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Judging the contact-times of multiple objects: Evidence for asymmetric interference

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ABSTRACT

The accuracy of time-to-contact (TTC) judgments for single approaching objects is well researched, however, close to nothing is known about our ability to make simultaneous TTC judgments for two or more objects. Such complex judgments are required in many everyday situations, for instance when crossing a multi-lane street or when engaged in multi-player ball games. We used a prediction-motion paradigm in which participants simultaneously estimated the absolute TTC of two objects, and compared the performance to a standard single-object condition. Results showed that the order of arrival of the two objects determined the accuracy of the TTC estimates: Estimation of the first-arriving object was unaffected by the added complexity compared to the one-object condition, whereas the TTC of the second-arriving object was systematically overestimated. This result has broad implications for complex everyday situations. We suggest that it is akin to effects observed in experiments on the psychological refractory period (PRP) and that the proactive interference of the first-arriving object indicates a bottleneck or capacity sharing at the central stage.

1. Introduction

Since David Lee's (e.g., 1976) seminal work, time-to-contact (TTC, that is the time remaining before an object reaches the observer or a specific point of interception) has been taken to be directly available to observers. The optical variable specifying TTC has been shown to be critical in numerous everyday tasks, such as interceptive actions (e.g., DeLucia, 2004; Peper, Bootsma, Mestre, & Bakker, 1994; Tresilian, 2005; Tresilian & Houseman, 2005; Tyldesley & Whiting, 1975). The accuracy of TTC perception has been assessed at length for single approaching objects (for a summary see Hecht & Savelsbergh, 2004). However, close to nothing is known about observers' ability to make simultaneous TTC judgments for two or more objects. Such judgments are required in many everyday situations, such as when crossing a multi-lane street or in multi-player ball games. A current theory that assumes the direct availability of TTC information would not predict any problems induced by a second or third approaching object. To investigate potential effects of added objects, the present study put observers in a position to judge the TTC of two simultaneously moving objects. We first describe the prediction-motion paradigm we used and then introduce the issue of multiple-object judgment before reporting our study.

The prediction-motion (PM) paradigm has been employed as a rather direct method to assess observers' absolute TTC judgments (e.g., Schiff & Detwiler, 1979). A moving object is occluded by a visible or invisible occluder some time (here referred to as *extrapolation time*) before it reaches the observer or a specified target. The observer is required to make a simple response (e.g., press a button) at the time the object would have reached the target, had it continued its trajectory. The main aim of a PM task is to determine which visual information is used by participants to judge or predict TTC, through careful manipulation of variables related to the object's motion (e.g., velocity, extrapolation distance and/or duration). It is generally found that participants are able to perform the task but that they underestimate TTC for longer extrapolation times and overestimate it for shorter extrapolations. The transition point between under- and overestimations is approximately at 1 s of extrapolation (e.g., Manser & Hancock, 1996; Schiff & Detwiler, 1979; Oberfeld & Hecht, 2008).

Most PM studies have used single objects as stimuli. To our knowledge, simultaneous TTC judgments on *multiple* objects have not been reported. One PM study that came close is that of Novak (1998). She presented multiple approaching objects but observers were only asked to judge one object. First, they saw one to eight objects approaching a finish line. Then, the target object was indicated by a visual cue after all objects had disappeared from the screen but before they would have reached the finish line. The observers may have made several TTC estimates and then dropped all but the relevant estimate. However, as they eventually produced only one single PM estimate (for the target object) they may also have used a different strategy.

Other studies that presented multiple objects always used a relative-judgment paradigm. In such tasks, observers had to indicate

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which of two or more objects would arrive first at a designated goal (e.g., DeLucia & Novak, 1997; Todd, 1981). Here again, observers may have computed and compared multiple TTC estimates, but they were only asked for one decision. The fundamental difference between such a relative-judgment task and a multiple-object PM task is that in the former, participants might misestimate the TTC of both objects in absolute terms (e.g., estimate a TTC of 0.5 s as being of 1 s) but could still give the correct answer, as long as the perceived order of arrivals was preserved. In contrast, in a multiple-object PM task, the *absolute* accuracy of TTC judgments is assessed. We expected observers to have a hard time to simultaneously produce two absolute TTC estimates if cognitive processing is involved. Indeed, it is assumed that a particular resource can only or mainly be used by one task at a time (Borst, Taatgen, & van Rijn, 2010). Thus, no interference occurs in dual tasks as long as the tasks require different resource (e.g., walking and talking). However, as soon as a particular resource is shared (e.g., writing and talking), that resource will behave as a bottleneck and delay the execution of the combined process (Borst, Taatgen, & van Rijn, 2010). Such dual task interference (cf. Pashler, 1994) is commonplace, but may not generalize to performance in more basic TTC tasks that could be based on a simple optical variable.

When estimating the TTC of two objects moving toward an interception point in a PM task, and comparing those results to a one-object condition, three outcomes are possible.

(1) *Parallel TTC processing with unlimited resources*: If TTC is judged directly and in parallel as implied by the initial concept (see Lee, 1976), we would observe no differences in TTC estimation as a function of the number of objects to be judged. Both the constant error (CE) corresponding to the difference between the estimated TTC of the object and its actual TTC, and the variable error (VE) reflecting the variability of TTC estimations, should remain unchanged. This would imply that observers are able to access and process the TTC of both objects in a completely parallel fashion without any interference between the two concurrent estimations.

(2) *Proactive interference*: Resource limitations may affect the additional objects but not the first one. This would correspond to an effect that Telford (1931) first highlighted and termed psychological refractory period (PRP). In a typical PRP experiment, two stimuli, each requiring a response, are presented one after another with temporal overlap between the two tasks. The experimenter manipulates the stimulus onset asynchrony (SOA), that is, the temporal delay between the presentations of these two stimuli. The usual finding is that for short SOAs (e.g., <100 ms), the response time to stimulus 2 (RT2) is delayed by several hundreds of milliseconds relative to a situation where the second task is presented alone. In contrast, the response time to stimulus 1 (RT1) remains broadly unaffected. However, the delay in RT2 is removed when the SOA is increased to several hundred milliseconds. One hypothesis that has received good empirical support (e.g., Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Lien, Ruthruff, & Johnston, 2006; Pashler, 1994) is the central bottleneck model (but see Navon & Miller, 2002, and Tombu & Jolicoeur, 2003). This model states that tasks are divided in three distinct processing stages: pre-central stage (e.g., stimulus identification), central stage (e.g., response selection), and post-central stage (e.g., response execution). While the pre-central and post-central stages are assumed to be conducted in parallel with any stage of the other task, this is not the case for the central stage that proceeds on only one task at a time. Hence, the central stage of the second task cannot start before the full completion of the central stage of the first task, thus delaying the response to the second stimulus (see Fig. 1). This model would thus assume a delayed answer for the second object, while the TTC estimation for the first object would remain unchanged.

(3) *Mutual interference*: The introduction of other objects may lead to a modification of the TTC estimation for *both* objects. According to a central capacity sharing model (e.g., Tombu & Jolicoeur, 2003, 2005), the central stage of information processing is capacity limited. Both TTC estimates could be performed in parallel, but the resources have to be split among the two tasks. Hence, the duration of the central stage would be increased for both tasks (Fig. 2). In our example, this increased processing time would lead to an increase in the TTC estimation for both approaching objects.

To summarize, on the basis of the existing literature on dual tasks, three distinct patterns of results can be predicted for the concurrent estimation of two TTCs. We designed an experiment to decide between these hypotheses. In a prediction-motion task, participants judged the TTCs of two objects approaching a target line with different

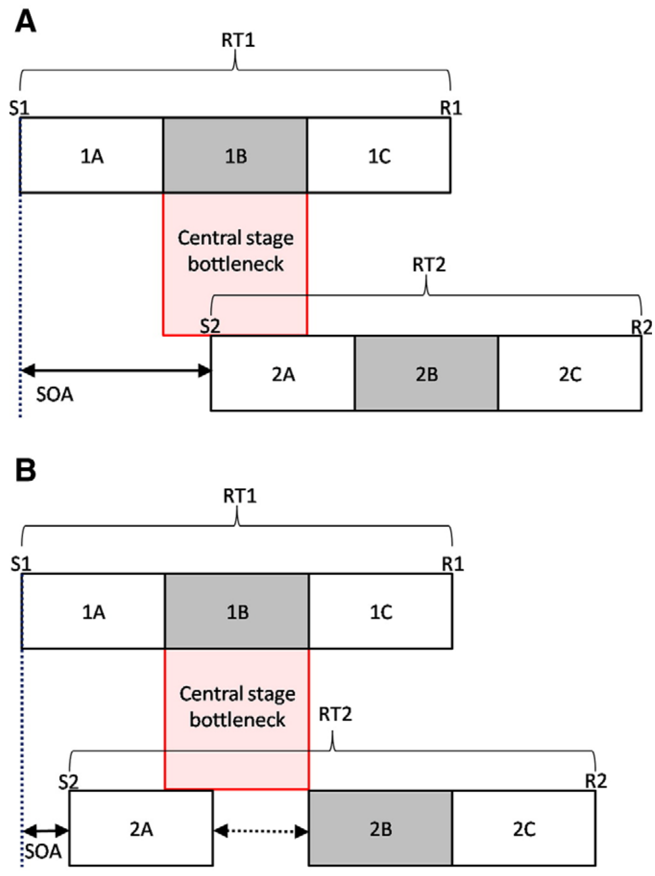

Fig. 1. PRP paradigm. Each task is divided into three distinct processing stages, pre-central stage (A), central stage (B) and post-central stage (C). Stages A and C are assumed to be realized in parallel with any other stage of the other task, while the 2B cannot start before the full completion of 1B. Hence, for long SOA (A panel), stage 1B is ended before stage 2B may begin. As a consequence, 2B can start immediately after the end of 2A, and RT2 is unaffected by the first task. However, for short SOA (B panel), stages 1B and 2B would overlap, what lead 2B to be delayed until the completion of 1B. RT2 is thus increased by this waiting period called bottleneck delay.

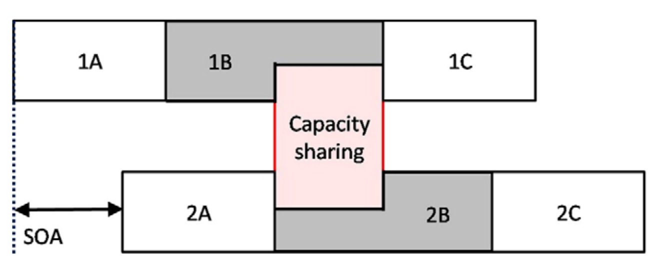

Fig. 2. Whereas the A and C stages are capacity free, the B stage is capacity limited for its part. Hence, for short SOA, an overlap of the B stages of the two tasks would require people to share processing capacity among tasks, and there would be thus less capacity for each individual task. As a consequence, performance in both tasks would be impaired.

velocities and extrapolation times. A single-object condition was introduced as a control condition. Results showed that the order of arrivals was a key factor influencing the accuracy of the TTC estimate: while no modification was observed in the TTC estimate of the leading object (the object which arrives first at the finishing line), compared to the one-object condition, the TTC estimate of the trailing object was systematically overestimated. This result is compatible with the proactive interference hypothesis.

2. Materials and methods

2.1. Subjects

Twelve students at the Johannes Gutenberg-Universität Mainz (9 women, 3 men, age 24.42 years ± 7.95 (mean ± *SD*), min age 19, max age 48) participated voluntarily after giving informed consent. All participants had normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Participants were naïve with respect to the purpose of the experiment, and either received partial course credit or were paid for their participation. This experiment was conducted in accordance with the Declaration of Helsinki.

2.2. Apparatus and experimental procedure

This experiment was realized using Cogent Graphics developed by John Romaya at the Laboratory of Neurobiology at the Wellcome Department of Imaging Neuroscience. Stimuli were presented on a HP computer equipped with a 1.80 GHz Intel Core2 Duo processor. The screen resolution was 1024 × 768 pixels (horizontal by vertical). The display rate was 60 Hz.

Participants sat on a chair facing a 15.3″ TFT computer display located at a viewing distance of approximately 0.55 m. The eyes were aligned with the screen center. In a first condition (hereafter termed “one-object condition”), time-to-contact (TTC) estimates for a black ball (diameter of 1 cm) moving at constant speed on the fronto-parallel plane from left to right were obtained using a prediction-motion (PM) task (cf. Schiff & Detwiler, 1979). During its motion, the ball passed behind a grey rectangle (hereafter referred to as ‘occluder’) that obscured its trajectory (see Fig. 3 for a representation of the two-objects condition described below). Participants were asked to press a response key at the instant when the ball would have collided with a vertically-oriented black arrival line. The scene was presented against a white background. The dimensions of the vertical arrival line were 0.3 cm wide and 15 cm long, and the dimensions of the occluder varied[1] according to the extrapolation time (see below and Table 1 for a complete description of the trajectories).

Participants pressed the spacebar key to start each trial. After a delay of 1.5 s, the ball started to move toward the arrival line with constant velocity (3, 6, or 12 cm/s). After a visible movement time of 800 ms, the ball passed behind the occluder and continued its movement to reach the arrival point after 0.5, 1, or 1.5 s. Once occluded, the ball did not reappear. Participants pressed the “y” key (French azerty keyboard) to indicate the instant at which the ball would have collided with the arrival line. No feedback was provided. Nine factorial parameter combinations were generated from the three velocities and the three extrapolation times. Each given trajectory was presented 5 times, for a total of 45 trials.

After completing this one-object condition, participants were tested in a second condition (hereafter termed “two-objects condition”; see Fig. 3), in which two balls were presented. TTC estimates were obtained using the same method as in the one-object condition.

[1] Please note that the task was not to detect which object will arrive first, but to estimate the absolute TTC of each object. Hence, even if the occluder length was informative on the order of arrival, it was of no help in the task to perform.

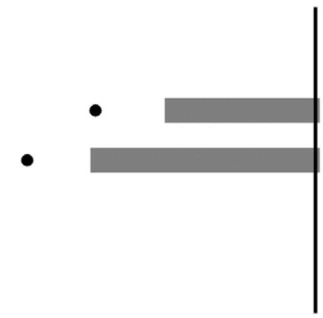

Fig. 3. Representation of the visual stimulus in the two-objects condition. Two balls were moving from the left to the right, and occluded by the occluder (grey rectangles). Participants had to press a button for each ball when thought to collide with an arrival line (vertically-oriented black line).

Participants were required to press the “y” key when they thought that the upper ball would have collided with the arrival line, and the “b” key for indicating the arrival of the lower ball. Here again, no feedback was given to the participants. The two balls moved on parallel horizontal trajectories from left to right. They were separated by 2 cm on the vertical axis. The presentation time was again 800 ms as in the one-object condition. The same three velocities and three extrapolation times as in the one-object condition were presented, with the restriction that the two balls could not have the same extrapolation time. Hence, for each of the 9 possible combinations of velocity and extrapolation time for one of the two balls, only 6 combinations were available for the second ball (3 velocities × 2 extrapolation times). This gave rise to 54 different trials, each presented 5 times, for a total of 270 trials in this second part of the experiment. To control for potential effects of the ball's position on the vertical axis, in half of the trials the upper ball was the first to collide with the arrival line, and in the other 50% trials the lower ball arrived first.

3. Results

3.1. One-object condition

For the analysis of the TTC estimates in the one-object condition, we determined the constant error (CE) on each trial. CE corresponds to the difference between the estimated TTC of the ball and its actual TTC. A positive value represents an overestimation of the TTC whereas a negative value represents an underestimation. We then computed the mean CE for each participant and each trajectory (extrapolation time × velocity), by averaging the CE across the five repetitions. We also computed the variable error (VE) in terms of the standard deviation (SD) of the CE in these five repetitions. CE and VE were separately analyzed in a 3 × 3 (extrapolation time × velocity) repeated-measures ANOVA using a univariate approach. The

Table 1
Description of the 3 (velocity) × 3 (extrapolation time) trajectories presented in the experiment. Note that the initial distance from the finishing line is the sum of travelled distance and occluder length.

Velocity (cm/s)	Visible time (s)	Extrapolation time (s)	Travelled distance while visible (cm)	Occluder length (cm)
3	0.8	0.5	2.4	1.5
6		0.5	4.8	3
12		0.5	9.6	6
3		1	2.4	3
6		1	4.8	6
12		1	9.6	12
3		1.5	2.4	4.5
6		1.5	4.8	9
12		1.5	9.6	18

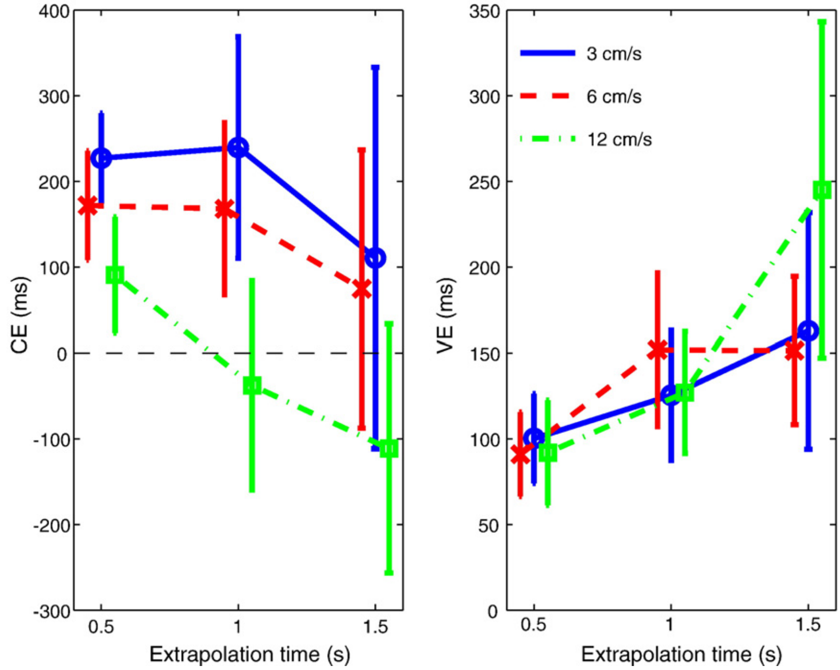

Fig. 4. Mean CE (left panel) and VE (right panel) for the one-object condition, as a function of extrapolation time and velocity. Error bars indicate the 95% confidence interval.

Huynh–Feldt correction for the degrees of freedom was used where applicable (Huynh & Feldt, 1976) and the value of $\tilde{\varepsilon}$; is reported. The within-subjects factors were extrapolation time and velocity. The ANOVA conducted on CE showed a main effect of extrapolation time, showing a decrease in CE as extrapolation time increases (Fig. 4, left panel), $F(2, 22) = 5.11$, $p = 0.041$, $\tilde{\varepsilon}$; $= 0.54$, $\eta^2 = 0.32$, a classical effect in such kind of task (e.g., Benguigui, Broderick, Baurès, & Amorim, 2008). Post-hoc pairwise comparisons between all pairs of levels of extrapolation time were computed using non-pooled error terms (i.e., by computing separate paired-samples *t*-tests; Keselman, 1994) and Hochberg (1988) sequentially acceptive step-up Bonferroni procedure, with an alpha level of 0.05. Only the difference between the CEs at extrapolation times 0.5 and 1.5 was significant.

The test also highlighted an effect of velocity, with CE decreasing as velocity increased (Fig. 4, left panel), $F(2, 22) = 38.54$, $p < 0.001$, $\tilde{\varepsilon}$; $= 1$, $\eta^2 = 0.78$. Post-hoc pairwise comparisons showed that only the CE of the highest velocity differed significantly from the other CEs. Finally, the ANOVA also showed an extrapolation time × velocity interaction, mainly confirming the velocity effect for each extrapolation time, and showing a larger velocity effect with longer extrapolation times than with short ones, $F(4, 44) = 3.21$, $p = 0.046$, $\tilde{\varepsilon}$; $= 0.63$, $\eta^2 = 0.23$. A similar ANOVA was conducted on VE. The VE increased with extrapolation time (Fig. 4, right panel), $F(2, 22) = 8.36$, $p = 0.008$, $\tilde{\varepsilon}$; $= 0.65$, $\eta^2 = 0.43$, and post-hoc pairwise comparisons indicated that the shortest extrapolation time led to a lower VE than the two other extrapolation times. No effect of velocity was found however, $F(2, 22) = 1.30$, $p = 0.292$, and the ANOVA showed an interaction effect extrapolation time × velocity, showing that the condition with the longest extrapolation time and the highest velocity led to the highest VE, $F(4, 44) = 3.58$, $p = 0.024$, $\tilde{\varepsilon}$; $= 0.75$, $\eta^2 = 0.25$.

3.2. Two-objects condition

To analyze the effect of having to produce absolute TTC estimates for two rather than for one object, we subtracted the mean CE in the one-object condition from the mean CE in the two-objects condition, for each participant and ball trajectory. For example, if for participant 1 the mean CE for a ball with an extrapolation time of 1 s and a velocity of 3 cm/s was 100 ms in the one-object condition, and the mean CE for a ball with the same trajectory combined with a second ball with an extrapolation time of 1.5 s and a velocity of 6 cm/s was −50 ms, then the change in CE relative to the one-object condition was $\Delta CE = -50\ \text{ms} - 100\ \text{ms} = -150\ \text{ms}$. Hence, ΔCE does not reflect the precision of the TTC estimation, but is an indicator of the shift in TTC estimation when required to produce two concurrent estimates of absolute TTC rather than only one. A positive value of ΔCE means an increase in CE in the two-objects condition compared to the one-object condition (i.e., a relative overestimation of TTC in the two-objects condition), and conversely a negative value means a decrease in CE in the two-objects condition compared to the one-object condition. The change in the variable error relative to the one-object condition (ΔVE) was computed analogously.

3.2.1. Comparing TTC estimates of a reference and a distractor object

As a first step, we arbitrarily defined the upper ball as being the target ball, and the lower ball as being a distractor.[2] We calculated the average ΔCE of the target ball for each combination of target and distractor extrapolation times, hence computing 6 values of ΔCE for each participant. Then, by means of a *t*-test for a single sample, we compared these ΔCEs of the target ball to a value of 0 ms, which would reflect that the TTC estimation of the target object is equivalent to the one realized in the one-object condition, and not influenced by the necessity to produce another TTC estimate simultaneously. Fig. 5 presents the results, showing that when the extrapolation time of the target ball was 0.5 s, ΔCE was not different from 0 ms when the extrapolation time of the distractor was 1 s, $t(11) = 0.99$, $p = 0.343$, nor when it was 1.5 s, $t(11) = 0.58$, $p = 0.575$. When the extrapolation time of the target ball was 1 s, ΔCE differed from 0 when the extrapolation time of the distractor was 0.5 s, $t(11) = 2.62$, $p = 0.024$, but not when it was 1.5 s, $t(11) = 0.46$, $p = 0.654$. Finally, when the extrapolation time of the target ball was 1.5 s, ΔCE was marginally different from 0 ms when the extrapolation time of the distractor was 0.5 s, $t(11) = 1.84$, $p = 0.093$, and significantly different from 0 ms when the extrapolation time was 1 s, $t(11) = 3.25$, $p = 0.007$. Hence,

[2] Note also that balls were visually identical, and no instructions were given to participants to selectively attend to either ball. This distinction is thus arbitrary, and is merely introduced for the purpose of the analysis.

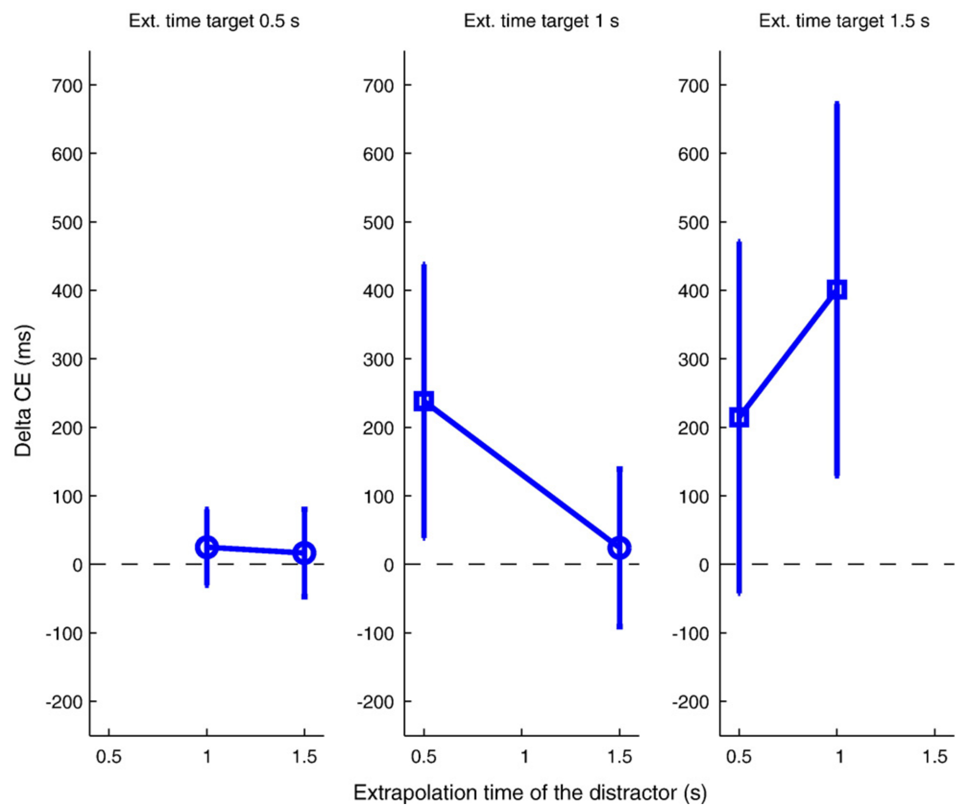

Fig. 5. Mean ΔCE of the target when its extrapolation times are 0.5, 1 and 1 s respectively, as a function of the extrapolation time of the distractor. Circle markers represent the case in which the reference ball is the leading object (i.e., the first ball to reach the finishing line), whereas square markers represent the case in which the reference ball is the trailing object (i.e., the last ball to reach the finishing line). Error bars show the 95% confidence interval. Error bars not covering 0 indicate that the mean value is significantly different from zero ($p<0.05$).

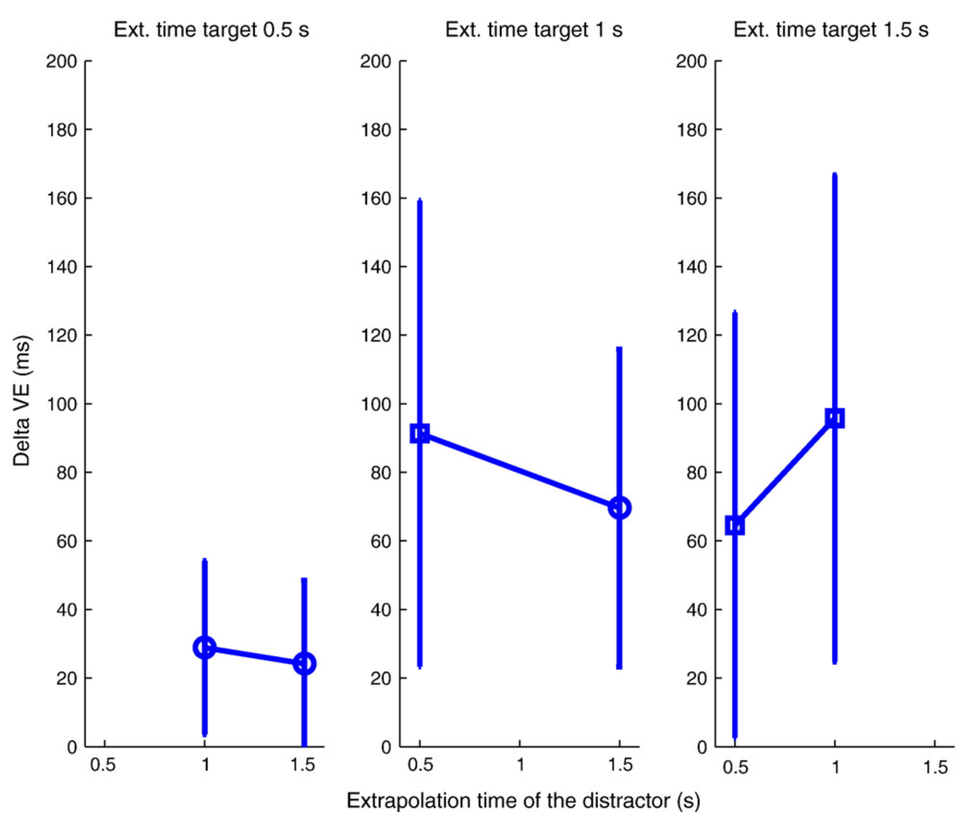

Fig. 6. Mean ΔVE of the target as a function of the extrapolation time of the distractor. Circle markers represent the case in which the reference ball is the leading object, whereas square markers represent the case in which the reference ball is the trailing object. Error bars indicate the 95% confidence interval.

the results show a clear influence of the distractor trajectory on the TTC estimation for the target ball: if the distractor arrived after the target ball (target here considered in this case as the leading object), then it had no effect on the constant error, relative to the one-object condition. However, if the distractor arrived before the target ball (target here considered in this case as the trailing object), the participants significantly overestimated the TTC of the target ball, relative to the one-object condition. Globally, the same pattern was observed for ΔVE (see Fig. 6).

3.2.2. Comparing TTC estimates of trailing and leading objects

Hence, the above analyses suggest that the TTC estimation of the leading object at the finishing line is not influenced by the presence of a second object for which a TTC estimate is to be produced simultaneously. However, the TTC estimation of the trailing object appears to be delayed due to the concurrent TTC estimation for the leading object. Consequently, in the next step of analyses, we compared the change in CE and VE brought about by the concurrent TTC estimate for the second object between trailing and leading objects. In the experimental design we used, an object with an extrapolation time of 0.5 s was always the leading object in the two-objects condition, while an object with an extrapolation time of 1.5 s was always the trailing object. For this reason, we restricted our analyses to objects with TTC = 1.0 s (termed *reference object* in the following). Across all trials in the two-objects condition, the reference objects were equally often the trailing and the leading object. We analyzed ΔCE for the objects with TTC = 1.0 s by means of a repeated-measures ANOVA with the within-subjects factors reference-object type (trailing/leading), reference-object velocity, second-object velocity, and screen position of the reference object (top/bottom).

The mean values of ΔCE for trailing and leading objects are shown by the squares in Fig. 7. As can be seen by the confidence intervals, the CE of the TTC estimate for leading objects did not significantly differ from the CE in the one-object condition (which is represented by a value of ΔCE = 0), while for trailing objects the concurrent TTC estimation to the other object resulted in a TTC overestimation of more than 200 ms, relative to the one-object condition. The ANOVA showed a significant effect of object type on ΔCE, $F(1, 11) = 13.27$, $p = 0.004$, $\eta^2 = 0.64$.

At this point, it is important to note that in a moderate proportion of trials (150 of the total of 2160 trials), participants' absolute TTC estimates indicated an incorrect perception of the order of arrival of the two objects. In other words, they perceived the object with the shorter TTC to arrive second. Such errors might represent a problem for the foregoing analysis. To demonstrate that the difference between ΔCE for trailing and leading objects is not an artifact caused by trials in which the order of arrivals was judged incorrectly, we repeated the preceding analysis for only those trials in which the order of arrivals was perceived correctly. To be able to compute the variable error, conditions where a given participant produced less than two valid trials (i.e., with the correct perceived order of arrivals) were also excluded. Because for four subjects the exclusion of trials resulted in missing values in some experimental conditions, the data were analyzed via a mixed-model analysis (SAS PROC MIXED; Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006) with Kenward–Roger's adjusted *F*-tests (Kenward & Roger, 1997; Kowalchuk, Keselman, Algina, & Wolfinger, 2004). The “heterogeneous compound symmetry (CSH)” structure was selected to model the covariance structure. This ANOVA again showed a significant effect of object type on ΔCE, $F(1, 12.9) = 61.51$, $p < 0.001$. The means are shown by the circles in Fig. 7. These results are compatible with the analysis of the complete data set.

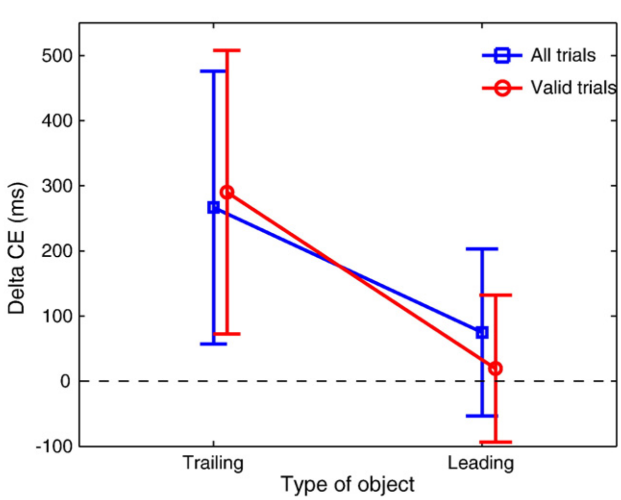

Fig. 7. Mean ΔCE for the objects with extrapolation time = 1 s, depending on whether the object was the trailing or the leading object. Means represented by red squares have been calculated on the complete data set whereas means represented by blue circles are calculated for the trials with the correct perceived order of arrivals (see text). Error bars show 95% confidence intervals.

3.2.3. Variable error

In summary, the above analysis confirmed the expectation that the critical parameter in the two-objects condition is whether an object arrives first or second. Only in the latter case did we find evidence that the TTC estimation is strongly affected by the presence of another TTC estimation to carry out. Nevertheless, even if the CE for the leading objects is independent of the number of simultaneous TTC estimations to realize, the TTC estimation might be more variable than in the one-object condition. To answer this question, we first computed the average change in the variable error relative to the one-object condition (ΔVE) for each participant included in the preceding ANOVA on ΔCE. Across all subjects, mean ΔVE was 86.9 ms (SD = 82 ms), showing a significant increase in the VE in the two-objects condition, $t(11) = 3.69$, $p = 0.004$.

To gain further insight into the effects of the concurrent TTC estimate on the VE, we analyzed ΔVE using the same type of four-factorial repeated-measures ANOVA as for ΔCE. The effect of object type was not significant, $F(1, 11) = 0.05$ (leading objects: $M = 0.09$ s, SD = 0.07 s; trailing objects: $M = 0.08$ s, SD = 0.10 s).

As for ΔCE, we repeated the analyses of ΔVE for only those trials in which the order of arrivals was perceived correctly. Again, mean ΔVE was slightly higher than 0 ms ($M = 58.0$ ms, SD = 71.5 ms), $t(11) = 2.80$, $p = 0.017$. A mixed-model analysis (PROC MIXED) showed a marginal significant effect of object type, $F(1, 198) = 3.25$, $p = 0.073$ (leading objects: $M = 0.05$ s, SD = 0.06 s; trailing objects: $M = 0.07$ s, SD = 0.09 s).

Thus, for the variable error we found a small effect of the concurrent TTC estimation, but the clear dissociation between leading and trailing objects demonstrated for the CE was not present for the VE.

3.2.4. The results are compatible with the notion of a psychological refractory period

In multiple reaction-time paradigms, typically a positive correlation between the RT to the first stimulus and the RT to the second stimulus is found, at least at short SOAs (e.g., Pashler & O'Brien, 1993). This correlation can be explained by assuming that the response selection for the first stimulus has to be completed before a response selection to the second stimulus is possible (cf. Pashler, 1994). Can these findings be applied to our task of producing two concurrent TTC estimates? Yes, the above analyses are consistent with the idea that the process of TTC estimation for the leading object delays the TTC estimation for the trailing object. If for example the prediction-motion (PM) response to the trailing object had to be delayed until the response selection (i.e., initiation of the motor command for the keypress) for the leading object was completed, then the delay of the response to the trailing object should be stronger on trials where participants produced a longer TTC estimate for the leading object. Was the trial-to-trial variability in the two TTC estimates compatible with such a pattern? To answer this question, we computed the regression of the constant error for the trailing object on the constant error for the leading object. As in the analyses on ΔCE and ΔVE above, only trials in which one object had a TTC of 1 s were used. Additionally, only trials in which the order of arrivals was perceived correctly were included. As the data are from a repeated-measures design, the observations contributed by each subject are correlated, and thus the ordinary-least-squares regression analysis assuming independent observations is inappropriate (see Burton, Gurrin, & Sly, 1998). Therefore, a subject-specific, random-effects model approach was used (SAS PROC MIXED; cf. Liang & Zeger, 1993). Subject-specific models assume regression parameters (i.e., intercept and slope) to vary from subject to subject. Random-effects models belong to the class of subject-specific models and model the correlation structure by treating the subjects as a random sample from a population of all such subjects. In the analysis, the variance–covariance matrix was specified as being of type "unstructured" (UN), that is, the procedure placed no constraints on the correlations across observations within one subject. For tests of significance, the degrees of freedom were computed according to the procedure suggested by Kenward and Roger (1997). The individual data together with the subject-specific and the overall regression lines are displayed in Fig. 8.

The slope of the overall regression line was 0.48 [standard error SE = 0.06, $t(7.92) = 3.30$, $p < 0.001$]. Thus, for an increase of 100 ms in the CE for the leading object, the CE for the trailing object increased by almost 50 ms. The intercept was 0.36 s [SE = 0.11 s, $t(11) = 3.3$, $p = 0.007$], indicating again a constant overestimation of the TTC of the trailing object relative to the leading object.

4. General discussion

The primary goal of our experiment was to determine what happens when producing two absolute estimates of time-to-contact (TTC) at the same time. On the basis of the previous literature about dual task performance (cf. Pashler, 1994), three potential outcomes were predicted: (1) In the case of unlimited-resource parallel TTC processing both TTC estimations should be equally accurate, and both should be as accurate is in the single-object case. (2) Proactive interference would predict a negative influence only on the TTC estimate for the trailing object. (3) Mutual interference would predict a drop in TTC estimation accuracy for both the leading object and the trailing object. The results of our experiment provide a clear answer to our question. Proactive interference (2) is the case. While the CE of the TTC estimate for the leading object is not influenced by having to produce a second TTC estimate simultaneously, the TTC estimate for the trailing object is systematically delayed. These findings indicate that perceived order of arrivals is the critical factor for absolute TTC estimates in a multiple-object condition, with a unilateral influence of the first TTC estimate on the second one.

Would the same results be observed if the participants were instructed to estimate TTC only for one of the two objects, and ignore the other object? In other words, do the effects arise because of the necessity to produce two concurrent absolute TTC estimates? In a recent study, Oberfeld and Hecht (2008) measured the effect of a moving but to-be-ignored distractor object on TTC estimates for a target object. In the most comparable condition, TTC estimates for the target object obtained in a PM task were significantly *smaller* than in the condition without distractor (cf. Fig. 10 in Oberfeld & Hecht, 2008). Thus, the distractor caused an underestimation of TTC regardless of whether the target object was the leading or the trailing object. For an absolute identification task, in which participants have to determine whether the target object had a short or long extrapolation time, Oberfeld and Hecht observed an underestimation of target TTC only if the target object was leading, but no significant effect if the target object was trailing. Thus, the effects of a to-be-ignored distractor on TTC estimates for a target are incompatible with the TTC overestimation observed only for trailing objects in the present study. These findings indicate that the pattern of effects reported here is linked to the necessity of producing two concurrent absolute TTC estimates.

4.1. Evidence for proactive interference

It is important to note that we found evidence for proactive interference using a task differing fundamentally from the typical PRP (psychological refractory period) experiments. In typical PRP experiments, the two stimuli appear one after another, and participants have to react to each of the two stimuli as fast as possible. In this situation, short SOAs delay the observer's reaction to the second stimulus. In our experiment, however, both objects appeared and disappeared from the screen simultaneously, and participants had to synchronize their responses with the anticipated arrivals of two stimuli. Hence, such a task does not correspond to a speeded reaction task but rather requires anticipating the arrivals of the stimuli (i.e.,

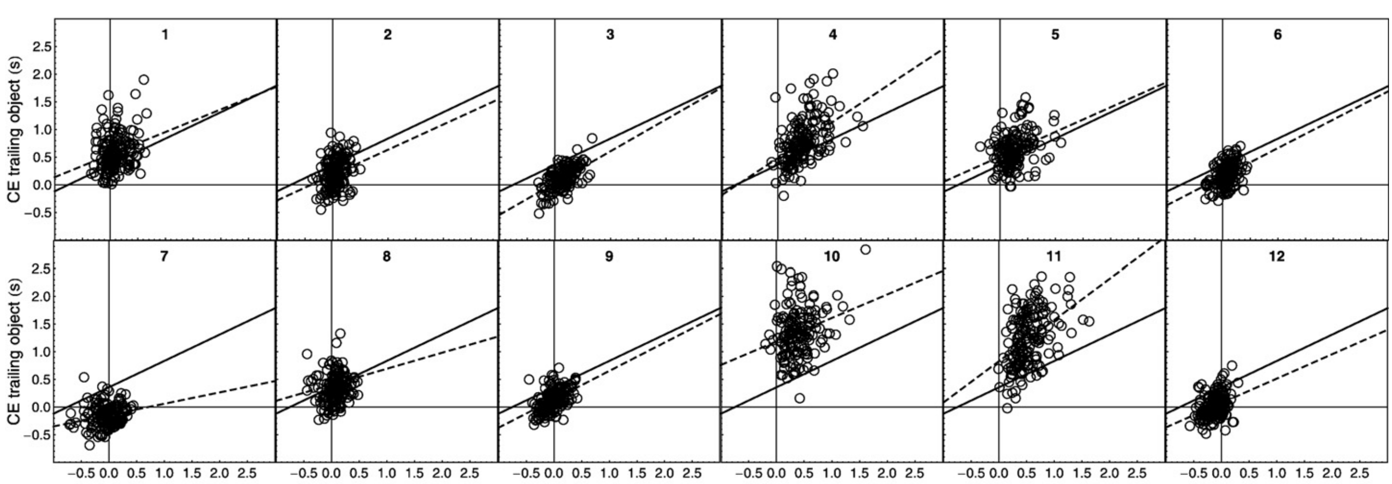

Fig. 8. CE for the trailing objects, plotted against CE for the leading object. Each panel represents one subject. Only trials with the correct perceived order of arrivals entered the analysis. Solid lines: estimated overall regression relationship. Dashed lines: estimated subject-specific regression relationship.

estimating their TTCs). Despite of this fundamental difference, our participants exhibited a pattern of results similar to the classical PRP experiments. Only the response to the trailing stimulus is delayed while the response to the leading stimulus remains unchanged.

The process of producing an absolute TTC estimate can be divided into at least three stages. In stage 1, information about the motion of each object is extracted from the optic flow. In stage 2, this information is used to produce the absolute TTC estimate, that is, to schedule the button press for the anticipated contact time. In stage 3, the motor response is executed.

Regarding stage 1, the extraction of TTC-relevant information can be assumed to occur during the visibility of the objects. It is also possible that this process continues after occlusion, using information stored in visual sensory memory. In principle, subjects should be able to finish the extraction of TTC of both objects shortly after these have disappeared from the screen, for example by using the optical variable τ (Lee, 1976). In fact, humans are able to produce quite accurate PM estimates at extrapolation times as short as 500 ms (Oberfeld & Hecht, 2008). Thus, if the leading object has an extrapolation time $t_A = 1.0$ s, and the trailing object has $t_B = 1.5$ s, then the extraction of t_A from the optical variables should be completed about 500 ms after the disappearance of the objects from the screen. In our example, this would leave at least another 1000 ms for the extraction of t_B, for example on the basis of information about the motion of the trailing object in visual sensory memory. Some studies even reported that the viewing time of the stimulus had no effect on TTC estimations when above 240 ms (Benguigui, 1997, see Rosenbaum, 1975, for a similar result). Hence, with a viewing time in our experiment of 800 ms, participants should have had ample time to extract the relevant information for TTC estimates from the optic flow even when processing the stimuli in a non-parallel fashion. Thus, interference at stage 1 seems unlikely. Generally, it is quite surprising that in this situation we find a significant increase in CE in the two-object condition (Fig. 5, center panel), especially since in PRP experiments the response delay to the second stimulus typically vanishes at SOAs of about 500 ms (e.g., Maquestiaux, Hartley, & Bertsch, 2004; Maquestiaux et al., 2008).

Even if the observers allocated more resources to the perceptual processing of the leading object, in the sense of selective attention, this should primarily cause variability in the TTC estimates of the trailing object. Rather specific assumptions would be required, however, to explain why selective attention during stage 1 should result in a systematic *overestimation* of the TTC of the trailing object, as our results show. Recording eye movements might permit to decide if both TTC estimates are updated equally often, and would thus permit to decide if selective attention during stage 1 plays a role.

In stage 2, the absolute TTC estimate (i.e., the button press) is prepared on the basis of the information about object motion extracted during stage 1. It is a matter of debate whether observers in a prediction-motion task use motion extrapolation in the sense of visual imagery, or estimate TTC at the moment the object disappears from the screen and then use a timing mechanism to delay their response until the virtual collision time, although data by DeLucia and Liddell (1998) favor the former alternative. Our data indicate that both potential processes represent a bottleneck and thus have to be completed before the PM estimate for the trailing object can be produced, or that limited resources are shared between the two tasks. In fact, for timing tasks it is known that concurrent temporal and non-temporal tasks cause the production of temporal intervals to become longer and/or more variable than in a single-interval timing condition (Brown, 1997; Brown, Stubbs, & West, 1991; Champagne & Fortin, 2008; Gooch, Stern, & Rakitin, 2009). More specifically, in an experiment by Brown and West (1990), subjects produced multiple and partially overlapping time intervals. The start of each interval was signaled by the appearance of a number on the screen, and the task was to erase the digit from the screen (after the number of seconds specified by the numerical value) by pressing a button corresponding to the position of the item. Thus, the information concerning the to-be-produced time interval was available to the subjects shortly after the appearance of each item from the screen, just as in our experiment the TTC information was available shortly after the disappearance of each object. Nevertheless, in the experiment by Brown and West (1990) the accuracy of the time-interval productions was impaired if two or more intervals had to be produced concurrently, but notably not for the interval that started first (see their Fig. 3). This pattern parallels our results. In a paradigm where subjects had to produce two 2-s time intervals starting with a variable SOA, van Rijn and Taatgen (2008) reported that longer first estimates yielded longer second estimates. This is again compatible with our findings (see Fig. 8) notwithstanding the authors' preference for a different origin of this result.

As stated above, the observed unilateral influence of the TTC estimate for the leading object on the TTC estimate for the trailing object could be due to proactive interference, assuming that after the central stage of the first task has been completed, the central stage of the secondary task still needs to be done *in totality*. However, it is also possible that participants would in a first step decide which object will arrive first and pay more attention to this object. Therefore, while the first response selection process would remain very accurate, the second process would be updated less frequently, and hence TTC of the trailing object would be misestimated. This should result in increased variability in the second TTC estimate, but the systematic overestimation of the second TTC observed in the present experiment can also be explained. If a clock-based timing mechanism was used in stage 2, and attention was directed to the leading object, then the clock for the trailing object would occasionally miss some pulses of the central clock, resulting in slower accumulation (cf. Zakay & Block, 1996). Note that comparable patterns could also be produced by sequential timing strategies using a single clock combined with a nonlinear underlying timescale (Taatgen, van Rijn, & Anderson, 2007; van Rijn & Taatgen, 2008).

In summary, our results clearly demonstrate proactive interference in a multiple TTC estimation task. It remains for future research to identify the exact mechanisms causing the observed pattern of results. For example, varying the SOA (a hallmark of PRP experiments) would provide information useful for a more detailed understanding of the effects, as for example concerning the time window in which proactive interference is observed. In addition, the effect of a third and further objects on concurrent TTC estimation should be investigated.

The finding of delayed TTC estimates when judging two concurrent TTCs has important practical consequences, such as in sport situations when a player has to estimate the TTC of an approaching ball at the same time as the TTC of an approaching opponent, or in multi-lane street crossing situations. For instance, when crossing a two-way road we predict that pedestrians would correctly estimate the TTC of the leading car (which they may let pass), but overestimate the TTC of the next approaching vehicle (in front of which they may decide to cross). An overestimation of TTC has important practical consequences, as observers have less time than thought to carry out the action. At the limiting case, such misestimate would cause them to initiate maneuvers at unsafe TTCs. As a consequence, driver and pedestrian safety education should emphasize the hazard of multiple approaching vehicles.

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