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Asymmetrical time-to-contact error with two moving objects persists across different vertical separations

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ABSTRACT

When human observers estimate the time-to-contact (TTC) of more than one object there is an asymmetric pattern of error consistent with prioritizing the lead object at the expense of the trail object. Here, we examined TTC estimation in a prediction motion task where two objects moved along horizontal trajectories (5 or 7.5 °/s) that had different vertical separation, and thus placed specific demands on visuospatial attention. Results showed that participants were able to accurately judge arrival order, irrespective of vertical separation, in all but two conditions where the object trajectories crossed close to the arrival location. Constant error was significantly higher for the object that trailed, as opposed to led, by 250 or 500 ms. Asymmetry in constant error between the lead and trail object was not influenced by vertical separation, and was also evident across a range of arrival times. However, while the lag between the two consecutive TTC estimations was scaled to the actual difference in object arrival times, lag did increase with vertical separation. Taken together, our results confirm that TTC estimation of two moving objects in the prediction motion task suffers from an asymmetrical interference, which is likely related to factors that influence attentional allocation.

1. Introduction

An individual's capacity to estimate the arrival time of a single moving object at a specific location, which is also known as time-to-contact (TTC), has often been assessed with the prediction motion (PM) task. Having seen the initial part of an object's trajectory prior to occlusion, the participant is required to make a response (e.g., button press) that coincides with arrival time of the now unseen object at a specified location. Typically, there is a linear relationship between estimated and actual TTC, with a slope that is less than one (Caird & Hancock, 1994; Yakimoff, Bocheva, & Mitrani, 1987; Yakimoff, Mateeff, Ehrenstein, & Hohnsbein, 1993), and a transition from overestimation to underestimation of TTC around 800–900 ms (Benguigui, Ripoll & Broderik, 2003; Manser & Hancock, 1996; Schiff & Detwiler, 1979; Schiff & Oldak, 1990). The implication is that participants misperceive the object's actual TTC, and are thus delayed (overestimation) or premature (underestimation) in pressing the response key. Importantly, however, this linear relationship between estimated and actual estimated TTC does not hold when the PM task involves two moving objects approaching the same location (Baurès, Oberfeld, & Hecht, 2010, 2011). This situation requires the participant to make two concurrent TTC estimations and results in an asymmetrical pattern of error. Participants exhibit the expected level of accuracy for the object that arrives first (i.e., lead object) but significantly overestimate TTC of the second object when it trails (the lead object) by a short temporal delay (Baurès, DeLucia, & Olson, 2017).

The asymmetrical pattern of error when estimating the arrival time of two objects has been described with reference to the Psychological Refractory Period (e.g., Pashler, 1994), according to which the realization of a primary task (i.e., TTC estimation of the lead object) disrupts the completion of a second task using the same central resource (i.e., TTC estimation of the trail object). As explained by Baurès et al. (2011), TTC estimation in the PM task requires 4 steps: (1) sensory registration of the TTC-relevant optical variables, (2) computation of an absolute TTC estimate on the basis of the information about the objects' motion extracted at step 1, (3) preparation/timing of the motor response to coincide with the estimated TTC, and (4) initiation and execution of the button press indicating the estimated TTC. Using a Sperling-like (Sperling, 1960) variation of the PM task where a cue indicated in advance which object's TTC had to be estimated, Baurès et al. (2011) ruled out the involvement of steps 3 and 4 in the occurrence of the PRP-like effect (i.e., there was only one motor response and thus attention sharing was not required). It was concluded that when two TTC estimations compete for the same limited resource during steps 1 or 2,

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priority is given to the lead object at the expense of the trail object. In this respect, it is feasible that the asymmetric pattern of error in the PM task is consistent with over-allocation of attention to the lead object rather than a capacity limitation (Arend, Johnston, & Shapiro, 2006; Martens & Wyble, 2010). By focusing attention on the lead object, participants are able to extract the necessary information (i.e., position and velocity) for accurate TTC estimation of that object alone.

Unlike the rapid serial visual presentation (RSVP) task typically used to examine the PRP, in the PM studies described above the two objects were both present, separated by 2° in the vertical axis, during the initial visible period leading up to occlusion. Therefore, it could be reasoned that sufficient information regarding the motion of the two objects should have been available for estimating TTC. However, it is worth noting that the two objects had identical size, shape and color (e.g., black circles that subtended 1°), which when combined with the vertical separation, could have impacted upon the ability to disambiguate the motion paths and thus estimate TTC. For instance, it is known that motion perception and pursuit eye movements both initially involve a process that averages spatially separate inputs (see Heinen & Watamaniuk, 1998), with the weighting influenced by spatial (Lisberger & Ferrera, 1997) and temporal (Marinovic & Wallis, 2011) proximity. This averaging process is subsequently surpassed by a winner-takes-all response once the decision has been made to overtly attend to a particular (e.g., lead) object (for the locus of attention during smooth pursuit see Khan, Lefèvre, Heinen, & Blohm, 2010; Van Donkelaar & Drew, 2002). From this point onwards, pursuit of a moving object places specific demands on visuospatial attention, which can influence processing of other objects depending on their relative location (Kerzel & Ziegler, 2005; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005).

In the current study, therefore, we conducted two experiments that examined the influence of vertical separation between two moving objects on accuracy of TTC estimation. In Experiment 1, we replicated the object features used in previous work (Baurès et al., 2010, 2011, 2017), whereas in Experiment 2 we modified the shape of one object in order to facilitate disambiguation. Importantly, the evolving horizontal separation between the two objects was dependent on their respective velocity and actual TTC, and thus would not independently account for any differences as a function of vertical separation. In addition, we ensured that the motion paths (horizontal axis) of the two objects did not cross prior to occlusion, thus minimizing this potential cue regarding arrival order and TTC. Based on our previous work, we expected that participants would accurately judge arrival order. In addition, we expected that TTC estimation error would be significantly greater for the object that trailed, as opposed to led, by a short temporal delay. Given the somewhat mixed findings regarding the effect of relative location on processing of multiple objects, we did not have a clear expectation regarding the effect of vertical separation. Shim, Alvarez, and Jiang (2008) reported that participants exhibit an impaired ability to track objects that move in near proximity (i.e., ≤2°) because of limitations in spatial resolution of attention. On the other hand, it has been shown that when overt attention is focused on a moving object, participants are less able to remember the location of stationary targets presented in the periphery than the fovea (Kerzel & Ziegler, 2005). In the PM task where participants are required to perform two concurrent TTC estimations, it follows that vertical separation between the two objects could influence the allocation of attention and thus impact upon TTC estimation error.

2. Experiment 1

2.1. Participants

Sixteen male volunteers (M_{age} = 21 years) completed the experiment having provided written consent. They reported having normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Participants were familiarized to the task and procedure, which was carried out in accordance with the Declaration of Helsinki and approved by the host University local ethics committee.

2.2. Materials and procedure

Participants were sat in a purpose-built dark room, facing a 22″ CRT monitor (Iiyama Vision Master 505) located on a workbench at a viewing distance of 0.9 m. The head was supported with a height-adjustable chin rest. Experimental stimuli were generated on a host PC (Dell Precision 670) using the COGENT toolbox (developed by John Romaya at the Laboratory of Neurobiology at the Wellcome Department of Imaging Neuroscience) implemented in MATLAB (Mathworks Inc). The stimuli were presented with a spatial resolution of 1280 × 1024 pixels and a refresh rate of 85 Hz. Estimation of TTC was determined from the moment the Y and B keys were pressed on a Razer Arcosa keyboard (1000 Hz Ultrapolling) with a QWERTY key layout.

TTC estimates were obtained for two, black circular objects (diameter of 0.5°) moving at constant velocity in the fronto-parallel plane against a white background. As shown in Fig. 1, the objects were initially presented on the left-hand side of the monitor for 2000 ms. At the same time, a vertically-oriented black arrival line (0.3° wide and 8° long) was presented in a fixed location (+11° from screen centre) on the right-hand side of the monitor. The vertical offset between the objects was 0.5 or 3° relative to screen centre. At the end of the 2000 ms stationary period both objects moved on parallel horizontal trajectories from left to right at 5 or 7.5 °/s. Then, after 600 ms the two objects passed behind an invisible “occluder” and continued to move, unseen, toward the vertically-oriented black arrival line. The two objects did not reappear after the occlusion and instead participants were asked to estimate when the objects would have made contact with the arrival line (i.e., TTC). Object velocity and TTC was randomized on a trial-by-trial basis, thus resulting in an offset between the initial locations of the two objects at the left-hand side of the screen. Importantly, the two objects did not cross paths in the horizontal axis during the initial visible period, thus preventing this simple cue from influencing TTC estimation.

TTC of one of the objects, hereafter referred to as the reference object, was fixed at 1900 ms. TTC of the other object, hereafter referred to as the distractor object, was 1400, 1650, 2150 or 2400 ms. Therefore, the reference object had a temporal difference of ± 250 ms or ± 500 ms relative to the distractor object (hereafter referred to as ΔTTC). In half the trials the reference object arrived at the vertical line first (lead), while in the other half the reference object arrived second (trail). Participants were asked to press the Y key with the right index finger and B key with the left index finger at the instant the upper and lower objects would have made contact with the arrival line. The Y and B keys were used to ensure spatial compatibility with the vertical offset between the two objects. No feedback on temporal estimation error was provided after the trial, which had a fixed duration of 5000 ms. At the end of each trial a white screen was presented for 1000 ms, after which the next trial commenced. No instructions were given to participants regarding how they should move their eyes during the trials.

There were sixteen unique combinations of the two object velocities and four ΔTTC (see Fig. 2), each of which was presented 6 times (N = 96). The presentation order was pseudo-randomly arranged for each participant and then divided equally into 3 blocks of 32 trials. This was done for both conditions of vertical separation, thus requiring participants to complete 6 blocks in total (N = 192). To control for potential effects of condition order, half of the participants completed the three blocks with the two objects separated by 0.5° in the vertical axis followed three blocks with the two objects separated by 3°. The condition order was reversed for the other participants. To control for potential effects of object position on the vertical axis, the reference

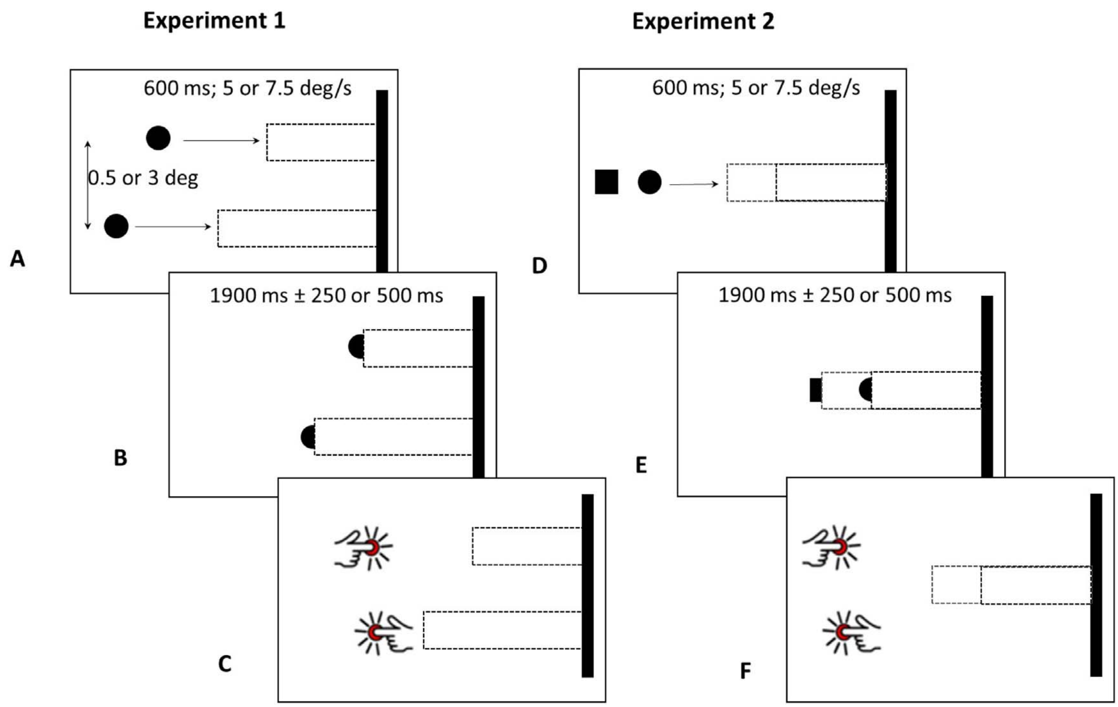

Fig. 1. Representation of the visual stimulus in experiment 1 (left panel) and experiment 2 (right panel). A. The visual scene initially contains two stationary objects and an arrival line (full black rectangle). The two dashed rectangles represent the forthcoming occlusion of the objects, but were not visible to the participants during the experiment. The two objects then move rightwards for 600 ms toward the arrival line with a velocity of either 5 or 7.5 °/s. B. Both objects are occluded at the same time, with the reference object reaching the arrival line after 1900 ms and the distractor object arriving either earlier or later by 250 or 500 ms. C. Participants press a key with the right and left index finger to coincide with the moment each object would have made contact with the arrival line. In experiment 1, the two objects are separated in the vertical axis by 0.5 or 3°. In experiment 2, the two objects are aligned or separated in the vertical axis by 3° (NB. not shown to avoid replication). To avoid feature assimilation in experiment 2, the two objects are either a circle or square.

object was presented at the lower or upper vertical position for an equal number of trials. This had the additional advantage of minimizing any potential influence of hand preference on participants' manual response.

2.3. Data analysis

For each participant, the number of correct responses was calculated for each combination of independent variables: 2 (vertical separation) × 4 (ΔTTC) × 2 (reference object velocity) × 2 (distractor object velocity). The data was then analysed in RStudio (Version 0.99.902) using a generalized linear mixed model (R Core Team), with a binomial distribution and logistic link function (i.e., binomial logistic regression). Starting with the full model, we followed an iterative process in order to find the simplest model that accounted for the highest proportion of variance in the data. We included only those terms involved with significant main and/or interaction effects, determined by the Wald Chi Square tests (i.e., $p < 0.05$).

We used two approaches for quantifying error in TTC estimation. Similar to Baurès et al. (2010, 2011, 2017), we first calculated constant error (CE) for each of the two objects relative to their respective arrival time (i.e., 1900 ms for the reference, 1400, 1650, 2150 or 2400 ms for the distractor). Positive CE indicates an overestimation of the objects arrival time, whereas negative CE indicates an underestimation of the objects arrival time. Second, the TTC estimation of the lead object was subtracted from the TTC estimation of the trail object, thus giving a positive measure of lag. Analysis of lag was important because it permitted us to determine if participants were simply responding to the trail object at a fixed time after the lead object, or if they were modulating the second response with respect to the actual difference in arrival times between the two objects. To minimize the influence of errors in perceiving arrival order on the effects of interest, such trials were excluded from the calculation of intra-participant mean data. CE and lag were analysed using a linear mixed model (lme4 v1.1-7; Bates et al., 2012), following the same iterative process described above in order to determine the most parsimonious model. Participants were included as a random effect (i.e., intercept) and the combination of independent variables input as fixed effects: 2 (vertical separation) × 4 (ΔTTC) × 2 (reference object velocity) × 2 (distractor object velocity). The inclusion of random intercepts for each participant was important in order to account for inter-participant variability in the magnitude of TTC estimation error.

3. Results

3.1. Arrival order

Arrival order was incorrectly perceived in 247 trials of a total 3072 trials (9%), with 1 participant exhibiting no correct trials in two of the conditions. As shown in Fig. 3, participants judged arrival order of the two objects with similar accuracy irrespective of vertical separation. Mean number of correct responses was 5.5 (CI.95% = 4.2: 6.8) in the 0.5° condition and 5.5 (CI.95% = 4.2: 6.8) in the 3° condition. The lack of moderation by vertical separation on the number of correct responses was confirmed by binomial logistic regression, which indicated no significant contribution from this factor when it was included as a main or interaction effect. The removal of vertical separation produced a reduced model that fit the data better than the null model ($\chi^2_{(15)} = 339.69$, $p < 0.001$), and accounted for 47% of the overall variance (conditional R-square). A further reduction to a main effects only model produced a significantly worse fit of the data ($\chi^2_{(10)} = 213.9$, $p < 0.001$) that accounted for only 29% of the overall variance. Therefore, the reduced model including main and interaction effects was accepted. As shown in Table 1, Wald Chi Square tests indicated the number of correct responses was significantly affected by the interaction between ΔTTC, reference object velocity and distractor object velocity. Tukey pairwise comparisons indicated that participants made more errors in judging arrival order when the lead object moved

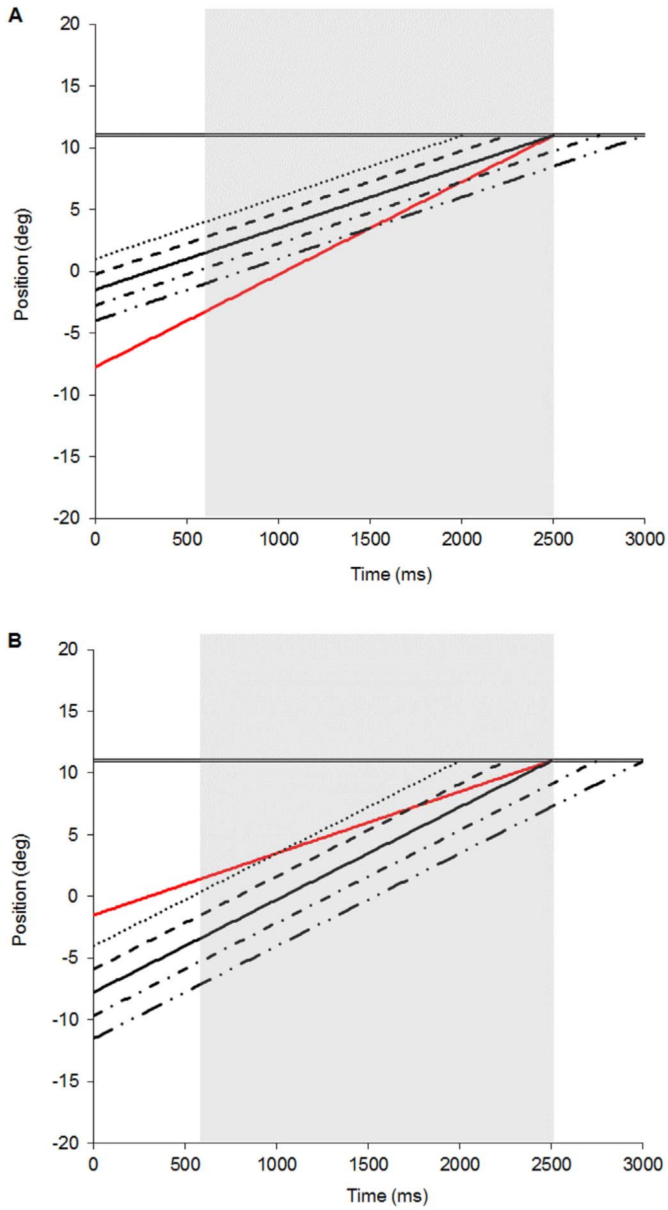

Fig. 2. Horizontal object position as a function of time. The solid black and red lines depict the reference object, which has a TTC of 1900 ms and was presented in every trial. The broken black lines depict the distractor object, which has ΔTTC of ± 250 or 500 ms. Panel A shows all position trajectories that included the 5 °/s object. Panel B shows all position trajectories that included the 7.5 °/s object. The light grey bar in each panel represents the onset of occlusion (600 ms) and arrival time of the reference object. NB. None of the objects became visible after they reached the arrival line. The double horizontal lines represent the location of the arrival line, which was constant at 11 ° from screen centre. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at 7.5 °/s and the trail object moved at 5 °/s with a delay of 250 ms (reference: M = 3.9; CI.95% = 1.6: 6.2; distractor: M = 4.4; CI.95% = 2.5: 6.6).

3.2. CE reference object

A full factorial model indicated that vertical separation did not moderate accuracy of estimated arrival time of the reference object. Mean CE was 529 ms (CI.95% = 283: 775) in the 0.5° vertical separation condition and 500 ms (CI.95% = 254: 747) in the 3° vertical separation condition. In a subsequent reduced factorial model, Wald Chi Square tests indicated there were main and interaction effects for ΔTTC,

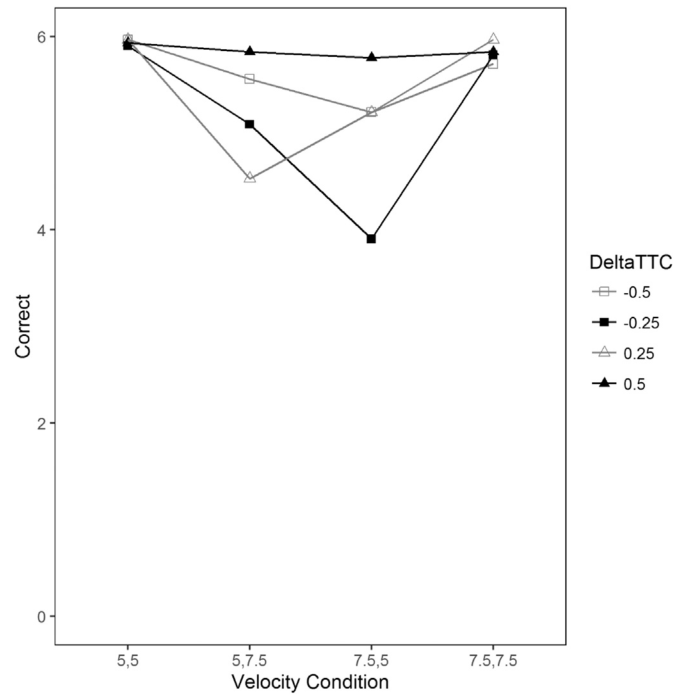

Fig. 3. Group mean number of correct responses in experiment 1 as a function of ΔTTC and velocity of the two objects (reference, distractor). NB. Negative ΔTTC indicates that the reference was the lead object, whereas positive ΔTTC indicates that the reference was the trail object.

Table 1
Type II Wald Chi-Square tests for the fixed effects included in the binomial logistic regression on number of correct responses in experiment 1. The accepted reduced model is shown. Factors included were: Delta.TTC (ΔTTC); Vref (reference object velocity); Vdis (distractor object velocity).

	Chisq	df	*p* value
Delta.TTC	52.85	3	0.000
Vref	0.78	1	0.378
Vdis	6.48	1	0.011
Delta.TTC:Vref	3.24	3	0.356
Delta.TTC:Vdis	9.58	3	0.023
Vref:Vdis	75.73	1	0.000
Delta.TTC:Vref:Vdis	16.06	3	0.001

Table 2
Type II Wald Chi-Square tests for the fixed effects included in linear mixed model regression on constant error of the reference (upper rows) and distractor (lower rows) object in experiment 1. The accepted reduced model is shown. Factors included were: Delta.TTC (ΔTTC); Vref (reference object velocity); Vdis (distractor object velocity).

	Chisq	df	*p* value
Reference			
Delta.TTC	395.19	3	0.000
Vref	19.83	1	0.000
Vdis	17.12	1	0.000
Delta.TTC:Vref	10.59	3	0.014
Delta.TTC:Vdis	6.45	3	0.092
Vref:Vdis	7.96	1	0.005
Delta.TTC:Vref:Vdis	10.82	3	0.013
Distractor			
Delta.TTC	320.06	3	0.000
Vref	19.79	1	0.000
Vdis	17.23	1	0.000
Delta.TTC:Vref	7.48	3	0.058
Delta.TTC:Vdis	10.38	3	0.016
Vref:Vdis	6.08	1	0.014
Delta.TTC:Vref:Vdis	0.73	3	0.865

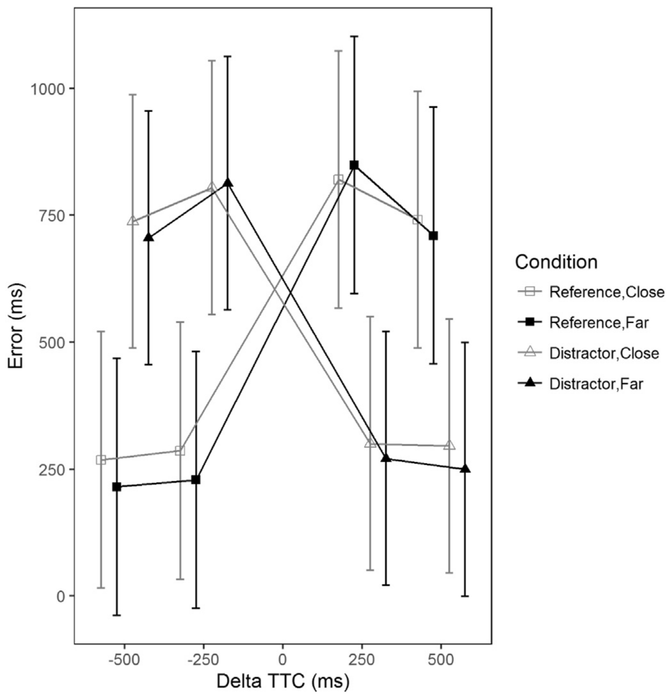

Fig. 4. Group mean CE (± 95% CI) as a function of Delta TTC, Vertical Separation (Close = 0.5°; Far = 3°) for the reference object (squares on black and grey lines) and distractor object (triangles on black and grey lines). Delta TTC is expressed relative to the reference object. Accordingly, −500 and −250 ms indicate the reference was the lead object and the distractor was the trail object. Conversely, 500 and 250 ms indicate the reference was the trail object and the distractor was the lead object. NB. To aid interpretation of the factor, Vertical Separation, an offset has been introduced on the horizontal axis.

reference object velocity and distractor object velocity (see Table 2 upper rows). The reduced model produced an equally good fit as the full factorial model ($\chi^2_{(16)} = 5.73$, $p > 0.1$) and a significantly better fit of the data than the intercept-only model ($\chi^2_{(15)} = 336.78$, $p < 0.001$). The reduced model accounted for 76% of the overall variance (conditional R-square). Tukey pairwise comparisons indicated that CE was greater ($p < 0.0001$) when both the reference and distractor object moved at 7.5 °/s compared to all other combinations of object velocity. Independent of object velocity, there was also a significant effect of ΔTTC ($p < 0.0001$). As can be seen in Fig. 4, CE was significantly lower when the reference object arrived before (ΔTTC −250: M = 257 ms; CI.95% = 9: 506, ΔTTC −500: M = 242 ms; CI.95% = −7: 490) compared to after (ΔTTC 250: M = 835 ms; CI.95% = 586: 1083, ΔTTC 500: M = 725 ms; CI.95% = 477: 974) the distractor object.

3.3. CE distractor object

Although the reference and distractor objects had identical visual features and an equal probability of moving at 5 or 7.5 °/s in the upper or lower vertical location, TTC of the reference object was fixed at 1900 ms, whereas TTC of the distractor varied by ± 250 ms or ± 500 ms. Therefore, the pattern of CE described above and reported in previous work (Baurès et al., 2010, 2011, 2017) could be specific to TTC of the reference object, which was constant across all trial types. To examine this issue, we repeated the same analysis on CE of the distractor object. The findings for the distractor object mirrored those of the reference object, thus indicating the effects were not specific to a single TTC (i.e., 1900 ms). Once again we found no significant effect of vertical separation on CE for the distractor object. Mean CE was 534 ms (CI.95% = 292: 777) in the 0.5° vertical separation condition and 509 ms (CI.95% = 267: 752) in the 3° vertical separation condition. In a subsequent reduced factorial model, there were main and interaction effects for ΔTTC, reference object velocity and distractor object velocity (see Table 2 lower rows). The reduced model produced a significantly better fit of the data than the intercept-only model ($\chi^2_{(15)} = 289.57$, $p < 0.001$) and accounted for 74% of the overall variance (conditional R-square). CE was greater ($p < 0.0001$) when the reference and distractor object both moved at 7.5 °/s (M = 674 ms; CI.95% = 429: 919) compared to all other combinations of object velocity. As can be seen in Fig. 4, CE was significantly lower when the distractor object arrived before (ΔTTC −250: M = 286 ms; CI.95% = 41: 531, ΔTTC −500: M = 272 ms; CI.95% = 28: 517) compared to after (ΔTTC 250: M = 808 ms; CI.95% = 564: 1053, ΔTTC 500: M = 722 ms; CI.95% = 477: 966) the reference object.

3.4. Lag between TTC estimations

A full factorial model indicated significant main effects for all factors, and an interaction between reference and distractor object velocities. A subsequent main-effects only model produced a better fit than the full factorial model ($\chi^2_{(25)} = 45.29$, $p < 0.01$), as well as the intercept-only model ($\chi^2_{(6)} = 184.61$, $p < 0.001$). The accepted main-effects model accounted for 63% of the overall variance (conditional R-square). Tukey pairwise comparisons indicated that lag was shorter ($p < 0.01$) when the objects were located closer (M = 856 ms; CI.95% = 733: 986) rather than further (M = 903 ms; CI.95% = 777: 1030) in the vertical axis. Also, lag was significantly shorter when the temporal separation between the reference and distractor objects (ΔTTC) was −250 ms (M = 798 ms; CI.95% = 669: 926) and 250 ms (M = 795 ms; CI.95% = 666: 924) compared to −500 ms (M = 980 ms; CI.95% = 852: 1108) and 500 ms (M = 953 ms; CI.95% = 825: 1081). Therefore, while participants did not make their second TTC estimation at a fixed time after the first TTC estimation, perceived lag between the two objects was modulated by vertical separation (see Fig. 4).

4. Discussion

While temporal proximity is undoubtedly a key factor in the asymmetric pattern of error found when making two concurrent TTC estimations in the PM task, here we examined if there was also an influence of vertical separation between the two objects. Consistent with Baurès et al. (2010, 2011, 2017), we found that temporal estimation was significantly more accurate for the lead object than the trail object. Extending upon previous work, we also found that the overestimation in CE for the trail object compared to the lead object was similar across a range of TTCs. Analysis of the lag between the two successive TTC estimations ruled out the possibility that participants gave their second TTC estimation at a fixed interval after the first estimation. Despite being overestimated per se, lag increased in accord with the actual difference between the arrival times (i.e., 250 and 500 ms). Interestingly, however, we did find that lag was shorter when the objects were located closer together in the vertical axis. It is not obvious from the CE data why this effect occurred. For instance, there was no interaction between ΔTTC and vertical separation, whereby participants consistently underestimated TTC of the lead object and/or overestimated TTC of the trail object. The finding that vertical separation mediated participants' overestimation of the interval between arrival of successive objects warrants further investigation.

In a second experiment, we examined participants' ability to make concurrent TTC estimations of two objects that were either separated by 3° or aligned in the vertical axis. We decided not to simply increase the vertical separation between the two objects because it is well known processing at more eccentric locations can be less accurate (Johnson, Keltner, & Balestrery, 1978; McKee & Nakayama, 1984) and possibly even suppressed (Kerzel & Ziegler, 2005). Instead, we were interested to determine whether the absence of vertical separation might influence the ability to individuate the motion paths of two objects due to overlapping attentional foci at some point during their approach to arrival location (He, Cavanagh, & Intriligator, 1997; Shim et al., 2008). Importantly, in order to minimize assimilation due to overlapping attention in feature space (Blaser, Pylyshyn, & Holcombe, 2000), we presented a circular and square object, which were matched with a particular key to ensure a clear stimulus-response compatibility. The same stimuli were also presented when the two objects were separated by 3°, thus enabling us to examine whether the previously reported asymmetrical TTC estimation error was related to the use of objects with identical features.

5. Experiment 2

5.1. Participants

Eighteen male volunteers (mean age: 21 years) completed the experiment having provided written consent. They reported having normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Participants were familiarized to the task and procedure, which was carried out in accordance with the Declaration of Helsinki and approved by the host University local ethics committee.

5.2. Materials and procedure

These were the same as experiment 1 except that participants estimated TTC of a black circular object (diameter of 0.5°) and black square (0.5°), which had a vertical offset of 0° or 3° relative to screen centre (Fig. 1 right panel). Again, the Y key was associated with the upper object and the B key with the lower object when there was a vertical separation. For half the participants, the upper object was the square and for the others it was the circle. This ensured spatial compatibility and minimized any unforeseen effects of object shape on TTC estimation. In addition, when there was a vertical separation, the reference object was presented at the lower or upper position on an equal number of trials. The same association between keys and object shape was used for each participant when the two objects were aligned in the vertical axis. To control for potential effects of condition order, half of the participants completed the three blocks with the two objects separated in the vertical axis followed three blocks with the two objects aligned in vertical axis. The condition order was reversed for the other participants.

6. Results

6.1. Arrival order

Arrival order was incorrectly perceived in 369 trials of a total 3456 trials (approximately 11%), with 5 participants exhibiting no correct trials in some of the conditions. Analysis of the full model indicated that arrival order was judged with similar accuracy irrespective of vertical separation. Mean number of correct responses was 5.3 (CI.95% = 3.8: 6.8) in the aligned condition and 5.4 (CI.95% = 3.9: 6.8) in the 3° vertical separation condition. The removal of vertical separation produced a reduced model that fit the data better than the null model ($\chi^2_{(15)} = 530.99$, $p < 0.001$), and accounted for 47% of the overall variance (conditional R-square). A main effects only model was rejected as it produced a significantly worse fit of the data than the reduced model ($\chi^2_{(10)} = 333.83$, $p < 0.001$), and accounted for only 28% of the overall variance. Wald Chi Square tests on the reduced model indicated the number of correct responses was significantly affected by ΔTTC, as well as the interaction between reference object velocity and distractor object velocity. Tukey pairwise comparisons indicated that participants made more errors in judging arrival order when the reference and distractor moved at a different compared to same velocity. Although not quite reaching conventional levels of significance, it can be seen in Fig. 5 that participants again tended to make more errors in estimating arrival order when the lead object moved at 7.5 °/s and the trail object moved at 5 °/s with a delay of 250 ms (reference: M = 3.5; CI.95% = 1.1: 5.8; distractor: M = 3.7; CI.95% = 1.4: 6.1) (Table 3).

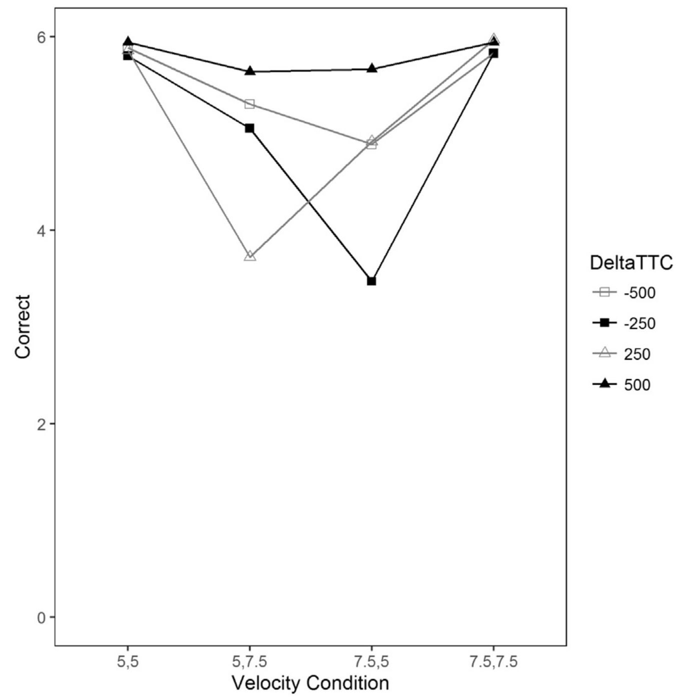

Fig. 5. Group mean number of correct responses in experiment 2 as a function of ΔTTC and velocity of the two objects (reference, distractor). NB. Negative ΔTTC indicates that the reference was the lead object, whereas positive ΔTTC indicates that the reference was the trail object.

Table 3
Type II Wald Chi-Square tests for the fixed effects included in the binomial logistic regression on number of correct responses in experiment 2. The accepted reduced model is shown. Factors included were: Delta.TTC (ΔTTC); Vref (reference object velocity); Vdis (distractor object velocity).

	Chisq	df	*p* value
Delta.TTC	89.81	3	0.000
Vref	18.90	1	0.000
Vdis	2.00	1	0.158
Delta.TTC:Vref	1.05	3	0.790
Delta.TTC:Vdis	3.73	3	0.292
Vref:Vdis	151.61	1	0.000
Delta.TTC:Vref:Vdis	7.22	3	0.065

6.2. Reference object

As can be seen in Fig. 6, the results were very similar to those of Experiment 1, with accuracy of estimated arrival time of both objects being unaffected by vertical separation. Mean CE was 420 ms (CI.95% = 34: 806) in the aligned condition and 402 ms (CI.95% = 16: 788) in the 3° vertical separation condition. A reduced model (see Table 4) not including vertical separation produced a significantly better fit of the data than the intercept-only model ($\chi^2_{(15)} = 324.33$, $p < 0.001$) and accounted for 91% of the overall variance (conditional R-square). Observation of the group mean data (see Fig. 6), and the outcome of Tukey pairwise comparisons, indicated that CE was greatest ($p < 0.0001$) when the reference and distractor object both moved at 7.5 °/s (M = 570 ms; CI.95% = 183: 957). Independent of object velocity, there was also a significant effect of ΔTTC ($p < 0.0001$). As can be seen in Fig. 5, CE was significantly lower when the reference object

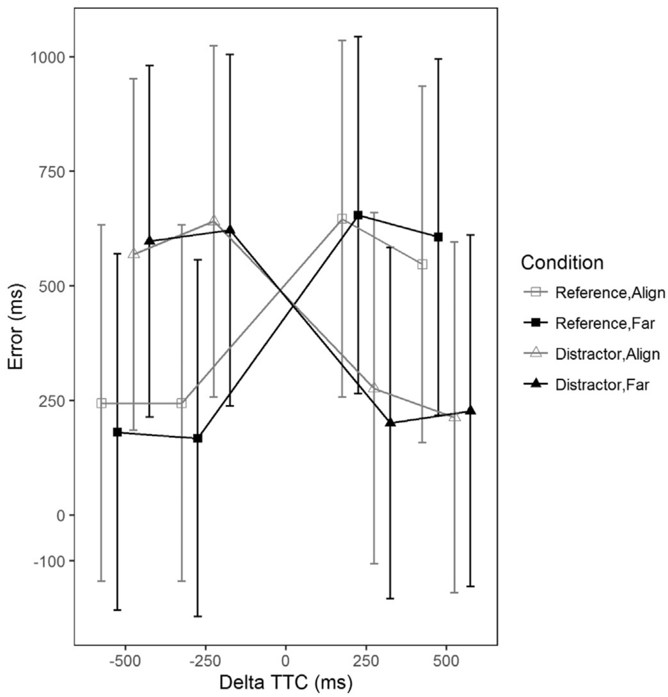

Fig. 6. Group mean CE (± 95% CI) as a function of Delta TTC, Vertical Separation (Close = 0.5°; Far = 3°) for the reference object (squares on black and grey lines) and distractor object (triangles on black and grey lines). Delta TTC is expressed relative to the reference object. Accordingly, −500 and −250 ms indicate the reference was the lead object and the distractor was the trail object. Conversely, 500 and 250 ms indicate the reference was the trail object and the distractor was the lead object. NB. To aid interpretation of the factor, Vertical Separation, an offset has been introduced on the horizontal axis.

Table 4
Type II Wald Chi-Square tests for the fixed effects included in linear mixed model regression on constant error of the reference (upper rows) and distractor (lower rows) object in experiment 2. The accepted reduced model is shown. Factors included were: Delta.TTC (ΔTTC); Vref (reference object velocity); Vdis (distractor object velocity).

	Chisq	df	*p* value
Reference			
Delta.TTC	346.06	3	0.000
Vref	10.69	1	0.001
Vdis	39.81	1	0.000
Delta.TTC:Vref	6.81	3	0.078
Delta.TTC:Vdis	2.40	3	0.494
Vref:Vdis	23.06	1	0.000
Delta.TTC:Vref:Vdis	1.81	3	0.614
Distractor			
Delta.TTC	230.64	3	0.000
Vref	8.92	1	0.003
Vdis	22.47	1	0.000
Delta.TTC:Vref	0.72	3	0.868
Delta.TTC:Vdis	6.31	3	0.098
Vref:Vdis	22.29	1	0.000
Delta.TTC:Vref:Vdis	4.47	3	0.215

arrived before (ΔTTC −250: M = 206 ms; CI.95% = −181: 593, ΔTTC −500: M = 212 ms; CI.95% = −175: 599) compared to after (ΔTTC 250: M = 650 ms; CI.95% = 263: 1037, ΔTTC 500: M = 577 ms; CI.95% = 190: 964) the distractor object.

6.3. Distractor object

The findings for the distractor object mirrored those of the reference object. There were no significant main or interaction effects involving vertical separation. Mean CE was 424 ms (CI.95% = 45: 804) in the aligned condition and 412 ms (CI.95% = 32: 791) in the 3° vertical separation condition. In a subsequent reduced factorial model, there were main and interaction effects for ΔTTC, reference object velocity and distractor object velocity (see Table 4). The reduced model produced a significantly better fit of the data than the intercept-only model ($\chi^2_{(15)} = 243.43$, $p < 0.001$) and accounted for 88% of the overall variance (conditional R-square). CE was greater ($p < 0.0001$) when the reference and distractor object both moved at 7.5 °/s (M = 576 ms; CI.95% = 195: 956). CE was significantly lower when the distractor object arrived before (ΔTTC −250: M = 238 ms; CI.95% = −143: 619, ΔTTC −500: M = 220 ms; CI.95% = −161: 601) compared to after (ΔTTC 250: M = 631 ms; CI.95% = 250: 1012, ΔTTC 500: M = 583 ms; CI.95% = 202: 963) the reference object (see Fig. 6).

6.4. Lag between TTC estimations

A full factorial model indicated significant main effects for all factors, but no interactions. A main-effects only model produced an equal fit as the full factorial model ($\chi^2_{(25)} = 12.49$, $p > 0.1$), and a significantly better fit than the intercept-only model ($\chi^2_{(6)} = 123.84$, $p < 0.001$). The reduced model accounted for 60% of the overall variance (conditional R-square). Tukey pairwise comparisons indicated that lag was shorter ($p < 0.01$) when the objects were aligned (M = 729 ms; CI.95% = 595: 862) rather than separated (M = 801 ms; CI.95% = 668: 934) in the vertical axis. Also, lag was significantly shorter when the temporal separation between the reference and distractor objects (ΔTTC) was −250 ms (M = 672 ms; CI.95% = 536: 807) and 250 ms (M = 662 ms; CI.95% = 526: 797) compared to −500 ms (M = 869 ms; CI.95% = 733: 1004) and 500 ms (M = 857 ms; CI.95% = 721: 992). Again, while participants did not make their second TTC estimation at a fixed time after the first TTC estimation, perceived lag between the two objects was modulated by vertical separation (see Fig. 6).

7. Discussion

We compared TTC estimations when two objects with different features (i.e., circle and square) moved on horizontal trajectories that were aligned or separated in the vertical axis. Our results confirmed the presence of an asymmetric pattern of error (i.e., PRP-like effect), with more accurate TTC estimation for the lead object than the trail object. This was evident across a range of absolute arrival times and occurred irrespective of vertical separation. Analysis of the lag between the two successive TTC estimations confirmed that participants moderated their response in accord with the difference between the object arrival times. However, while participants waited on average and extra 170 ms between their two responses when ΔTTC was 500 compared to 250 ms, lag per se was largely overestimated. As can be seen in the CE data, this was predominantly due to overestimating TTC of the trail object. We also found that vertical separation moderated lag such that it was shorter when the objects were aligned. Observation of the CE data indicated that this was not due to a systematic misestimation in TTC of either the lead or trail object. It would seem, therefore, that vertical separation between two moving objects does exert a small but significant on the delay between successive TTC estimations.

8. General discussion

During our daily interactions within our normal surrounds, it is not unusual to make TTC estimations regarding the approach of more than one object. For instance, while cycling in a town or city one might follow the motion of other road users as they approach a junction or several pedestrians while walking along a busy street (Baurès, Oberfeld, Tournier, Hecht, & Cavallo, 2014; Gould, Poulter, Helman, & Wann, 2012). Such behaviours require attention to be allocated to multiple objects that can have different spatiotemporal properties and physical features (for a commentary on different attentional models see Tombu & Seiffert, 2008). Notably, while individuals are able to keep track of the spatial evolution of multiple objects with reasonable accuracy (Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988), there is a systematic pattern of error when estimating TTC of two objects at a known location. Specifically, it has been shown using a prediction motion (PM) task that TTC estimation error of the lead object is similar to single-object conditions, whereas TTC estimation error of the trail object is significantly increased when it arrives after a short delay (Baurès et al., 2010, 2011, 2017). This pattern of error is akin to the well-known Psychological Refractory Period (PRP), which is thought to be a result of attentional allocation rather than a capacity limitation (Arend et al., 2006; Martens & Wyble, 2010). In the PM task, for example, it is possible that participants increase overt attentional focus on the lead object, to the detriment of the trail object, because the former demands the more behaviorally urgent response (Lin, Franconeri, & Enns, 2008).

The current study compared TTC estimation in two experiments where the two moving objects had different vertical separation. The logic was that vertical separation might modulate allocation of attention between the lead and trail object (He et al., 1997; Shim et al., 2008), thereby influencing the pattern of TTC estimation error. In both experiments, each with different groups of participants, we found the expected asymmetrical error in TTC estimation (Baurès et al., 2010, 2011). Participants exhibited much larger error in estimating TTC of the trail object compared to the lead object when they had close temporal proximity (i.e., < 750 ms; Baurès et al., 2017). In addition, we showed here for the first time within a single study that this effect was not specific to a single TTC. However, and somewhat contrary to our initial expectations, we found no effect of vertical separation between the two objects on their respective constant error. The next part of our analysis examined if participants made their second response at a constant delay after the first response, such as might be a strategy if they were only able to determine arrival order. We ruled out this explanation by showing that participants modulated the lag between successive responses in accord with the difference between the object arrival times (i.e., 250 or 500 ms). In other words, participants showed evidence of estimating TTC of the two objects and not TTC of the lead object only. That said, lag per se was overestimated by approximately 300–600 ms, predominantly due to greater error in response to the trail object. Moreover, overestimation was reduced when the two objects were close together (0.5° in Experiment 1) or aligned (Experiment 2) in the vertical axis. Despite being of small amplitude (i.e., approximately 60 ms), the effect of vertical separation on lag was present in both experiments (with different participants) and was not due to a systematic misestimation of either the lead or trail object.

How, then, do we interpret the combined findings for constant error and lag between successive TTC estimations? To answer this question, we start from the positon that TTC estimation in the PM task involves several stages that are influenced by attention. As described above, we suggest that the asymmetrical error in TTC estimation is consistent with participants increasing attention on the lead object because it demanded the more behaviorally urgent response (Lin et al., 2008). An increase in attention on the lead object likely coincides with gaze location. For instance, we have previously shown that TTC estimation is more accurate when participants are permitted to pursue the moving object (Bennett, Baurès, Hecht, & Benguigui, 2010), and that having been cued to overtly pursue the trail object during the initial visible period, participants shift gaze to the lead object during occlusion (Baurès, Bennett, & Causer, 2015). Although yet to be confirmed, we suspect that having made their first response (TTC estimation) with gaze located on the lead object, participants in the current study shifted overt attention to the trail object, which added a small but significant delay when the two objects were located further apart in the vertical axis. A shift of overt attention could add delay through a combination of saccadic programming and interrupted processing of the trail object due to saccadic suppression. The implication is that the effect of vertical separation was a consequence of attentional allocation that occurred at a later stage than the perception of information required for accurate TTC estimation. It is important to recognize, however, that we were careful to ensure the horizontal trajectories did not cross during the initial visible period, thereby eliminating this simple cue to arrival order. Had this not been the case, estimation of TTC may have been mediated by vertical separation. For example, the crossing of horizontal paths during the initial visible period might exert a stronger influence on motion processing (e.g., distraction, vector averaging, assimilation) that underpins perception of TTC if the two objects are located close together or aligned in the vertical axis.

When modifying velocity and TTC of two objects in the PM task, there will be a unique change in horizontal separation between the evolving trajectories (see Fig. 2). Although this spatial variable would not independently account for any differences as a function of vertical separation in the current study, the influence of horizontal separation on accuracy of arrival order, and TTC estimation error, was indirectly considered in our regression modelling. For estimation of arrival order in experiment 1, the significant three-way interaction between velocity of the two objects and ΔTTC provided some indication that a spatial variable could have been involved for specific combinations of our parameters. For instance, participants made more errors in judging arrival order in trials where the lead object (i.e., reference or distractor) moved at 7.5 °/s and the trail object moved at 5 °/s with a 250 ms delay. A similar effect was evident in experiment 2, although the three-way interaction did not quite reach the conventional level of significance. Notably, however, 3 of the 18 participants did in fact exhibit no correct trials in these two conditions. It is possible, therefore, that participants failed to perceive that the horizontal motion paths of the two objects crossed late during the occlusion interval (see Fig. 2), and thus at a time when the ability to extrapolate object motion has begun to deteriorate (Bennett & Benguigui, 2016; Tanaka, Worringham, & Kerr, 2009; Wexler & Klam, 2001). Consequently, they may have incorrectly estimated that the formerly closer object (in space) also had the shorter TTC. As often found in children (Benguigui, Broderick, Baurès, & Amorim, 2008; Keshavarz et al., 2010), one explanation is that on some trials adult participants used a heuristic (e.g., distance) that did not provide reliable information to accurately estimate TTC (DeLucia, 2004). Intermittent use of either a temporal or spatial variable is supported by the finding that there was no effect of this particular combination of parameters on TTC estimation error or lag between TTC estimations (i.e., errorful trials omitted). It will be interesting in future work to a compare a wider range of conditions in which the motion paths cross at different times during the occlusion period.

Together with the results of our recent series of studies, here we confirmed that participants are unable to perform two concurrent TTC estimations with similarly high accuracy. Consistent with over-allocation of attention on the most salient object, participants systematically overestimated TTC of the trail object. Although recent work has indicated that this asymmetric pattern of error is not identical to the PRP effect exhibited in the RSVP task (for a detailed discussion see Baurès et al., 2017), these findings could have some important practical consequences. For instance, there could be some value in making participants aware that there is a tendency to over-allocate attention to the lead of two approaching objects, and then provide training or stimulus conditions that encourage a more even allocation of attention. This might be important in numerous ball-sport situations, where the player has to estimate TTC of the ball while concurrently estimating TTC between themselves and several opponents. Novice players are known to “ball watch” and are thus less aware of their surroundings. If the novice player does not correctly estimate the closing gap (and thus TTC) between themselves and surrounding players, this could result in a collision or give an advantage to the opposition. A similar situation could occur for the novice driver, who has to decide whether or not there is enough time to exit a junction when there are two cars approaching from the opposite direction. By recognizing and then over-allocating attention to the car that will pass the junction first, the driver might not update their TTC estimate of the second car, resulting in an inappropriately timed behaviour. Future studies with stimuli that are more representative of real world settings are required to confirm whether over-allocating attention on the lead object does indeed occur outside of the laboratory PM task in situations where asymmetrical estimation of TTC could have serious consequences.

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