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# Temporal-range estimation of multiple objects: Evidence for an early bottleneck

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ABSTRACT

When making parallel time-to-contact (TTC) estimates of two approaching objects, the two respective TTC estimates interfere with one another in an asymmetric fashion. The TTC of the later-arriving object is systematically overestimated, while the estimated TTC for the first-arriving object is as accurate as in a condition presenting only a single object. This asymmetric interference points to a processing bottleneck that could be due to early (e.g., during the estimation of the TTC from the optic flow) or late (e.g., during the timing of the response or the motor execution) constraints in the TTC estimation process. We used a Sperling-like prediction-motion task to differentiate between these two possibilities. Participants produced an absolute estimate of the TTC of only one of two objects approaching a target line. The target object to which the response was to be made was indicated by an auditory cue that occurred either at motion-onset or at the instant at which the two objects disappeared from the screen (occlusion-onset). The cue at motion-onset should disengage visual processing of the irrelevant stimulus. The cue at occlusion-onset, in contrast, requires visual processing of both relevant and irrelevant stimulus until occlusion. A single-object condition was introduced as a control condition. Results show symmetric interference in the motion-onset condition. In the occlusion-onset condition however, the results were congruent with asymmetric interference. Thus, the processing bottleneck in TTC estimation is originating at the earlier stages.



## 1. Introduction

We interact with multiple objects on a daily basis, but most of the literature on time-to-contact estimation (TTC, that is the time remaining before an object reaches the observer or a specific point of interception) focuses on a single approaching object (see e.g., Hecht & Savelsbergh, 2004). For example, studies of TTC estimates when driving exist for a single approaching car (e.g., Gray, 2005, Gray & Regan, 2005), but not for situations where drivers have to base decisions on multiple TTC estimates as required when passing between two cars during street crossing or when crossing several lanes on a multiple-lane highway. We address the issue of multiple-object TTC estimation.

Seminal experiments that assessed simultaneous TTC judgments have been conducted by DeLucia and Novak (1997) and Novak (1998). In these experiments one to eight objects were presented and participants were required to indicate either at which time a cued object collided with a finishing line, or which object would hit them first. These manipulations mainly showed that both relative and absolute TTC judgments were affected by set-size, with a decrease in accuracy as set-size increased. Processing load thus seems to influence the accuracy of TTC estimations. We employed a dual-task paradigm to better understand these effects.

The connection with dual-task performance, and the associated theories could shed some light on these results. Dual-task performance has been studied within the framework of the psychological refractory period (see e.g., Pashler, 1994). In this paradigm, two stimuli S1 and S2 are presented in succession. Participants are required to make separate responses, R1 to S1, and R2 to S2. When the time interval between S1 and S2 (stimulus onset asynchrony, SOA) is long enough, then the processing of S1 is finished before the processing of S2 may start. Hence, participants simply perform one task after the other with no increase in the reaction times RT1 and RT2 to the respective stimuli, compared to the same tasks performed in isolation. At short SOAs however, S1 is still being processed while S2 is presented. In this case, RT2 can be delayed by several hundreds of milliseconds while RT1 remains unaffected (e.g., Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Maquestiaux, Laguë-Beauvais, Ruthruff, Hartley, & Bherer, 2010).

We have recently shown that the concurrent TTC estimations of two objects were not only dependent on the optical variables specifying the objects' TTC, but also reflected the existence of asymmetric interference akin to the effects found in psychological refractory period experiments (Baurès, Oberfeld, & Hecht, 2010). Having seen the initial part of two objects' trajectories prior to occlusion, participants were asked to estimate when the objects

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would reach a given point in space, referred to as a prediction motion (PM) paradigm. Importantly, our method differed from Novak's (1998) in that our participants were required to indicate the arrival time of both objects and not only of the cued one. Comparing the TTC estimates with a one-object condition in which the moving object had the same motion parameters (velocity and TTC), the results showed that the TTC estimates for the first-arriving object (hereafter referred to as the leading object) did not differ from the estimates in the one-object situation. However, participants significantly overestimated the TTC of the later-arriving object (the trailing object), relative to the one-object condition. Moreover, the closer in time the two objects reached the finish line, the more delayed was the response for the trailing object. We concluded that asymmetric interference between objects arriving in the near future is present in a multiple TTC estimation task. The results were compatible with the notion that due to an inability to process two TTCs simultaneously and independently, the error of the TTC estimate for the leading object is not influenced by having to produce a second TTC estimate simultaneously, but the TTC estimate for the trailing object is systematically delayed.

These findings indicate that the perceived order of arrivals is the critical factor, however, the cause of the bottleneck in the TTC estimation process is still unclear. It could reside in any of the stages of the TTC estimation process. The first stage is the sensory registration of the TTC-relevant optical variables. Observers may simply be unable to pay attention to the relevant optical variables for two objects. It has also been shown that the TTC discrimination threshold is affected by object eccentricity in the visual field (Regan & Vincent, 1995). Hence, maintaining one of the objects in foveal vision might result in a more precise registration of the optical flow for this object than for the second object. In the second stage, the absolute TTC estimate is prepared on the basis of the information about the objects' motion extracted during stage 1. Again, this process might be capacity limited (e.g., DeLucia & Novak, 1997). Note, however, that it is not easy to explain why limitations at stages 1 and 2 should cause an *asymmetric* interference favoring the TTC estimation for the first arriving object. During extraction of the optical variables, and during the extraction of TTC from these variables, the observer does not know yet which object will arrive first, simply because he or she has not yet completed the TTC extraction. During stage 3, observers time their motor response to coincide with the estimated TTC. However, it is still unclear whether observers in a prediction-motion task use motion extrapolation in the sense of visual imagery, or whether they 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. Data by DeLucia and Liddell (1998) favor the former alternative. The hypothesis that stage 3 may represent a bottleneck in concurrent TTC estimation tasks arises from timing tasks showing 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 (e.g., Brown, 1997; Brown, Stubbs, & West, 1991; Champagne & Fortin, 2008; Taatgen, van Rijn, & Anderson, 2007; van Rijn & Taatgen, 2008). Note also that the timing of the motor action requires knowledge about the forthcoming movement duration (Tresilian, 2005). In this sense, this stage is related to the upcoming motor action of stage 4, even though the variance associated with the motor response is typically much smaller than the interval-timing variance, at least for temporal intervals longer than 300 ms (e.g., Wing, 1980). Finally, in stage 4, observers initiate and execute their button press indicating the estimated TTC. It has been proposed that a motor bottleneck could also account for the delayed response to S2 in psychological refractory period experiments (e.g., De Jong, 1993; Ulrich et al., 2006; Bratzke, Rolke, & Ulrich, 2009; Fernandez & Ulrich, 2010). For example, Ulrich et al. (2006) showed that RT2 increased when the execution time related to S1 increased. The authors conclude that response execution creates a motor bottleneck. However, it is a matter of debate whether the motor bottleneck corresponds to an incapacity to initiate several movements close in time (De Jong, 1993) or more generally also includes parts of the response execution (Bratzke et al., 2009).

To answer the question from which of the above stages the asymmetric interference originates, we used a Sperling-like variant (Sperling, 1960) of our prediction motion task (Baurès et al., 2010). Participants produced an absolute estimate of the TTC of only one of two objects approaching a target line with different velocities and TTCs. The target object to which the response was to be made was indicated by a tone (auditory cue). The target object was cued either at motion-onset, or at the instant at which the two objects disappeared from the screen (occlusion-onset). As a result of this experimental design, participants were required to estimate and report only one TTC in the motion-onset condition; whereas participants were required to estimate two but report only one TTC in the occlusion-onset condition. A single-object condition was introduced as a control condition. We formulated three hypotheses to predict the potential outcomes of this experiment.

Firstly, in the motion-onset condition, since participants know from the beginning which object is task-relevant and which object is to be ignored, no asymmetric interference due to a bottleneck is expected at any of the four stages.

In the occlusion-onset condition on the other hand, because of the uncertainty for which of the two objects to eventually produce an absolute TTC estimate, observers need to perform stages 1 and 2 concurrently for both objects. In stages 3 and 4, in turn, have to be performed only on the relevant object. Consequently, our second hypothesis states that if asymmetric interference as reported by Baurès et al. (2010) were found in the occlusion-onset condition but not in the motion-onset condition, then this would indicate a bottleneck at an early level of the TTC estimation process, during stage 1 or stage 2.

Finally, our third hypothesis predicts that on the other hand, if both the motion-onset and the occlusion-onset condition fail to show asymmetric interference then the bottleneck can be attributed to the later level of the TTC estimation process, during stages 3 or 4.

## 2. Material and methods

### 2.1. Subjects

Twelve students at Paris Sud University (5 women, 7 men, age 26.25 years ± 2.86 (mean ± SD), min age 21, max age 32) 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. 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 an HP computer equipped with a 1.80 GHz Intel Core2 Duo processor, with a 15.3″ TFT screen. The screen resolution was 1024 × 768 pixels (horizontal by vertical). The display rate was 60 Hz.

Participants sat on a chair facing the 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 frontoparallel plane from left to right were obtained using a prediction-motion task (cf. Schiff & Detwiler, 1979). During its motion, the ball passed behind an invisible rectangle (hereafter referred to as "occluder") that obscured its trajectory (see Figure 3 of Baurès et al. (2010) for a representation of the two-objects condition described below, but note that in the present experiment we used invisible occluders). Participants were asked to press a response key at the instant 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 according to the TTC (see Table 1 for a complete description of the trajectories). Participants pressed the spacebar to start each trial. After a delay of 1500 ms, the ball started to move from different starting positions at the left edge of the screen toward the arrival line with constant velocity (2, 4, or 8 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 500, 1000, 1500, 2000, or 2500 ms. Once occluded, the ball did not reappear. Participants pressed a key to indicate the instant at which the ball would have collided with the arrival line. No feedback was provided.

Fifteen factorial parameter combinations were generated from the three velocities and the five TTCs. Each given trajectory was presented 5 times, for a total of 75 trials. After completing this one-object condition, participants were tested in a second condition (hereafter termed "two-objects condition"), in which two balls were presented. Participants were required to estimate the TTC of one of the two balls, indicated by an auditory tone presented via headphones. A high tone (1 kHz, 150 ms) indicated that the TTC of the upper ball was to be estimated, whereas a low tone (250 Hz, 150 ms) indicated that the TTC of the lower ball was to be estimated. The tone was presented either at motion-onset (hereafter referred as the motion-onset condition) or at occlusion-onset (hereafter referred as the occlusion-onset condition). The TTC estimate was obtained using the same method as in the one-object condition. Depending on the tone frequency, participants were required to press the "y" key for indicating the arrival of the upper ball at the finishing line, or 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 800 ms, just as in the one-object condition. The same three velocities as in the one-object condition were presented. One of the two balls, hereafter referred to as the *reference object*, always had a TTC of 1500 ms. The reason for selecting this design was to maintain the number of trials in the two-objects condition at a manageable level. The other ball had TTC of $TTC_{ref} + \Delta TTC$, where $TTC_{ref} = 1500$ ms is the TTC of the reference object, and ΔTTC was set to values of −1000, −500, +500, or +1000 ms, producing TTCs of 500, 1000, 2000, 2500 ms respectively for the second ball (hereafter referred to as the *second object)*. Hence, the motion's parameters of the reference object gave rise to three different trajectories (3 velocities × 1 TTC) whereas the second object was presented with 12 combinations of velocity and TTC (3 velocity × 4 ΔTTC). The occluders were varied in size such that the TTC remained constant for the reference object, and for the second object corresponded to its TTC. As a result, depending on the motion parameters of the two objects, the invisible occluders could be of same or different lengths. Please note that the reference object started its motion at a farther initial distance than the second object in 50% of the trials, whereas the occluded distance of the reference object was larger than the occluded distance of the second object in 56% of the trials. Therefore, the initial and occluded distances were not informative about the objects' order of arrival, which had to be assessed by estimating the TTCs of the respective objects. The combination of each single trial for the reference and second objects gave rise to 36 different conditions, each presented 5 times. In total, participants completed 360 trials in this second part of the experiment. To control for potential effects of the ball's position on the vertical axis, the position of the reference object (upper vs. lower ball) was balanced across the two-objects condition. The tone was randomly assigned to the reference or the second objects. Thus, in the motion-onset condition, observers knew during the visible motion which object had to be judged. In the occlusion-onset condition, the target object requiring a TTC estimate was signalled only when both objects had just disappeared from the screen.

**Table 1**
Description of the 3 (velocity) × 5 (TTC) 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) |
|---|---|---|---|---|
| 2 | 0.8 | 0.5 | 1.6 | 1 |
| | | 1 | | 2 |
| | | 1.5 | | 3 |
| | | 2 | | 4 |
| | | 2.5 | | 5 |
| 4 | | 0.5 | 3.2 | 2 |
| | | 1 | | 4 |
| | | 1.5 | | 6 |
| | | 2 | | 8 |
| | | 2.5 | | 10 |
| 8 | | 0.5 | 6.4 | 4 |
| | | 1 | | 8 |
| | | 1.5 | | 12 |
| | | 2 | | 16 |
| | | 2.5 | | 20 |

## 3. Results

### 3.1. One-object condition

For the analysis of the TTC estimates in the one-object condition, we determined the individual signed error on each trial. Individual signed errors correspond 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 constant error (CE) for each participant and each trajectory (TTC × Velocity), by averaging the individual signed errors across the five repetitions. We also computed the variable error (VE) in terms of the standard deviation (SD) of the individual signed errors in these five repetitions. CE and VE were separately analyzed in a 5 × 3 (TTC × Velocity) repeated-measures ANOVA using a univariate approach. The Huynh–Feldt correction for the degrees of freedom was used where applicable (Huynh & Feldt, 1976) and the value of $\tilde{\epsilon}$; is reported. The within-subjects factors were TTC and velocity.

The ANOVA conducted on CE showed no effect of TTC, $F(4, 44) = 1.82$, $p = .142$, and no effect of velocity, $F(2, 22) = 4.2594$, $p = .057$, $\tilde{\epsilon}; = 0.57$. These two variables interacted however, $F(8,88) = 3.75$, $p < .001$, $\tilde{\epsilon}; = 1.0$, $\eta^2 = 0.25$ (see Fig. 1, left panel) with the effect of TTC on the CE being most pronounced at the slowest velocity. A similar ANOVA was conducted on VE. The VE increased with TTC (see Fig. 1, right panel), $F(4,44) = 18.67$, $p < .001$, $\tilde{\epsilon}; = 0.87$, $\eta^2 = 0.63$. No effect of velocity, $F(2, 22) = .09$, $p = .918$, nor a TTC × Velocity interaction, $F(8, 88) = 2.10$, $p = .098$, $\tilde{\epsilon}; = 0.49$, was found.

### 3.2. Two-objects condition

To analyse the influence of a second object on the TTC estimates, we focused on the performance of participants when estimating the TTC of the reference object (i.e., when the cued object had a TTC of 1500 ms). For this recurring TTC, the experimental design provided us with a symmetric range of TTCs for the second object (i.e., $\Delta TTC = \pm 500$ ms or $\Delta TTC = \pm 1000$ ms), thus allowing for a well-balanced and direct assessment of the influence of earlier and later arrivals of the second object upon the TTC estimation for the reference 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

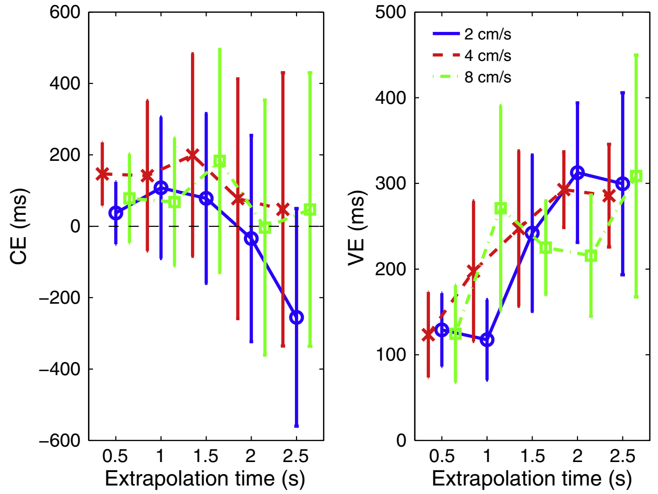


**Fig. 1.** Constant error (CE; left panel) and variable error (VE; right panel) as a function of TTC and velocity in the one-object condition. Note that the interaction is not significant for VE. Error bars show the 95% confidence interval obtained from the *t*-tests.

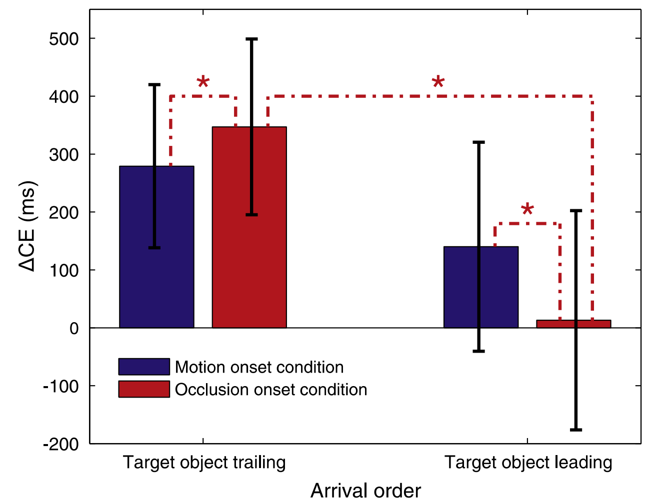


**Fig. 2.** Difference between the CE in the two-objects and in the single-object condition (ΔCE), as a function of cue-condition. Blue bars represent the average data, whereas blue and brown bars distinguish cases where the second object reaches the arrival line respectively before or after the reference object. Asterisks indicate significant differences ($p<.05$) between the different conditions. Error bars show the 95% confidence interval obtained from the *t*-tests.

trajectory. For example, for participant 1, the mean CE was 100 ms in the one-object condition for the trials combining a TTC of 1500 ms and a velocity of 2 cm/s, and −50 ms in the two-objects condition when a ball with the above trajectory was combined with a second ball with a TTC of 500 ms and a velocity of 4 cm/s. Hence, the change in CE due to the addition of a second object was ΔCE = −50 ms −100 ms = −150 ms. Note that the ΔCE does not reflect the precision of the TTC estimation, but serves as an indicator of the shift in the TTC estimates when confronted with two objects as opposed to one object in isolation. 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 over-estimation of TTC in the two-objects condition), and conversely a negative value signifies a relative under-estimation. Note that ΔCE is a dependent variable, whereas ΔTTC is an independent variable. The change in the variable error relative to the one-object condition (ΔVE) was computed analogously.

We first analyzed ΔCE, which can be thought as the second object-induced change in the CE, as a function of cue-condition and the arrival order (i.e., for positive and negative values of ΔTTC) by means of a 2×2 (Cue Condition×Arrival Order) repeated-measures ANOVA (Fig. 2). The results showed no influence of cue-condition, $F(1, 11)=.79$, $p=.394$. For each cue-condition, we compared the value of ΔCE averaged across arrival order to 0 ms by means of *t*-tests. A value of ΔCE = 0 ms would reflect that the TTC estimation of the reference object is equivalent to TTC estimates in the one-object condition, and thus not influenced by the presence of a second object moving simultaneously. Post-hoc pairwise comparisons between all pairs of levels of TTC 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 .05. This showed that for both cue-conditions, the ΔCE was significantly higher than 0, $t(11)=3.83$, $p=.003$, and $t(11)=2.78$, $p=.018$ in the motion-onset and occlusion-onset conditions, respectively. This analysis indicates that the presence of a second object leads to an increase in the TTC estimation regardless of the cue-condition, contrary to our hypothesis. However, the ANOVA showed the expected significant influence of arrival order, $F(1,11)=7.00$, $p=.023$, $\tilde{\varepsilon};=1$, $\eta^2=0.39$, with a higher ΔCE when the target was trailing ($M=313$ ms, $SD=228$ ms) than when the target was leading ($M=76$ ms, $SD=291$ ms). Importantly, cue-condition and arrival order interacted, $F(1, 11)=18.26$, $p=.001$, $\tilde{\varepsilon};=1$, $\eta^2=0.62$. As visible in Fig. 2, the post tests showed that in the cue-at-motion-onset condition, ΔCE did not differ as a function of the arrival order, $t(11)=1.41$, $p=.186$, whereas for the cue-at-occlusion-onset condition, ΔCE was significantly higher when the target was trailing, $t(11)=3.89$, $p=.003$. Moreover, whereas ΔCE was significantly higher in the occlusion-onset condition than in the motion-onset condition when the target was trailing, $t(11)=2.51$, $p=.029$, ΔCE was significantly lower in the occlusion-onset condition when the target was leading, $t(11)=2.56$, $p=.027$. This indicates that the arrival order is an important feature shaping TTC estimation. Indeed, in agreement with our hypothesis, the arrival order affected the TTC estimation in a way consistent with an asymmetric interference in the occlusion-onset condition, but did not influence the TTC estimation in the motion-onset condition, with ΔCE being independent of the arrival order in this case.

Finally, we compared ΔCE to 0 ms, for each cue condition, and arrival order. As can be seen by the confidence intervals in Fig. 2, when the target was trailing, and for both cue-conditions, ΔCE differed significantly from 0 ms, indicating a delayed TTC estimation regardless of the cue-condition. On the contrary, when the target was leading, ΔCE did not differ from 0 ms for the motion-onset and occlusion-onset conditions. This analysis shows that the TTC estimation was impaired in both cue-conditions when the target was trailing, which contradicts the hypotheses formulated above. The significant difference in ΔCE between the two cue-conditions when the reference object was leading (Fig. 2, right part of the graph) is not predicted by any of our initial hypotheses, neither is the significant increase in CE when the cue is given at motion-onset and the target is trailing (Fig. 2, difference from 0 ms of the blue bar of the target object trailing condition).

To understand the origin of this effect, we analyzed the ΔCE for each level of ΔTTC, rather than merely distinguishing the two orders of arrival of the objects. We thus analyzed ΔCE by a 2×3×4×3 (Cue Condition×Reference Object Velocity×ΔTTC×Second Object Velocity) repeated-measures ANOVA. The ANOVA demonstrated a significant Cue Condition×ΔTTC interaction, $F(3,33)=10.82$, $p<.001$, $\tilde{\varepsilon};=0.85$, $\eta^2=0.45$ (Fig. 3). Post-hoc analyses were used to gain a better insight into this interaction. We firstly divided our data-set into two groups, differentiating trials in which the target object was leading (ΔTTC = 500 and 1000 ms) or trailing (ΔTTC = −1000 and −500 ms). Hence, we conducted two separate repeated-measures ANOVAs 2×3×2×3 (Cue Condition×Reference Object Velocity×ΔTTC×Second Object Velocity), on each data-set.

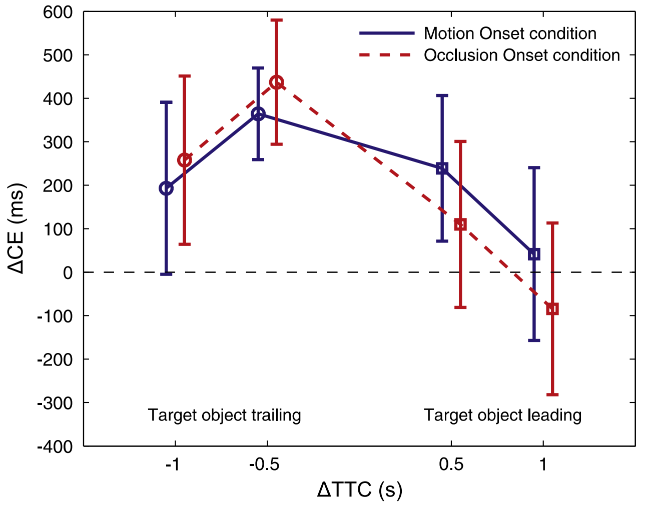


**Fig. 3.** ΔCE in the cue-at-motion-onset condition (solid blue line) or cue-at-occlusion-onset condition (dashed red line), and as a function of ΔTTC. Circles represent the conditions in which the second object reaches the finishing line before the reference object, whereas squares represent the conditions in which the second object reaches the finishing line after the reference object. Error bars show the 95% confidence interval obtained from the *t*-tests.

The first post-hoc test showed that for negative ΔTTCs, that is, when the target object was trailing, the results showed a significant influence of cue-condition, $F(1,11)=6.30$, $p=.029$, $\tilde{\varepsilon};=1$, $\eta^2=0.36$, showing higher ΔCE in the occlusion-onset than in the motion-onset condition. The results also highlighted a significant effect of ΔTTC, $F(1,11)=7.34$, $p=.020$, $\tilde{\varepsilon};=1$, $\eta^2=0.40$, with higher ΔCE when ΔTTC was −500 ms compared to −1000 ms. No interaction appeared between these two factors, $F(1, 11)=0.04$, $p=.853$.

The second post-hoc test revealed that for positive ΔTTC, that is when the reference object was leading, the results also showed a significant influence of cue-condition, $F(1,11)=6.54$, $p=.027$, $\tilde{\varepsilon};=1$, $\eta^2=0.37$, but now showing a higher ΔCE in the motion-onset than in the occlusion-onset condition. Again, the results evidenced a significant influence of ΔTTC, $F(1,11)=33.55$, $p<.001$, $\tilde{\varepsilon};=1$, $\eta^2=0.75$, with higher ΔCE when ΔTTC was 500 ms rather than 1000 ms. Finally, no interaction emerged from these two factors, $F(1, 11)=0.01$, $p=.929$.

These post-tests elucidate two important features. Firstly, the influence of the cue-condition differs depending on the order of arrival, as demonstrated by the first analysis reported above. On the one hand ΔCE was higher in the motion-onset condition for positive ΔTTC, but on the other hand ΔCE was higher in the occlusion-onset condition for negative ΔTTC. This indicates that two different processes are engaged to estimate TTC depending on the cue-condition, which are differently affected by the different levels of ΔTTC. Secondly, arrivals of the two objects close in time (ΔTTC = ±500 ms) led to higher ΔCE than arrivals far in time (ΔTTC = ±1000 ms). The temporal proximity of the arrival of the two objects thus modulates the change in the TTC estimates caused by the second object.

Returning to the four-factorial ANOVA on the complete data set, the analysis failed to show a main effect of the cue-condition, $F(1, 11)=0.79$, $p=.394$ and of reference object velocity, $F(2, 22)=2.29$, $p=.125$. However, ΔTTC had a significant influence on ΔCE, $F(3, 33)=8.49$, $p<.001$, $\tilde{\varepsilon};=0.46$, $\eta^2=0.44$, with ΔCE increasing then decreasing while ΔTTC increases. Finally, second object's velocity influenced ΔCE, $F(2,22)=34.74$, $p<.001$, $\tilde{\varepsilon};=0.79$, $\eta^2=0.76$, with ΔCE increasing significantly for each increase in second object's velocity as shown by post-hoc pairwise comparisons. The cue-condition interacted with second object's velocity, $F(2,22)=8.83$, $p=.003$, $\tilde{\varepsilon};=0.85$, $\eta^2=0.45$, showing a general increase in ΔCE with an increase in velocity, but with a higher ΔCE in the motion-onset than in the occlusion-onset condition for the lower velocity (2 cm/s) and equivalent ΔCEs for the higher velocities (4 and 8 cm/s). Finally, the ANOVA showed a significant Cue Condition × ΔTTC × Reference Velocity interaction, $F(6, 66)=3.66$, $p=.003$, $\tilde{\varepsilon};=0.94$, $\eta^2=0.25$. The data reproduced the ΔCE pattern represented in Fig. 3, but with higher ΔCE for the lower velocity (2 cm/s) than for the two higher velocities (4 and 8 cm/s), which show equivalent ΔCE.

Finally, to have a clearer understanding of how ΔTTC affected ΔCE, we compared once again the ΔCEs of the reference ball for each level of ΔTTC and each cue-condition to a value of 0 ms. It is important to note that in the motion-onset condition, participants know as soon as the trial starts which ball's TTC is to be estimated, and hence, are not expected to estimate the other object's TTC. In other words, participants are only required to estimate and report one TTC. As can be seen by the confidence intervals in Fig. 3 (solid blue line), in the motion-onset condition ΔCE did not differ from 0 ms when ΔTTC was −1000 or 1000 ms. When ΔTTC was −500 or 500 ms, however, then ΔCE was significantly higher than in the one-object condition. In contrast, in the occlusion-onset condition, participants did not know which TTC was to be reported until the occlusion-onset, and as a consequence needed to estimate the two TTCs during the visible interval. In other words, in this condition participants were required to estimate two TTCs but report only one. As can be seen by the confidence intervals of Fig. 3 (dashed red line), for negative ΔTTC, that is, when the target was trailing, the CE was significantly higher than in the one-object condition. When ΔTTC was positive however, that is when the reference object was leading, then the CE did not significantly differ from the CE in the one-object condition.

To gain further insight into the effects of the concurrent TTC estimate on the VE, we analyzed ΔVE using t a 2×3×4×3 (Cue Condition × Reference Object Velocity × ΔTTC × Second Object Velocity) repeated-measures ANOVA, as for ΔCE. No influence of the cue condition was found, $F(1, 11)=2.05$, $p=.18$, nor of the reference object velocity, $F(2, 22)=.05$, $p=.95$. However, ΔTTC had a significant influence on ΔVE, $F(3, 33)=46.92$, $p<.001$, $\tilde{\varepsilon};=0.66$, $\eta^2=0.81$, showing an approximately linear increase of ΔVE with ΔTTC. The second object's velocity influenced ΔVE, $F(2,22)=13.37$, $p=.002$, $\tilde{\varepsilon};=0.59$, $\eta^2=0.55$, and post test analysis revealed that ΔVE was significantly lower when the second object moved at 2 cm/s than at 4 or 8 cm/s. Finally, no interaction was significant, in particular cue condition and ΔTTC did nor interact, $F(3, 33)=.66$, $p=.58$.

Taken together, these analyses indicate two different patterns depending on the cue-condition. In the motion-onset condition, the *temporal proximity* of the second object and the reference object is the key feature explaining the second object-induced change in TTC estimates. Accordingly, the TTC estimate of the reference object was delayed when both objects reached the finishing line close in time (i.e., ΔTTC = ±500 ms), irrespective of their order of arrival. These results are in general agreement with previous findings on the influence of second objects on TTC estimation, even if the direction of the error is subject to contradictory findings (underestimation of CE in the presence of a distractor, e.g., Oberfeld & Hecht, 2008; or overestimation of CE in the presence of a distractor, Novak, 1998). In contrast, in the occlusion-onset condition, the key determinant of second object-induced change in the TTC estimates is the *arrival order*. Indeed, participants performed just as in the one-object condition if the target was leading, whereas the TTC estimate for the trailing object was delayed. This last result replicates the findings of Baurès et al. (2010), witnessing that participants are unable to accurately process two TTCs at the same time. Since participants reported only one TTC, and thus had only one motor action to perform, the bottleneck evidenced here cannot be attributed to an interference in the later stages of the TTC estimation process, that is during the timing of the response (stage 3), or action initiation and execution (stage 4). Hence, the delay of the second TTC estimate is most likely due to a bottleneck situated at an early level of the TTC estimation process, either during the sensory-registration of the TTC-relevant optical variables (stage 1) or the preparation of the TTC estimate on the basis of the available visual information (stage 2).

## 4. General discussion

While the accuracy of TTC judgments for single approaching objects is well researched, little is known about our ability to make simultaneous TTC judgments for two or more objects. Following the work of DeLucia and Novak (1997) and Novak (1998), we have recently shown that participants performing two TTC judgments exhibited an error pattern in agreement with a psychological refractory period (e.g., Pashler, 1994). The leading and the trailing objects have asymmetric effects on the TTC-estimate of the respectively other object: when having to estimate two absolute TTCs, and comparing the performance to a one-object condition, the TTC estimate of the first-arriving object is not affected by the presence of a second object. However, the TTC estimate of the later-arriving object is significantly overestimated by the participants, as a consequence of the presence of the other object (Baurès et al., 2010). This asymmetric interference points to a processing bottleneck. The main objective of the current experiment was to get a better understanding of the observed asymmetric interference. In particular, we were interested in the location of the bottleneck assumed as the origin of the observed asymmetric interference. The bottleneck could in principle be located in one or more of four stages involved in the TTC estimation process: (1) sensory registration of the TTC-relevant optical variables, (2) computation of the TTC estimate on the basis of the visual information obtained, (3) timing of the motor response to coincide with the estimated TTC and (4) initiation and execution of the response.

In a Sperling-like prediction motion task participants faced two moving objects, but had to report the arrival time of the cued object only. The critical experimental manipulation was the time at which a cue designated the target. This auditory cue was given either at motion onset, or at occlusion-onset, which changed the associated results. If the cue is given at motion-onset, then participants know as soon as the trial begins which object's TTC is to be estimated. In this condition, participants do not need to estimate the second object's TTC, and the task comes down to a one-object TTC estimation, in the presence of a second object. Accordingly, the results do not indicate asymmetric interference. Rather, the TTC estimation was independent of whether the target object was trailing or leading. Thus, the TTC estimates of the cued object in the motion-onset condition seemed to be influenced primarily by the temporal proximity of the second object, with a delayed TTC estimation when both objects arrived close in time, in general agreement with previous findings (e.g., Oberfeld & Hecht, 2008).

However, if the cue was given after occlusion-onset, then our participants had to estimate the TTC of both objects, but reported only the TTC of the cued object. In this case, the results replicate the asymmetric interference found by Baurès et al. (2010): while the TTC estimate of the reference object is not modified when it is the leading object, participants greatly overestimate the TTC of the reference object when it is the trailing object. In addition to and in agreement with an asymmetric interference, the closer in time the reference object arrived after the second object (i.e., corresponding to short SOAs) the more delayed was its TTC estimate. Also, since participants reported the estimated arrival time of one object only, a bottleneck related to the later stages of the TTC estimation process, in the timing or initiation/execution of the motor action cannot explain our findings. Instead, our results suggest that the bottleneck is located during the earlier stages of the TTC estimation process, during the sensory registration of the optical variables, or the extraction of TTC from these variables. As noted in the Introduction, this appears as a surprising result as the asymmetric nature of the interference is not foreseen by a bottleneck located in stage 1 or 2, in which the observer does not yet know which object will arrive first. This might witness a more serial process in which the observers first establish a rough estimate of the two TTCs, and then attend to the object which will arrive first based on this estimation. This observation may give an answer to the question raised by DeLucia and Novak (1997) whether multiple TTC estimations are resulting from parallel or serial visual search. As a consequence, the updating of the TTC estimation for the second-arriving object would be impaired, reflecting the bottleneck at the early stages of the TTC estimation process highlighted in the present experiment. An experiment recording eye position might be used to test this hypothesis.

Note that while the observed asymmetric interference represents an analogy to the results from PRP experiments, the specific experimental tasks differ in several aspects. In experiments from the PRP domain, participants react immediately after the stimuli are presented (e.g., Maquestiaux et al., 2008, 2010), whereas in our task, participants first watch the objects for a defined time and react only at the moment they judge the target object to have reached the finishing line. Thus, further exploring the similarities or dissimilarities between a TTC estimation task involving two objects and the traditional PRP tasks, for example by varying the stimulus onset asynchrony (SOA) between the two objects (cf. Pashler, 1994), appears as a promising venue for future experiments.

Our results indicate that humans are unable to process the relevant information to compute two TTC estimates in parallel. In summary, our results demonstrate that asymmetric interference in a multiple-object TTC estimation task likely originates in the visual registration of the relevant information, or in the computation of TTC from the visual information. This finding has important practical consequences. When the TTC of an approaching object is being overestimated, observers have less time than thought to carry out the action. For example, in numerous ball-sport situations, the player may need to simultaneously estimate the TTC of the ball and of several opponents to decide and organize his next actions. A failure in one of these estimations is likely to degrade the action. In multi-lane street crossing situations, pedestrians or drivers may encounter potentially harmful situations. For example, in a situation in which a pedestrian has to decide whether or not he has enough time to cross a two-lanes street, it may happen that the pedestrian would correctly estimate the TTC of the leading car, and decide to let it pass. If the observer does not update his estimate (e.g., lack of attention, occlusion of the second car by another pedestrian), then the pedestrian would overestimate the TTC of the second car, and decide to cross in front of it despite the lack of time to complete the action. As a consequence, driver and pedestrian safety education might point out the hazard of multiple approaching vehicles.

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