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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