Title: Temporal estimation with two moving objects: overt and covert pursuit.

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Abstract

The current study examined temporal estimation in a prediction motion task where participants were cued to overtly pursue one of two moving objects, which could either arrive first (i.e., shortest TTC) or second (i.e., longest TTC) after a period of occlusion. Participants were instructed to estimate TTC of the first-arriving object only, thus making it necessary to overtly pursue the cued object while at the same time covertly pursuing the other (non-cued) object. A control (baseline) condition was also included in which participants had to estimate TTC of a single, overtly pursued object. Results showed that participants were able to estimate the arrival order of the two objects with very high accuracy irrespective of whether they had overtly or covertly pursued the first-arriving object. However, compared to the single-object baseline, participants' temporal estimation of the covert object was impaired when it arrived 500 ms before the overtly pursued object. In terms of eye movements, participants exhibited significantly more switches in gaze location during occlusion from the cued to the non-cued object but only when the latter arrived first. Still, comparison of trials with and without a switch in gaze location when the non-cued object arrived first indicated no advantage for temporal estimation. Taken together, our results indicate that overt pursuit is sufficient but not necessary for accurate temporal estimation. Covert pursuit can enable representation of a moving object's trajectory and thereby accurate temporal estimation providing the object moves close to the overt attentional focus.

Keywords: Time-to-contact estimation; Multiple object; Attention; Overt and covert pursuit; Eye movements

1. Introduction

Human capacities to estimate the time remaining before a single moving object reaches the observer or a specific point of interception (i.e., time-to-contact - TTC) are now well documented (e.g., Tresilian 1991; DeLucia, Kaiser, Bush, Meyer & Sweet 2003; Hecht & Savelsbergh 2004). These are typically assessed with the use of a prediction motion (PM) task in which a moving object is occluded by a visible or invisible occluder before it reaches the observer or a specified target. The observer is required to make a simple response (e.g., press a button) at the time the object would have reached the target, had it continued along its trajectory. Using the PM task (see Lugtigheid & Welchman 2011), it is generally found that participants overestimate shorter TTC and underestimate longer TTC, with the transition point occurring at approximately 1000 ms (e.g., Manser & Hancock 1996; Schiff & Detwiler 1979; Oberfeld & Hecht 2008). Overt pursuit of the moving object is the default response in the PM task (Rosenbaum 1975) and is important for achieving accurate TTC estimation, with greater error exhibited if participants are instructed to fixate on a static location compared to when permitted to freely move their eyes (Bennett, Baurès, Hecht & Benguigui 2010; Makin & Poliakoff 2011; Peterken et al. 1991). Furthermore, it is known that temporal estimation accuracy is negatively affected by attentional capture from a secondary task (Terry, Chartlon & Perrone 2008; Marinovic & Wallis 2011), thus indicating the importance of focused attention on the moving object throughout its trajectory.

Despite being prevalent in everyday life, much less is known about temporal estimation in situations where more than one object is approaching. For instance, it is often necessary while driving to follow the motion of several cars as they approach a junction or to judge the approach of several pedestrians while walking along a busy street (e.g., Gould, Poulter, Helman & Wann 2013; Baurès, Oberfeld, Tournier, Hecht & Cavallo 2014). These situations require perception of more than one motion trajectory and thus sharing or subdivision of attentional resource (for a commentary on different attentional models see Tombu & Seiffert 2008). Evidence from multiple object tracking indicates that participants can simultaneously track the motion of several objects for the purpose of latter identification (e.g., Pylyshyn & Storm 1988; Pylyshyn, et al. 1994; Sears & Pylyshyn 2000; Cavanagh & Alvarez 2005). The implication is that participants are able allocate their attention (with or without eye movements; Pylyshyn & Storm 1988) to different parts of the visual field in order to continuously update their spatial representation of moving objects (Tombu & Seiffert 2008). This ability to allocate attention between more than one location can also explain how, while overtly pursuing a cued object (i.e., gaze tracking), participants can extract motion characteristics (i.e., velocity) of a second, covertly pursued object (Poliakoff, Collins & Barnes 2004; 2005). Moreover, when tracking more than one object in the prediction motion task, attention has been implicated in the finding of asymmetrical temporal estimation error. For instance, temporal estimation is accurate for the first-arriving object but is overestimated for the second-arriving object when there is a short stimulus-onset-asynchrony (Baurès, Oberfeld & Hecht 2010, 2011). These findings are consistent with the influence of a Psychological Refractory Period (e.g., Pashler 1994), according to which the realization of a primary task (i.e., TTC estimation of first-arriving object) disrupts completion of a second task using the same central resource (i.e., TTC estimation of second-arriving object).

To our knowledge, no study to date has examined whether the human capacity to estimate TTC (i.e., not simply spatial location or velocity) is influenced by gaze location in a shared attention condition that involves two moving objects approaching a single target. For example, it remains unknown if observers, confronted with two moving objects, benefit from pursuing and thereby directing overt attention to the specific object for which they intend to estimate TTC. Here, then, we present a novel method that further explores the basis of temporal estimation error in the PM task with two objects. A PM task was performed in which participants were cued to overtly pursue one of two moving objects. The cued object could either arrive first (i.e., shortest TTC) or second (i.e., longest TTC) but this could only be reliably determined from the ongoing motion. Participants were instructed to estimate TTC of the first-arriving object only (cf. Baurès et al. 2010, 2011) thus making it necessary to overtly pursue the cued object while at the same time covertly pursuing the other (non-cued) object. A control (baseline) condition was also included in which participants had to estimate TTC of a single, overtly pursued object.

By comparing temporal estimation error in the single and two object conditions we aimed to determine if perception of TTC was influenced by the need to allocate attention between two moving objects rather than having to overtly pursue a single object only. We expected that if participants could simultaneously attend to several locations (i.e., two target and final point of contact) in the visual field (Pylyshyn, et al. 1994) and importantly perceive TTC of two objects without negative consequence, there should be no difference compared to a single TTC estimation condition. Additionally, by comparing temporal estimation error in the two-object condition between the cued and non-cued objects we sought to determine if and how perception of TTC was influenced by overt and covert tracking. Specifically, we examined if the accuracy of TTC estimation in the case of two moving objects was improved by overt pursuit of the object to arrive first. Finally, by recording eye movements while participants performed the two-object PM task, we determined if object arrival order and relative proximity to the point of arrival influenced participants gaze to the unseen object trajectories during occlusion (i.e., did they maintain gaze on the cued object throughout or switch to non-cued object under certain circumstances). Having done so, we then compared TTC estimation as a function of different gaze location during occlusion in order to investigate if there was a facilitatory effect.

2. Materials and methods

2.1. Subjects

Eleven male participants (mean age: 24 years) completed the experiment. Participants were familiarized to the current task and procedure, and were instructed on how to pursue the moving objects during a trial (see below for more detail). All participants had normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Written consent was obtained before the experiment, and in accordance with the Declaration of Helsinki, the protocol was approved by the Liverpool John Moores University local ethics committee.

2.2. Apparatus

Participants were sat in a purpose-built dark room, facing a 22” CRT monitor 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 1280x1024 pixels and a refresh rate of 85 Hz. Estimation of TTC was determined as the moment the space bar was pressed on a keyboard connected to host PC (Razer Arctosa 1000Hz Ultrapolling). Movement of the right eye was recorded at 1000 Hz using an EyeLink eye tracker (SR Research). The host PC and EyeLink were synchronised using TTL signals.

2.3. Task and procedure

In a “single-object” condition, TTC estimates were obtained for a circular object (diameter of 0.5 deg) moving at constant velocity (5 or 7.5 deg/s) in the fronto-parallel plane against a white background (cf. Schiff & Detwiler, 1979). The object was initially presented at a position on the left-hand side of the monitor for 2000 ms. Simultaneously, a vertically-oriented black arrival line (0.3 deg wide and 8 deg long) was presented in a fixed location (+12 deg from screen centre) on the right-hand side of the monitor. The horizontal distance between the object start position and the arrival line was varied on a trial-by-trial basis in order to achieve TTC of 1000, 1250, 1500, 1750 or 2000 ms (see Figure 1 for a pictorial representation of the stimulus presentation). The vertical position of the object was either coincident with screen centre or offset by +3 deg. The circular object was green during the initial stationary part of the trial, after which it changed colour to black and started to move rightwards. The moving object was visible for 800 ms and then passed behind an invisible "occluder" that obscured its trajectory. The object continued to move, unseen, toward the vertically-oriented black arrival line but did not reappear. Participants were asked to press the keyboard space bar at the instant the object would have made contact with the arrival line. No feedback on TTC 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. There were ten combinations generated from the two object velocities and the five levels of TTC, each of which was presented 6 times (N=60). The presentation order was pseudo-randomly arranged and then divided equally such that 30 trials were received in 2 separate blocks.

Insert figure 1 here

In a two-object condition, participants were cued prior to motion onset to overtly pursue one of two objects that moved on parallel horizontal trajectories from left to right. The two objects were initially presented on the left-hand side of the monitor for 2000 ms. The vertical offset between the objects was fixed at 3 deg (i.e., screen centre and +3 deg), while the horizontal offset varied on a trial-by-trial basis in accord with the object's TTC. The cued object was green during the initial stationary period, while the non-cued object was red. After the 2000 ms stationary period both objects changed colour to black and then moved on parallel horizontal trajectories from left to right for 800 ms with velocity of 5 or 7.5 deg/s. Each object could have one of the two velocities, independently of the other object, leading to four velocity conditions. TTC of the cued object was 1500 ms, whereas TTC of the non-cued object was 1000, 1250, 1750, or 2000 ms. Irrespective of which object had been cued, the first-arriving object had a temporal difference of -500 or -250ms relative to the second-arriving object (hereafter referred to as ΔTTC). In half the trials the cued object arrived at the vertical line first, while in the other half the cued object arrived second. Participants were asked to press the keyboard space bar to coincide with the moment the first-arriving object, be it cued or non-cued, would have made contact with the arrival line. 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.

The motion parameters of the cued object gave rise to two combinations of velocity with a single TTC, whereas the non-cued object was presented with 8 combinations (2 velocity × 4 TTC). In total, therefore, there were sixteen different trial types for the combinations of cued and non-cued object motion, each of which was presented 6 times (N=96). The presentation order was pseudo-randomly arranged for each participant and then divided equally such that 32 trials were received in 3 separate blocks. To control for potential effects of condition order, half of the participants started the experiment with the two-object condition, whereas the remaining participants started with the single-object condition. To control for potential effects of the object's position on the vertical axis, the cued object was presented at screen centre or +3 deg offset on an equal number of trials.

2.4. Data analysis

In order to ensure that participants complied with the instructions in the two-object condition, we first determined if gaze was maintained on the cued object. To this end, we identified and then excluded trials in which there was saccade during the initial visible part of the trajectory to the non-cued object, the arrival line or a non-specified location. Due to an excessive number of invalid trials, and thus non-compliance with the instructions, one participant was excluded from the group analysis. For the remaining participants, a total of 111 trials were excluded from subsequent analyses (approximately 10% of the total number of trials).[1]

In the one-object and two-object conditions, we determined the constant error (CE) on each trial. CE corresponds to the difference between the estimated TTC of the moving object and its actual TTC. A positive value represents an overestimation of the TTC (i.e., moving objected estimated to arrive after its true arrival) whereas a negative value represents an underestimation (i.e., moving objected estimated to arrive before its true arrival). We then computed the mean CE for each participant and each trajectory, by averaging the CE across repeated trials. Next, to determine if estimation of TTC differed between the one-object and two-object conditions, and subsequently if this was influenced by sharing of attention between overtly and covertly pursued objects, we computed an index of change in constant error (i.e., ΔCE) by subtracting mean CE in the two-object condition from the mean CE of the one-object condition (i.e., baseline). Note that while ΔCE does not reflect the precision of the TTC estimation, it indicates the shift in the TTC estimates when confronted with two objects as opposed to one object in isolation. A positive value of ΔCE indicates 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.

Individual participant ΔCE was computed for each of the 16 different trial types and submitted to a 2 pursuit (overt, covert) x 2 cued object velocity (5, 7.5 deg/s) x 2 non-cued object velocity (5, 7.5 deg/s) x 2 ΔTTC (-500, -250 ms) repeated measures ANOVA. ΔTTC reflected the fact that participants were required to estimate TTC of the first-arriving object when there was a long (-500 ms) or short (-250 ms) temporal gap relative to the second-arriving object. Partial η^2 is reported as a measure of association strength. The Huynh–Feldt correction for the degrees of freedom was used where applicable (Huynh & Feldt, 1976) and the value of ε;~ is reported. Post-hoc pairwise comparisons 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. Then to determine if ΔCE was significantly different from 0 ms we computed the 95% confidence intervals (95% CI) of means for each combination of factors. In the event that the 95% CI overlapped zero, it can be implied that there was a statistical difference between the one-object and two-object conditions, and thus an influence of a second moving object on the capacity to accurately assess TTC. The 95 % CI of means are reported between square brackets.

2.5. Eye movements analysis

There were two reasons for the measuring eye movements in this study. First, as described above, we wanted to ensure that participants followed the instruction to pursue the cued (i.e., overt) object during the initial visible period, and thus did not move their gaze to the non-cued (i.e., covert) object. Second, we wanted to characterize participants' gaze behavior during the occlusion (i.e., did they continue to direct gaze to the unseen trajectory of the cued object during occlusion irrespective of whether or not it would arrive first at the final point of contact), and then to determine if this influenced TTC estimation. To this end, we counted the number of trials with a change of gaze position in the Y-axis from the cued object location to the non-cued object location (see Figure 2). When a switch occurred, we noted the time and whether the non-cued object was closer, further or at the same distance from the arrival location than the cued object. To be defined as being at the same distance at the moment of gaze shift, the non-cued object and cued object had to be separated in the X-axis by less than or equal to 0.5 deg. We also noted the non-cued object's ΔTTC.

Insert figure 2 here

Based on the spatial and temporal characteristics of the non-cued object relative to the cued object in the event of a switch, trials were assigned to categories and expressed as percentage of the total number of switches. For example, if a participant made a total of 20 switches, 5 of which occurred when the non-cued object had ΔTTC of -250 ms and was closer to the arrival line than the cued object, these trials were defined as "ΔTTC = -250 ms / Closer" and accounted for 25% of the total number of switches. Note that while ΔTTC was a function of the experimental design, the relative distance at which a switch occurred was determined by the participant. The percentage for each of the eight categories was then arcsin transformed (Winer et al. 1991) and submitted to 4 ΔTTC (-500, -250, 250 and 500 ms) × 2 spatial proximity (closer, further) repeated-measures ANOVA.

3. Results

3.1. TTC estimation

In the two-object condition, we initially examined if participants were able to determine which object would contact first with the arrival line (i.e., shortest TTC). The data indicated that this was achieved with very high accuracy irrespective of whether participants overtly pursued (96.3%) or covertly pursued (94.8%) the first-arriving object during the initial visible period. Paired t-test on the arcsin transformed data (Winer, Brown, & Michels 1991) indicated no difference between these two conditions; t(10) = 0.61, *p* = .56. Subsequent single-sample t-tests indicated that accuracy was well above chance (50%) in both the overt and covert pursuit condition; t(10) = 15.74, *p* < .001 and t(10) = 12.54, *p* < .001.

ANOVA performed on delta CE showed a significant main effect of pursuit, F(1, 10) = 19.65, *p* =.001, ε;~ = 1, η_p^2 = 0.66, with mean ΔCE = -8.32 ms [-95.19; 78.55] in the overt condition and mean ΔCE = 139.61 ms, [14.87; 264.36] in the covert condition. There was also a main effect of ΔTTC, F(1, 10) = 41.80, *p* < .001, ε;~ = 1, η_p^2 = 0.81, with mean ΔCE = 18.48 ms, [-67.66; 104.63] for the short temporal gap and mean ΔCE = 112.81 ms, [4.75; 220.87] for the long temporal gap. These two main effects were superseded by a significant interaction between pursuit and ΔTTC, F(1, 10) = 11.38, *p* = .007, ε;~ = 1, η_p^2 = 0.53 (Figure 3). Post-hoc tests showed that ΔCE did not differ in the overt pursuit condition when ΔTTC was short, with mean ΔCE = -14.13 ms, [-101.03; 72.77] or long, mean ΔCE = -2.51 ms, [-93.96; 88.94]. However, in the covert pursuit condition, ΔCE was significantly larger for the long, mean ΔCE = 228.14 ms, [80.39; 375.89], compared to short ΔTTC, mean ΔCE = 51.1 ms, [-60.75; 162.95]. Finally, while there was no main effect of cued object velocity on ΔCE, F(1, 10) = .02, *p* = .884, there was a main effect of non-cued Object velocity, F(1, 10) = 5.189, *p* = .046, ε;~ = 1, η_p^2 = 0.34. These was also a significant interaction between these two factors, F(1, 10) = 8.58, *p* = .015, ε;~ = 1, η_p^2 = 0.46.

Insert figure 3 here

3.2. Eye movements

There were significantly more switches from the cued to the non-cued object for negative ΔTTC (-500 and -250 ms) than for positive ΔTTC (250 and 500 ms), F(3, 30) = 89.82, *p* < .001, ε;~ = 0.87, η^2 = 0.90. Mean percentage of switch (arcsin transformed) was

0.83, [0.75; 0.90] for ΔTTC = -500; 0.90, [0.77; 1.02] for ΔTTC = -250, 0.11, [0; .23] for ΔTTC = 250; 0.06, [-0.01; 0.12] for ΔTTC = 500. There were also more switches when the non-cued object was closer to the arrival line, $F(1, 10) = 170.80$, $p < .001$, ε;˜ = 1, $\eta^2 = 0.94$. Mean percentage of switch was 0.77, [0.74; 0.80] when the non-cued object was closer and 0.17, [0.09; 0.26] when it was further. There was also an interaction between these two factors, $F(3, 30) = 173.28$, $p < .001$, ε;˜ = 1, $\eta^2 = 0.95$ (Figure 4). Post-hoc testing showed that most switches were made to the non-cued object when it was closer to the finishing line and arrived -500 ms before the cued object (52% of the total of switches in gaze location were produced in this condition). Slightly fewer switches, but still significantly more than zero (37% of the total amount), were made when the non-cued object was closer to the finishing line and arrived -250 ms before the cued object. As can be inferred from the 95% confidence interval of the means, the percentage of switches in gaze location to the non-cued object in these categories was consistently high across participants. There was no difference in the percentage of switches irrespective of spatial proximity of the non-cued object to the finishing line when it arrived after the cued object.

Insert figure 4 here

Next we calculated the average switching time based on all trials from all conditions in which there was a switch in gaze location during occlusion. As can be seen in Figure 5, on average switches in gaze location occurred 391 ms after occlusion [315.52; 467.25], and had a distribution that was typically skewed with a long tail in direction of longer latencies. There was also a sub-set of switches in gaze location that occurred less than 100ms after occlusion.

Insert figure 5 here

Having found that certain combinations of object arrival order and relative proximity to the point of arrival resulted in a high percentage of switches in gaze location during occlusion, we then sought to determine if there was any relationship between this eye movement behavior and accuracy of TTC estimation. To this end, we computed for each participant the median CE in switch and no-switch trials for the two conditions leading to the greatest number of switches (i.e., ΔTTC = -500 and -250 ms).[2] We included in the analysis only those trials in which the correct arrival order was perceived in order to avoid any artificial influence on TTC estimation of an incorrect response based on TTC of the object that arrived second. Because there was an asymmetrical number of trials containing a switch than no switch in gaze location, median CE data were then subjected to a permutation test (e.g., Ernst, 2004). Accordingly, the difference between median CE for trials with and without a switch in gaze location was calculated for each participant, separately for each condition of ΔTTC (-500 and -250 ms). These difference values were then randomly assigned a weight (-1 or +1) and the group median was calculated. The random weight assignment was repeated 10000 times to produce a new distribution of 10000 group median difference values. This bootstapping technique produces a distribution centered on zero, which can be used to determine whether the actual median difference in participants' CE between the switch and no-switch trials occurred by chance. Following application of the permutation test, we found that there was no significant difference in median CE between the trials with a switch and those without a switch during occlusion (p = .89 for the ΔTTC = -500 ms condition and p = .32 for the ΔTTC = -250 ms condition).

4. Discussion

During pursuit of a single object, overt attention is typically located close to the location of eye gaze (Van Donkelaar & Drew 2002; Khan et al. 2010), and is thought to influence object identification (Lovejoy et al. 2009), as well as perception of temporal properties of motion (Marinovic & Wallis 2011). However, it is often necessary to pursue the motion of more than one object when interacting within our surroundings (e.g., Gould et al. 2013). While this can be achieved for the purpose of spatial updating and subsequent object identification with the eyes held stationary (Pylyshyn & Storm 1988), the typical response is to pursue the objects of interest (or their centroid) such that they are kept close to the fovea (Fehd & Seiffert 2008; 2010). Simultaneously tracking more than one object therefore involves a sharing of attentional resource between the overt gaze location and covert location of the other object and distractors; for differences in cortical activation between overt and covert pursuit see Ohlendorf et al. (2007). Indeed, the need to share attention when confronted with two moving objects in a PM task could be the cause of asymmetrical temporal estimation error (Baurès et al. 2010, 2011).

To better understand how allocation of attention, as inferred from gaze location, influences the ability to estimate temporal arrival of two moving objects, here we instructed participants to overtly pursue one of the objects (i.e., cued), which could either arrive first (i.e., shortest TTC) or second (i.e., longest TTC) at a predetermined location after a period of occlusion. Both objects were initially visible for 800 ms, while start location and velocity was varied randomly from trial-to-trial such that arrival order (first or second) and time could only be reliably determined from the ongoing motion. Our results showed that irrespective of whether the first-arriving object had been overtly or covertly pursued, participants were able to make an accurate relative TTC estimation and thereby determine the correct arrival order of the two objects. Having made this distinction, absolute TTC estimation of the overtly pursued object remained unaffected by the presence of the non-cued object. For the covertly pursued object, this was only the case when the temporal separation to the overtly pursued object was short (i.e., ΔTTC of –250 ms). In such instances, the covert object moved in close proximity to the overt object, with a mean absolute spatial separation of 3 ± 2.11 deg during the initial visible period and 2.5 ± 1.69 deg at the moment of occlusion. With such spatial separation the two objects would have tended to be in the foveal (i.e., 0-2 deg eccentricity) and/or parafoveal region (i.e., 2-5 deg eccentricity), which may have enabled participants to better share attention and extract the motion characteristics. On the other hand, for ΔTTC of −500 ms, there was a larger mean absolute spatial separation during the initial visible period (3.63 ± 2.67 deg) and at occlusion (3.13 ± 2.60 deg) between the overt and covert pursued objects. Notably, this spatial separation between objects was more evident at the moment of occlusion for ΔTTC of 500 ms compared to 250 ms, which is also when information for temporal estimation in the PM task is particularly important (Benguigui & Bennett 2010). Indeed, only in this situation did TTC estimation differ compared to the single object condition. It will be interesting in future work to determine if such motion characteristics result in a higher incidence of switching during the initial visible period from a cued object to non-cued object if participants are not given explicit instructions regarding their eye movements.

Having overtly pursued the cued object during the initial visible period, participants were free to decide whether to maintain gaze in the direction of this object during occlusion or to switch gaze to the non-cued object. Our analysis of eye movements during occlusion indicated that in trials where the cued object arrived first (ΔTTC of 250 and 500 in Figure 4), participants very rarely switched gaze to the covertly pursued object (i.e., 12 of a total 528 trials). However, when the cued object arrived second (ΔTTC of -250 and -500 in Figure 4), participants exhibited a significant percentage of trials (i.e., greater than zero) in which they switched gaze during occlusion to the covertly pursued object. This was particularly evident when the covertly pursued was closer to the finishing line, both temporally and spatially, than the overtly pursued object. Analysis of when these switches in gaze occurred indicated that this was on average 391 ms after occlusion, and thus not simply a reactive response to the loss of visual input. That said, we did find that approximately 12% of the switches in gaze location were made with a very short latency equal to or less 100 ms after occlusion. Such switches in gaze location to the non-cued object are likely to be indicative of anticipatory saccades initiated while both objects were visible or express saccades in response to sudden occlusion. Given the large percentage of trials with a switch to the non-cued object when it arrived first, we then sought to determine whether this change of gaze location benefited TTC estimation. Interestingly given the clear dominance of gaze switching behaviour, our analysis indicated that there was no significant difference in TTC estimation between trials with or without a switch to the non-cued object during occlusion.

Together the above data indicate that the first-arriving object, whether it was overtly or covertly pursued during occlusion, attracted gaze and thus a reallocation of overt attention. This is in agreement with previous findings in which it was suggested that gaze, and thereby overt attention, is directed to the object that demands the more behaviorally urgent response (Lin, Franconeri & Enns 2008). Moreover, it is also consistent with the suggestion that gaze during an occlusion, and therefore overt attention, tends to follow the forward motion of the object (e.g., representational momentum) and rarely switches to a location behind and opposing motion (Lovejoy et al. 2009). Interestingly, however, switching gaze from the cued to non-cued object during occlusion did not appear to be influence TTC estimation. One might suggest that this indicates a lack of contribution from eye movements. That said, we doubt that participants would maintain similarly accurate TTC estimation if they had not been permitted to move their eyes to pursue the visible and subsequently occluded objects. For instance, it has been shown that TTC estimation differs between conditions of fixation compared to pursuit when presented with a single moving object (Bennett et al. 2010; Makin & Poliakoff, 2011), and that pursuit is the typical response when participants are not giving explicit instructions (Rosenbaum, 1975). Indeed, as suggested previously, we feel it is likely that participants extract sufficient information from the initial visible part of the presentation to represent the moving object's trajectory, as well as to make an accurate TTC estimation.

Here we have shown that participants can do this when confronted with two moving objects, and in particular when one of them is covertly pursued.

In sum, our results demonstrate that overt pursuit is sufficient but not always necessary for accurate TTC estimation when faced with two moving objects. Participants are able to perceive TTC of a covertly pursued object providing it moves close to the location of overt gaze. In this respect, the novel method used here provides an important step towards understanding the relationship between temporal estimation and attention allocation when faced with multiple objects. It remains for future research to measure precisely the extent of temporal and spatial separation, as well as velocity differential, between the two objects that permits accurate TTC estimation.

Conflict of interest

The authors declare that they have no conflict of interest

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Footnote

1. While such a percentage of rejected trials might seem quite high, it is important to remember that additional objects in the visual scene often attract visual attention (e.g., Marinovic & Wallis, 2011, Gould et al., 2013), even if the additional object is explicitly known to be task-irrelevant (e.g., Oberfeld & Hecht, 2008, Baurès et al., 2011). In the current experiment, the second object was in fact task-relevant (e.g., would it arrive before or after the other object?), we preferred to proceed with a high rejection rate and thus minimize a potential source of bias in our results.

2. Given the very low number of switches in gaze location exhibited by all participants in the conditions ΔTTC = 250 and 500 ms, it was not reasonable, and in some cases possible, to compute median data.

Figure captions

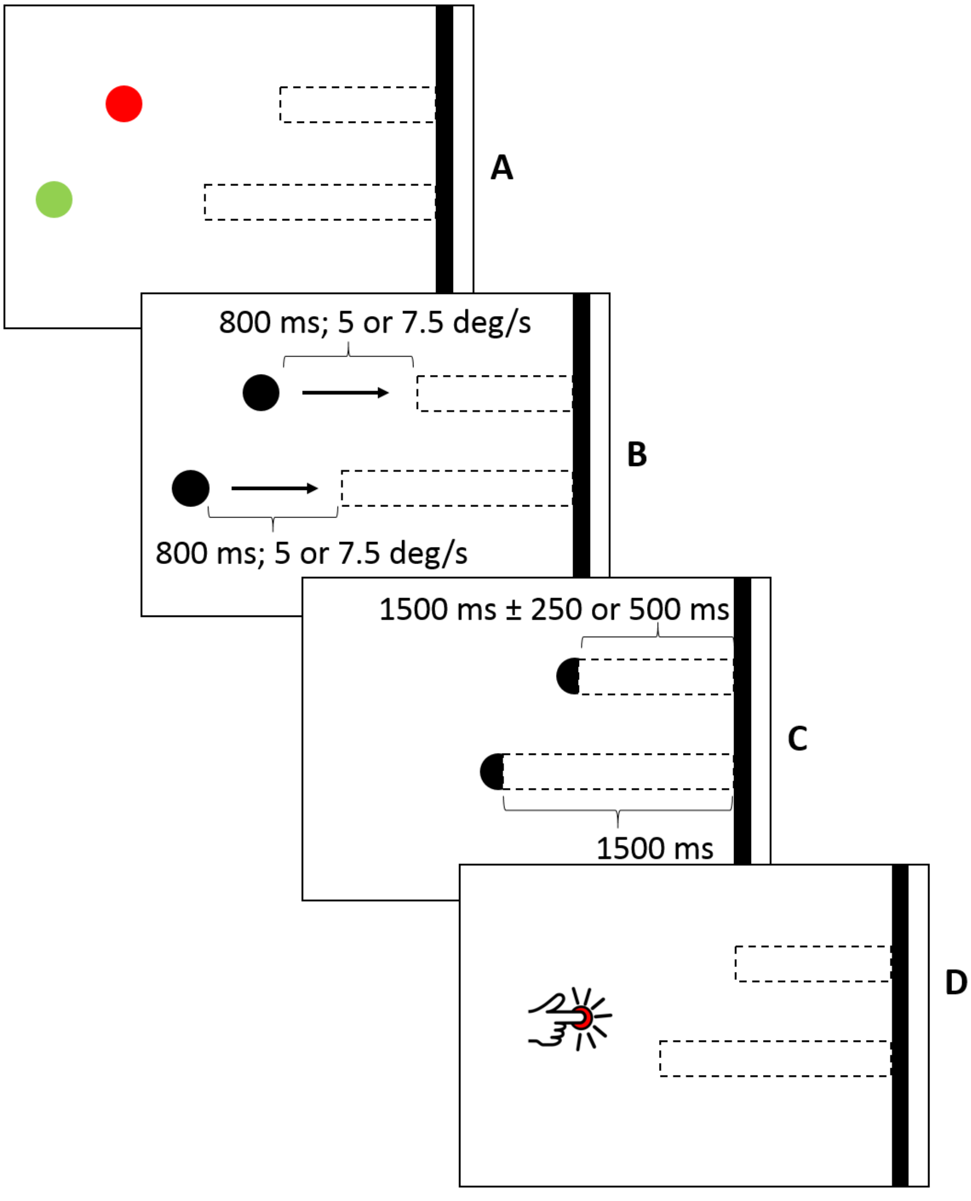
Figure 1: Representation of the visual stimulus in the two-object condition. A. The visual scene contains two stationary circular objects and an arrival line (full black rectangle). One of the objects is green to indicate it should be pursued while visible (cued object), whereas the other object is red (non-cued object). The two dashed rectangles represent the forthcoming occlusion of the objects, but were not visible to the participants during the experiment. B. The two objects turn black and start moving for 800 ms toward the arrival line with a velocity of either 5 or 7.5 deg/s independently of each other. C. Both objects are occluded at the same time, with the cued object reaching the arrival line after 1500 ms and the non-cued object arriving either earlier or later by 250 or 500 ms. D. Participants pressed a button to coincide with the moment the first-arriving object, be it cued or non-cued, would have made contact with the arrival line.

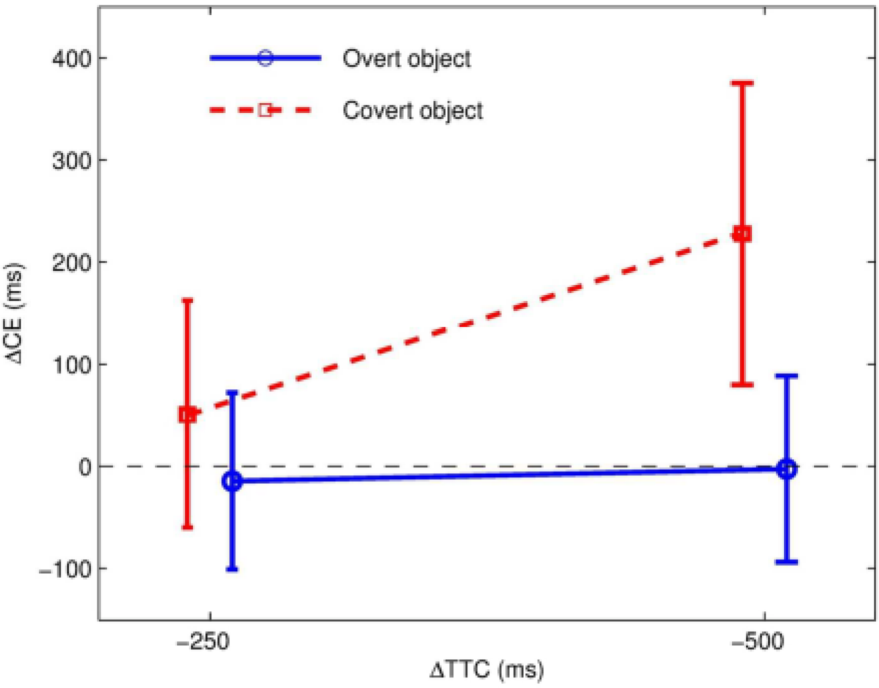
Figure 2: ΔCE as a function of the attention condition and ΔTTC. Error bars show the 95% confidence interval obtained from the ANOVA.

Figure 3: Example of a switch from the overt to the covert object in the two-object condition. The blue lines indicate overt pursuit on the X-axis (solid line) and Y-axis (dashed line), whereas the green lines indicate the covert pursuit on the X-axis (solid line) and Y-axis (dashed line) after the switch is made. White (on) and black (off) bars below the abscissa indicate target visibility. At the time the switch is made during the occlusion, the covert object (dotted black line) is closer to the finishing line (solid black line) and with a ΔTTC of -500 ms.

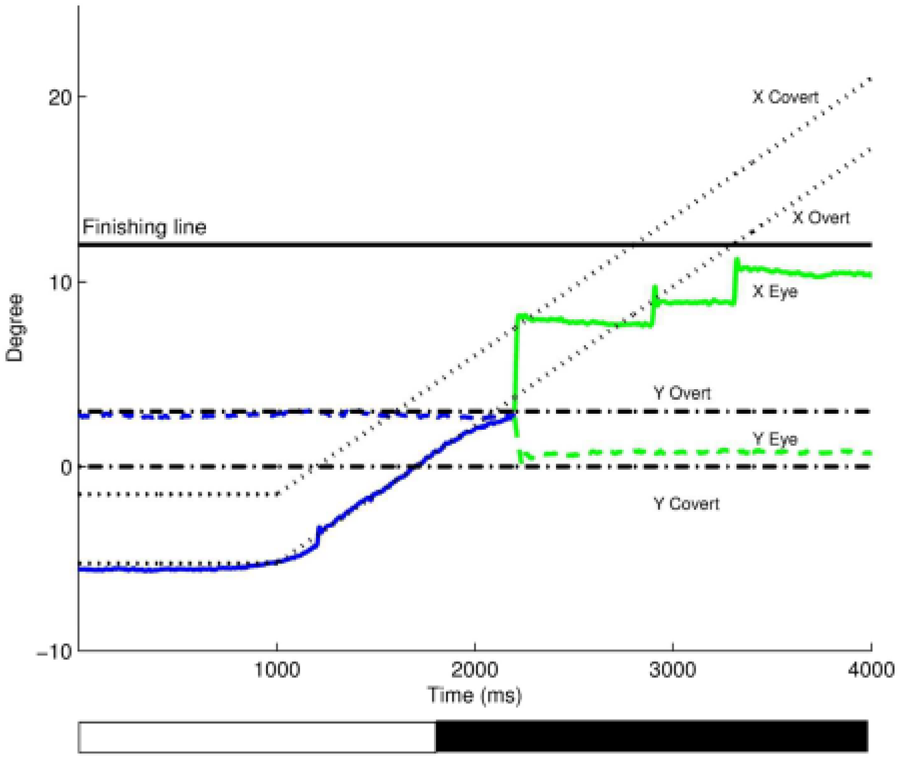
Figure 4: Percentage (in arc sin transforms) of switch occurrence away from the cued object as a function of ΔTTC and the non-cued object spatial proximity (closer or further away) with the finishing line at the time of the switch. Bars indicate the 95% CI.

Figure 5: Histogram showing percentage switch occurrence away from the cued object as a function of time after occlusion. Bins are equal to 20ms intervals.

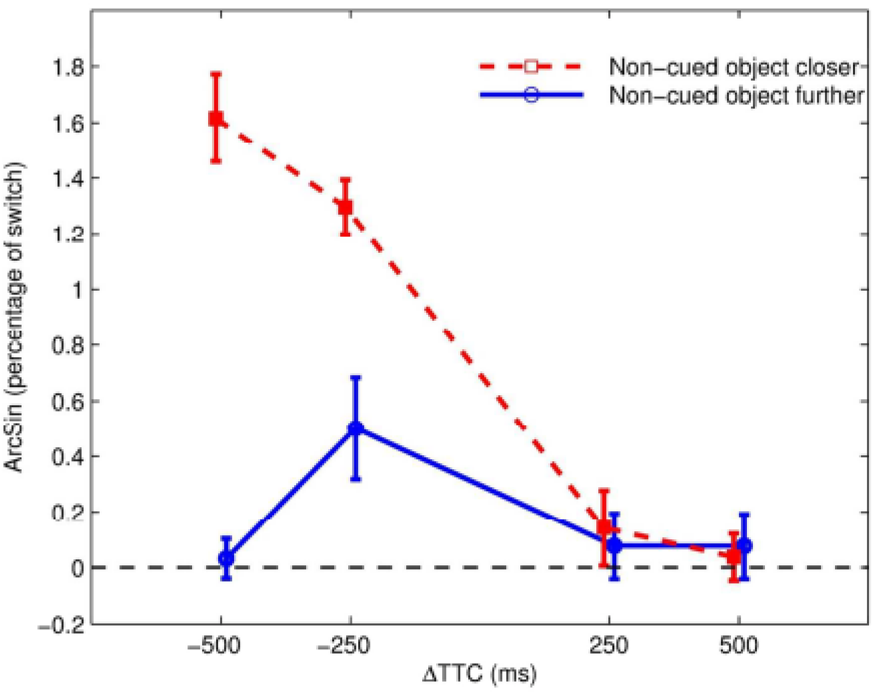

A
800 ms; 5 or 7.5 deg/s
800 ms; 5 or 7.5 deg/s
B
1500 ms ± 250 or 500 ms
C
1500 ms
D

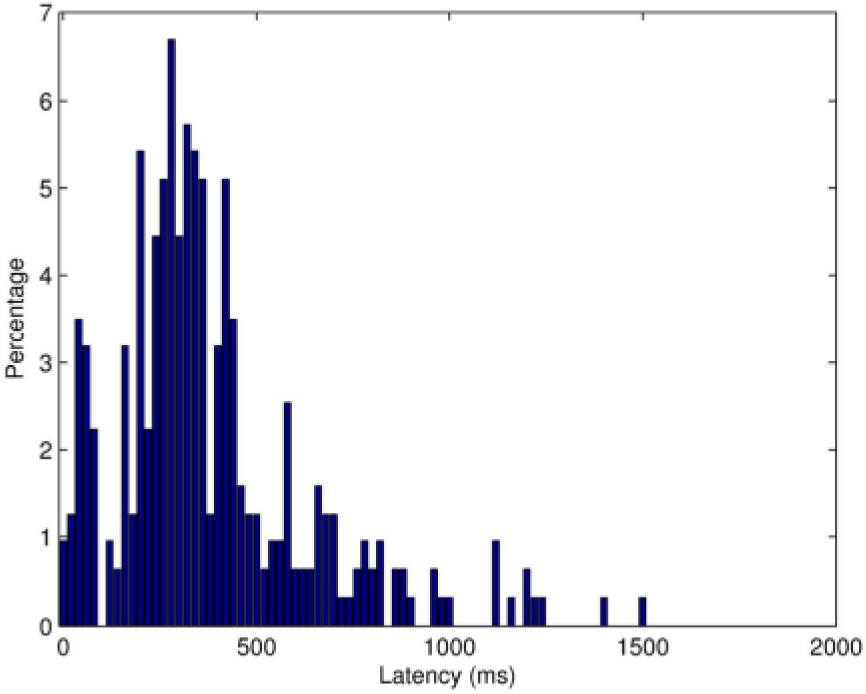


Overt object
Covert object
400
300
200
100
0
−100
ΔCE (ms)
−250
−500
ΔTTC (ms)



X Covert
X Overt
Finishing line
X Eye
Y Overt
Y Eye
Y Covert
Degree
Time (ms)
20
10
0
−10
1000
2000
3000
4000


Non−cued object closer
Non−cued object further
ArcSin (percentage of switch)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−500
−250
250
500
ΔTTC (ms)



Percentage
Latency (ms)
0
1
2
3
4
5
6
7
0
500
1000
1500
2000