

Prestudies

All of the studies to be described in this article were done as computer simulations. We did one complete replication of Todd's (1981) Experiment 1. As in the original, two squares, set side by side with the midpoints of their abutting edges centered on the observer's cyclopean line of gaze, moved head-on toward him or her. The simulated object sizes (R) were 7.6 and 38.1 cm, the velocities (v) were 6.1, 9.1, 12.2, 15.2, 18.3, 21.3, 24.4, and 27.4 $\mathrm{m \cdot s^{-1}}$, the arrival time (t_A) of the standard was 3 s, and the t_As of the test were 3.3, 3.2, 3.15, 3.1, 3.05, 3.02, and 3.01 s, respectively. A total of 512 unique trials could be generated by randomly drawing pairs of R and v, and by interchanging the left–right positions of the standard and test. The viewing distance was 76.2 cm for a screen size of 21.6 × 16.5 cm. Objects were optically specified by 2 × 24 dots, spaced evenly along the objects' outer contours. Dots did not magnify during approach, and squares did not deform, thus corresponding to parallel projection.[4] The stimuli were turned off shortly after the edges of one object had hit the edges of the screen. One lay observer, who had not taken part in a similar experiment before, participated. As in Todd's original experiment, the participant was asked to respond "as quickly as possible without sacrificing accuracy" (p. 799), and she was informed that responses would be recorded only as long as both objects were completely visible—and that invalid

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[3] In Macmillan and Creelman's (2005, pp. 113–120) systematization, this procedure is regarded as a two-response classification task that presupposes the perceptual one-dimensionality of the stimulus. Note that these authors also assigned Fechner's (1860) method of constant stimuli—the method used by most of the authors listed in Table 1 (plus ourselves)—to this category.

[4] Todd (1981) had generated his stimuli not trigonometrically, but according to a hyperbolic approximation (object size divided by distance), and, for the sake of comparability, so did we. Although this compromises quantitative analyses of τ-type information in terms of visual angles, it leaves the qualitative differences between the types of τ, as materialized in the stimuli, unaltered.

Table 2 A comparison of Todd's (1981) original experimental regime and our new regime

	Todd's original regime	Our new regime
Object sizes (m)	0.076 and/or 0.381	0.15~0.25
Ranges of visual angles at start (deg)	0.0017~3693	0.0049~4.8777
Velocities ($\mathrm{m \cdot s^{-1}}$)	6.1~27.4 (in steps of 3~3.1)	1.19~1.31 (≡ Pedestrian) 3.56~3.94 (≡ Bicycle) 10.69~11.81 (≡ Car in town) 26.38~29.16 (≡ Car on highway)
Ranges of angular velocities shortly before end ($\mathrm{deg \cdot s^{-1}}$)	17.9~273.7	5.4~174.7
Standard t_A (s)	3	1.5~2.5
Δt_As (s)	0.01~0.3 (in steps of 0.01~0.1)	0.05~0.15 (in steps of 0.025)
Number of trials	1,050	250
Order of trials	According to Δt_A	Random

Δt_A = Difference between t_As of the standard and test. Except for t_A and Δt_A, pairwise sampling from the ranges was random throughout

trials would be repeated at the end of a session (this only happened on 1.6 % of trials). Answers were given by pressing a right-hand response key if the object on the right side was judged to arrive first, and by pressing a left-hand response key in the alternative case. Feedback was not provided because Todd's observers seem to have ignored it most of the time. The procedure was spatial 2AFC for a total of 1,050 trials that were ordered into 21 blocks with three repetitions of each arrival-time difference (Δt_A) and Δt_A decreasing. Sessions were distributed over three consecutive days.

Contrary to the results with Todd's (1981) trained observers, our participant did not reach ceiling at Δt_A = 300 ms, nor did her performance drop below chance at Δt_A < 50 ms. Rather, it *improved* during the final blocks, and was still 57 % correct at Δt_A = 10 ms. More importantly, on average, she scored 70 % correct on trials with no size difference between the objects (i.e., $\Delta R = 0$), 75 % correct on trials with identical velocities ($\Delta v = 0$), and 90 % correct on trials with both $\Delta R = 0$ and $\Delta v = 0$. These observations suggest that differently parameterized trials were handled differently by our participant (or posed different tasks in the first place), and that the whole experiment provided ample opportunity for perceptual learning.

Although we had used Todd's (1981) original instruction, our participant soon found out that responding as *late* as possible was advantageous: Her distribution of response times was extremely skewed, with a singular mode at 2.578 s. As our participant revealed afterward, her strategy had been occasioned by trials in which she saw the apparently smaller, but faster, object overtaking the apparently larger one in the very last moment before stimulus wipeout. Also, she claimed to have benefited from becoming familiar with the average trial duration. Finally, fitting a psychometric function for trials with both $\Delta R \neq 0$ and $\Delta v \neq 0$ (cf. Wichmann & Hill, 2001) yielded a just noticeable difference (JND) of 240 ms (Weber fraction: 0.08). After deselection of the first and final Δt_A blocks (see the next paragraph), these values became 179 ms and 0.06, respectively.

Todd's (1981) original experiment is extremely time-consuming. In order to simplify subsequent data collection, effects of the procedure were tested before substantial changes were introduced. For our second prestudy, only five different Δt_As (20~200 ms) were used, assuming a difference threshold to lie somewhere within this range. Conditions $\Delta R = 0$ and $\Delta v = 0$ were eliminated, and blocks with different Δt_As of 50 trials each were ordered randomly. Thus, the total number of trials could be reduced to 250. One new participant attained a JND of 174 ms (Weber fraction: 0.06). Two other participants, however, performed at chance level at all of the Δt_As.

For our third prestudy, trials were drawn at random from the blocks defined in the second prestudy. Two of the observers who had served for Prestudies 1 and 2 both now attained a JND of 98 ms (Weber fraction: 0.03), again indicating a gain from perceptual learning. The other two participants from Prestudy 2, however, once again performed at chance level. One of them explained that her response strategy had been to always select the apparently larger object, thus ignoring velocity information. Obviously, such a strategy must lead to chance performance in a Δt_A task with $\Delta R \neq 0$.

Taken together, our prestudies suggested that fewer trials than were used by Todd (1981) suffice for determining t_A difference thresholds, *if* observers are sensitive to differences in optic flow velocities at all. Conversely, differences in projected size sometimes seem to have distracted from the task (cf. the "size arrival effect" described by DeLucia, 1991, 2004). For our main experiment, we therefore reduced the differences in size and velocity while at the same time making velocity information more salient and size information less prominent.

Main experiment

On the basis of the theoretical considerations presented in the introduction, we constructed new stimuli (Fig. 1), and on the basis of the findings and observations from our prestudies, we developed a new experimental regime (Table 2). For our main experiment, in a 2 × 2 design, Todd's (1981) original stimuli and our new ones were factorially crossed with experimental regimes—namely, our new regime and the second, abbreviated version of Todd's regime as used in our third prestudy.

Method

Participants A group of 40 observers, ten for each cell of our design, participated. The participants were recruited on campus, and were—in balanced proportion—psychology or physics undergraduates. None had taken part in a t_A experiment before.

Stimuli As we already indicated in the introduction, two amorphous clouds, composed of 24 random dots each, were constructed. The clouds did not exhibit any obvious contours, and thus almost eliminated $\tau_L{}^{(2)}$ information while keeping the $\tau_L{}^{(1)}$ information from Todd's (1981) original dotted-outline squares, which were used as alternative stimuli. For reasons of comparability, as in the case of Todd's stimuli, the dots of our new stimuli did not change size during approach.

Experimental regimes In order to avoid the possible adaptation effects that had been reported by the observer of our complete replication of Todd's (1981) Experiment 1, in our modified experimental regime there was no fixed standard, and all variables except Δt_A were drawn at random from predefined ranges. To counter delusive effects of object size, a narrow range (0.15~0.25 m) was chosen for this variable. Velocities were sampled in pairs from ecologically meaningful ranges: 1.19~1.31 $\text{m}\cdot\text{s}^{-1}$ (pedestrian), 3.56~3.94 $\text{m}\cdot\text{s}^{-1}$ (bicycle), 10.69~11.81 $\text{m}\cdot\text{s}^{-1}$ (car in town), and 26.38~29.16 $\text{m}\cdot\text{s}^{-1}$ (car on highway). t_A varied between ~1.5 and ~2.5 s, and Δt_A varied in steps of 25 ms between ~50 and ~150 ms. The procedure remained 2AFC for 250 trials, which were drawn according to the scheme used in Prestudy 3. The abbreviated version of Todd's regime that had been used in the latter prestudy was used for comparison.

Results and discussion

The mean difference thresholds—computed as half of the difference between the 25 % and 75 % points on fitted psychometric functions (cf., again, Wichmann & Hill, 2001)—are listed according to conditions in Table 3. For our observers, Todd's (1981) abbreviated experimental regime proved much more difficult than our revision of it, $F(1, 34) = 27.118$, $p < .001$, $\eta^2 = .444$. We found no main effect of stimulus variants, and no significant interaction between experimental regimes and stimuli (both Fs < 1).

For two of the participants, psychometric functions could not be fitted. Although this can partly be blamed on our choice of a narrow range of Δt_A, it also reflects the original experimental regime's difficulty, because fits worked well for all observers who had been tested under the modified regime. As is evident from the standard deviations, there were tremendous interindividual differences: For our new experimental regime, the estimated thresholds ranged between 69.25 and 374.69 ms, and for the abbreviated Todd regime, between 152.83 and 973.66 ms.

Since 2AFC decisions were not generally determined by projected object size or its rate of expansion at the time of the observers' responses, Todd (1981, p. 801: Table 1) reasoned that his participants probably used the ratio of these variables (i.e., τ), which, as we explained in the introduction, specifies t_A (Lee, 1974; the differentiation between the three types of τ had not yet been published at the time Todd did his experiments; the τ implied was a special case of $\tau_L{}^{(1)}$, which referred to the side lengths of the squares used as stimuli; also, Todd's analysis was in terms of image sizes, not visual angles—which are equivalent in this case, however). We drew up the same statistics, and additionally counted the number of trials for which an object's larger visual angle (θ) or larger rate of angular change ($\mathrm{d}\theta/\mathrm{d}t$) provided valid information about earlier arrival (Table 4). This also afforded a control of the randomization routine that we had used. It turned out that trials under Todd's (1981) abbreviated experimental regime were almost balanced with regard to whether the apparently larger or smaller object, or the apparently faster or slower one, would be the first to arrive, but that our new regime was biased in favor of the larger and faster (or closer) object.[5] Despite this confound, it is obvious from Table 4 that observers relied on visual angle information most of the time—except for the cloud stimuli presented under our new experimental regime, $F(3, 36)_\theta = 24.785$, $p < .001$, $\eta^2 = .674$; $F(3, 36)_{\mathrm{d}\theta/\mathrm{d}t} = 19.204$, $p < .001$, $\eta^2 = .615$.

Unfortunately, the interpretation of the aforementioned statistics is not straightforward, because visual angles and their derivatives, under ecological conditions, are unavoidably correlated—which correlation also extends to τ (cf. Regan & Hamstra, 1993; Schrater, Knill, & Simoncelli, 2001, for ways to unconfound these variables). Therefore,

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[5] Note that "apparently faster or slower" does not imply truly faster or slower, because angular velocities are affected by both objective velocity and distance.

Table 3 Mean difference thresholds and standard deviations according to the stimuli and experimental regimes

Experimental Regimes	Stimuli	
	Dotted Squares	Dot Clouds
Todd's abbreviated regime	372.89 ms ($n_4 = 9$) *SD*: 169.15 ms	426.32 ms ($n_3 = 9$) *SD*: 246.37 ms
Our regime	136.00 ms ($n_2 = 10$) *SD*: 87.63 ms	138.24 ms ($n_1 = 10$) *SD*: 62.13 ms

The indices of *n* denote the four independent subsamples

Todd's (1981) conclusion, that his observers were sensitive to τ, seems premature. For our experiment, the percentages of trials in which participants' responses were consistent with the use of θ or $\mathrm{d}\theta/\mathrm{d}t$ were always greater than the percentage referring to τ (Table 4). On the other hand, the percentages were not too different for the cloud stimuli under our new experimental regime, and also, the percentages of trials for which responses were consistent with the use of τ were generally greater for the new regime than they had been in Todd (1981), $F(3, 36)_\tau = 16.865$, $p < .001$, $\eta^2 = .584$. Taken together, these findings suggest that by reducing the size difference between objects (ΔR), we were successful at emphasizing velocity and optic flow information, so that under our experimental regime—with the cloud stimuli, in particular—observers may have used $\tau_L^{(1)}$-related information more readily than in the other conditions.

General discussion

Here we have shown that t_A difference thresholds are strongly affected by experimental regimes. This effect seems closely related to DeLucia's (1991) size arrival effect, because changing the relative sizes of objects was one of our major modifications of Todd's (1981) original regime. The absence of a main effect of stimulus variants, on the other hand, may indicate great flexibility of mechanisms in the extraction of information from optic flow. Yet, we also have to consider the possibility that many observers on many trials may not have used τ-type variables at all.

Several authors (e.g., DeLucia, 2004) have suggested that observers in a t_A situation may use multiple sources of information (see Yan, Lorv, Li, & Sun, 2011, for a recent review and perspective). One of the virtues of Todd's (1981) stimulus scenario is that it isolates—to a fair approximation—those variables that theoretically suffice to deal successfully with impending, head-centered collisions: one or more visual angles (θ_i), those angles' rates of change ($\mathrm{d}\theta_i/\mathrm{d}t$), and the ratios of these terms (τ_i; cf. Regan & Hamstra, 1993, who presented evidence that well-practiced observers may be able to utilize any of these sources of information independently from the others; Schiff, Caviness, & Gibson, 1962; and Wang & Frost, 1992, who used even simpler, single-object scenarios, apt for animal research). Crucially, in all of these simulations, there was no information about distance. This entails that a "cognitive" strategy to compute t_A by dividing perceived distance and perceived velocity is unlikely to be successful—if it is applied at all (Tresilian, 1991). Still, observers may attempt to infer distances from apparent object sizes (Gibson, 1950) and respond to *distance to arrival* (d_A) instead of t_A (see Liu, Niu, & Wang, 2008, for evidence of accordingly tuned neurons in the pigeon, although d_A is believed to be obtained from velocity- and τ_G-sensitive neurons, on the basis of the equality of $d = v \cdot t$). In a 2AFC scenario, such a response strategy would show up as overreliance on the difference of visual angles ($\Delta\theta_{i,j}$)—exactly what we found.

Eventually, how do we account for the individual differences between our observers? Under our simplified experimental

Table 4 Proportions of trials for which, at the time of participants' responses, the larger visual angle of one object, or the larger angular velocity of one object, provided valid information for correct responses, and proportions of trials on which participants selected this object to be the first to arrive, split up into actually correct versus erroneous decisions

Regime and Stimulus	Larger θ = Valid Cue	Larger θ Selected	Answer		Larger $\mathrm{d}\theta/\mathrm{d}t$ = Valid Cue	Larger $\mathrm{d}\theta/\mathrm{d}t$ Selected	Answer		Smaller τ Selected	Correlations Between θ and $\mathrm{d}\theta/\mathrm{d}t$
			Correct	Incorrect			Correct	Incorrect		
Todd's Regime										
Squares	.59	.94	.55	.39	.64	.90	.56	.35	.57	.65
Clouds	.59	.94	.55	.39	.63	.92	.56	.36	.57	.61
Our New Regime										
Squares	.74	.91	.68	.23	.83	.86	.70	.16	.71	.33
Clouds	.80	.77	.64	.14	.89	.76	.67	.09	.70	.32

The last column lists correlations between θ and $\mathrm{d}\theta/\mathrm{d}t$. θ = plane visual angle of objects, referred to maximum horizontal diameter. $\mathrm{d}\theta/\mathrm{d}t$ = instantaneous change of θ at time of participants' responses. $\tau = \theta \div \mathrm{d}\theta/\mathrm{d}t$. τ was always a valid cue, and if the corresponding answers were selected, they were necessarily correct. The proportions "selected" do not add up across θ and $\mathrm{d}\theta/\mathrm{d}t$ because the variables were correlated. The proportions "correct" and "incorrect" add up to the proportions "selected" regime, several participants attained t_A difference thresholds almost as low as those that were achieved by Todd's (1981) trained observers. Others, however, especially when tested under variants of Todd's original regime, failed completely. As has been confirmed by other researchers (personal communications by F. T. J. M. Zaal, July 2, 2007, and E. Brenner, May 11, 2010), self-reported t_A-critical activities like sports, driving, or computer game proficiency do not in general predict these individual differences. Whether they are related to deficits in basic skills of discriminating visual angles and their changes is an issue to be investigated in future studies.

In sum, it seems that the discrepancies between Todd's (1981) original data concerning Δt_A thresholds and later findings are best explained by effects of the experimental regimes, and that these effects in turn come about because observers tend to base decisions about time to arrival more on apparent object sizes than on temporal cues.

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