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RESEARCH ARTICLE

Availability of attention affects time-to-contact estimation

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Abstract
To estimate the time-to-contact (TTC) of a moving object, numerous studies have focused on the type of information or gaze strategy used by the observer. However, it remains to be determined whether and how attention could affect TTC estimation. In particular, how does TTC estimation operate when less attention is available? To answer this question, we conducted two experiments in which the participants had to perform an absolute (Experiment 1) or relative (Experiment 2) prediction-motion task, either alone (i.e., in single-task condition) or along with a secondary, visual working-memory task (i.e., in dual-task condition). In both experiments, we found that TTC estimation was superior in dual-task condition relative to single-task condition. This finding suggests that the reduction of available attention actually improves TTC estimation. We discuss possible explanations as well as theoretical implications for this seemingly counter-intuitive finding. Further research is needed to investigate if (in)attention facilitates or only shifts TTC estimation.

Keywords Time-to-contact estimation · Attention · Dual task · Prediction motion

Introduction

In many day-to-day situations, people often have to estimate when a moving object will reach a spatial location, such as a pedestrian crossing the street, an opponent in a basketball game, or a landing plane for those working as air-traffic controllers. But how do people estimate time-to-contact (TTC), that is the time separating the current position of an object from its final spatial location? In the prediction-motion (PM) paradigm, observers are presented with a moving object that disappears at some points for a more or less long period of time (usually a few hundreds of milliseconds). Observers are asked to press a button when they estimate the object has reached the arrival point.

Two alternative strategies have been suggested to explain performance in the PM paradigm (DeLucia and Liddell 1998). According to the first strategy, the observer mentally simulates the moving object (cognitive motion extrapolation strategy) and behaves as in a real interceptive action with vision continuously available. As such, the coincident response (i.e., a simple keypress with one finger) would be triggered when a perceptual variable reaches a threshold value composed of the movement time added to a visuo-motor delay (e.g., Tresilian 2004, 2005). One such perceptual variable is tau, the instantaneous visual angle subtended by the object divided by its instantaneous rate of expansion (for looming objects, see Lee 1976; for objects moving in the fronto-parallel plan, see, e.g.; Bootsma and Oudejans 1993). In case of complex motor responses (e.g., moving the whole hand to the right location), an alternative account is that the perceptual variable continuously guides the hand movement without need for a "trigger" to start the button press (e.g., Peper et al. 1994).

In the second strategy, observers would estimate TTC by using cognitive clocking: the estimation of the TTC obtained

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during the visible part of the trajectory is counted down, and the observer presses the button when the elapsed time since occlusion corresponds to the estimated TTC (again here minus the movement time added to a visuo-motor delay, Tresilian 1995; Benguigui and Bennett 2010).

Whatever the strategy adopted by the observer, a common question is how the mind “fills the gap” (Bosco et al. 2015) during the occlusion time and compensates for the lack of visual information. As stated by Zhao and Warren (2015, p. 200): “under exceptional conditions, such as visual occlusion, near visual threshold, or repeated object motion, action may be controlled by simple off-line strategies such as heuristics, mappings, or spatial memory”. Consistent with this statement, it has often been demonstrated that TTC estimation is influenced by cognitive factors, such as prior knowledge pertaining to the target’s speed, acceleration, or size (e.g., familiar size and prior knowledge, see Baurès and Hecht 2011; DeLucia 2005; Hosking and Crassini 2011; López-Moliner et al. 2007; McIntyre et al. 2001; Zago et al. 2004).

If prior knowledge influences TTC estimation in a PM paradigm, could other cognitive mechanisms interfere with the estimation? In the present study, we wished to determine whether and how cognitive processes influence TTC estimation, with a special focus on the role played by attention, using the PM paradigm. To this end, we addressed the issue of whether attention is necessary to estimate TTC, while the object is out of sight. With full attention devoted to the TTC estimation, both the clocking strategy (see Matthews and Meck 2016)[1] and the cognitive motion extrapolation strategy (see Kerzel 2003; Makin and Poliakoff 2011)[2] predict an increase of accuracy, compared to a shared-attention condition.

To investigate this, we manipulated the amount of available attentional resources by asking participants, while performing a TTC task, to either simultaneously maintain in working memory a configuration of colored rectangles (dual-task condition) or ignore it (single-task condition). As mentioned by Engle (2002, p. 20), “WM capacity is not about individual differences in how many items can be stored per se but about differences in the ability to control attention to maintain information in an active, quickly retrievable state” (for a similar proposition, see also Barouillet et al. 2004, 2007). As such, by using a working-memory task in the dual-task condition, our task actually manipulates the amount of attention available for the TTC task depending on the requirement of memorizing or not the squares’ color. This manipulation was directly inspired by Vickery et al. (2010) study, in which it was found that performance on a visual-search task was slower in the dual-task condition relative to the single-task condition. Therefore, we assumed that less attention is available in the dual-task condition than in the single-task condition. Because attention is generally found helpful in many perception tasks (see, e.g., Lachter et al. 2004), a possible prediction is that TTC estimation should suffer in the dual-task condition relative to the single-task condition. In contrast, there is an existing literature showing that, when too much attention is available and devoted to the task, performance actually suffers. For instance, it has been shown that focusing attention on task components actually impairs perceptual performance (such as face recognition; see, e.g., Schooler and Engstler-Schooler 1990) or motor performance (such as golf putting; see, e.g., Chauvel et al. 2013). This negative effect of attention on performance may stem from a temporary disruption of fast processes by slower processes. Following this view, a possible prediction is that TTC estimation would actually be facilitated in the dual-task condition relative to the single-task condition, because the reduction of the amount of available attention diminished the possibility to focus too much attention while estimating the TTC task.

Experiment 1

Participants

Twenty students (mean age = 22.9 years; SD = 2.5 years; range = 19–31 years; 8 women) were recruited from Université Toulouse 3—Paul Sabatier. They participated after giving informed consent. All participants had normal or corrected-to-normal vision, and were healthy and without any known oculomotor abnormalities. Participants were naïve with respect to the purpose of the experiment, which was conducted in accordance with the Declaration of Helsinki and approved by the host University local ethics committee.

Apparatus and experimental procedure

Stimulus presentation, timing, and collection of responses were performed using a Hewlett Packard computer, equipped with a 3.4 GHz Intel i5 processor and a 27-in. HP screen, and controlled by software E-Prime 2.0.10. The screen resolution was 1920 × 1200 pixels (horizontal by vertical). The monitor refresh rate and display update rate were 60 Hz. Participants sat on a chair and viewed the computer display from approximately 0.55 m. The screen center was positioned in the middle of the two eyes.

[1] According to Matthews and Meck (2016), two hypotheses may explain why attention may influence the clocking strategy: because an attentional gate controls the flow of pulses from a pacemaker into an accumulator, or because attention determines the latency with which the flow of pulses begins after the stimulus onset.

[2] Kerzel (2003) and Makin and Poliakoff (2011) argue that attention may be necessary to maintain mental extrapolation of target motion.

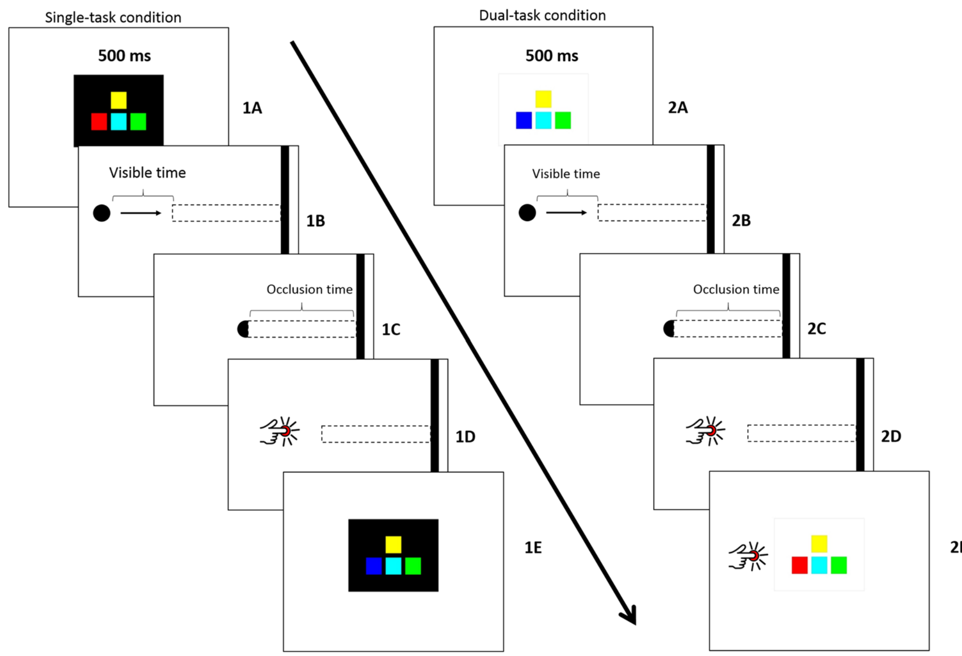

Fig. 1 The two types of time-to-contact (TTC) trials used in Experiment 1. In the single-task condition, the moving target (the black circle, 1B) suddenly disappeared (1C) and participants were required to estimate when it reached the vertical bar (1D). In dual-task condition, participants had to retain in working memory the four colored squares (2A) while performing the TTC task and then indicate for which of the four squares the color had changed (2E). Note that in 1B and 2B, the starting point of the ball varied depending on the ball's velocity and occlusion time

Figure 1 shows a description of a TTC trial performed in single-task condition or in dual-task condition. Each trial started with the presentation of four colored squares for 500 ms (1A, 2A). For one-half of the trials, the color of the background was black and indicated that the squares had to be ignored. For the other half of the trials, the color of the background was white and indicated that the squares had to be memorized and recalled at the end of the trial (dual-task condition). Background color (black or white) changed randomly from one trial to another. Then, the prediction motion (PM) task started. First, a black target was presented against a white background and remained stationary for 1000 ms. The target then started to move horizontally, from left to right, in the direction of a black vertical line (the arrival line), with a constant velocity of 5 or 10 cm/s (1B, 2B). After 1000 ms of visible movement time, the target disappeared and remained occluded for a varying duration of 500, 1000, 1500 or 2000 ms (1C, 2C). Participants were instructed to press a key on the keyboard as soon as they estimated that the occluded target had entered into contact with the arrival line (1D, 2D). The arrival line was always positioned on the right side of the screen. Because varying velocities and occlusion times were used, the starting position of the target was varied. To end a trial, the four colored squares were presented but one of them had a different color. In the dual-task condition (white background), participants were instructed to indicate which square had a different color (2E), while in the single-task condition, participants were just told to wait for the next trial (1E). Participants received visual feedback (in the form of a happy or a sad face icon) for their performance at the Visual Working Memory (VWM) task (on dual-task trials). No feedback was presented for the TTC performance. The single-task and dual-task trials, hereafter generally termed as the Attention condition, were randomly intermixed in presentation order. There were 12 repetitions for each of the 16 possible combinations (2 Attention condition $\times$ 4 TTC $\times$ 2 Velocity), resulting in a grand total of 192 experimental trials. The whole experiment lasted about 1 h.

Data analysis

Constant error (CE) is the main dependent variable and is calculated for each trial as the TTC estimate (i.e., based on participants' response) minus the TTC actual value.[3] A positive CE indicates that the participants overestimated the actual TTC (i.e., pressed the button too late). On the contrary, a negative CE indicates that the participants underestimated the actual TTC (i.e., pressed the button too early). Figure 2 presents the distribution of CE as a function of the Attention Condition and TTC. Variable error (VE) is a secondary dependent variable and is computed as the standard deviation of CE for a specific experimental condition.

Only dual-task trials for which the visual working-memory (VMW) task was performed correctly were analyzed. Mean accuracy on the VMW task was 93.85% [95% confidence interval (89.68, 98.02%), well above chance, $p < 0.001$]. CE and VE were then analyzed with a 2 (Attention: single or dual-task) $\times$ 4 (actual TTC: 500, 1000, 1500

[3] Because TTC can be both an independent variable (the occlusion time applied to the moving object) and also the dependent variable that has to be judged (the moment the object is thought to arrive at the finishing line), we will refer to actual TTC as being the independent variable and estimated TTC as the judgement of the participants.

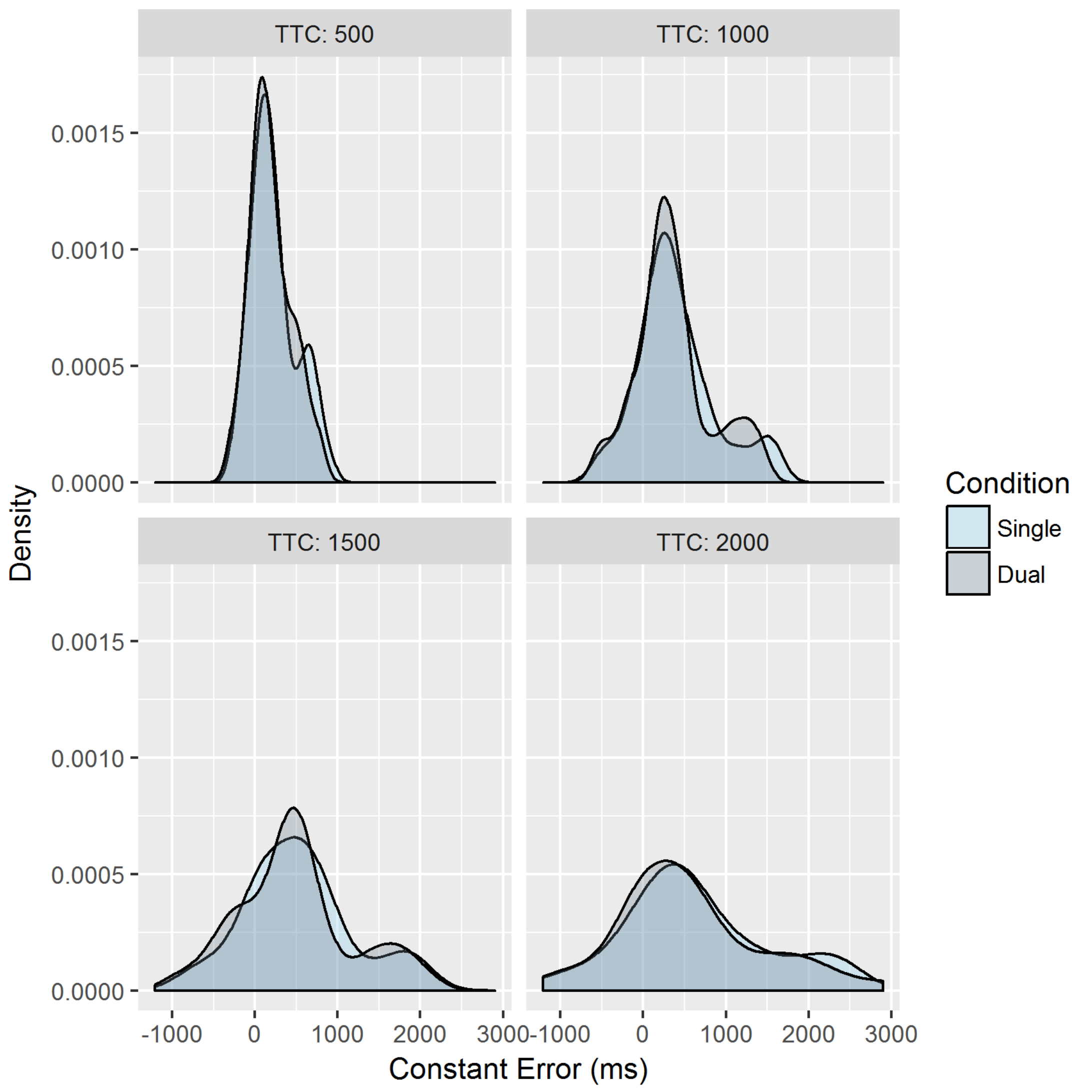

Fig. 2 Distribution of constant error as a function of the attention condition and actual TTC

or 2000 ms) × 2 (Velocity: 5 or 10 cm/s) repeated measures ANOVA. The Huynh–Feldt correction for the degrees of freedom was used where applicable (Huynh and Feldt 1976), and the value of $\tilde{\varepsilon}$ is reported. Post hoc comparisons among all levels of actual TTC were conducted using nonpooled error terms (i.e., by computing separate paired-samples *t* tests; Keselman 1994) and Hochberg's (1988) sequentially acceptive step-up Bonferroni procedure, with an alpha level of 0.05.

Results

When analyzing CE, the main effect of Attention condition was significant, $F(1, 19) = 9.20$, $p = 0.007$, $\eta^2_p = 0.33$, with TTC estimation more accurate (i.e., closer to 0 ms) in the dual-task condition (mean CE = 395 ms, 95% CI = [139:651]) than in the single-task condition (mean CE = 447 ms, 95% CI = [185:708]). This advantage in the dual-task condition was of 52 ms, 95% CI = [16:88]. Cohen's d following Läkens (2013)'s formula was of $d_z = 0.68$, indicating a moderate effect of attention over CE. Finally, the common language effect size (CL, see Läkens 2013)[4] indicated that after controlling for individual differences, there was a likelihood of 75% that a person had a lower CE in the dual-task rather than in the single-task condition.

The ANOVA also confirmed the classical effects found in PM task: accuracy decreased as actual TTC increased, *F*(3,

[4] According to Läkens (2013), "CL effect size expresses the probability that a randomly sampled person from one group will have a higher observed measurement than a randomly sampled person from the other group (for between-designs) or (for within-designs) the probability that an individual has a higher value on one measurement than the other".

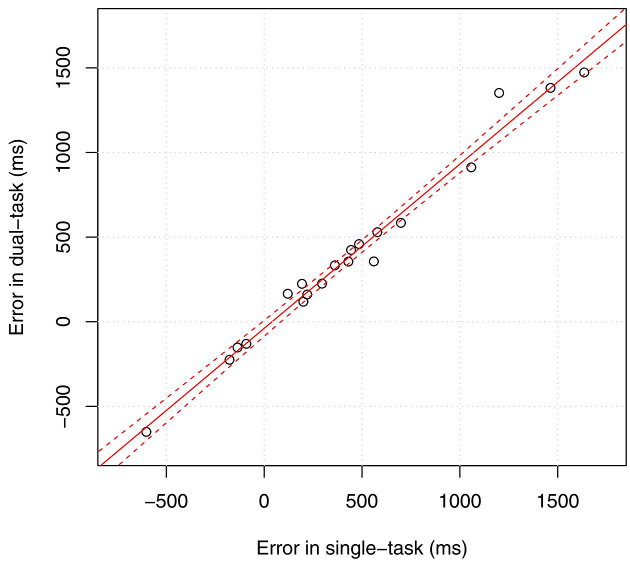

Fig. 3 Correlation of constant error (CE) in the dual-task condition as a function of CE in the single-task condition. Open circles represent the 20 participants. The continuous red line represents the regression line and dashed red lines the 95% confidence intervals

57) = 7.30, $p = 0.012$, $\tilde{\varepsilon} = 0.36$, $\eta^2_p = 0.33$, and increased as Velocity increased, $F(1, 19) = 23.47$, $p < 0.001$, $\eta^2_p = 0.55$. There was a significant interaction between Velocity and actual TTC, $F(3, 57) = 14.80$, $p < 0.001$, $\tilde{\varepsilon} = 0.63$, $\eta^2_p = 0.44$, with a smaller decrease in accuracy as actual TTC increases for the larger Velocity. The interaction between Attention and Velocity almost reached statistical significance, $F(1, 19) = 4.23$, $p = 0.053$, with a tendency of a larger difference in accuracy as a function of velocity in the dual-task condition relative to the single-task condition. All the remaining interactions, in particular with Attention condition, were non-significant (all $ps > 0.46$).

Additionally, we examined the correlations between CEs in the dual-task and single-task conditions. Because absolute TTC estimation is very variable among individuals (Lugtigheid and Welchman 2011), we wondered if the decrease in CE due to the secondary task would vary depending on the level of CE in the single-task condition. We reasoned that a weak correlation would indicate a very variable influence of the attentional load, which would influence the participants with a different magnitude of reduction in CE. On the contrary, a strong correlation would indicate that each participant's performance is influenced by the attentional load, with the same magnitude. This latter prediction was actually confirmed, $t(18) = 30.61$, $p < 0.001$ (see Fig. 3). The correlation coefficient was extremely high, with $r = 0.99$, CI = [0.976:0.996], $r^2 = 0.98$. The regression gave the following equation relating CE in the dual-task condition to the CE in the single-task condition:

$$\mathrm{CE}_{\mathrm{Dual-task}} = 0.97 \times \mathrm{CE}_{\mathrm{Single-task}} - 38.88.$$

Table 1 Mean CE and mean VE depending on the attention condition and TTC

	TTC (ms)	Single-task	Dual-task
Mean CE (ms)	500	225 [99:351]	188 [75:302]
	1000	398 [170:626]	361 [145:577]
	1500	527 [222:833]	476 [160:792]
	2000	637 [234:1040]	554 [158:950]
Mean VE (ms)	500	179 [138:220]	176 [144:207]
	1000	277 [230:325]	247 [202:292]
	1500	356 [280:432]	372 [288:456]
	2000	433 [355:510]	442 [343:542]

Numbers in brackets represent the 95% confidence interval

It therefore appears that dual-task condition influences each participant's TTC estimation performance in the same way by favoring a more accurate estimation. Additionally, it confirms that attention is a key factor in such a task for all of them. Finally, the analysis of VE showed neither a main effect of Attention, $F(1, 19) = 0.04$, $p = 0.85$, (mean VE = 311 ms, 95% CI = [257:365] in the single-task condition, and mean VE = 309 ms, 95% CI = [252:366] in the dual-task condition), nor an interaction of Attention with the other factors (all $ps > 0.59$, see Table 1).

Discussion of Experiment 1

The results of Experiment 1 showed that TTC estimation was actually closer to 0 ms when participants were estimating in the dual-task condition relative to the single-task condition, that is when less attention was available to estimate the TTC. But with no change in VE, our results are consistent with a change in the bias (as expressed by CE) of the estimation, while the sensitivity (as expressed by VE) remains unaffected by the attentional condition. Experiment 2 aimed at replicating these results with a different method.

Experiment 2

In this experiment, participants had to estimate when a moving target that suddenly disappeared would reach the vertical bar, relative to an external, auditory event. We call such a task a relative TTC estimation task. Using this task, we then applied a method consisting in fitting a psychometric function onto the data, in order to determine bias and sensitivity among observers, in each Attention condition (for a comparison of the absolute and relative TTC estimation methods, see Lugtigheid and Welchman 2011).

Except where noted, the procedure was identical to the one used in Experiment 1.

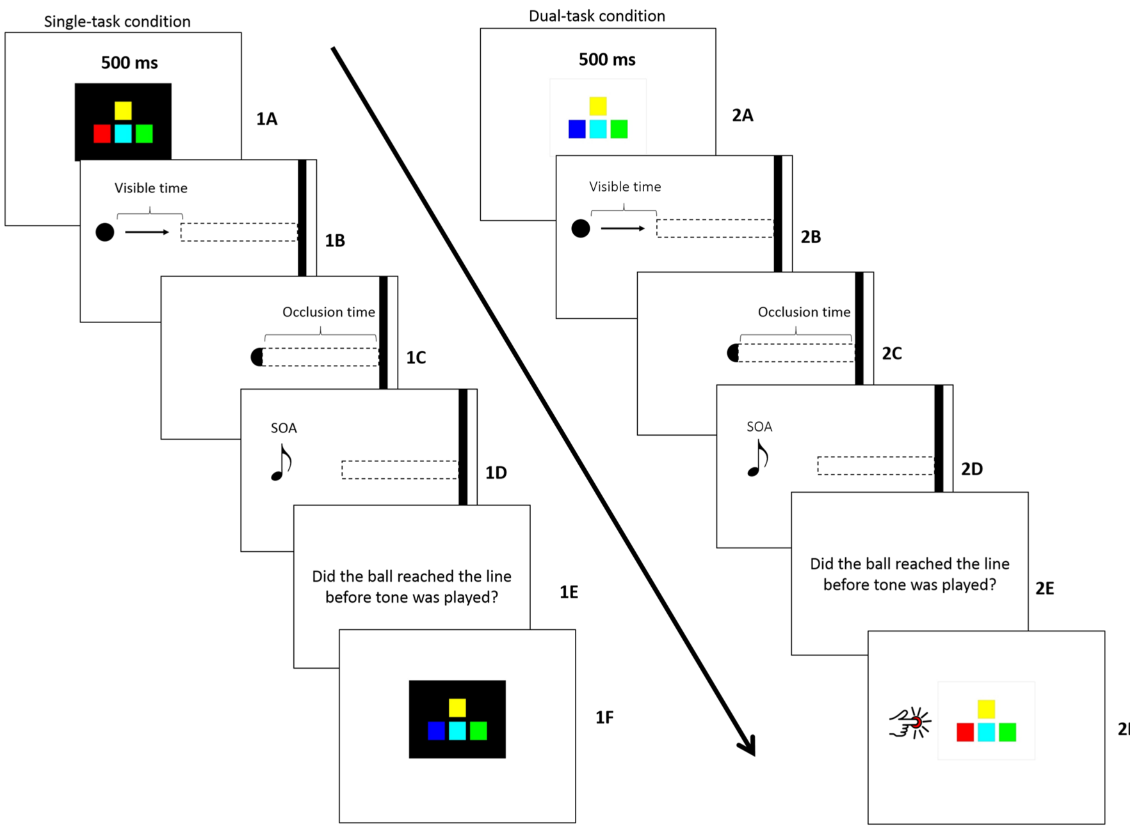

Fig. 4 The two types of time-to-contact (TTC) trials used in Experiment 2. In single-task condition, the moving target (the black circle, 1B) suddenly disappeared (1C) and a tone was played at various Stimulus Onset Asynchrony (SOA) respective to the arrival of the target at the vertical bar (1D). Participants were required to estimate if the target reached the vertical bar before or after the tone was played (1E). In dual-task condition, participants had to retain in working memory the four colored squares (2A) while performing the TTC task and then indicate for which square the color had changed (2E). Note that in 1B and 2B, the starting point of the ball varied depending on the ball's velocity

Participants

Eight students (range = 23–25 years; 3 women) were recruited from Université Toulouse 3—Paul Sabatier, including a graduate student in charge of testing the participants. They were all between 23 and 25 years of age and participated after giving informed consent. All participants had normal or corrected-to-normal vision, and were healthy and without any known oculomotor abnormalities. With the exception of the graduate student (Participant 01), all participants were naïve with respect to the purpose of the experiment, which was conducted in accordance with the Declaration of Helsinki and approved by the host University local ethics committee.

Apparatus and experimental procedure

As shown in Fig. 4, participants were presented with a black target against a white background. After 1000 ms without movement, the target started to move toward a finishing line, remained visible for 1000 ms (1B, 2B), and got occluded for another 1000 ms (1C, 2C). During the occlusion time, an auditory tone (duration = 100 ms, frequency = 44 100 Hz) was played, at various Stimulus Onset Asynchrony (SOA) respective to the moving target's arrival time. SOA was of either − 600, − 300, − 200, − 100, + 100, + 200, + 300 or + 600 ms (1D, 2D). A negative SOA indicates that the tone was played before target's true arrival, while a positive SOA indicates that the tone was played after target's arrival. Participants were instructed to press one of two keys to indicate if the target had reached the line before the tone was played. Following their answer, participants completed the VMW task or switched to the next trial depending on the Attention condition (single or dual-task conditions). The single-task and dual-task trials were randomly intermixed in presentation order. Participants performed 100 repetitions for each of the 16 possible combinations (2 Attention Condition × 8 SOA), for a total of 1600 trials. The experiment was divided in 10 sessions of 160 trials, each lasting about 50 min, and run on separate days.

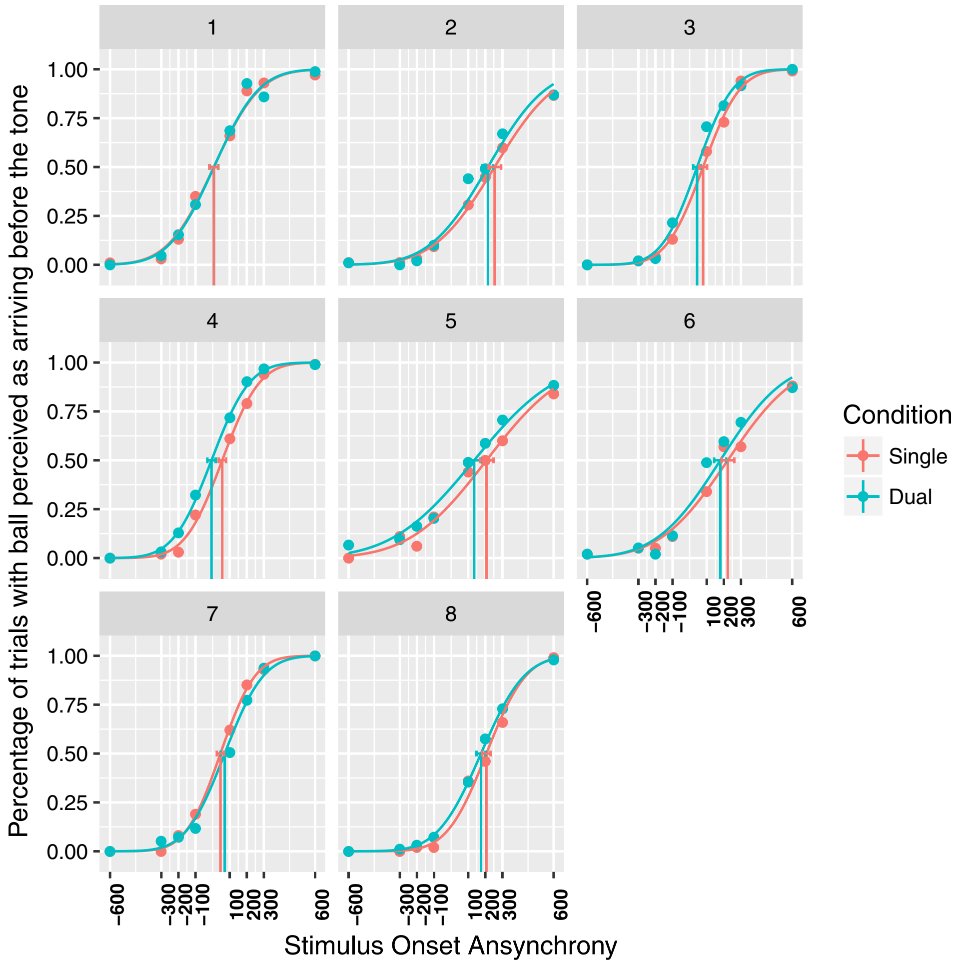

Fig. 5 Psychometric function relating the percentage of trials with the target perceived as arriving before the tone, for each participant (one per panel) as a function of stimulus onset asynchrony and Attention (single-task condition or dual-task condition). Points correspond to the actual response of the participants and vertical lines correspond to the individual PSS

Data analysis

Only trials for which VWM was successful were analyzed. Mean accuracy on the VMW task was 93.73% (95% confidence interval of [90.67:96.79] %, well above chance, $p < 0.001$). Successful trials were used to fit for each participant a psychometric function using R (R Core Team 2016) and the quickpsy package (Linares and López-Moliner 2016), with 10,000 bootstrap repetitions. Individual point of subjective synchrony (PSS), that is, SOA for which a participant declared the moving target reached the vertical bar before the tone was played in 50% of the trials (see Fig. 5), and sensitivity (expressed as the inverse standard deviation of the psychometric function) were subjected to a paired Student's *t* test.

We also analyzed accuracy in order to determine whether the target reached the line before the tone was played (Accuracy) and whether it would depend on the Attention condition, SOA and the reaction time to give the answer at the TTC task (RT). However, it appeared that for a very few trials, RT was very long (maximal value of 24 s), indicating outlier values. As participants were not instructed to give their answer as fast as possible, we considered as outliers any trials with RT above 5000 ms (0.2% of the trials were excluded using this method). Logistic regression analyses were used to determine whether accuracy was under the influence of Attention, SOA and RT.

Results

Figure 5 shows the psychometric function relating the percentage of trials with moving target perceived as arriving before the tone and SOA, for each participant and in each Attention condition. The analysis of PSS confirmed a difference in bias depending on the Attention condition, $t(7) = 2.87$, $p = 0.023$, with a Cohen's dz of 1.02 (i.e., this indicates a strong effect). Consistent with the results of Experiment 1, TTC estimation was more accurate (i.e., PSS closer to 0 ms) in the dual-task condition (mean = 103 ms, 95% CI = [32:173]) than in the single-task condition (mean = 134 ms, 95% CI = [54:216]). The CL effect size indicated that, after controlling for individual differences, the likelihood that a person had a lower PSS in the dual-task

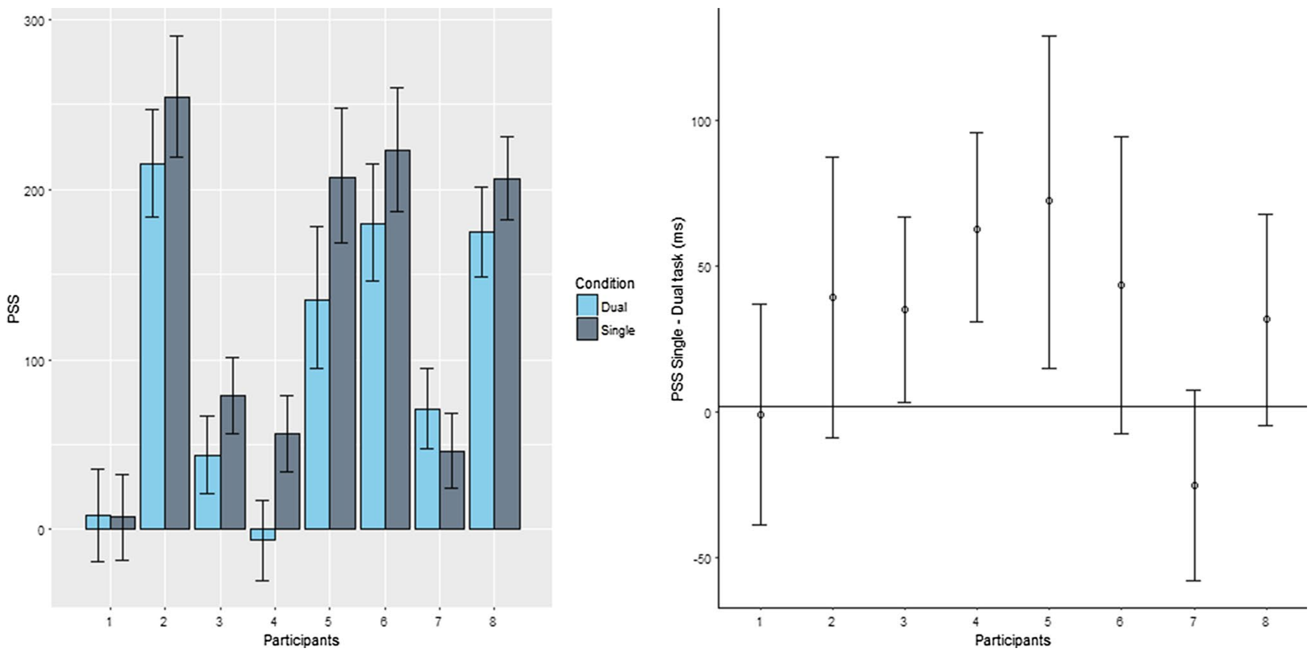

Fig. 6 Left panel: PSS for each participant in the single-task and dual-task condition. Right panel: difference in PSS in both Attention conditions for each participant. Positive values indicate a standard deviation greater in the single-task condition. Error bars represent the 95% confidence interval of the mean

than in the single-task condition was very high (85% of chances).

The bootstrap procedure also allowed for testing the Attention condition for each individual participant. Figure 6 shows individual PSS in the single and dual-task conditions, and difference between these conditions. Error bars in the right panel represent the 95% confidence interval; hence, error bars not covering the 0 ms value indicate a significant difference for the particular participant in-between the two attention conditions. Three participants (participants 3, 4 and 5) have a significant difference and three others a nearly significant difference (participants 2, 6 and 8), thus overall showing a PSS closer to 0 ms in the dual-task condition. However, two other participants present a different pattern. Participant 1 is the graduate student that carried out the experiment. It appears likely that knowing both the purpose and the design of the experiment, she developed a response strategy that led to the very identical results observed in the two Attention conditions. All the analyses have therefore been re-run excluding her results, which did not change the outcomes; therefore, all results are presented including this participant. However, and in contrast with the majority of the participants, participant 7 showed a trend for a PSS closer to 0 ms in the single-task condition rather than in the dual-task condition.

The slope of the psychometric function, expressing the sensitivity of the participants to SOA, is given through the standard deviation of the curve (a low standard deviation indicating a steeper curve with an important slope). A paired-samples t test showed no difference between the attention conditions in the standard deviation, $t(7) = 0.52$, $p = 0.62$ (Fig. 7). The analysis of individual standard deviation confirmed this group effect, as no participant showed a significant or even a trend for difference in standard deviation depending on the Attention condition.

Finally, the analysis of participants' accuracy at determining the relative order of target's arrival and tone (Accuracy) through a logistic regression showed many significant effects (see Table 2). In particular, although Attention was only marginally significant on its own, it interacted with RT. As can be seen in Fig. 8, RT influenced Accuracy differently as a function of SOA and Condition. First of all, Accuracy was generally lower in the dual-task rather than in the single-task condition. Moreover, as RT increased, Accuracy decreased for most of the SOAs (−600, −300, −200, −100, 300 and 600 ms). However, for the SOAs surrounding the mean PSS (i.e., SOAs of 100 and 200 ms), the opposite effect was found: accuracy increased as RT increased (except for the dual-task condition, SOA = 200 ms).

The observation that Accuracy is generally smaller in the dual-task condition than in the single-task condition, for a given RT, is surprising and at odds with the previous results of Experiment 2. Because mean PSS is closer to 0 ms in the dual-task condition, it could be assumed that Accuracy would be higher in the dual-task condition. However, it could also be the case that RT is lower in the

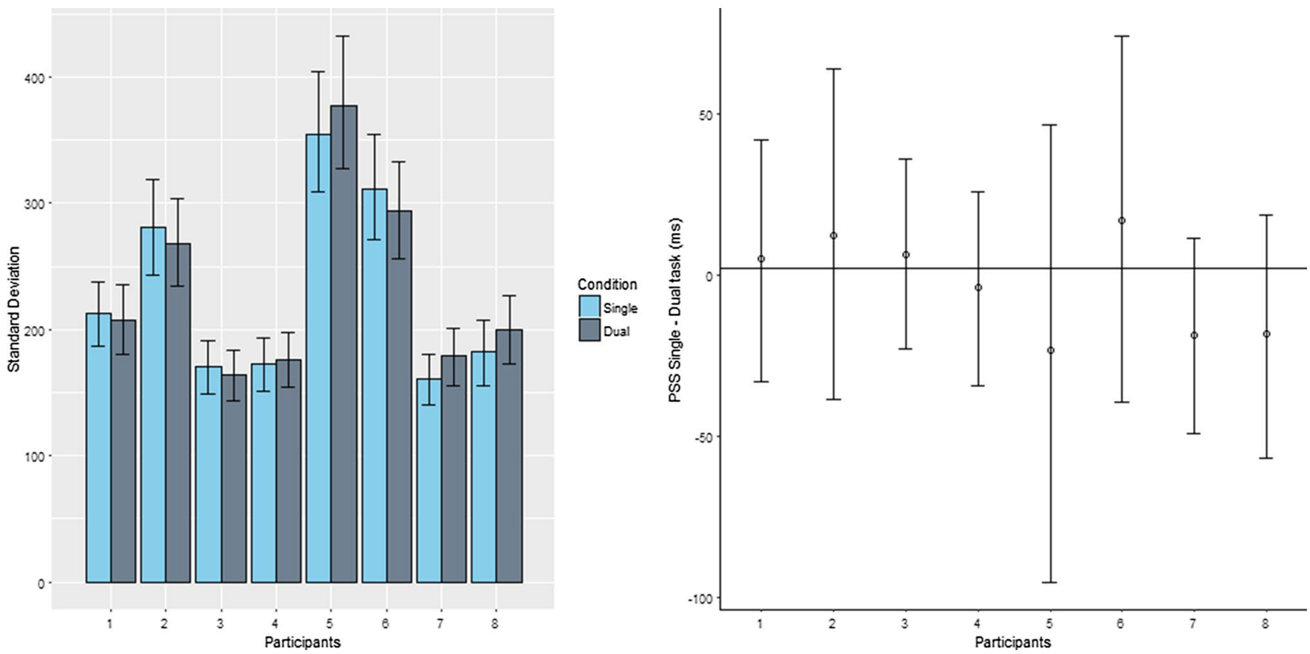

Fig. 7 Left panel: standard deviation for each participant in the single-task and dual-task conditions. Right panel: difference in standard deviation for each participant. Positive values indicate a standard deviation greater in the single-task condition. Error bars represent the 95% confidence interval of the mean

Table 2 Output of the logistic regression analysis

	Estimate	SE	*z* value	*p*
(Intercept)	2.05E+00	5.02E−02	40.766	< 0.001
RT	− 6.39E−04	5.28E−05	− 12.091	< 0.001
Attention (single-task)	− 1.26E−01	7.15E−02	− 1.767	0.077
SOA	− 1.39E−03	1.46E−04	− 9.55	< 0.001
RT × attention (single-task)	2.13E−04	7.52E−05	2.831	0.005
RT × SOA	6.30E−07	1.75E−07	3.6	< 0.001
Condition (single) × SOA	− 1.95E−04	2.05E−04	− 0.951	0.341
RT × attention (single-task) × SOA	− 9.56E−08	2.39E−07	− 0.399	0.689582

dual-task condition rather than in the single-task condition. A paired *t* test on RT as a function of Attention condition confirmed this, $t(7) = 3.26$, $p = 0.014$, Läkens' formula of Cohen's $d = 1.15$ showing a very strong effect, with a lower RT in the dual-task condition (mean = 570.02 ms, 95% CI = [508.41:631.64]) rather than in the single-task condition (mean = 607.40 ms, 95% CI = [544.01:670.78]). Finally, the CL effect size indicated that after controlling for individual differences, the likelihood that a person has a lower RT in the dual-task rather than in the single-task condition is 88%.

Discussion of Experiment 2

Mirroring the results of Experiment 1, those of Experiment 2 showed a change in the bias when Attention was driven away from the TTC estimation, with a bias closer to 0 ms, while the sensitivity remained unaffected. Consistent with Experiment 1's finding, reducing the amount of available attention led to a shorter TTC estimation. This shift suggests that the criterion used to decide target–tone synchronicity is closer to 0 ms when attention resources are diverted toward a secondary, attention-demanding task, albeit the subjective flow of time remains unaffected (time does not fly for the observers). But when attention is fully available, accuracy at determining event order (target arrival before tone occurrence and vice versa) is lower as evidenced by participants tending to seemingly adopt a strategy consisting in responding sooner.

What does the analysis of RT and accuracy tell us? One interpretation is that, when uncertainty is high—presumably when SOA is close to PSS—then a longer decision time is needed to answer correctly. However, for easier conditions

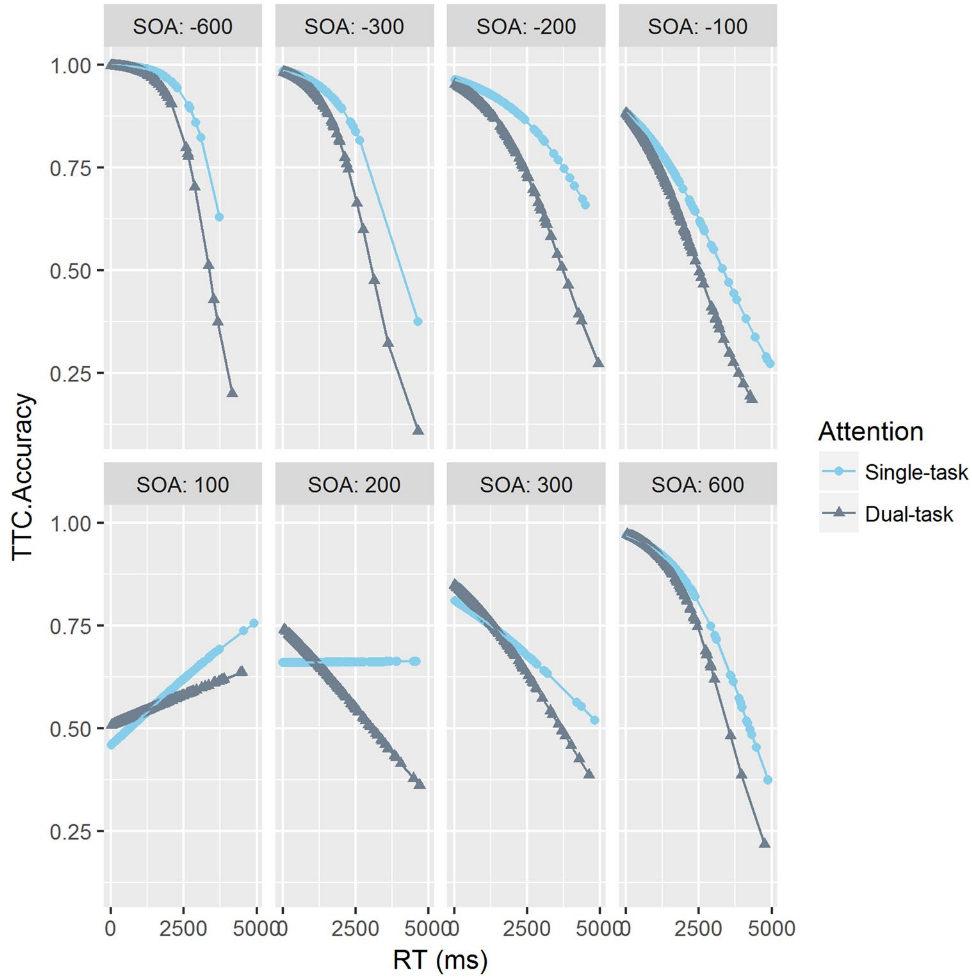

Fig. 8 Accuracy as a function of SOA (different panels) and attention condition. Red circles represent the single-task condition while blue triangles the dual-task condition

(when SOA markedly differs with mean PSS), a longer decision time is, on the contrary, detrimental to the accuracy of the answer. In addition, higher RT leads to a decay in accuracy and this is more pronounced in the dual-task condition, presumably because task 2 places higher demands on VWM; to cope with this, participants may have responded earlier in this condition. The secondary task therefore not only changes the TTC perception, but also increases the urgency to indicate that perception.

Discussion

Tracking a moving object with one's gaze generally helps when estimating its TTC (e.g., Bennett et al. 2010). However, what is the attentional cost of TTC estimation when the moving object is out of sight? Attention is generally found helpful in many tasks, from basic mechanisms like contrast sensitivity (Ling and Carrasco 2006), contextual cuing (Vickery et al. 2010), to higher visual tasks like multiple object tracking (Allen et al. 2004). In line with these results, it would seem natural to expect better TTC estimation when attention is fully available. For instance, it might be the case that the strategies involved in a PM task—cognitive clocking or cognitive motion extrapolation—are performed less efficiently when less attention is available. To evaluate this case, we sought to determine whether reducing the amount of available attention would negatively influence performance on a PM task. While our two experiments bring very consistent results with two different methods, they do not allow us to make definitive conclusions regarding the influence of directing attention away from the TTC estimation. There are indeed two viable interpretations to these results.

A better TTC estimation?

In our two experiments, the CE (Exp. 1) and bias (Exp. 2) are closer to 0 ms in the dual-task condition, reflecting a more accurate TTC estimation when attention is driven away from the TTC task. This finding is not consistent with the general view according to which perceptual performance suffers when less attention is available. Our results indicate that it had an opposite influence: when participants could not devote full attention to the PM task (i.e., in the dual-task condition), their TTC estimation was actually more accurate. However, it is consistent with the literature according to which focusing too much attention actually impairs performance. It is indeed important to acknowledge that full attention available for a perceptual task does not systematically lead to a better performance: numerous studies have indeed found a detrimental influence of attention. For example, Olivers and Nieuwenhuis (2005, 2006) investigated how the attentional blink, that is, the reduced ability to detect the second of two targets if presented shortly after the first (typically less than 500 ms), is affected by the presence of a secondary task. The results demonstrated that the attentional blink is reduced (performance improves) if the participants had to perform a secondary task.

Consistent with our results, Fruchtman-Steinbok and Kessler (2016) showed that performance in detecting a target was increased (i.e., faster detection time) when participants had to memorize a set of squares of varying colors and positions. In addition, the larger was the set, the better was the performance at the detection task. This effect was true however only when SOA between the initial presentation of the square and the target to detect was short but not long. Perhaps the larger the set of squares to memorize, the larger the amount of mobilized effort to perform the detection task, more so at the shortest SOA when the sense of urgency to complete the task was the highest.

Motoyoshi et al. (2015) investigated how attention modulates several visual parameters. They found that attention directed toward a second Rapid Serial Visual Presentation (RSVP) task increased sensitivity to detect a global (Experiment 1) but not a local (Experiment 2) motion. They also found that it decreased sensitivity to detect motion differences (Experiment 3). In addition, the facilitation of global motion detection was observed when attention was directed away from central vision (Experiment 5) and attentional load (i.e., task 2 difficulty) modulated the influence attention had upon task 1 performance. Namely, when task 2 became too difficult, no facilitation of global motion detection was anymore observed. The authors argued that when attention is broadly spread over all the visual scene due to attention drawn onto a secondary task, this facilitates spatial integration of different motions. This hypothesis could also offer a good explanation for the current results: even if there is only one moving object in the TTC estimation task, participants also have to consider the arrival line. By doing so, a broadly spread attention would induce a global motion processing of the stimulus which would, in turn, favor TTC estimation.

Beilock et al. (2002) offer an alternative explanation to the results. According to these authors, expertise in a given task allows an automatic execution of the task, with a minimal attentional control. This feature of expertise explains why experts can perform a secondary task without any perturbation for a well skilled task (i.e., no change compared to the task done in isolation), as shown by Leavitt (1979) or Smith and Chamberlin (1992). It is worth noting however that in these studies, attention is directed toward a second task not related to the main task. If attention is on the contrary directed toward a task related to the main task to execute then, as shown by Beilock et al. (2002), performance is impaired. These authors suggested that when attention is directed toward a component of the main task, this prevents its automatic execution in favor of a step-by-step control of the task, which is harmful to skilled performance.

Possible explanations of how attention could affect performance in a PM task

Regarding the underlying theories of TTC perception, the current results confirm that the unavailability of vision in the PM task allows for cognitive cues and internal representations to fill the gap (Bosco et al. 2015) and play a role in the TTC estimation process as demonstrated with the role of prior knowledge (e.g., McIntyre et al. 2001). However, full attention devoted to the task was expected to increase the performance in the TTC task, which is contrary to our current results. How could attention affect performance in a PM task? Based on the aforementioned studies, we see and suggest several explanations:

1. While the object is visible, Motoyoshi et al.'s (2015) results could argue for a better sensitivity to the motion parameters that are used to elaborate the TTC estimation or simulate the object's motion during the occlusion time. The strategy used during the occlusion time, either the motion extrapolation or clocking strategy, would therefore make use of a better perceptual phase, and consequently be more accurate in the dual-task condition.
2. The lack of attention could alter the strategy used during the occlusion phase, for example by modifying the tracking velocity of the mental simulation of the object or altering the chronometer that counts down the TTC. The availability of attention could also modify a higher cognitive mechanism: it has been suggested that extrapolation tasks in general, as in the PM task, but also when extrapolating other changing features of an object (number, color, etc.) could all rely on a common rate controller (Makin and Chauhan 2014; Makin and Bertamini 2014, see; Makin 2017, for a recent summary). Attention could therefore affect the functioning of this common rate controller and therefore change the dynamic of the mental simulation. However, this hypothesis would predict larger differences between the single-task and dual-task conditions as occlusion time increases, which was not confirmed by the data in Experiment 1 (no interaction between TTC and Attention condition). It

remains to be assessed if that interaction would appear with larger occlusion times, leaving more room for the common rate controller to operate with two different dynamics depending on the attention condition.

3. One possible explanation pertains to the Beilock et al.'s (2002) hypothesis, regarding the well-established distinction between two types of knowledge: declarative knowledge that needs attention to operate and is accessible to conscious report vs. procedural knowledge that operates without attention and is difficult to verbalize (Cohen and Squire 1980). In case attention is drawn away from the TTC task, observers can mainly rely upon procedural knowledge. Assuming that this type of knowledge is the most suitable knowledge in case the occlusion time is short (as was the case in the present study), it predominates when less attention is available and this predominance would explain observers' better TTC estimates in the dual-task condition. But in case attention is fully directed toward the TTC task, observers can rely upon both types of knowledge (for a demonstration of the coexistence of these two types of knowledge, see Willingham and Goedert-Eschmann 1999). Assuming that declarative knowledge is not well suited for short occlusion times, its use when attention is fully available would explain why TTC estimates are less accurate in the single-task condition. According to this theory, our dual-task condition would have forced the participants to carry out the task under an automatic mode of control, preventing them to "think too much" about the task.

A shorter TTC estimation?

Does the lack of attention truly improve performance or, more modestly, remove a bias to overestimate occlusion duration? Indeed, *shorter* estimation in the dual-task condition means better estimation only if the single-task error is positive. However, if the baseline error (the single-task condition) is negative, a shorter TTC estimation would imply an even more underestimated estimation—a worse performance. Therefore, our data only show that reduced attention leads to a shorter TTC estimation, but remains ambiguous to conclude that it is a truly better estimation. An important question that remains to be answered to unequivocally argue that a lack of attention leads to a better TTC estimation is as follows: how would have been the error in the dual-task condition if the baseline was initially negative? A true benefit from drawing attention away from the TTC task would predict an increase of the error, i.e., a less negative error that would be closer to 0 ms in the dual-task condition (i.e., a change in the sensitivity of the observer). On the contrary, if the secondary task only leads to an underestimation of the TTC, irrespectively of the initial baseline level (i.e., a simple decrease in judgment bias), the error should be even more negative; and it could not be argued anymore that a lack of attention is beneficial to the TTC estimation. In our first experiment, the participants would respond earlier to the TTC task to be able to answer the WM task as soon as possible. Note however that this explication cannot hold in the second experiment, as the participants do not indicate the TTC itself, but the relative order of two events (the ball's arrival vs the tone), therefore, the moment of the keypress does not affect the response of the participants.

It is visible from Fig. 3 that 4 participants, out of 20, have a negative mean CE in the single-task condition, and an even more negative CE in the dual-task condition, with an average shift of 37 ms. These 4 data points would therefore argue in favor of this "shorter TTC estimation hypothesis". However, because absolute TTC tasks are prone to a huge variability in the TTC estimation (Lugtigheid and Welchman 2011), we feel it may be hard to choose between the two hypotheses, a better or shorter TTC estimation, based on 4 points only. Further experiments should attempt to address this question, by using various conditions of TTC and velocity in order to lead to a more systematic occurrence of negative CE in the single-task condition. With more negative CEs, it would then be easy to see if the CE in the dual-task condition would be even more negative, confirming the "shorter" hypothesis, or closer to 0 ms, confirming the "better" hypothesis.

In any case, whether performance is considered better or worst depends on the context. For example, during a left-hand turn amidst oncoming traffic, a driver's overestimation of the time at which the approaching vehicle would arrive at the intersection would be considered worse than an underestimation because thinking there is more time that can lead to late turns and collisions. In contrast, while crossing an intersection, a driver's underestimation of the time at which a vehicle crossing their path of travel clears their path can result in late braking and a collision because the vehicle would still be in the driver's path of travel. For a ball hitting task, an underestimation or overestimation of the TTC both would lead to a failure at the task, as the player would simply miss the ball.

An anonymous reviewer questioned whether mind wandering could explain the pattern of results observed in our two experiments. In the single-task condition, the repetition of trials (approximately 200 in Experiment 1, 1600 in Experiment 2) in which an answer has to be given approximately every 4–8 s, may allow the participant to let their mind wander, focusing on task-irrelevant topics. On the contrary, in the dual-task condition, the presence of a secondary task may constrain the participants to stay focused on the two tasks. Under this hypothesis, the pattern of results would come from a detrimental effect of mind wandering, instead of attention fully dedicated to the TTC task; this would affect the single-task condition. As we did not measure mind wandering, this alternative hypothesis can neither be confirmed or discarded as an account of our data. It is worth noting however that mind wandering may not have a detrimental influence on perceptual tasks, as imagined at first glance. Krimsky et al. (2017) presented their participants one (low memory load) or two faces (high memory load) and asked their participant 3500 ms later if a test face was identical to the memorized face. On a regular basis, the participants were asked to evaluate their mind wandering on a 6-point Likert scale. The results showed that mind wandering increased with trial repetition, and at a greater rate for the high load trials than low load trials. This indicates that an easy task, compared to a more difficult task, does not necessarily facilitate mind wandering. As such, it remains very uncertain that our lower results in the single-task condition would emerge from a mind-wandering effect.

Summary and conclusions

In the present study, we sought out to determine whether attention is needed when estimating the arrival time of a moving object that disappeared. To this end, we carried out two experiments in which the amount of available attention was varied while participants were performing a motion-prediction task. More specifically, a set of colored squares had to be retained in working memory for one-half of the trials (therefore less attention is available; i.e., the dual-task condition) but ignored for the other half (therefore more attention is available; i.e., the single-task condition). We found converging evidence of more accurate TTC estimation in the dual-task condition relative the single-task condition. It also indicates that movement prediction depends on cognitive processes that can operate without much attentional effort. Therefore, it is perhaps a better strategy of not thinking too much when perceiving moving objects that are no longer visible.

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Compliance with ethical standards

Conflict of interest The authors declared no conflicts of interest with respect to the authorship or the publication of this article.

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