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Evaluating methods to measure time-to-contact

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A B S T R A C T

Many every-day activities necessitate an estimate of the time remaining until an object will hit us: the time-to-contact (TTC). Observers' skill in estimating TTC has been studied by considering the use and combination of key visual signals (e.g. looming and disparity). However, establishing observers' proficiency in estimating TTC can be complicated, as the variable of interest (time) is typically highly correlated with other signals (e.g. target velocity or displacement). As a result, observers' responses may be based on correlates of TTC rather than on TTC itself. Here we evaluate two widely-used TTC tasks: one absolute task in which observers pressed a button to indicate the estimated TTC, and a relative task in which TTC was judged relative to a reference. We test how a wide range of experimental variables that co-vary with TTC contribute to observers' judgments. We systematically vary the correlation between TTC and its covariates and test how psychophysical judgments are affected. We show that for both absolute and relative estimation tasks, observers' responses are best explained on the basis that they judge TTC rather than one (or more) of its covariates. Our results suggest that relative tasks are preferable when assessing TTC, and we suggest a number of analyses methods to ensure that participants' judgements correspond to the variable under investigation.

1. Introduction

A key function of the visual system is to provide information about objects moving in depth so we can initiate interceptive or evasive actions (e.g. catch a ball; avoid a car crash). Frequently, the brain requires an estimate of the time remaining until an object will hit us or another object: the time-to-contact (TTC). Observers' skill in estimating this quantity has been examined by a large number of studies in both laboratory- and applied-settings. For example, applied studies have tested TTC for ball interception (e.g. Bootsma & van Wieringen, 1990; Caljouw, Van der Kamp, & Savelsbergh, 2004; Gray & Sieffert, 2005; Peper et al., 1994) and the visual control of braking (e.g. Coull et al., 2008; Lee, 1976; Rock & Harris, 2006), while other work has sought to isolate the key visual signals required when judging TTC (e.g. DeLucia, 1991, 2005; Gray & Regan, 1998; Heuer, 1993; Lee & Reddish, 1981; Lee et al., 1983; Regan & Hamstra, 1993; Rushton & Wann, 1999; Todd, 1981).

To examine the basis of TTC judgments, observers are typically required to tune an action (e.g. a simple button press or an interceptive movement) to a visual target. However, inferring the observers' proficiency in estimating TTC in such tasks is not always straightforward, as the variable of interest (time) is typically highly correlated with other signals (e.g. the target's velocity or displacement). Thus, observer's responses may be based on correlates of TTC, rather than on TTC itself. Fig. 1A illustrates the investigator's dilemma: varying the target's TTC (the solid diagonal) while keeping the target's starting distance (the ordinate) constant would confound TTC with the approach speed (abscissa). As a result, observers might respond on the basis of trial-by-trial variations in the target's approach speed, even though their task was to estimate TTC. A simple approach to discourage the use of covariates is to randomise the signals (e.g. speed, distance) and thereby reduce their correlation. However, this does not necessarily prevent observers using a covariate when responding (i.e. the lower correlation of the covariate with TTC would simply make judgments appear noisier). Therefore, it is important to test whether this manipulation is successful – evidence that many previous studies have not provided.

When presented with an approaching target, observers might exploit one or more of a range of variables to judge the likely time of impact. For instance, based on retinal size cues, they may be able to estimate TTC directly using 'tau', the ratio of the object's angular size to its rate of looming rate (Lee, 1976; Lee and Reddish, 1981; Lee et al., 1983; Regan & Hamstra, 1993; Wann, 1996). Alternatively, their judgments might relate to the looming rate when the approaching object is of a known size (López-Moliner, Field, & Wann, 2007). Based on binocular cues, observers might use the first derivative of disparity divided by the second derivative (Regan, 2002) or the rate of change of disparity (Gray & Regan, 1998), as well as the combination of monocular and binocular signals (Gray & Regan, 1998). Given the dense intercorrelation

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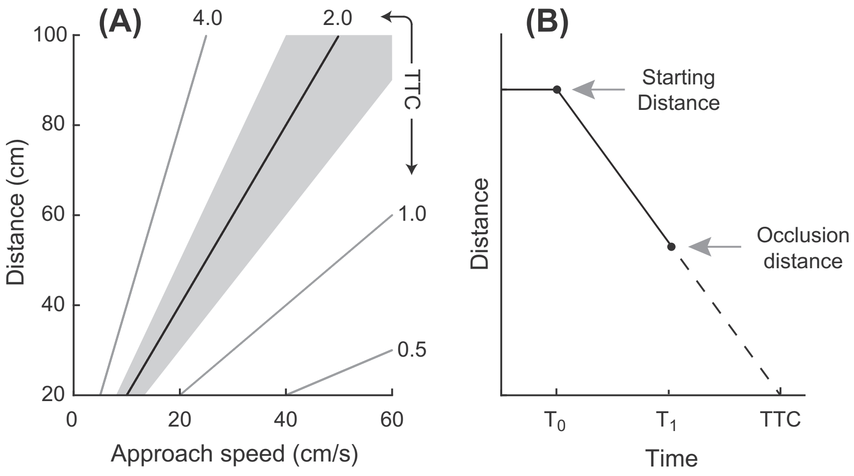

Fig. 1. Representation of stimulus parameters involved in time-to-contact experiments. (A) TTC as a function of distance and approach speed. A single TTC can be produced from a range of combinations of distance and approach speed (solid contour lines). We sampled our values of distance and approach speed from the shaded area, with average values shown as the solid black diagonal (TTC = 2.0 s). (B) Illustration of the predictive motion paradigm (Tresilian, 1995), with distance shown as a function of time. The target remains at its starting distance for 500 ms and at time T_0 starts approaching the observer. At time T_1 the object is removed from the display. Had it continued along it is trajectory towards the observer (dashed line) it would hit a point between the participant's eyes at time TTC.

between these signals, it can be difficult to determine whether observers judgments relate to a full temporal estimate of TTC or rather covariates that do not unambiguously signal TTC when considered alone.

One approach to the issue of covariation was developed by Regan and colleagues (Gray & Regan, 1998; Regan & Hamstra, 1993; Regan & Vincent, 1995) in which TTC was made orthogonal to other sources of information through a factorial design. For instance, Regan and Hamstra (1993) provided evidence that under monocular presentation, observers judge TTC independently from two possible covariates (retinal size and rate of expansion). While attractive, this design is unwieldy if more than two or three potential covariates are considered. Moreover, while this manipulation ensures that the looming rate is orthogonal to tau and retinal size at the *start* of the trajectory, this separation no longer holds as the trajectory unfolds towards the observer (the more critical period of the trial). Finally, observers in these studies were generally provided with feedback, complicating the interpretation of the results. Specifically, depending on the feedback regime, observers are able to discriminate covariates of TTC (e.g. the initial rate of expansion) with the same precision as TTC (see Regan and Hamstra (1993) Experiments 3A and 4A), making it difficult to know whether the experimental task reflects typical behaviour when judging TTC.

In this paper we seek to establish which source(s) of information participants use to judge TTC. Previous work has focused largely on the use and combination of monocular and binocular optical signals that underlie TTC judgments (i.e. looming rate, angular size and changing binocular disparity signals). Here we consider a wider range of experimental variables that also co-vary with TTC (e.g. presentation duration and occlusion distance). Our goal is to determine whether observers judge the TTC of an approaching target when instructed to do so, or rather judge one (or more) of its covariates.

In the first experiment, we use an absolute task in which observers press a button to indicate their estimate of TTC. In a second experiment, we use a relative task in which observers judge the time-to-contact relative to an auditory reference. For both experiments we consider a range of potential covariates and we systematically vary the correlation of these covariates with TTC by manipulating the amount by which covariates are randomised. We determine how performance in TTC tasks is affected by randomisation to assess whether observers' judgments rely on the actual TTC or a covariate. To preview our findings, we find that performance in both tasks suggests participants judge TTC rather than its covariates.

2. General methods

2.1. Apparatus

Stimuli were presented stereoscopically using a two-monitor haploscope in which the two eyes viewed separate 21 inch CRTs (ViewSonic FB2100x) through front-silvered mirrors. Viewing distance was 50 cm. We adjusted the haploscope so that inter-pupillary distance and vergence angle were configured correctly for each individual. Stimulus presentation was controlled by a Windows PC with an NVIDIA Quadro FX4400 graphics card. CRTs displayed 1600×1200 pixels at 100 Hz. Individual pixels subtended approx. 1.75×1.75 arcmin. The two CRTs were matched and linearised using photometric measurements. Head movements were restricted using a chin rest. Responses were collected via the PC's keyboard.

2.2. Stimuli

The target was a wireframe sphere (16 lines of longitude and latitude) that had a mean radius of 2 cm, randomly varied between trials from a uniform distribution in the range of ±0.2 cm (cf. Welchman, Lam, & Bülthoff, 2008). To enhance the subjective impression of 3D structure, the sphere rotated around its centre (rotation speed of 40°/s around the *x*-axis and 80°/s around the *y*-axis). In addition to the target, a peripheral reference volume of textured cubes was visible throughout all experiments, creating the impression of viewing the target at the centre of a short tunnel. The frontal plane of the 'tunnel' was aligned with the plane of the screen and the tunnel extended 30 cm behind the screen. This provided observers with a constant stationary reference. Stimuli were created using C# and OpenGL graphics libraries and were rendered using anti-aliasing and geometric perspective projections from each eye, taking the observer's inter-pupillary distance (IPD) into account.

2.3. Procedure

Observers sat in the dark and viewed the motion excursion of an approaching target. At the start of each trial, the target appeared at

Table 1
Ranges of starting distance, occlusion distance and time-to-contact in five conditions used in Experiments 1 and 2. Values were sampled from a uniform distribution (shown here as mean ± range).

Randomisation level	Start distance (cm)	Occlusion distance (cm)	TTC (s)
0	95 ± 0.0	60 ± 0.0	2.0 ± 0.0
1	95 ± 3.0	60 ± 6.0	2.0 ± 0.3
2	95 ± 6.5	60 ± 13.0	2.0 ± 0.3
3	95 ± 8.0	60 ± 18.0	2.0 ± 0.3
4	95 ± 10.0	60 ± 20.0	2.0 ± 0.5

a randomly chosen starting distance along the cyclopean line of sight. It remained at this starting distance for 500 ms to allow observers to fixate and fuse the stimulus. The target then started to approach the observer along the cyclopean line of sight at a constant (real world) speed. The target was removed from the screen at a chosen 'occlusion' distance from the observer (see Fig 1B). As a consequence, observers made their response based on a prediction of the target's motion (Tresilian, 1995). Observers were free to move their eyes and no feedback was provided.

2.4. Choice of stimulus parameters

To reduce the correlation between stimulus variables, we randomised the start distance, the occlusion distance, the TTC of the target when it started moving towards the observer and its physical size. This also randomised the approach speed of the target, the presentation duration, the rate of expansion, and the total angular expansion. To maintain a comfortable range of binocular fusion (Hoffman et al., 2008), while still allowing enough randomisation of start and occlusion distances, we set the maximum visible motion trajectory between 105 cm and 40 cm from the observer. To reduce the correlation between variables, we employed five conditions of increasing randomisation. We kept the mean value of the starting distance (95 cm), occlusion distance (60 cm) and the TTC (2 s) constant across conditions, while systematically increasing the range of the uniform distribution from which we sampled. We included one condition in which we randomised none of the variables (Randomisation level 0, Table 1), one condition in which we maximised the randomisation within the range of distances we chose (Randomisation level 4, Table 1) and three intermediate conditions (Randomisation levels 1–3, Table 1). Each observer participated in each condition in a quasi-random order.

2.5. Variables considered as potential covariates

We considered the influence of a number of variables that could, potentially, have been used by observers when making their judgments (even though some of these potential covariates would not represent entirely rational choices). We included the spatiotemporal variables of looming rate, change in binocular disparity and the target's approach velocity. We also considered spatial variables, such as the vergence distance (expressed in angular units) and the target's retinal size, and temporal variables, such as the TTC and the presentation duration. Finally, we considered the target's total change in angular size and the total change in vergence (i.e. the relative disparity between the starting point and the occlusion of the target). Where applicable we considered these variables both at the start of the trial and at occlusion. We conducted repeated-measures ANOVAs in SPSS and used sphericity corrections where required. Other data processing and statistical tests were performed using Matlab (The MathWorks Inc.).

2.6. Observers

Observers were recruited from the staff and students of the University of Birmingham (average age across all participants 26.9 ± 4.6 years); all gave written informed consent. Observers were screened to ensure that they could discriminate at least 1 arcmin of disparity in a briefly presented (300 ms) random dot stereogram.

3. Experiment 1: Absolute task

Perhaps the most direct measure of a person's ability to estimate TTC is to show them an approaching target for a specified time and ask them to indicate the point in time when the target would reach a specified position (e.g. hit them on the head or reach their hand). This absolute estimation approach has been taken by a number of studies (e.g. Cavallo & Laurent, 1988; Geri, Gray, & Grutzmacher, 2010; Heuer, 1993; López-Moliner, Field, & Wann, 2007; McLeod & Ross, 1983; Rushton & Wann, 1999; Schiff & Detwiler, 1979), although the question of whether task-irrelevant variables (rather than TTC) were used was not addressed directly. In this experiment we use an absolute estimation task to assess observers' performance in judging time to contact. To identify the information used by observers, we vary the correlation between potentially informative variables (see Table 1) and assess how randomisation influences judgments.

3.1. Methods

Observers (the authors and five naive observers) viewed a single motion trajectory of an approaching target and pressed a button when they thought the target would hit them (had it continued towards them at a constant speed after being removed from the screen). Participants made 160 judgments for each of the five experimental conditions (i.e. five levels of randomisation). Each condition was tested in a separate experimental block.

4. Results

We compared observers' estimates of the TTC with the physically presented TTC, and examined the central tendency (the median) and spread (the median absolute deviation, or MAD) of this (typically skewed) error distribution. The median provided a measure of accuracy (i.e. how close observers' judgments were to the presented TTC) and the MAD measured precision (i.e. how reliably observers made their judgments). The most notable feature of these data was the large between-subjects variability in accuracy (Fig. 2A): some individuals reported the target would have arrived long after it would have hit them (e.g. Observer MH responds around 800 ms after it would have hit him), while others reported an arrival time before the TTC (e.g. observer BH responds around 250 ms before target arrival).

Randomising the experimental parameters did not systematically influence observers' accuracy ($F_{4,24} < 1$, $p = .52$); this is expected, as the mean values remained constant so it is unlikely that a systematic bias would be introduced by our manipulation. However, parameter randomisation affected precision ($F_{4,24} = 3.246$, $p = .02$), with participants producing less precise responses as randomisation was increased. This suggests that at least some information carried by the covariates contributes to participants' judgments. To determine which source(s) of information best accounted for participants' judgments, we used a regression approach. Previous studies have used stepwise multiple linear regression to determine which linear combination of variables best explains observers' responses (e.g. Gray & Regan, 1998). However,

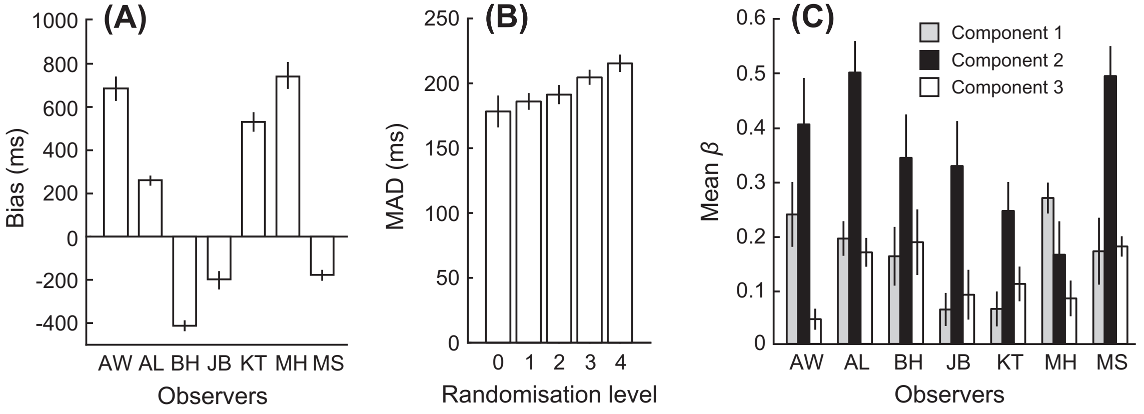

Fig. 2. Results from the absolute task (Experiment 1). (A) The median error for each observer, collapsed across all levels of randomisation. Bars show bootstrapped median errors; error bars show the 95% confidence intervals. (B) The median absolute deviation (MAD) for the four levels of randomisation, collapsed across all observers. Bars show the bootstrapped MAD for the four levels of randomisation we used (see Table 1); error bars show 95% confidence intervals. (C) Mean standardised regression coefficients (β) of the three PCA components for each observer, averaged across all degrees of randomisation. Higher values are consistent with a larger influence of the component on observers' judgments. Error bars show 95% confidence intervals for the parameter estimates.

Table 2
Variable composition of the extracted components ordered by the percentage variance explained (in brackets). Note, this analysis relates to values of the stimulus variables generated by the computer, not the participants' judgments.

1. "Occlusion" (∼51%)	2. "TTC" (∼28%)	3. "Start" (∼16%)
– Looming rate at occlusion – Rate of disparity change at occlusion – Presentation time – TTC at occlusion – Vergence distance at occlusion – Retinal size at occlusion – Change in vergence (relative disparity between the start and end of motion) – Change in angular size while the target was visible	– TTC at the start of target motion – Looming rate at the start of the trial – Rate of disparity change at the start of the trial – Approach velocity of the target	– Vergence distance at the start of the trial – Retinal size at the start of the trial

in our setting, this approach is problematic as our predictor variables are highly correlated with one another (i.e. the data have multicollinearity). In consequence, the results of a stepwise removal or addition of predictor variables would be unstable and have poor cross-validation.

To avoid this problem, we used a principal components analysis (PCA) to identify orthogonal components in the predictor variables. Having identified these components we performed a regression analysis of the data projected onto the principle component axes. Because our variables have different units, we conducted our PCA on the correlation matrix of all variables under consideration, using a varimax rotation (using Matlab's 'rotatefactors' function) to maximise the loading of each variable on one of the extracted factors while minimising the loading on all other factors. This resulted in three main components. (Note that this analysis relates to the stimulus variables generated by the computer, and does not yet relate to observers' judgments). The first principle component consisted of variables that mainly depended on the occlusion of the target (e.g. the looming rate at occlusion, the rate of disparity change at occlusion, the vergence distance at occlusion and the target's retinal size at occlusion); the second component consisted of the TTC, the target's approach velocity and spatio-temporal variables at the start of the trial (i.e. the initial looming rate the initial rate of disparity change); the third component consisted of spatial variables related to the start of the trial (i.e. the initial retinal size and the initial vergence distance). Table 2 provides an overview of the components and their variable composition.

To quantify which component best described the observers' responses, we used the factor scores (i.e. the transformation of the variables into component space) of the extracted components as regressors in a multiple regression analysis, with the observers' TTC response as the dependent variable. We found that the three components accounted for observers' behaviour to a different extent ($F_{2,12} = 10.55$, $p < .01$), with the component relating to the TTC and the approach speed of the target (component 2) explaining most of the variance for six out of seven observers (Fig. 2C). There was no influence of the amount of randomisation on the reliance on each component ($F_{3,18} = 2.14$, $p = .131$) and there was no interaction ($F_{6,36} = 3.76$, $p = .072$). This result suggests that participants' judgments are best explained on the basis that they use TTC, the approach speed, the initial looming rate and initial rate of disparity change rather than other covariates. In the next experiment, we use a different method to examine TTC separate from all other covariates.

5. Experiment 2: Relative task

The results from Experiment 1 suggested large between-subjects variability in the accuracy with which individuals judge TTC in a lab-based testing situation. One means of avoiding the influence of differences in individuals' response criteria, is to ask observers to view two objects—either in sequence or simultaneously—and judge which would reach them first (e.g. DeLucia, 1991, 2005; Field & Wann, 2005; Kim & Grocki, 2006; Todd, 1981). This two-alternative forced choice format reduces the impact of an individual's decision criterion. However, this approach does not guarantee the use of TTC information: observers could make their judgments by comparing a TTC covariate (e.g. presentation duration for the two alternatives), rather by comparing the

TTC variable of interest. Thus, it is important to establish which source(s) of information form the basis of observers' judgments. If a single-presentation design is used, observers can be asked to judge TTC against some internal criterion such as the mean of the stimulus set (McKee, 1981; Regan & Hamstra, 1993). Here, we take the approach developed by Gray et al. (1998) in which observers make judgments relative to an auditory tone (also see López-Moliner, Brenner, & Smeets, 2007). Having obtained TTC judgments using this task, we consider how well the different potential sources of information can account for the observers' judgments by fitting psychometric functions. We then test how psychophysical responses described in this way are affected as stimulus randomisation is varied.

5.1. Methods

Observers (the authors and six naive observers) viewed a single presentation of an approaching target (as in Experiment 1). In this experiment, we presented a brief auditory cue (duration of 50 ms, frequency of 1 kHz) as a reference cue against which observers judged the target's time-to-contact. The timing of the reference tone could be coincident with the visually-specified TTC, or displaced from it with ±150, 300 or 600 ms (method of constant stimuli). Observers pressed a key to indicate whether they thought the target would have hit them before or after they heard the tone (had it continued on its trajectory at a constant speed). Observers were tested in five conditions of increasing amounts of randomisation (Table 1).

6. Results

To assess which source of information best explained participants' judgments, we calculated psychometric functions (proportion of "after the tone" responses) expressed in terms of TTC and a range of possible covariates (cf. Harris & Watamaniuk, 1995; McKee, 1981) by binning continuous variables into equally spaced bins (e.g. Fig. 3C). We fit these psychometric functions with a cumulative normal (psignifit toolbox; Wichmann & Hill, 2001) and used the standard deviation parameter to quantify the discrimination threshold.

Inspecting the psychometric functions expressed in terms of different variables suggested that only two variables could reasonably account for participant's judgments: TTC and the time difference between the offset of the visual stimulus and the sounding of the tone: ΔT (Fig. 3). To formalise this interpretation across all the participants, we calculated the 68% confidence interval for each threshold to express the range of likely underlying thresholds. We divided this confidence range by the range of stimulus values tested in the experiments. If this ratio exceeded 1, it suggested our testing range would capture the underlying thresholds. However, values below 1 suggested our data would not capture thresholds reliably. For all the participants tested, the only variables that exceeded a ratio of 1 were TTC and ΔT.

To investigate further which of these variables best described psychophysical performance, we examined how thresholds changed as stimulus parameters were subject to increasing amounts of randomisation. Increasing the amount of parameter randomisation had the effect of reducing the correlation between TTC and ΔT ($R = 1.0$ with no randomisation, and $R = 0.78$ for randomisation level 4). We found that judgments expressed in terms of TTC were relatively unaffected by variations in parameter randomisation, but this was not true when judgments were expressed in terms of ΔT (Fig. 4). This suggests that observers' judgments are best understood in terms of judging TTC rather than simply the time interval between the disappearance of the target and the onset of the tone.

To quantify this result across observers, we fit a line to the data relating the correlation between the variables and the observer's threshold (i.e. linear regression), and then compared the slope of these lines (Fig 4A). A slope value of zero would indicate no influence of randomisation, while higher slope values suggest a higher influence of randomisation. For all observers, the amount of randomisation affected thresholds related to both TTC and ΔT (Fig. 4B). However, the influence on thresholds expressed in terms of ΔT was systematically larger ($t_7 = 3.854$, $p < 0.01$). This provides strong evidence that observers' responses are best expressed in terms of the TTC rather than its covariates.

In summary, asking observers to judge the TTC of an approaching target against a reference tone anchors their judgments and eliminates bias. By quantifying performance as the correlation between TTC and its covariates was reduced, we find that performance is best explained on the basis that observers judge TTC and not its covariates.

7. Discussion

7.1. Are perceptual judgments based on TTC?

In this paper we investigated which source(s) of information observers use to estimate TTC in a laboratory test. We assessed whether perceptual judgments were based on the task-relevant TTC information, or whether observers based responses on one of its many covariates. We assessed TTC judgments under two paradigms. First, we collected data using an absolute task (Experiment 1). To gain insight in the source(s) of information that best accounted for participant's judgments we conducted a principle components analysis (PCA) of the stimulus variables and regressed the resulting component scores onto the estimated TTC. For six of seven observers we found that the second component (containing the variables TTC, approach speed, initial looming rate and initial rate of disparity change) best accounted for observers' judgments. Although this provides evidence that observers responded on the basis of TTC, we could not fully dissociate TTC from other variables. As a result, it is possible that observers based their estimates on the approach speed (e.g. observers indicated a longer TTC when the approach speed was slow), the initial looming rate or the initial rate of disparity change, rather than on the TTC.

In Experiment 2, we used a relative task and classified TTC judgments in terms of all the covariates under consideration. We compared discrimination thresholds for TTC in terms of individual covariates and found that only two variables could reasonably account for observers' judgments: the presented TTC and the time interval between target occlusion and the auditory cue (ΔT). We then showed that systematically increasing the amount of randomisation (thereby reducing the correlation between these two variables) increased discrimination thresholds for ΔT while thresholds expressed in terms of TTC were reasonably unaffected. This indicates that observers' perceptual judgments are based explained on the basis of judging TTC rather than the ΔT covariate. These results are consistent with previous reports that observers will judge TTC when asked (e.g. Gray & Regan, 1998). Moreover, we show that this is true for naive subjects and when no feedback is provided.

One potentially surprising result from our study is that judgments expressed in terms of looming or retinal size produce flat psychometric functions (Fig. 3). This seems at odds with reports that humans are selectively sensitive to these cues (Regan & Hamstra, 1993). We considered the possibility that this finding may be due to our data analysis. Specifically, in Experiment 2 we measured psychometric functions for TTC judgments. To investigate the influence of other variables, we then expressed our psychometric functions in terms of potential covariates by binning the data. As a result, each

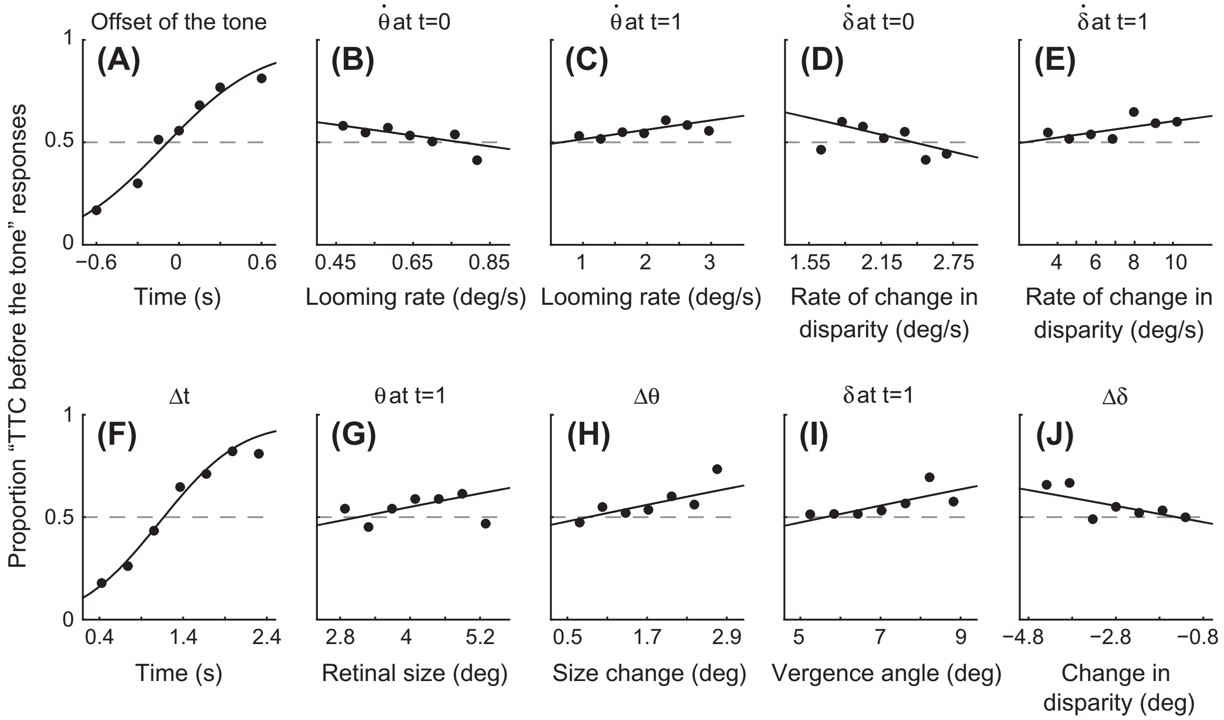

Fig. 3. Psychometric functions from the relative task (Experiment 2), averaged across observers. Ten of the sources of information we considered are plotted: (A) the offset of the auditory cue, relative to the presented TTC; (B) looming rate at the start of the trial; (C) looming rate at occlusion; (D) rate of change in disparity at the start of the trial; (E) rate of change in disparity at occlusion; (F) the time interval between occlusion and the tone (ΔT); (G) the angular size of the target at occlusion; (H) the total change in the target's angular size during the visible trajectory; (I) the vergence angle at occlusion; and (J) the total change in disparity (the relative disparity between the positions at the start and at occlusion).

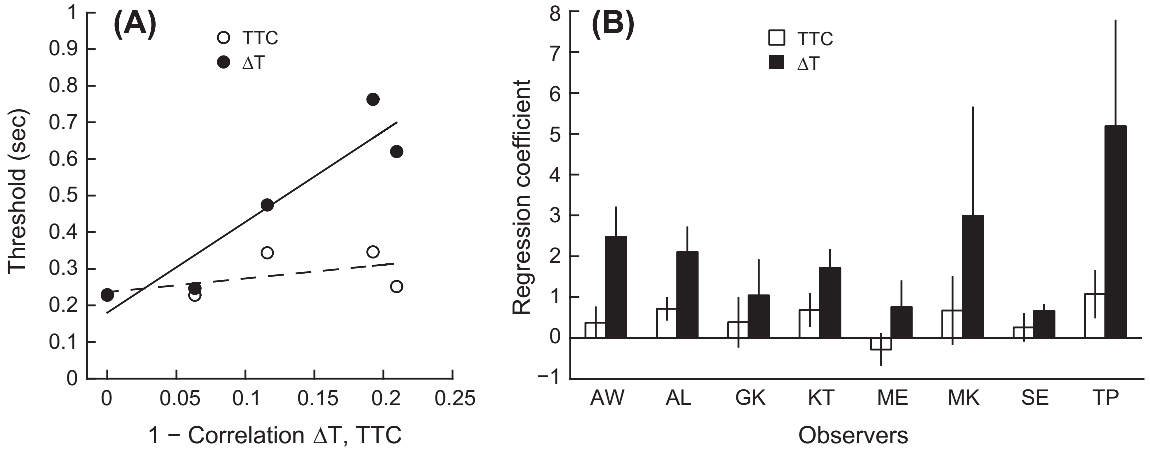

Fig. 4. Effects of randomisation on discrimination thresholds for TTC and ΔT in Experiment 2. (A) Thresholds of TTC (open symbols) and ΔT (closed symbols) for one observer, as a function of the correlation between ΔT and TTC (here represented as 1 – correlation, such that larger values are consistent with an increase in parameter randomisation). The fitted lines represent the linear regression lines for TTC (dashed line) and ΔT (solid line). (B) The slope of the regression line from (A) for thresholds expressed in terms of TTC (white bars) and ΔT (black bars) for all observers. A higher value is consistent with a greater effect of randomisation. Error bars show 95% confidence intervals associated with the regression coefficients.

bin that forms a point for the psychometric contains trials on which the auditory probe offset was at -600 ms and trials in which it was at +600 ms. At these extreme points, performance is likely at floor or ceiling: i.e. at the +600 ms point observers may always respond "before", because it may be obvious – from multiple cues – that the target will arrive before the tone. Likewise, at the −600 ms point observers may never respond "before". This is not a problem when we express our psychometric function in terms of the manipulated variable, because these extreme points contribute to ceiling and floor points of the function. However, when we plot the psychometric function in terms of one of the covariates the ceiling and floor points at +600 ms and −600 ms are averaged into each data point across the range. This could potentially mask any contribution from the covariate with the result that the psychometric function would be flat.

One solution to this issue is to calculate discrimination thresholds (expressed as Weber fractions: the standard deviation of the fitted Gaussian divided by its mean) for each covariate on a reduced range of temporal offsets, excluding the data points at ±600 and ±300 ms. The standard deviation of the function fitted

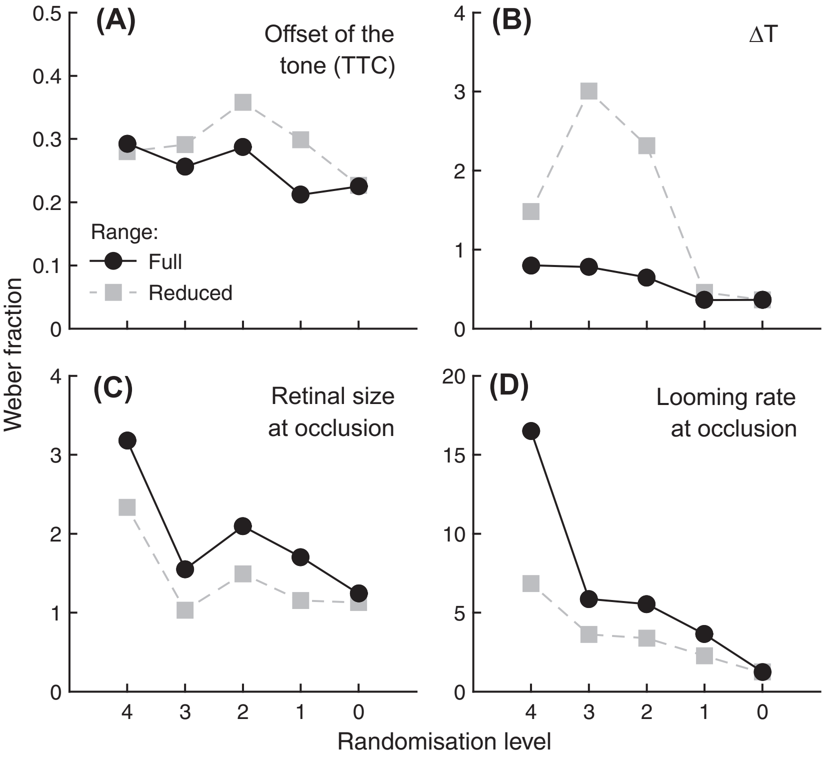

Fig. 5. Weber fractions calculated on the full range of offsets of the auditory probe (black circles) and the reduced range excluding the extreme points (grey squares). Four of the sources of information we considered are plotted: (A) offset of the auditory probe, or TTC; (B) ΔT; (C) retinal size at occlusion; and (D) looming rate at occlusion.

on this reduced range should then more accurately assess the contribution of other variables to the decision made within the critical range. Fig. 5 shows an overview of the weber fractions for four variables, calculated on the reduced range (black circles) and on the full range (grey squares). It is clear that Weber fractions on the reduced range are lower for most variables, thereby confirming the idea that the reduced range allows a better assessment of the contribution of covariates. However, results using this reduced range demonstrate that observers' judgments are best accounted for on the basis that they judge TTC (average Weber fraction = 0.3). Moreover, all covariates of TTC are affected by randomisation (Fig. 5B–D): decreasing the randomisation results in a decrease of Weber fractions (this may – in part – be due to the increasing correlation of TTC with other variables). However, consistent with the results shown in Fig. 4, the Weber fractions for TTC are relatively unaffected. This provides more evidence that observers' judgments were determined by TTC and not covariates.

As reviewed in Section 1, recent work has suggested that looming rate is an important cue in judging interception. Here we find that looming rate does not provide a good account of our observers' judgments. This apparent discrepancy may reflect differential sampling of the approach trajectories by our study in relation to previous work. Specifically, to minimize cue conflicts, we occluded the trajectory at around 37% of it is visible approach toward the observer. Had the object continued closer towards the observer, it is possible that a threshold value of looming rate may be reached that drives action initiation (Caljouw, Van der Kamp, & Savelsbergh, 2004; López-Moliner, Field, & Wann, 2007; Michaels, Zeinstra, & Oudejans, 2001).

7.2. How well can observers judge time-to-contact?

Having established that our observers' responses were based on TTC information, we consider their psychophysical performance. First, results from the absolute task (Experiment 1) show large systematic and esoteric errors in observers' accuracy in judging TTC using an open loop experimental task, with errors up to 850 ms (42%), with an average error of 430 ms (21%). This result is potentially alarming, considering the high precision accuracy (and precision) that is often necessitated by real-world interceptive or evasive actions. Yet, poor accuracy in estimating TTC is commonly reported in studies using absolute estimation tasks (typically 10–40%: Cavallo & Laurent, 1988; Schiff & Detwiler, 1979; Heuer, 1993; although see Rushton and Wann (1999) who employed fast motions in a VR setup). There are several potential explanations for these errors. First, in the context of systematic error (or bias), it is relevant to consider feedback regimes and the availability of a reference cue. Specifically, providing feedback will provide the observer with direct information about errors in their estimates and they can adjust their decision criterion to minimize their error (Karanka, Rushton, & Freeman, 2007). Similarly, a reference cue will anchor the observers' decision criteria. As we did not provide either in Experiment 1, estimates depended on individual (and unconstrained) decision criterion, resulting in large systematic and variable errors. Second, our fixed viewing distance setup involved cue conflicts (e.g. between vergence and accommodation) so estimates of approach and time-to-contact are likely to be less reliable than they would have been in a natural viewing situation.

In Experiment 2, in which observers made their perceptual judgments relative to an auditory cue, we found that errors are much lower (20–120 ms, all underestimates). Observers' judgments were reasonably precise: discrimination thresholds ranged from 180 to 600 ms; the lower range is compatible with previously reported thresholds (about 125–300 ms, Gray & Regan, 1998). The higher thresholds were associated with the naïve psychophysical observers, potentially explaining the wider range of performance relative to that reported by Gray and Regan (1998) whose observers were experienced.

8. Conclusions

In summary, observers' responses under experimental tasks that use absolute estimates or relative judgments of TTC appear to be best explained on the basis that they judge the presented TTC, rather than its covariates. Our results suggest that the single-trial relative paradigm is the more favourable method to study perceptual judgments of TTC as it reduces the impact of the systematic and variable errors that can be seen with an absolute method.

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