



The detrimental influence of attention on time-to-contact perception

Robin Baurès¹ · Marianne Balestra¹ · Maxime Rosito¹ · Rufin VanRullen¹

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Abstract

To which extent is attention necessary to estimate the time-to-contact (TTC) of a moving object, that is, determining when the object will reach a specific point? While numerous studies have aimed at determining the visual cues and gaze strategy that allow this estimation, little is known about if and how attention is involved or required in this process. To answer this question, we carried out an experiment in which the participants estimated the TTC of a moving ball, either alone (single-task condition) or concurrently with a Rapid Serial Visual Presentation task embedded within the ball (dual-task condition). The results showed that participants had a better estimation when attention was driven away from the TTC task. This suggests that drawing attention away from the TTC estimation limits cognitive interference, intrusion of knowledge, or expectations that significantly modify the visually-based TTC estimation, and argues in favor of a limited attention to correctly estimate the TTC.

Keywords Visual perception, · Time-to-contact perception, · Attention, · Dual task performance

Introduction

In many situations, such as road crossing or ball catching, the observer has to estimate the time-to-contact (TTC) of the moving object, i.e., the time remaining before the moving object reaches the observer or a point in space where a collision could occur. It has been suggested that an observer may accurately estimate the TTC through the pick-up of different optical cues, in particular $\tau(\theta)$ (tau, the instantaneous visual angle subtended by the object divided by the instantaneous rate of expansion (Lee, 1976), when the object directly moves toward the observer) or other tau-like variables (e.g., Bootsma & Oudejans, 1993, when the object moves on the fronto-parallel plan).

The accuracy of TTC perception has been assessed at length for single approaching objects (for a summary see Hecht & Savelsbergh, 2004). However, and to our knowledge, close to nothing is known about observers' ability to make TTC judgments while engaged simultaneously in a second cognitive task.

In all the aforementioned studies, the observers only had to estimate the TTC of the moving object, with their full attention devoted to the task. This is at odds with the daily observation that we often have to estimate the TTC of an approaching object, like a car when crossing the street for example, while engaged in a phone conversation or keeping in memory our shopping list. The literature of dual task generally shows a decrease of performance in the principal task while a secondary task has to be performed concurrently (e.g., Strayer, Drews, & Johnston, 2003), because attention has to be shared on both tasks. Therefore, the more attention demanding is task one, the higher should be its performance's drop-out due to the secondary task.

Interestingly however, it has been suggested that these visual cues allow TTC perception “without undue call on cognitive resources” (Rushton & Wann, 1999). Indeed, in the ecological framework, perception is direct (Gibson, 1979), without the need for internal model or knowledge (Zhao & Warren, 2015), and the putatively limited pool of attentional resources (see, e.g., Carrasco, 2011) is not involved in TTC perception. Rather, “education of attention” occurs (e.g., Huet et al., 2011), in which observers learn to rely on more reliable information with practice. Therefore, provided that visual access to the optical cues is available, observers can be engaged in any other secondary task without consequence. According to this view, the TTC estimation should therefore be immune to any secondary, attention-demanding task.

However, attention could be involved when the access to the optical cues is not granted, for example if the ball is occluded

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✉ Robin Baurès
robin.baures@cnrs.fr

¹ CerCo, Université de Toulouse, CNRS, UPS, CHU Purpan, Pavillon Baudot, 31059 Toulouse Cedex 9, France

during its trajectory and our brain has consequently to “fill the gaps” (e.g., Bosco, Delle Monache & Lacquaniti, 2008; Bosco et al., 2015). In this case, it has been shown that prior knowledge may play a role in the TTC estimation, such as knowledge pertaining to the target’s speed, its acceleration, or its size (e.g., familiar size and prior knowledge, e.g., Baurès & Hecht, 2011; DeLucia, 2005; Hosking & Crassini, 2011; Lopez-Moliner, Field & Wann, 2007; McIntyre, Zago, Berthoz & Lacquaniti, 2001; Zago et al., 2004). According to these findings, drawing attention away from the TTC estimation task should decrease the observer’s performance.

Attention may therefore be requested pending the complete availability of the visual information. However, how should it influence the TTC estimation? Indeed, it remains unclear how attention removal should affect TTC estimation. Attention is generally found to be helpful in many tasks, from basic mechanisms like contrast sensitivity (Ling & Carrasco, 2006a), to higher visual tasks like multiple object tracking (Allen, McGeorge, Pearson & Milne, 2004) or contextual cueing (Vickery, Sussman & Jiang, 2010). However, previous studies also demonstrated an opposite – and counterintuitive – effect of attention: full attention devoted to the task may also impair perception, and as such, performance was found to be higher when the participants had to share their attention with a secondary task. For example, it has been found that the wagon wheel illusion, in which a wheel is perceived to rotate backward, is present only if the full attention is devoted to the task. When the attention is drawn away by a Rapid Serial Visual Presentation (RSVP) secondary task (VanRullen, Reddy & Koch, 2005), the illusion is then almost eliminated and motion direction discrimination performance is thereby improved. Other authors also confirmed that apparent motion processing was impaired when observers’ attention was directed toward the stimulus, demonstrating a lower ability to discriminate motion direction under full attention (Yeshurun & Hein, 2011), or that attention impaired performance in a texture segregation task when the stimulus was presented in central vision (while favoring performance at peripheral locations; Yeshurun & Hein, 2011). In addition, because attention increases contrast sensitivity, it also leads to a stronger contrast adaptation (decrease in sensitivity as a function of presentation time). This combination shows that the initial benefit of attention on contrast sensitivity turns detrimental after a persisting exposure to the stimulus (Ling & Carrasco, 2006b). Finally, 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 demonstrate that the attentional blink is reduced if the participants had to perform a secondary task. All these studies tend to demonstrate that visual performance may benefit from a diffusion of attention in numerous tasks. Given all this contradicting evidence on the influence of attention on

various aspects of visual perception, it remains uncertain how beneficial or detrimental attention could be to TTC perception. We therefore carried out an experiment to determine how attention may participate in TTC estimation.

Materials and methods

Participants

Twelve students (mean age = 24.17 years; SD = 3.61 years; range = 21–32 years; 5 women) were recruited from Université Toulouse 2 and 3. 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. The sample size was determined using G*Power (Faul, Erdfelder, Lang & Buchner, 2007) after having analyzed the results of a previous experiment investigating the same research question. When focusing on the attention factor only (by averaging the data across the other factors), the previous experiment showed a Cohen’s *d* of .67 ($N = 20$, achieved power = .89) and for a desired power of .75 regarding the current experiment.

Apparatus and experimental procedure

The experiment was conducted with the use of Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard & Pelli, 2007; Pelli, 1997). Stimuli were presented using a Dell Precision computer equipped with two Intel 2.5 GHz processors, and a 27-in. screen. The screen resolution was 1,920×1,200 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.

The task of the participants combined two paradigms. In the Prediction Motion (PM) task, a grey ball was presented against a black background and remained stationary for 1,000 ms (see Fig. 1). The ball then started moving horizontally, from right to left, in the direction of a gray vertical line (the arrival line). After 1,000 ms of visible movement time, the ball disappeared and remained occluded for a varying duration of 500, 1,000, 1,500, or 2000 ms. Participants were instructed to press a key on the keyboard as soon as they estimated that the ball had entered into contact with the arrival line. The arrival line was always positioned on the left side of the screen. Ball’s velocity could be set at a constant velocity of 4 or 6 °/s. Velocity was varied to prevent a perfect correlation between the occlusion time and occlusion velocity. As a consequence of the varying velocities and occlusion times that were used, the starting

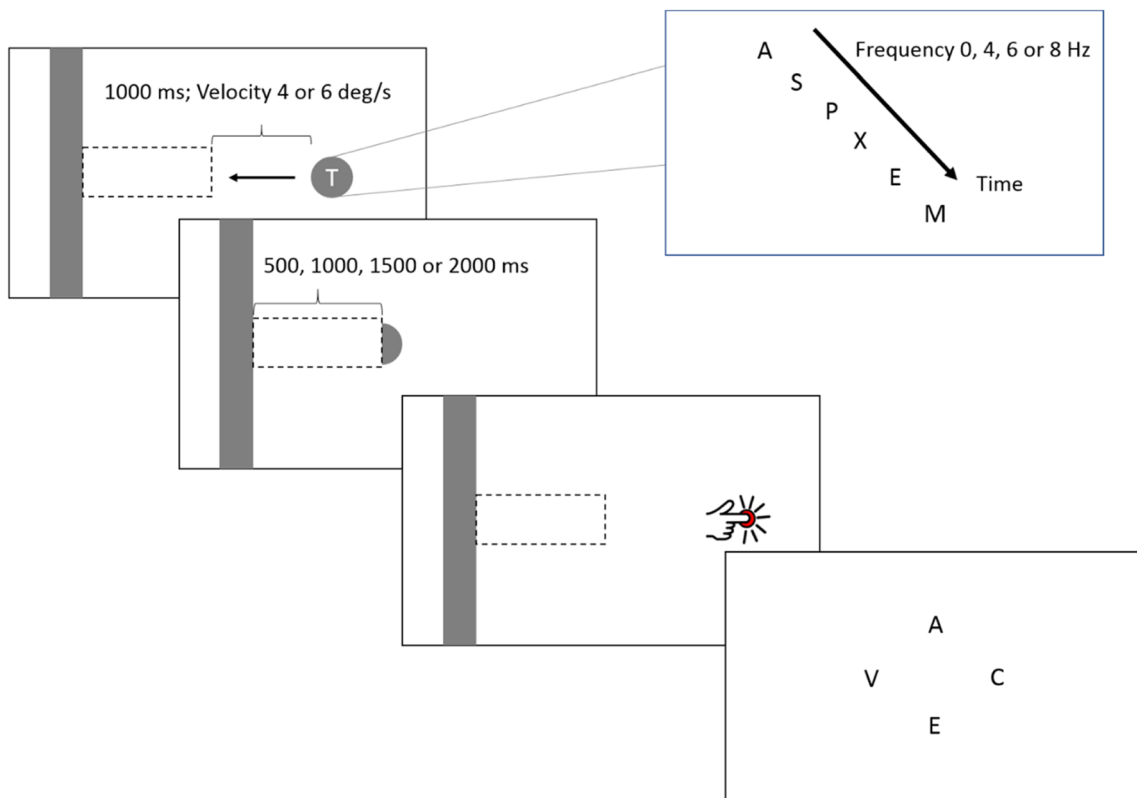


Fig. 1 Schematic representation of the experiment. A ball moves toward the arrival line for a visible duration of 1,000 ms. Inside this ball, a stream of letters is flashed at a frequency of 4, 6, or 8 Hz. Participants have to detect and memorize which letter immediately follows an X. The condition 0 Hz indicates that no letter was displayed and only the TTC

estimation was performed. The ball then disappears, for a duration of between 500 to 2,000 ms, and participants have to press a key to indicate its estimated arrival time. Finally, when the stream of letters is present, participants have to determine which among four letters presented on the screen followed the X

position of the ball was varied, but could not allow the participants to infer the occlusion time from it.

In addition to this primary task, a second Rapid Serial Visual Presentation (RSVP) task could be combined in some trials. A stream of letters was presented within the ball. This stream was presented only when the ball started its movement toward the finishing line. The letters moved together with the ball during the whole ball’s movement. The letters could be flashed at a frequency of 4, 6, or 8 Hz. For the sake of convenience, trials in which there was no RSVP task (single-task condition) are hereafter labeled as having a 0 Hz RSVP Frequency.¹ Letter frequency was varied as it is unclear if the mere presence of a secondary task to perform would influence the TTC estimation, or if the magnitude of the attentional load required by the secondary task matters. Participants were instructed to identify which letter followed an “X” (which could not appear as the first letter of the stream). After having given their answer to the PM task, four letters were presented. Participants pressed a key to indicate which of

these letters they identified as following the “X” in the stream of letters. Participants received no feedback regarding their performance, either for the PM or for the RSVP task. The single-task and dual-task trials were randomly intermixed and participants were not cued on the presence of a secondary task before the trials started. This was done to avoid the participants preparing themselves more in the dual task condition to face the increased difficulty, which could eventually lead to a better performance in the dual-task condition (Tombu & Jolicoeur, 2004). There were ten repetitions of each of the 32 possible combinations (4 RSVP frequency × 4 TTC × 2 Velocity), thus resulting in a total of 320 experimental trials. The whole experiment lasted about 1 h.

Data analysis

Two dependent variables were computed: Constant Error (CE), which is calculated for each trial as the estimated TTC minus the actual TTC. A positive CE indicates that the participants overestimated the actual TTC. On the other hand, a negative CE indicates that the participants underestimated the actual TTC. The second dependent variable was Variable Error (VE), expressed as the standard deviation of the CE over

¹ Should we have included a stream of letters in the single-task condition but instructed our participants not to pay attention to it? See Supplemental Material 1 to investigate what the presence or absence of the letter stream changes.

the repetitions of a same trial. Constant Error represents an overall bias to overestimate or underestimate TTC across trials, whereas Variable Error represents the trial-to-trial variability around this mean value, and, therefore, the spatio-temporal precision of the system. Only dual-task trials for which the RSVP task was performed accurately were taken into account to compute these variables.² Mean accuracy on the RSVP task was 82.61% (95% confidence interval (CI): 77.61–87.60, well above chance set at 25%, $p < .001$). The letter frequency significantly decreased the accuracy of identifying the letter, with a success rate of 94.48% (95% CI: 92.10–96.86) in the 4-Hz condition, 85.63% (95% CI: 79.28–91.97) in the 6-Hz condition, and finally 67.71% (95% CI: 60.41–75.01) in the 8-Hz condition. Therefore, attentional load increased as a result of the letter frequency. This indicates a significant difference in the attentional load drawn away from the TTC task.

Assumption of normality was judged on the histogram of the dependent variable (Garcia-Perez, 2012; Wells & Hintze, 2007), following which CE and VE were then analyzed with a 4 (RSVP Frequency: 0, 4, 6, or 8 Hz) \times 4 (TTC: 500, 1,000, 1,500, or 2,000 ms) \times 2 (Velocity: 4 or 6 °/s) repeated measures ANOVA. The Huynh–Feldt correction for the degrees of freedom was used where applicable (Huynh & Feldt, 1976), and the value of $\tilde{\epsilon}$ is reported. Post-hoc comparisons among all levels of TTC were conducted using non-pooled error terms (i.e., by computing separate paired-samples t-tests; Keselman, 1994) and Hochberg’s sequentially acceptable step-up Bonferroni procedure (Hochberg, 1998), with an alpha level of .05.

Results

TTC significantly influenced CE, $F(3, 33) = 7.41, p < .001, \tilde{\epsilon} = .37, \eta^2_p = 0.40$, showing a general increase in CE, switching from negative to positive values as TTC increases. The effect of RSVP Frequency was not significant, $F(3, 33) = 0.38, p = .77$. However, these two factors interacted, $F(9, 99) = 3.62, p < .001, \tilde{\epsilon} = .30, \eta^2_p = 0.25$ (equivalent to a Cohen’s d of 1.15; Cohen, 1988). As can be seen in Fig. 2, CE tends to switch from less negative to less positive values when participants perform the RSVP task (Frequency of 4, 6, and 8 Hz) compared to the single-task condition (Frequency of 0 Hz). In other words, TTC estimation is more accurate when attention is not fully available³.

To determine how the RSVP Frequency influences the error at each level of TTC, we conducted separate ANOVAs. The results showed that for TTC = 0.5, RSVP Frequency significantly influenced the error, $F(3, 33) = 6.60, p = .001, \tilde{\epsilon} = 1, \eta^2_p$

$= 0.38$. Pairwise comparisons were applied, with Benjamini and Hochberg’s (1995) procedure for multiple comparisons to control for the False Discovery Rate. The results showed that error is significantly more negative in the single-task condition (RSVP Frequency = 0) than in any other of the dual-task conditions (Fig. 3). For TTC = 1 and 1.5, there was no influence of RSVP Frequency, with respectively $F(3, 33) = 0.64, p = .59$ and $F(3, 33) = 0.09, p = .97$. When TTC = 2, there was a marginal influence of RSVP Frequency, $F(3, 33) = 2.35, p = .09$, with a trend for a higher (positive) error in the single-task condition compared to all the other dual-task conditions.

The results seem to indicate that error switches from negative to positive values in the single-task condition, while remaining approximately constant (and close to zero) in all the dual-task conditions. To gain more knowledge on this observation, we computed the regression of the mean CE against TTC for each RSVP Frequency and for each participant. These slopes were then analyzed in two ways. We first aimed at determining if the mean slopes in the different RSVP Frequency conditions were different from 0, indicating a linear relationship between TTC and error. Consistently with the observation of Fig. 2, the slope of the correlation was significantly different from 0 in the single-task condition (RSVP Frequency = 0 Hz), with a mean slope of 0.39, 95% CI: 0.16–0.61, $t(11) = 3.82, p = .003$, and in the dual-task condition for RSVP Frequency = 4 Hz, with a mean slope of 0.24, 95% CI: 0.03–0.44, $t(11) = 2.53, p = .028$. For the two other dual-task conditions, however, the slope was not significantly different from 0, with, respectively, a mean slope of 0.16, 95% CI: [-0.09–0.41, $t(11) = 1.44, p = .18$ in the 6-Hz condition and a mean slope of 0.13, 95% CI: -0.11–0.37, $t(11) = 1.13, p = .28$ in the 8-Hz condition (Fig. 4). In a second analysis, we conducted a pairwise comparison (with Benjamini & Hochberg, 1995 correction) to determine if RSVP Frequency influenced the value of the slopes. This was indeed the case, the comparison showing that all the slopes were statistically different from the others. Taken together, these results indicate that the slope relating occlusion time and TTC estimation monotonically and significantly decreases as RSVP Frequency increases, until it nullifies. The amount of attention invested in the secondary task seems therefore to play a role in the ability to accurately estimate the ball’s TTC.

Finally, analysis of VE showed that only TTC affected the precision of judgement, with an increase in VE as TTC increases, $F(3, 33) = 25.87, p < .001, \tilde{\epsilon} = .74, \eta^2_p = 0.70$.

Discussion

To estimate an object’s TTC, it is well accepted that one should look at the object. However, it appears that we should not pay attention to it. Surprisingly, participants have a better TTC estimation when concurrently engaged in the secondary

² What is found on trials where participants make errors on the RSVP task? See Supplemental Material 2 for an analysis of those trials.

³ Could a Psychological Refractory Period partly explain our results? See Supplemental Material 3 for an analysis of this possibility.

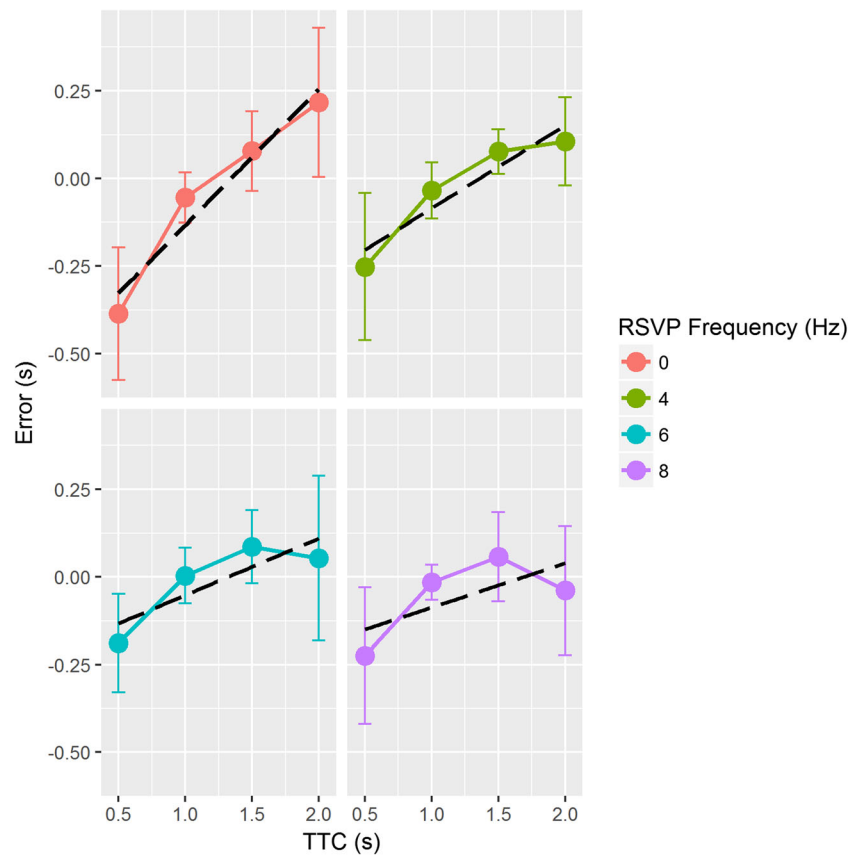


Fig. 2 Constant Error (CE) as a function of TTC, depending on the Frequency of the RSVP task (in panels). Error bars represent the 95% confidence interval of the mean, adjusted with the Morey (2008) correction. Straight dashed lines represent the linear regression of CE by TTC

task, so that when attention is driven away from the TTC estimation, participants are more accurate at estimating it.

The slope of the relationship between occlusion time and error (see the dashed lines in Fig. 2) is a key factor to interpreting our results, and allows for two important points. Firstly, imagine a scenario in which the slopes would be equivalent across the different attentional conditions, and would only differ at the intercepts. In this case, the linear relationship between occlusion time and CE in the single- and dual-task conditions would simply be parallel. Under this scenario, a *shorter* estimation in the dual-task condition would mean a *better* estimation only if the single-task error is positive. On the contrary, if the single-task error is negative, a shorter TTC estimation would imply an even more underestimated estimation – a worse performance. This pattern would indicate a simple negative or positive shift of the estimation, as if the perceived time was accelerating or decelerating given the attentional involvement in the secondary task. This is not what the data show, as the slopes significantly differ depending on the attentional conditions. Consequently, it can be seen that the error is systematically closer to 0 ms in the dual-task condition, compared to the single-task condition. Hence, the lack of attention does not lead to a general

underestimation, or overestimation, of the TTC, compared to the single-task condition baseline, but causes a genuine benefit from the secondary task, independent of the initial level of error in the single-task condition.

Secondly, the attentional load devoted to the secondary task matters. If the secondary task is easy (the 4-Hz condition, which has a success rate of 94.48%), the slope does not markedly differ from the single-task condition, and remains statistically significant. However, as task difficulty increases, the slope gradually nullifies (Fig. 4). This shows that the influence of attention is not binary, a simple on-off mechanism that would be triggered by the mere presence of a secondary task, but that the attentional load induced is a critical component of our results.

How may attentional load interfere with TTC perception? TTC perception can basically be divided into two phases. In the first phase during which the object is visible and moves toward the arrival line, the observer has to pick up optical cues to determine the TTC estimate. In the second phase however, the object is no longer visible, requiring the observer to extrapolate the object’s movement. Our results suggest that the variation of attention affects one of these phases, if not both. However, it is unclear why the pick-up of the optical cues

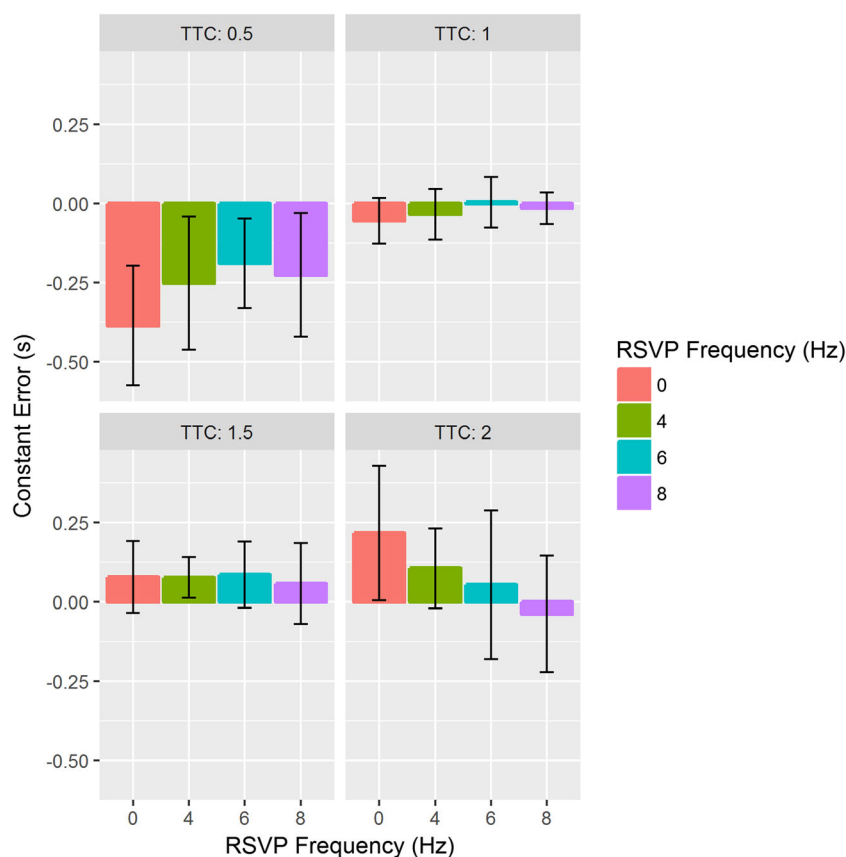


Fig. 3 Constant Error (CE) as a function of the Frequency of the RSVP task and TTC (in panels). Error bars represent the 95% confidence interval of the mean, adjusted with the Morey (2008) correction. Figure 3 presents the same data as in Fig. 2, but organized by TTC instead of RSVP frequency

would be degraded if full attention is devoted to the task. On the contrary, the second phase appears to be a much better candidate to explain the current effect. Indeed, the error pattern is consistent with a change in the slope relating occlusion time and error, due to the presence or absence of the secondary task. In traditional Prediction Motion (PM) tasks, error is usually found to be linearly related to occlusion time. This supports the idea that as the visual information becomes more remote, the extrapolation of the object's motion is influenced more by the intrusion of knowledge or expectations that significantly modify the visually-based representation of its motion, and consequently the TTC estimation. Our results would thus show that when attention is directed to the secondary task, there is no room anymore for knowledge or expectations to influence the TTC estimation, due to the allocation of attentional resource elsewhere. Under this hypothesis, the visually-based TTC estimation would not be modified by cognitive interferences, therefore cancelling the linear relationship between occlusion time and error.

While in agreement with the general conclusion of previous work showing a detrimental influence of having too much attention on various visual tasks (Ling & Carrasco, 2006b; VanRullen et al., 2005; Yeshurun & Hein, 2011; Yeshurun &

Carrasco, 1998), the origin of our effect appears markedly different. Indeed, it is important to note that all these studies favor a very neuronal hypothesis to explain how having too much attention impairs visual perception, like change in the contrast gain of the neurons (Ling & Carrasco, 2006b), enhancement of spatial resolution (Yeshurun & Carrasco, 1998), or a discrete perceptual sampling (VanRullen et al., 2005). The current results argue on the contrary for a much higher-level interpretation, namely, lack of attention as a way to prevent cognitive interference to modify the visual TTC estimation. Note, however, that these two types of explanation are not mutually exclusive; it would be of interest to record the activity of neurons implied in the TTC perception (Field & Wann, 2005; Sun & Frost, 1998; Wang & Frost, 1992) to determine if the lack of attention also modulates their response.

How could these results be applied in a real-world task? In a typical interception or avoidance task, the moving object is continuously visible through its entire trajectory, and our results may not apply here. However, it may also occur that the object is occluded by an object in the scene, as when estimating the TTC of a car that passes behind a bus for example. In other situations, as in tennis for example, the ball sometime moves so fast (during the serve or a smash) that the eyes

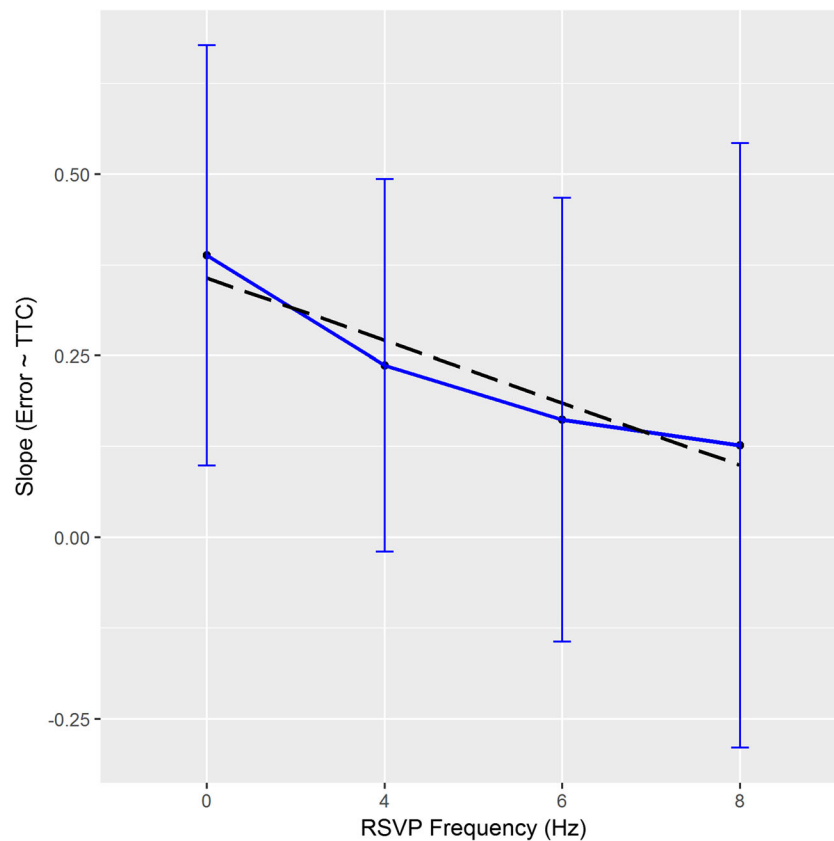


Fig. 4 Mean slope and 95% confidence interval of the regression CE as a function of TTC in the different RSVP Frequency conditions. Straight dashed lines represent the linear regression of the slope by the RSVP Frequency

cannot track it anymore, when the velocity exceeds the approximate 100 °/s tracking velocity of the human visual system (Spering & Gegenfurtner, 2008). In such a scenario, observers appear to track the ball during its initial part of the trajectory, followed by an anticipatory saccade to the predicted bounce point (e.g., Land & McLeod, 2000), to finally again pursue the ball until the contact point (e.g., Mann, Spratford, & Abernethy, 2013). Returning a fast ball shot therefore genuinely appears to be like the prediction motion paradigm used in the current experiment. Imagine a tennis situation against Roger Federer. What could be the best advice for his opponent to return his shot? It appears that while looking at the ball or during its occlusion period, we should not pay attention to it. Surprisingly, participants have a better TTC estimation when concurrently engaged in the secondary task, so that when attention is driven away from the TTC estimation, participants are more accurate at estimating it. A secondary task while tracking the ball therefore appears insightful.

What kind of secondary task should be recommended to defeat Roger Federer? The secondary task should allow the observer to “keep [his] eyes on the ball” (Spering, Schütz, Braun, & Gegenfurtner, 2011), to access the optical cues allowing the TTC estimation. In addition, it has been shown that when experts are requested to perform a secondary task related to the main task, performance is impaired, probably

because it prevents its automatic execution in favor of step-by-step control of the task, which is harmful to skilled performance (Beilock, Carr, MacMahon & Strakes, 2002). Given all this, to return Roger Federer’s shot, potentially good advice would be as follows: “keep your eyes on the ball, don’t pay attention to it, and don’t think about tennis.” Individual results may vary.

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R. Baurès developed the study concept and M. Rosito created the experimental program. Testing and data collection were performed by M. Balestra. R. Baurès and R. VanRullen performed the data analysis and interpretation. R. Baurès drafted the manuscript, and R. VanRullen provided critical revisions. All authors approved the final version of the manuscript for submission.

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