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Effects of a Moving Distractor Object on Time-to-Contact Judgments

Daniel Oberfeld and Heiko Hecht
Johannes Gutenberg-Universität Mainz

The effects of moving task-irrelevant objects on time-to-contact (TTC) judgments were examined in 5 experiments. Observers viewed a directly approaching target in the presence of a distractor object moving in parallel with the target. In Experiments 1 to 4, observers decided whether the target would have collided with them earlier or later than a standard (absolute identification task). A contrast effect was observed: If the distractor arrived later than the target, it caused a bias toward *early* responses, relative to the condition without a distractor. The early-arriving distractor had no significant effect. The pattern of results was unaltered when potentially confounding information from individual visual cues was removed. The availability of stereoscopic information reduced the effect. The contrast effect was also observed if target and distractor were abstract geometric objects rather than simulations of real-world vehicles, rendering less likely a simple safety strategy activated by a potentially threatening distractor. Experiment 5 showed that the effect of the late-arriving distractor generalized to a prediction-motion task. The results indicate that task-irrelevant information in the background has to be considered in revision of time-to-contact theory.

Keywords: time to arrival, task-irrelevant object, TTC theory, contrast effect, visual motion

People frequently have to judge the remaining time to contact (TTC) of an approaching object in the presence of other, potentially distracting objects. For instance, before a driver initiates a passing maneuver on a multilane motorway, the rearview mirror may show a car in the passing lane whose TTC is critical for the decision to change lanes. The mirror may also show a car in another lane that is irrelevant for the decision to pass. Will the irrelevant car influence the driver's decision to switch lanes? We suggest that our understanding of the effects of irrelevant context on such judgments will advance our theoretical understanding of TTC estimation. We first sketch the current state of TTC theories. Many of the basic assumptions made since David Lee's (1976) seminal article have recently become controversial (for an in-depth discussion, see Hecht & Savelsbergh, 2004). One assumption that has not yet been questioned is that the visual system is capable of isolating the information that is relevant for TTC estimation. We felt the need to find out whether this is the case and, accordingly, whether task-irrelevant information can, indeed, be successfully ignored. Thus, in the current article we investigated to what extent other objects in the visual field might affect the TTC judgment of the task-relevant object. We found a small but consistent context effect in an unexpected direction. Given the idea of a TTC detector, one might suppose that it is leaky in the sense that its output is averaged with the output of neighboring TTC detectors whose answer is task irrelevant. Instead, we observed a contrast effect that cannot be explained by lower level averaging. The results point to a figure–ground separation that occurs between the target and its context. Before reporting five experiments, we distinguish task-relevant from task-irrelevant contexts and summarize the current TTC debate, which led up to the investigation of task-irrelevant context.

Daniel Oberfeld and Heiko Hecht, Department of Psychology, Johannes Gutenberg-Universität Mainz, Mainz, Germany.

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Correspondence concerning this article should be addressed to Daniel Oberfeld, Department of Psychology, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany. E-mail: oberfeld@uni-mainz.de

The Current State of TTC Theory

Traditionally, when judging the TTC or the time to passage (TTP) of a single object, observers have been thought to rely on object-based information that is encoded in a single optical variable. The ratio of the retinal extent of the object and its instantaneous rate of expansion, called tau (Lee, 1976), is often favored to be this optical variable. A given magnitude of tau indicates the time remaining until the approaching object will collide with the observer. A large body of literature suggests that the visual system possesses a dedicated processor that continuously computes tau. The constantly available tau information is then taken by the visual system to inform decisions such as when to start swinging the baseball bat or when to initiate a braking motion (see, e.g., Tresilian, 1995). More recently, a growing body of literature has suggested that the processor uses simpler, alternate optical variables, such as expansion rates or even simple image velocities (see, e.g., Kerzel, Hecht, & Kim, 2001; Smith, Flach, Dittman, & Stanard, 2001). For instance, performance degrades gracefully when information is diminished to the extent that tau is no longer available, proving that other optical variables as well can be used for TTC estimation. This also suggests that simple optical variables might be used all along. For instance, when a flow field is reduced to just a few not-expanding dots, TTP estimates are made on the basis of retinal eccentricity, which is often highly correlated with target distance (e.g., Kerzel, Hecht, & Kim, 1999). Such a flexible strategy would allow for a less sophisticated TTC processor, which could perform in rich and diminished optical flow fields.

Other image effects, such as the size-arrival effect (DeLucia & Warren, 1994), back up this notion. Retinally large objects are judged to arrive earlier regardless of their true TTC, which suggests that the would-be TTC processor utilizes simple retinal properties, such as area. Be this as it may, there seems to be agreement that a more or less sophisticated TTC processor singles out a perceptual object while ignoring other objects in the visual field. We do not know, however, whether this basic notion of an object-based processor is valid. If it is, then task-irrelevant context outside the approaching object should be ignored, and it should not factor into TTC judgments.

Context Effects on TTC Judgments

The relative rate of object expansion is often taken as a given, although it typically has to be extracted from a rich optical flow pattern. In pigeons, dedicated neurons have been shown to respond to object expansion while ignoring context (Frost & Sun, 2004; Sun & Frost, 1998). When the whole visual field expanded—thereby indicating self-motion—these neurons were silent, but when the object moved independently, they responded to the particular TTC value to which they were tuned. Unfortunately, such clear-cut evidence has not been found in human observers. To the contrary, when displays suggest self-motion in the same direction as the observer or in the opposite direction, the object motion tends to be pulled toward the direction of the background motion (Gray, Macuga, & Regan, 2004). For example, the closing speed of an object approaching the observer in a condition of simulated backward self-motion in depth was judged to be slower than the closing speed in a condition without simulated self-motion. The opposite result was obtained by DeLucia and Meyer (1999), who observed background effects when the background, consisting of a grid, suggested self-motion. When backward motion was suggested, TTC estimates fell short of the actual TTCs. The differences between the two studies can be reconciled when we assume that local background expansion and a large visual field are required to successfully suggest self-motion. In DeLucia and Meyer's displays, viewing angle was approximately 30°, whereas Gray at al. used locally expanding dots and a 65° horizontal field of view. An underestimation of TTC might be expected if the rate of gap closure, rather than the estimated self-motion, is taken as the cue for TTC estimates. At any rate, such background effects (see also Smeets, Brenner, Trébuchet, & Mestre, 1996) in humans suggest that the visual system might not be very good at removing those components of the optic flow that are caused by self-motion. Vestibular information seems to be required to successfully discount self-motion components (Hecht, 2007).

Apart from background effects related to self-motion, irrelevant moving objects might also interfere with the TTC estimation of a target. By *irrelevant,* we designate all context that is not necessary to perform the task. For instance, in the case of two objects approaching an observer on parallel trajectories, if the observer is to judge the TTC of one object by pressing a key 2 s before collision, the other object is irrelevant. If, conversely, the observer is to decide which of the two objects will pass him or her first, both objects become task relevant.

Typically, experimenters have only used more than one moving object as a by-product of a convenient judgment task. Hence, most experiments involving two or more moving objects used a relative judgment task (cf. Tresilian, 1995). For example, in a study by Law et al. (1993), the observers decided which of two objects would arrive sooner at a designated stationary target. That is, both objects were relevant to the task. Data by DeLucia and Novak (1997) showed that observers could identify the object that would arrive first, even if as many as eight objects were present in the display, with only weak evidence for a capacity limit. Andersen and Kim (2001) conducted a related experiment in which it was the observers' task to decide whether any of one to eight moving objects was on a collision course, rather than making TTC judgments. Performance declined with set size, indicating a limited-capacity process for collision detection. Novak (1998) also studied multiple-object TTC estimation, using a Sperling-like prediction-motion (PM) task. The observers saw one to eight objects approaching a finish line. The target object was only indicated by a visual cue presented after the objects had disappeared from the screen. Estimated TTC slightly increased with set size, especially so for the shorter arrival times. Note that, again, all objects were relevant to the task, as all of the objects were assigned to be the target with equal probability.

Despite this evidence that human observers can simultaneously estimate TTCs of multiple objects, it remains unclear how effectively observers can select the relevant TTC information and ignore irrelevant information. To our knowledge, the only study that presented an irrelevant distractor object in what might be termed a TTC task was conducted by Lyon and Waag (1995, Experiment 2), although the authors' intent was to study motion extrapolation. They required observers to extrapolate the motion of a target along a circular path in the frontoparallel plane and to decide whether the target would have passed an "end line" that appeared at a variable delay after the target had disappeared from the screen. An irrelevant distractor object appeared when the target disappeared. If the distractor moved in the same direction as the target and if its velocity was larger than the target velocity, observers underestimated the TTP of the target relative to the condition without a distractor. If the distractor velocity was much smaller than the target velocity, observers overestimated the TTP of the target. The data are compatible with the assumption that the motion of the distractor object interferes with motion extrapolation, but the exact mechanism remains unclear. In the experiments presented in this article, the focus is on distractor effects on TTC estimates of a target on a collision course. The optical variables involved in TTC judgment for motion in the mid-sagittal plane were different from the visual cues relevant to TTC estimation in the frontal plane, and thus the effects found by Lyon and Waag (1995) cannot necessarily be expected to generalize.

Effects of Task-Irrelevant Distractor Objects on TTC Judgments

What effects can a distractor object be expected to have on TTC judgments for a target object? In signal-detection theory (SDT) terms, the distractor could have an effect on the sensitivity, resulting, for example, in large variability of absolute TTC judgments or in low accuracy of relative judgments. The distractor could also influence the response bias, resulting in a systematic under- or overestimation of target TTC. While the majority of TTC experiments have focused on either response bias (e.g., Schiff & Detwiler, 1979) or accuracy (e.g., Regan & Hamstra, 1993; for an exception, see Tresilian, 1994), it must be emphasized that to fully understand the effects of the task-irrelevant object, it is important to gather information about the distractor-induced changes in both sensitivity/accuracy and response bias. Measuring both sensitivity and bias allows one to distinguish between four possible patterns. (a) If the TTC detectors assigned to each moving object in the display operate in parallel, if they show no "leakage," and if the TTC estimates from the different TTC processors are not combined at higher processing stages, then there should not be an effect on sensitivity or on bias. (b) If the simultaneous processing of TTC information from multiple objects is capacity limited, then the distractor should have an effect on the sensitivity but not on response bias. (c) If there is a lossless combination of TTC information from the different objects, then the distractor should have an effect on response bias but not on sensitivity. (d) Finally, if the process of combining TTC information introduces noise, we should observe an effect of the distractor on both sensitivity and bias.

In the experiment by DeLucia and Novak (1997), the sensitivity for detecting which of two to eight objects would arrive first was only weakly influenced by the display size, indicating that the visual system was capable of effectively processing TTC information from multiple objects. Thus, we expected no effect of a single task-irrelevant object on sensitivity.

With respect to response bias, if TTC is processed in parallel and if there is no interaction between the different TTC estimates, then a distractor should have no effect on the bias. Alternatively, as discussed above, one could maintain the assumption that TTC processing is not capacity limited but that the output of a given TTC detector is averaged with the output of other TTC detectors. In other domains, a distractor also frequently introduces a systematic bias, which can be described as assimilation or an averaging of target and distractor information (Michels & Helson, 1954). For instance, spatial summation at the neural level often occurs for motion in the same plane (e.g., Meese & Harris, 2001). In the visual domain, there have been reports that the remembered location of objects is biased toward other elements in the display (memory averaging; e.g., Hubbard, 1995; Kerzel, 2002a, 2002b). Another related phenomenon is the so-called vector averaging found for the perceived direction of a moving stimulus in the presence of another moving stimulus (e.g., Kim & Wilson, 1997).

Given the universality of such averaging or summation phenomena,[1] we expected the perceived TTC of the target object to be a weighted average between target and distractor TTCs. To give an example, our hypothesis was that a distractor object arriving at the observer later than the target object would result in a subjective lengthening of target TTC—that is, an overestimation. In the five experiments presented in this article, we found the opposite to be true. We observed a contrast effect. If the distractor object arrived later than the target, the observers underestimated target TTC.

Overview of the Experiments

We report five experiments that were designed to explore the role of task-irrelevant objects. Observers judged TTCs of a directly approaching target object in the presence of an additional moving distractor object. The distractor also moved toward the observer but was not on a direct collision course. It was at all times irrelevant to the task of judging TTC of the target object because it provided no information about target TTC. The target and the distractor moved with constant velocity and on parallel trajectories.

In our standard paradigm, the target disappeared from the screen before it reached the observer (blanking paradigm; for a discussion of potential consequences of this paradigm, see Hancock & Manser, 1997). The distractor arrived at the observer's eye plane either earlier or later than the target. In Experiments 1 to 4, an absolute identification (AI) task was used (see Braida & Durlach, 1972; Macmillan & Creelman, 2005). Only two discrete values of target TTC were presented during the experiment: an early TTC and a late TTC. The observers decided whether the target object would have collided with them early or late had it continued its trajectory. In Experiment 5, the observers were tested in a PM task (e.g., Schiff & Detwiler, 1979). The target object again disappeared from the screen before reaching the observer. The observers were asked to press a button at exactly the moment they thought the object would have arrived at their position had it continued its trajectory.

In Experiment 1, we tested the averaging hypothesis by presenting distractor objects that arrived at the observer's eye plane either earlier or later than the target object. Contrary to our expectation, the distractor that arrived later than the target caused a bias toward *early* responses (relative to the control condition without a distractor object). The distractor that arrived earlier than the target had no significant effect.

In Experiment 2, we used essentially the same procedure and conditions as in Experiment 1 but reduced the information provided by the final display size of the target object by varying the physical sizes of target and distractor. The effect of the distractor object on the TTC judgments was virtually the same as in the first experiment, indicating that the distractor effects observed in Experiment 1 did not depend on the correlation between target TTC and final object size.

In Experiments 1 and 2, we observed a small but nonsignificant bias toward *late* responses in the condition presenting the target object by itself. As the absence of stereoscopic information in our displays might account for the bias, in Experiment 3 we presented the same virtual scenes already used in Experiment 2, but we added binocular information by using a head-mounted display. The distractor again induced the same pattern in the mean data as in the first two experiments. Stereoscopic information reduced the effect of the distractor object, but it did not remove the effect completely.

A potential explanation for the bias toward *early* responses induced by the late-arriving truck is the threatening connotation of the real-world stimulus. In Experiment 4, we presented neutral targets and distractors consisting of abstract geometric objects not typically encountered in people's daily environments. The abstract objects should have been less likely to elicit a safety strategy. Contrary to this hypothesis, the distractor had essentially the same effect on response bias as in the first three experiments. Experiment 5 demonstrated that the relative underestimation of target

[1] See Oberfeld (2007) for a recent discussion of assimilation phenomena in the auditory domain and Geldard (1975) for related findings concerning tactile perception.

TTC caused by the late-arriving distractor was also observed in a PM task. The early-arriving distractor caused a significant underestimation of target TTC, which was even larger than the effect of the late-arriving distractor.

Experiment 1

The observers judged TTC of a single target object (a car presented in a virtual environment) in an AI task. In a test of the averaging hypothesis, each observer received trials without a distractor and with a task-irrelevant distractor object arriving at the observer's eye plane either earlier or later than the target object. The distractor object was a truck moving in parallel to the car.

Method

Observers

Eleven students at the Johannes Gutenberg-Universität Mainz (10 women, 1 man; age = 20–29 years) participated in the experiment voluntarily. All had normal or corrected-to-normal vision. They either received partial course credit or were paid for their participation. All observers were naive with respect to the aim of the experiment.

Apparatus and Stimuli

The observers viewed a virtual scene that was rendered three-dimensionally via the animation software Vizard (WorldViz, 2004) and presented on a thin-film transistor color display (43-cm diagonal, refresh rate 60 Hz noninterlaced). The observers thus saw a two-dimensional projection of a 3D scene. The animation update rate was approximately 60 frames per second. The display had a resolution of 1,280 × 1,024 pixels (horizontal by vertical) and subtended 46° of visual angle horizontally and 37° vertically. A Pentium IV computer (Dell Precision 650) equipped with an NVIDIA Quadro4 900 XGL graphics adaptor was used for animation and experimental control. The observers were tested individually in a dimly lit room watching the thin-film transistor display binocularly from a distance of 40 cm. A chin rest was used to align the line of sight with the center of the display.

The target stimulus was a car moving toward the observer at constant speed on a collision course. The approaching car was horizontally centered on the screen and moved on the left side of a road (as seen by the observer). For an observer fixating the midpoint of the object, the object moved on the mid-sagittal plane. The distractor object was a truck with trailer also moving toward the observer (but not on a direct collision course) at constant speed, on the right side of the road and in parallel to the car. Figure 1 shows a screenshot of a trial.

In the 3D-simulation, eye height of the observer was 1.5 m. The car was a red sports car 2.4 m wide, 1.8 m high, and 5.6 m long. The dimensions of the truck were 5.4 m × 5.8 m × 26.2 m (width × height × depth). The horizontal distance between the midpoints of the two objects was 5 m. The road was 20 m wide. Across observers and conditions, the car subtended a horizontal visual angle between 2.88° and 10.02° at the instant before it disappeared.

Procedure

The observers judged the TTC of the target stimulus (the car) with their eye point in an AI procedure by indicating which of two discrete values of car TTC was presented in a given trial. AI tasks have been shown to have better temporal resolution than PM tasks

Figure 1. Screenshot of a trial from Experiment 1, showing the target object (car) and the distractor object (truck). The original displays were in color.

(see, e.g., Regan & Hamstra, 1993). The two TTCs were individually selected (see the *Individual calibration* section) for their difference to be close to the observer's discrimination threshold; mean TTC was 4,000 ms for each observer. For example, if the early TTC was selected to be 3,800 ms and the late TTC was 4,200 ms, the observer had to indicate for each display whether it was of the late or the early kind. Note that we designate by *TTC* the time between the appearance of the object on the screen and the instant at which the object would have collided with the observer. Heuer (1993) termed this time span *initial time to contact.* For the time between the instant at which the object disappeared from the screen and the instant at which the object would have reached the observer, we use the term *extrapolation interval.*

In each trial, the car was presented for 3,000 ms and then blanked from the screen. As a result, the mean extrapolation interval was 1,000 ms. The scene (road, sky, etc.) was visible until response. The distractor object continued to move after the target had disappeared from the screen. Therefore, it remained visible until it passed the observer or until the observer pressed the response key. In the main part of the experiment, three distractor conditions were presented. Either the truck would have reached the observer earlier or later than the car or no truck was presented.

On keypress, the virtual scene appeared, with the target object moving at constant speed toward the observer, who was instructed to mentally extrapolate the movement of the car and to decide whether it was the early-arriving or the late-arriving stimulus. At response, the screen turned gray. The system did not react to responses that were made while the car was still visible. If the observer did not respond within 3 s after the car had disappeared from screen, a warning message was issued, and the trial was repeated immediately.

Individual calibration. In the first experimental block, a weighted up–down adaptive procedure (Kaernbach, 1991) was used to determine the individual difference between early and late contact time (ΔTTC_{Th}) corresponding to a performance level of 75% correct. No distractor was presented. The car was presented for 3,000 ms and then blanked from the screen. The early car contact time remained constant at 4,000 ms. The late contact time was adjusted by the adaptive procedure. In each trial, the car's starting distance was randomly set to 100 m, 110 m, or 120 m, and the velocity was selected to produce either the early contact time (4,000 ms) or the late contact time (4,000 ms + ΔTTC). Initially, the difference between late and early car contact time (ΔTTC) was 600 ms. After each correct response, ΔTTC was decreased by one step. After each incorrect response, ΔTTC was increased by three steps. Step size was 100 ms until the 6th reversal and 30 ms for the remaining 10 reversals. The observers received visual trial-by-trial feedback. The discrimination threshold ΔTTC_{Th} was computed as the arithmetic average of ΔTTC at the final 10 reversals.[2]

Data collection. In the main part of the experiment, the individual discrimination thresholds (ΔTTC_{Th}) obtained in the first part of the experiment were used as the difference between the two car contact times. The early and the late contact times of the car were set to 4,000 ms $-$ $\Delta TTC_{Th}/2$ and 4,000 ms + $\Delta TTC_{Th}/2$, respectively. The car's largest starting distance was 150 m for all observers. For this distance, a car velocity was selected such that the late contact time resulted. Subsequently, a smaller distance was computed that resulted in the early contact time for the same velocity. Next, a velocity was determined that corresponded to the late contact time with the distance computed in the previous step. This procedure was iterated until three different car velocities and four different starting positions were determined. In other words, six Velocity $\times$ Starting Distance combinations were selected, such that each contact time was presented with the same set of three different velocities.

On trials presenting the distractor, truck TTP was either earlier or later than car TTC. The truck appeared simultaneously with the car and at the same distance. We selected distractor TTP to be the mean target TTC plus or minus one just-noticeable difference (ΔTTC_{Th}). The early truck TTP was 4,000 ms $-$ ΔTTC_{Th}, and the late truck TTP was 4,000 ms + ΔTTC_{Th}. The participants were instructed to concentrate on the car and to ignore the truck, so it can be assumed that the car was viewed foveally and the truck peripherally. The observers were informed that the truck provided no information concerning car contact time. Figure 2 depicts the temporal structure of a trial.

Design

In the main part of the experiment, participants received the two car contact times factorially combined with the three velocities and the three distractor conditions (no distractor, distractor arriving earlier, and distractor arriving later). Because of the factorial combination, distractor TTP provided no cue to target contact time. Each observer received each of the 2 (target TTC) $\times$ 3 (target velocity) $\times$ 3 (distractor condition) combinations 15 times, which resulted in a total of 270 trials. Presentation order was randomized. No feedback was provided. The test session lasted approximately 45 min, including two brief rest periods.

Results

In the AI task used in the experiment, there were two possible states of the world (early or late car TTC) and two possible responses (*early* or *late*). We represent the decision outcomes by a 2 $\times$ 2 matrix containing the proportions of response alternatives conditional on whether the late-arriving or the early-arriving car had been presented, just as in signal-detection experiments involving two states of the world and two response alternatives (Green & Swets, 1966). We present the results in terms of response bias and sensitivity, in the SDT sense. As the measure of sensitivity, we use the SDT index d' because it allows us to estimate sensitivity

[2] The estimate of the discrimination threshold measured by the weighted up–down procedure may be biased in tasks involving only one presentation per trial (e.g., a yes–no task). Unlike in two-alternative forced-choice tasks, it cannot be assumed that response bias is negligible (see Green & Swets, 1966). In terms of a signal-detection model, such a bias can be treated as being independent of sensitivity. In the adaptive procedure used here, however, a response bias would result in a larger estimate of ΔTTC_{Th} because more errors are made if there is a bias toward one of the response alternatives. Unfortunately, there is no adaptive procedure for the measurement of discrimination thresholds in a one-interval task that is as widely accepted as the transformed or weighted up–down methods originally designed for two-alternative forced-choice tasks (Green, 1993; Kaernbach, 1990, 1991; Leek, 2001; Levitt, 1971). As our primary concern was not the precise determination of a discrimination threshold but an efficient selection of individual values of ΔTTC corresponding to about 75% correct, we decided to use the simple weighted up–down procedure.

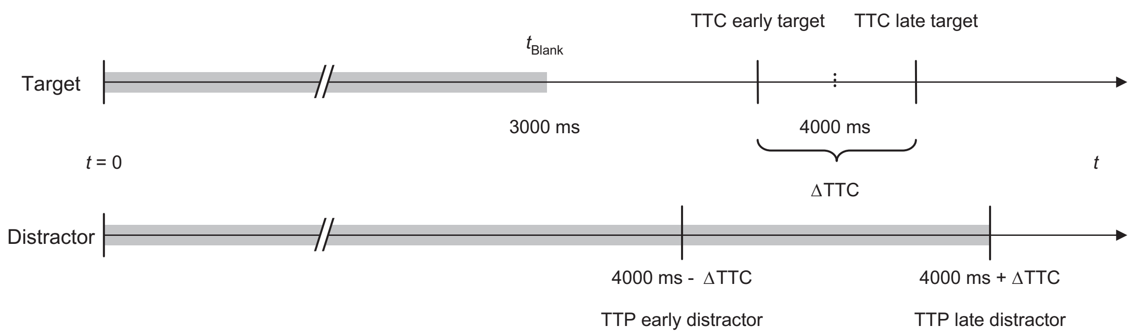

Figure 2. Schematic depiction of a trial (Experiments 1–3). At $t = 0$, the target (a car) and the distractor (a truck; see Figure 1) appeared on the screen and immediately started moving with different but constant velocities. The car was blanked from the screen at $t_{\mathrm{Blank}} = 3{,}000$ ms. Simulated time to contact (TTC) of the early-arriving car was 4,000 ms − ΔTTC/2; TTC of the late-arriving car was 4,000 ms + ΔTTC/2. We individually selected the difference between late and early contact time (ΔTTC) to obtain a performance level of 75% correct. Time to passage of the truck was either 4,000 ms − ΔTTC or 4,000 ms + ΔTTC. The truck continued to move until it had passed the observer or until the observer pressed the response key. In the control condition, no distractor was presented.

independently from response bias or criterion placement (for a discussion, see Macmillan & Creelman, 2005). This property is important because we expected an effect of the distractor on response bias. We report response bias in terms of the proportion of *late* responses, denoted by *P*(*late*). The reason not to use an SDT measure of response bias like *c* (cf. Macmillan & Creelman, 1990), is that *P*(*late*) can be observed directly and is therefore more illustrative and easier to grasp intuitively than a measure based on signal detection theory.

Proportion of Late Responses (Response Bias)

Because the early-arriving and the late-arriving car were presented equally often, unbiased responding corresponded to a proportion of *late* responses, *P*(*late*) = .5. On trials presenting the target object only, there was a slight bias toward *late* responses (see Figure 3), which was not significant, one-sample $t(10) = 1.20$.

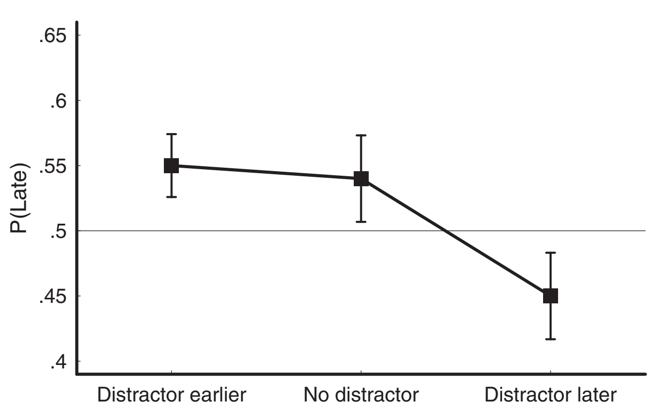

Figure 3. Experiment 1: Mean proportions of *late* responses as a function of distractor condition. The horizontal line represents unbiased responding (*P*[*late*] = .5). Error bars show plus and minus one standard error of the mean computed on the basis of the 11 individual proportions.

The proportion of *late* responses was analyzed via a two-factor (3 × 3) repeated-measures analysis of variance (ANOVA) based on a univariate approach with Huynh–Feldt adjusted degrees of freedom (cf. Keselman, Algina, & Kowalchuk, 2001; Maxwell & Delaney, 2004). The two within-subject factors were distractor condition and target velocity. As expected, the main effect of distractor condition was significant, $F(2, 20) = 5.95$, $\tilde{\varepsilon} = .68$, $p = .021$ (the parameter $\tilde{\varepsilon}$ is the Huynh–Feldt correction factor for the degrees of freedom; Huynh & Feldt, 1976). Neither the main effect of target velocity, $F(2, 20) = 0.15$, nor the Distractor Condition × Target Velocity interaction, $F(4, 40) = 1.24$, was significant at an alpha level of .05. The distractor arriving at the observer later than the car reduced the proportion of *late* responses. All observers showed this pattern. The decrease in *P*(*late*) observed with the late-arriving distractor constitutes the opposite pattern compared to the averaging of target TTC and distractor TTP we had predicted. The truck that arrived earlier than the car, conversely, had no effect, on average (see Figure 3), whereas in the individual data both increases and decreases in *P*(*late*) were found, relative to the condition without a distractor.

Post hoc analyses were used to gain a better understanding of the distractor effect. A 2 × 3 (Distractor Condition × Target Velocity) repeated-measures ANOVA showed that judged TTC was earlier (i.e., *P*[*late*] was lower) when the distractor arrived later than the target, as compared to the no-distractor condition, $F(1, 10) = 29.03$, $p = .001$. The main effect of target velocity and the Distractor Condition × Target Velocity interaction were not significant. A similar ANOVA was used to analyze the conditions without the distractor and with the distractor arriving earlier than the car. There was no significant effect of the distractor, $F(1, 10) = 0.13$. The main effect of target velocity and the Distractor Condition × Target Velocity interaction were also not significant.

Sensitivity

The average proportion of correct responses, *P*(*C*), was .77 (*SD* = .13), indicating that the individual calibration that aimed at a

ΔTTC corresponding to 75% correct was successful. Across observers and experimental conditions (Distractor Condition × Target Velocity), $P(C)$ ranged from .43 to 1.00. The effect of distractor condition on sensitivity was analyzed in terms of an SDT model assuming equal-variance Gaussian distributions (Green & Swets, 1966). For each observer, the proportion of hits—that is, the proportion of *late* responses on trials presenting the late target TTC (P[*late* | late-arriving target])—and the proportion of false alarms (P[*late* | early-arriving target]) were computed for each of the three distractor conditions.[3] We aggregated the hit rates and false-alarm rates across target velocity to focus on the effect of the distractor object, ignoring potential effects of other experimental parameters. In each distractor condition, there were 90 trials per observer. Only cases with at least two false alarms were used in the analysis. Given this reasoning, Observer 11, who showed a particularly high level of performance, had to be excluded from the analysis. Another participant (Observer 9) produced only one false alarm in the condition with the late-arriving distractor as well as in the condition without a distractor.

Table 1 displays the mean values of d' estimated in the three distractor conditions. A univariate repeated-measures ANOVA showed no significant effect of distractor condition on d', $F(2, 16) = 0.60$. Note that because of the exclusion of cases with fewer than two false alarms, only 9 of the 11 observers entered the analysis. It can be concluded that the distractor had no effect on sensitivity.

Table 1
Mean and Standard Deviation of the Sensitivity Index d′ Obtained in the Three Distractor Conditions of Experiments 1–4

Distractor condition	d' *M*	d' *SD*	d' *n*
Experiment 1			
Later than target	1.63	0.32	9
No distractor	1.58	0.34	9
Earlier than target	1.69	0.35	10
Experiment 2			
Later than target	1.10	0.81	10
No distractor	0.98	0.68	10
Earlier than target	1.24	0.75	10
Experiment 3			
Later than target	0.77	0.41	9
No distractor	0.68	0.44	9
Earlier than target	0.64	0.46	9
Experiment 4			
Later than target	0.88	0.29	19
No distractor	0.88	0.31	19
Earlier than target	0.89	0.38	19

Note. The rightmost column displays the number of observers who entered the analysis.

Discrimination Thresholds

The individual differences between late and early TTC corresponding to 75% of correct responses (ΔTTC_{Th}) measured in the adaptive procedure ranged from 294 to 1,011 ms (M = 582.0 ms, SD = 272.9 ms). Thus, the individual Weber fractions (i.e., the ratio between ΔTTC_{Th} and the minimum TTC of 4,000 ms) ranged from 0.074 to 0.25. Regan and Hamstra (1993) reported the Weber fraction for the TTC of simple expanding stimuli to be 0.07 to 0.13, which is very similar the thresholds found here.

Discussion

We had entertained the hypothesis that an averaging of target and distractor TTC might occur. On the basis of this hypothesis, the distractor arriving at the observer later than the target should have resulted in a higher proportion of *late* responses. We were surprised to find that the data showed exactly the opposite pattern in this condition (see Figure 3): Relative to the condition without a distractor, the observers responded less often that the late-arriving car had been presented if the truck arrived later than the car. In other words, the data indicate a contrast effect rather than assimilation or an averaging between target TTC and distractor TTP. There was no significant effect of the distractor arriving earlier than the target, however. A closer look at the early-arriving distractor revealed a contrast effect for 4 observers, which was nulled by an opposite effect for the remaining observers.

In the condition without the distractor, observers showed a small but not significant bias toward responding that the late-arriving target had been presented—that is, target TTC was slightly overestimated. Although most experiments using a PM task have found an underestimation of TTC (e.g., McLeod & Ross, 1983; Schiff & Detwiler, 1979), cases of TTC overestimation have also been reported, particularly for extrapolation intervals smaller than 1,000 ms (e.g., Hecht, Kaiser, Savelsbergh, & Van der Kamp, 2002; Heuer, 1993; Smith et al., 2001). The extrapolation intervals in the present experiment were about 1,000 ms.

Other methods are likely to hide response biases when the issue is not explicitly addressed. For instance, Regan and Hamstra (1993) used an identification task to study TTC estimation for simple expanding stimuli. Unfortunately, they did not analyze the data in terms of response bias. Visual inspection of their plots of the psychometric functions indicates that response bias was virtually absent, which is not too surprising as trial-by-trial feedback was provided in the experiments.

Although the significant effect of the distractor condition on response bias indicates that the observers were not successful in ignoring the distractor, sensitivity was not impaired by the distractor. This dissociation between the effects on sensitivity and bias is compatible with Pattern c discussed in the introduction.

[3] For computation of the sensitivity measure d', the proportions of hits and false alarms were converted to standard normal deviates, via the relation $z = F^{-1}(P)$, where z is the standard normal deviate corresponding to the proportion P and $F^{-1}(x)$ is the inverse cumulative density function of a normal distribution with mean 0 and standard deviation 1, evaluated at point x. The sensitivity index is given by $d' = z_{\text{hit}} - z_{\text{false alarm}}$.

Experiment 2: Variation of Object Size

Given the surprising pattern of results found in Experiment 1, we decided to replicate the effects of a distractor object on TTC judgments with a different group of observers and with some methodological refinements, using essentially the same setting as in Experiment 1. First, the value of ΔTTC_{Th} obtained during individual calibration in Experiment 1 apparently overestimated the just-noticeable TTC difference for some observers, resulting in high percentages of correct responses. High performance levels resulted in a ceiling effect that could have reduced the effect of the distractor. Additionally, d' cannot be computed if there are no false alarms, as was the case for 1 observer in Experiment 1. To avoid these problems, Experiment 2 started with two successive adaptive measurements of ΔTTC_{Th}.

The second issue addressed in Experiment 2 was the correlation between single visual variables and contact time. It is not possible to vary TTC independently of other physical or optical variables (Gray & Regan, 1998; Novak, 1998). For example, for a rigid, nonrotating object approaching an observer on a collision course and at constant speed, TTC(t) is uniquely defined by the ratio of the instantaneous distance $D(t)$ and the velocity v, at any point in time t. Now, if two or more values of TTC are to be presented in an experiment, it is possible to combine each value of TTC with the same set of at least two velocities (v_0, v_1, . . ., v_n), such that target velocity by itself provides no information about TTC. This is exactly what we did in Experiment 1, in which, for each of the two car contact times, the velocity was equally often set to one of three values. In this situation, however, because of the relation TTC = Dv, the smallest and the largest starting distance presented in the experiment unambiguously indicate the early and the late arrival time, respectively. Depending on the stimulus configuration and the experimental procedure, several other optical variables are correlated with TTC. That is, for the identification task with constant presentation duration used in Experiment 1, the visual angle subtended by the target object at blanking time (θ_{Blank}) as well as the distance from the observer at blanking time provided a cue to contact time. For a given simulated contact time TTC, the horizontal visual angle subtended by the target object at blanking time is

$$\theta_{Blank} = 2\ \arctan\frac{s/2}{v(TTC - t_{Blank})}, \tag{1}$$

where t_{Blank} is blanking time, and s is the physical width of the object.

For a given velocity, late contact times correspond to smaller visual angles at blanking time. If for each TTC the velocity is sampled from the same set to make TTC independent of v, as in Experiment 1, mean θ_{Blank} will be smaller for the late TTC. For this reason, the observers could use θ_{Blank} as a cue to contact time (cf. Gray & Regan, 1998; Regan & Hamstra, 1993). The confound is inevitable, but to reduce the information provided by θ_{Blank} and D_{Blank}, one could vary presentation duration (Gray & Regan, 1998). We chose not to do so to ensure that the time during which target and distractor were both visible remained the same and information uptake could be assumed to be comparable in all trials. Instead, we reduced the information provided by θ_{Blank} by scaling the physical sizes of the target and distractor as well as the horizontal distance between the midpoints of the two objects. The scaling factor was 0.6, 1.0, or 1.4 in each trial. As a result, θ_{Blank} was still correlated with TTC but no longer provided an unambiguous cue to the correct response. The scene was not scaled but remained constant.

Method

Observers

Ten students at Johannes Gutenberg-Universität Mainz (9 women, 1 man; age = 19–31 years) participated in the experiment voluntarily. All had normal or corrected-to-normal vision. They either received partial course credit or were paid for participation. All observers were naive with respect to the aim of the experiment. None of them had participated in Experiment 1.

Stimuli and Apparatus

The same stimuli and apparatus as in Experiment 1 were used, except for two changes. First, the car now moved in the center rather than on the left side of the road. As before, the car was horizontally centered on the screen. Second, three scaling factors (0.6, 1.0, or 1.4) were used to vary the physical dimensions of target and distractor. Across observers and conditions, the car subtended a horizontal visual angle between 1.79° and 14.45° at the instant before it disappeared.

Procedure

Individual calibration. To avoid overly large values of ΔTTC and the resulting high performance levels, Experiment 2 started with two successive adaptive measurements of ΔTTC_{Th}. The same procedure as in Experiment 1 was used, except that the early TTC remained constant at 3,800 ms rather than at 4,000 ms. Maximum ΔTTC was now 2,000 ms, and the scaling factor of 0.6, 1.0, or 1.4 was randomly selected in each trial. The smaller of the two estimates of ΔTTC_{Th} was used in the main experiment. Additionally, if the minimum ΔTTC_{Th} was larger than 800 ms, ΔTTC was set to 800 ms in the main experiment, thereby disallowing inattention to interfere with the calibration.

Data collection. In the main part of the experiment, the combination of car velocity and starting distance was determined by a different algorithm than in Experiment 1. The intermediate car velocity was set to 27 m/s (97.2 km/hr) for all observers. For this velocity, we selected two starting distances to produce the early and the late contact times. Then we computed a smaller velocity, producing the late contact time for the smaller starting distance. In the next step, a starting distance was determined that corresponded to the early contact time with the velocity computed in the previous step. This procedure was also applied to the larger starting distance computed in the first step and was iterated until three different car velocities were determined for each car TTC. Table 2 shows the velocity–starting distance combinations corresponding to ΔTTC = 400 ms. Again, each contact time was presented with the same set of three car velocities. The six factor combinations were presented equally often (63 times).

Design

In the main part of the experiment, three distractor conditions were presented. Either the truck arrived at the observer's eye plane

Table 2
Example Target TTC × Velocity Combinations (Experiments 2–4)

Starting distance	Velocity		
	v_0 (24.43 m/s)	v_1 (27.0 m/s)	v_2 (29.84 ms/s)
d_0 (92.83 m)	TTC = 3,800 ms		
d_1 (102.6 m)	TTC = 4,200 ms	TTC = 3,800 ms	
d_2 (113.4 m)		TTC = 4,200 ms	TTC = 3,800 ms
d_3 (125.34 m)			TTC = 4,200 ms

Note. For all observers, mean time to contact (TTC) was 4,000 ms, and the intermediate velocity (v_1) was 27.0 m/s. The difference between late and early contact time (ΔTTC) depended on the individual calibration. The table shows parameter values for ΔTTC = 400 ms.

earlier than the car, the truck arrived later than the car, or no truck was presented. The two car contact times were factorially combined with the three car velocities, the three size scaling factors (0.6, 1.0, 1.4), and the three distractor conditions (no truck, truck earlier, truck later). Car and truck were always scaled by the same scaling factor. Each observer received each factor combination seven times, which resulted in a total of 378 trials. Presentation order was randomized. No feedback was provided. The testing session was completed in approximately 1 hr, with two brief rest periods.

Results

Proportion of Late Responses

The proportion of *late* responses was analyzed via an ANOVA with the within-subject factors distractor condition, target velocity, and scaling factor. The main effect of distractor condition was significant, $F(2, 18) = 4.21$, $\tilde{\varepsilon} = 1.0$, $p = .032$. As in Experiment 1, the distractor arriving at the observer later than the car reduced the proportion of *late* responses (see Figure 4). All except 3 observers exhibited this pattern. On average, the truck arriving earlier than the car had virtually no effect (see Figure 4). Neither the main effect of target velocity, $F(2, 18) = 0.96$; the main effect of scaling factor, $F(2, 18) = 0.72$; nor any of the two- and three-way interactions was significant ($p > .18$). Post hoc analyses were used to analyze the effects of the late-arriving and the early-arriving distractor separately. A 2 × 3 × 3 (Distractor Condition × Target Velocity × Scaling Factor) repeated-measures ANOVA conducted for the data obtained without the distractor and with the distractor arriving later than the target showed a marginally significant effect of the distractor, $F(1, 9) = 3.91$, $p = .079$. The remaining effects were not significant. A similar ANOVA was used to analyze the data obtained in the conditions without the distractor and with the distractor arriving earlier than the car. There was no significant effect of distractor condition, $F(1, 9) = 0.38$. None of the other main or interaction effects was significant.

On trials presenting the target object only, there was again a small bias toward responding that the late car contact time had been presented ($M = .52$, $SD = .03$). However, a one-sample t test showed that the proportion of *late* responses was not significantly different from .5, $t(9) = 1.03$.

Sensitivity

The average proportion of correct responses was .69 ($SD = .11$), which was smaller than the mean P(C) in Experiment 1, but the difference was not significant, $t(19) = 1.54$. The repeated measurement of ΔTTC_{Th} during the individual calibration and the restriction of ΔTTC to values smaller than or equal to 800 ms were successful in avoiding unduly high performance levels; individual average values of $P(C)$ ranged from .55 to .89. The frequencies of hits and false alarms were summed across target velocity and scaling factor, such that in each distractor condition there were 126 trials per observer. There were no cases with fewer than two false alarms, which again demonstrates the utility of the improved measurement of ΔTTC_{Th}. Table 1 displays the mean values of d' estimated in the three distractor conditions. A univariate repeated-measures ANOVA showed no significant effect of distractor condition on d', $F(2, 18) = 1.98$.

Discrimination Thresholds

As discussed above, the discrimination threshold ΔTTC_{Th} was measured in two separate adaptive tracks. Across observers, the average minimum value of ΔTTC_{Th} was 555.6 ms ($SD = 354.7$ ms). Individual values ranged from 95 ms to 998 ms. If minimum ΔTTC_{Th} was larger than 800 ms for an observer, ΔTTC = 800 ms was used in the main experiment. The average maximum ΔTTC_{Th} was 823.3 ms ($SD = 405.0$ ms). The grand mean was 689.4 ms ($SD = 374.5$ ms). This indicates that the introduction of the size variation made the task more difficult than in Experiment 1, in which the mean discrimination threshold was 582.0 ms. The difference in average ΔTTC_{Th} was not significant, however, $t(19) = -0.76$.

Discussion

Experiment 2 closely replicated the pattern of results found in Experiment 1, using an improved estimation of the individual discrimination thresholds and a different group of participants. It also addressed the correlation between target TTC and size at blanking time by introducing variations in object size. The dis-

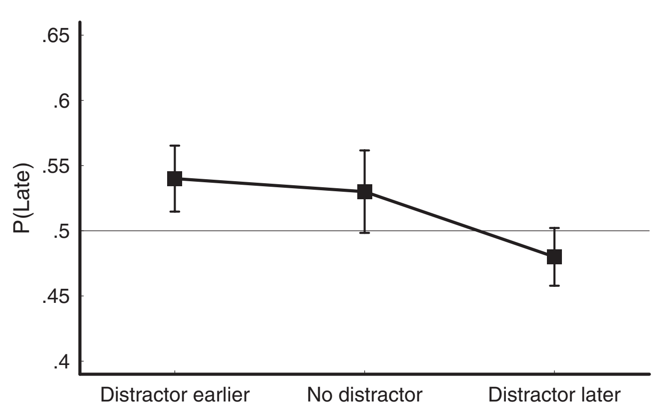

Figure 4. Experiment 2: Mean proportions of *late* responses observed in the three distractor conditions. The horizontal line represents unbiased responding ($P[late] = .5$). Error bars show plus and minus one standard error of the mean of the 10 individual proportions.

tractor arriving at the observer later than the target again caused a bias toward *early* responses (a contrast effect), while the early-arriving distractor had no significant effect. The absence of both a significant main effect of the scaling factor and an interaction between distractor condition and scaling factor indicates that the distractor effects observed in Experiment 1 cannot be attributed to the correlation between target TTC and object size at blanking time. It should be noted, however, that the simulated distance between observer and car at blanking time was still a cue to contact time. This issue is addressed in Experiment 4.

Experiment 3: Stereoscopic Presentation

The stimuli in Experiments 1 and 2 were two-dimensional projections of 3D objects. While TTC judgments have often been studied with two-dimensional objects or even with monocular viewing (Hecht & Savelsbergh, 2004), it is known that stereoscopic information can be exploited and probably plays an important role in natural TTC settings (Bennett, van der Kamp, Savelsbergh, & Davids, 1999; Gray & Regan, 1998; Gray et al., 2004). The absence of stereoscopic information in our displays might be able to explain, at least in part, the small bias toward *late* responses. Accommodation remained constant at the viewing distance of 40 cm, as is generally the case in virtual-reality displays. Consequently, the oculomotor cues accommodation and convergence failed to indicate change in depth and thereby approach of the simulated object. Also, binocular disparity remained constant while the simulated object approached the observer, such that this stereoscopic depth cue also indicated a fixed object. It could be argued that the three depth cues indicating no motion in depth at all resulted in an underestimation of object velocity and, consequently, an overestimation of TTC. Therefore, we presented the same virtual scenes already used in Experiment 2 but added binocular information by using a head-mounted display. In this setting, the oculomotor depth cues still remained constant, but the head-mounted display changed accommodation to about 2 m, thus avoiding accommodative change. Note that the closest target position before blanking was 22.1 m in front of the observer. To ensure that binocular disparity provided easily noticeable depth information and to be within the resolving power of the stereo system (Banks, Gepshtein, & Landy, 2004), we artificially enlarged the interocular distance. We expected this manipulation to reduce the bias toward *late* responses if stereo information had been an issue in the previous experiments.

Method

Observers

Ten students at the Johannes Gutenberg-Universität Mainz (8 women, 2 men; age = 20–32 years) participated in the experiment voluntarily. All had normal or corrected-to-normal vision. They either received partial course credit or were paid for participation. All observers were naive with respect to the hypotheses under test.

Stimuli and Apparatus

The same stimuli as in Experiment 2 were used, supplemented by the viewpoint for the other eye (stereoscopic presentation). An nVisor SX (NVIS, Reston, VA) head-mounted display was used. Display resolution was 1280 × 1024 pixels/eye (horizontal × vertical). The diagonal of the monocular field of view was 60°. The refresh rate was 60 Hz. In a pretest, the virtual interocular distance used as the basis for the stereoscopic projection was determined for each observer separately. Initially, it was set to the observer's actual interocular distance multiplied by a factor of 3.1. If the observer indicated double vision or discomfort, the factor was gradually decreased until perception was comfortable. The resulting virtual interocular distances ranged from 1.3 to 3.1 (M = 1.83, SD = 0.73).

Design and Procedure

The same design and procedure as in Experiment 2 were used, except for the presentation of a practice block after the two adaptive tracks and before the main part of the experiment. The reason for including this block was that (as in Experiments 1 and 2) the ranges of contact times, car velocities, and starting distances were comparable but not identical for the adaptive tracks and the main experiment. In the additional practice block, the observer received one each of the 18 no-distractor conditions actually presented in the main experiment. Visual trial-by-trial feedback was provided during practice only.

Results

Proportion of Late Responses

The proportion of *late* responses was smaller with the late-arriving distractor, compared to the condition without a distractor (see Figure 5). This pattern was observed for all except 2 participants. Unlike in the two previous experiments, the truck arriving earlier than the car also caused a slight decrease in P(*late*).

We conducted an ANOVA with the within-subject factors distractor condition, target velocity, and scaling factor. The main effect of distractor condition was not significant, $F(2, 18) = 2.54$, $\tilde{\varepsilon} = 1.0$, $p = .114$. Neither the main effect of target velocity, $F(2, 18) = 0.85$; the main effect of scaling factor, $F(2, 18) = 0.32$; nor any of the two-way and three-way interactions was significant.

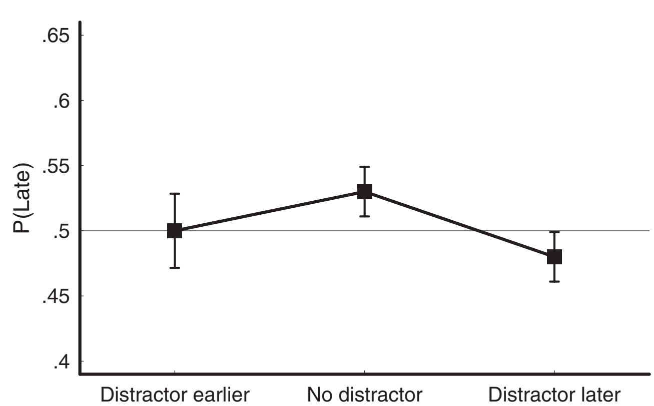

Figure 5. Experiment 3: Mean proportions of *late* responses observed in the three distractor conditions. The horizontal line represents unbiased responding (P[*late*] = .5). Error bars show plus and minus one standard error of the mean of the 10 individual proportions.

Despite the nonsignificant main effect of distractor condition, we conducted additional ANOVAs to separately analyze the effects of the early-arriving and the late-arriving distractor. In Experiments 1 and 2, post hoc analyses indicated that the main effect of the distractor was due to the condition presenting the late-arriving distractor. Thus, we expected a significant difference between the condition without a distractor and the condition with the late-arriving distractor. In fact, a 2 × 3 × 3 (Distractor Condition × Target Velocity × Scaling Factor) repeated-measures ANOVA comparing targets without a distractor and targets with late-arriving distractors showed a marginally significant effect of the distractor, $F(1, 9) = 5.00$, $p = .052$. The remaining effects were not significant. A similar ANOVA conducted for the data obtained in the conditions without a distractor and with the distractor arriving earlier than the car showed no significant effect of distractor condition, $F(1, 9) = 1.73$. None of the other main or interaction effects was significant.

Contrary to our expectation, there was again a small bias toward responding *late* on trials presenting the target object only ($M = .53$, $SD = .019$). This proportion was not significantly different from .5, one-sample $t(9) = 1.57$.

Sensitivity

The average value of $P(C)$ was .66 ($SD = 0.11$, range = .53–.91), which is comparable to the value observed in Experiment 2. The frequencies of hits and false alarms were summed across target velocity and scaling factor. Observer 3 was excluded from the analysis because there were two conditions with fewer than two false alarms. Table 1 displays the mean values of d' estimated in the three distractor conditions. A univariate repeated-measures ANOVA showed no significant effect of distractor condition on d', $F(2, 16) = 1.00$.

Discrimination Thresholds

Across observers, the arithmetic mean of the smaller of the two ΔTTC_{Th} estimates obtained during the individual calibration was 292.0 ms ($SD = 139.2$, range = 103–613 ms). The average maximum ΔTTC_{Th} was 733.2 ms ($SD = 407.1$ ms). The grand mean was 512.6 ms ($SD = 253.5$ ms). This value is smaller than the grand mean of ΔTTC_{Th} observed in Experiment 2, but the additional availability of stereoscopic depth information did not result in significantly improved thresholds, $t(18) = 1.24$.

Discussion

Stereoscopic presentation did not have the expected effect of completely removing the small bias toward *late* responses. Qualitatively, the distractor caused the same pattern of results as in the two previous experiments. That is, $P(late)$ was smaller with the late-arriving distractor than without distractor, although this effect was only marginally significant. The effect of the distractor was smaller in Experiment 3 than in the first two experiments. The difference between $P(late)$ observed without the distractor and with the distractor arriving later than the target was .050, while in Experiments 1 and 2 the difference was .091 and .054, respectively. We have deliberately chosen to maximize the potential effect of stereopsis by increasing the interocular distance. Even this measure was unable to remove the contrast effect induced by the to-be-ignored distractor object. The contrast effect thus appeared to be a robust effect.

Experiment 4: Abstract Objects

A potential explanation for the contrast effect is a *safety strategy,* albeit not a straightforward one. Generally, an additional approaching object may be identified as a potential threat, causing observers to adopt a bias toward *early* responses. To explain the pattern of results observed in Experiments 1–3, one could argue that the truck activated the safety strategy only in those cases in which it arrived late: If the danger is far, action is permissible, and a safety strategy seems in order. Conversely, if the danger is near (truck arriving earlier than the car), action is not permissible. A safety strategy would not be activated, as action is prohibited to begin with.

We subjected the safety strategy hypothesis to a critical test by presenting as target and distractor abstract geometric objects not typically encountered in people's daily environments—namely, expanding disks moving on a uniformly black background. Such disks should be nonthreatening and thus fail to elicit a safety strategy.

Method

Observers

Nineteen students at the Johannes Gutenberg-Universität Mainz (8 men, 11 women; age = 19–35 years) participated in the experiment voluntarily. All had normal or corrected-to-normal vision. They received partial course credit for participation. Six observers ran the experiment as part of an undergraduate research project; they were aware of the general experimental hypothesis. The remaining observers were naive with respect to the aim of the experiment.

Stimuli and Apparatus

The target object was a red solid disk with a diameter of 4.5 m, presented in virtual reality. It was centered horizontally and vertically on the display screen and moved with constant velocity on a trajectory orthogonal to the display surface and passing through the eye point of the simulated observer. Thus, participants simply viewed an expanding stimulus. Color and luminance remained constant. A uniformly black background was used. Across conditions and observers, the target object subtended a visual angle between 2.04° and 31.83° when it disappeared. The distractor object was a blue disk with the same diameter as the target. It was presented to the right of the target (as viewed by the observer) and at the same vertical position on the screen (see Figure 6).

The distance between the midpoints of the two objects was 5 m. The distractor moved with constant velocity on a trajectory parallel to the target trajectory. The observer thus saw two expanding objects, one of which slightly changed its shape from a nearly perfect circle to an ellipse as it approached. The same apparatus as in Experiments 1 and 2 was used—that is, the stimuli were presented on a thin-film transistor display without stereoscopic information.

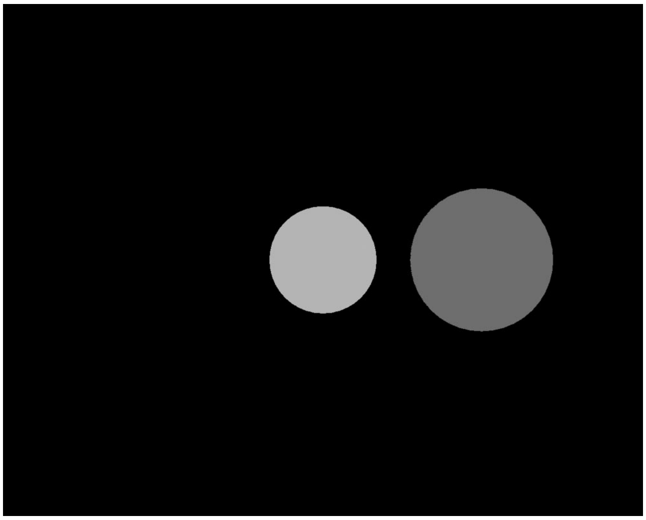

Figure 6. Screenshot of a trial from Experiment 4. The disk on the left is the target object (presented in red color). The disk on the right is the distractor object (presented in blue color).

Procedure

The same task as in Experiments 1 to 3 was used. To further reduce the correlation between TTC and single optical variables, such as the distance from the observer at blanking time, we varied the presentation duration (on time) of the target in Experiment 4. On trials presenting the distractor object, the distractor remained on the screen until the observer pressed a response key or the distractor had passed the observer.

The experiment started with two adaptive tracks measuring individual discrimination thresholds (ΔTTC_{Th}), just as in Experiments 2 and 3. To make the range of contact times and target velocities more similar to the values presented in the main part of the experiment, we used slightly different parameters than in Experiments 2 and 3. Mean target TTC was set to 4,000 ms. In each trial, either an early TTC (4,000 ms − ΔTTC/2) or a late TTC (4,000 ms + ΔTTC/2) was selected at random. Target velocity was randomly selected from a range between 27 m/s − 30% and 27 m/s + 30%. For each velocity, starting distance was computed to match the designated TTC. A size scaling factor of 0.6, 1.0, or 1.4 was randomly selected in each trial. Presentation duration was randomly set to 2,100 ms, 2,600 ms, or 3,100 ms in each trial. The smaller of the two estimates of ΔTTC_{Th} was used, and maximum ΔTTC was chosen to be 800 ms in the main part of the experiment.

As in Experiment 3, a practice block was run following the second adaptive track. It comprised the 18 no-distractor conditions presented in the main experiment. Only trials without a distractor were presented. Visual trial-by-trial feedback was provided in the adaptive tracks and in the practice block but not in the main part of the experiment. In the main part of the experiment, the same procedure as in Experiments 2 and 3 was used, except for the variation of presentation duration.

Design

Target TTC was factorially combined with the three target velocities and the three scaling factors. Target and distractor were always scaled by the same scaling factor. In each trial, one of the three presentation durations (t_{Blank} = 2,100 ms, 2,600 ms, or 3,100 ms) was randomly selected. The reason not to vary presentation duration factorially was to limit the duration of an experimental session to approximately 1 hr. Three distractor conditions were presented. Either the blue disk arrived at the observer's eye plane earlier than the target, the distractor arrived later than the target, or no distractor was presented. Each observer received each factor combination eight times, which resulted in a total of 432 trials. Presentation order was randomized. No feedback was provided. The observers were informed that the size, the speed, and the presentation duration of the objects would be varied and that none of these variables provided a reliable cue to contact time. It was emphasized that observers should mentally extrapolate the movement of the target object and give their answer on this basis.

Results

Proportion of Late Responses

The proportion of *late* responses was analyzed via an ANOVA with the within-subject factors distractor condition, target velocity, and scaling factor. We did not include presentation duration as a factor, because it had not been varied factorially. Below, an additional ANOVA is presented with presentation duration as a factor and the data averaged across target velocity.

The main effect of distractor condition was significant, $F(2, 36) = 7.75$, $\tilde{\varepsilon} = .82$, $p = .003$. Relative to the condition without a distractor, the distractor arriving at the observer later than the car reduced the proportion of *late* responses (see Figure 7). Of the 19 observers, 15 exhibited this pattern. On average, the distractor arriving earlier than the target also resulted in a slight decrease in *P*(*late*), but this effect was not consistent across observers. Neither the main effect of target velocity, $F(2, 36) = 0.49$; the main effect of scaling factor, $F(2, 36) = 0.41$; nor any of the two- and three-way interactions was significant. A 2 × 3 × 3 (Distractor Condition × Target Velocity × Scaling Factor) repeated-measures ANOVA conducted for the data obtained without a distractor and with the distractor arriving later than the target showed a significant effect of the distractor, $F(1, 18) = 28.15$, $p = .001$. The

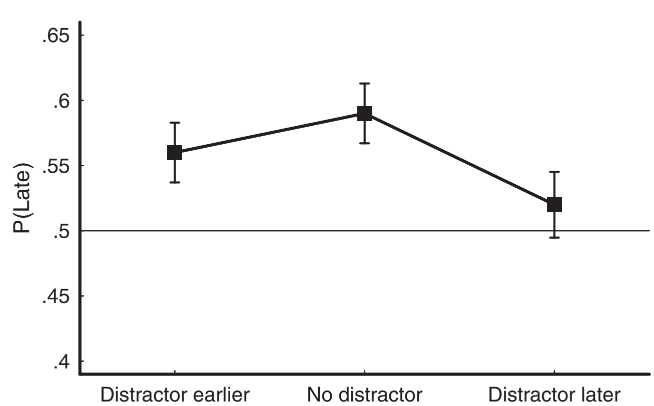

Figure 7. Experiment 4: Mean proportions of *late* responses observed in the three distractor conditions. The horizontal line represents unbiased responding (*P*[*late*] = .5). Error bars show plus and minus one standard error of the mean of the 19 individual proportions.

remaining effects were not significant. A similar ANOVA was used to analyze the data obtained in the conditions without a distractor and with the distractor arriving earlier than the target. There was no significant effect of distractor condition, $F(1, 18) = 2.99$. None of the other main or interaction effects was significant.

On trials presenting the target object only, there was a bias toward responding that the late car contact time had been presented ($M = .59$, $SD = .10$). A one-sample t test showed that the proportion of *late* responses was significantly different from .5, $t(18) = 3.94$, $p = .001$.

An additional ANOVA was used to analyze the effect of the presentation duration. The three within-subject factors were distractor condition, scaling factor, and presentation duration. The effect of distractor condition was again significant, $F(2, 36) = 8.34$, $\tilde{\varepsilon} = .90$, $p = .002$. There was also a significant main effect of presentation duration, $F(2, 36) = 32.23$, $\tilde{\varepsilon} = .56$, $p = .001$, because the proportion of *late* responses decreased strongly with presentation duration. Means for the short, intermediate, and long presentation durations were .73 ($SD = .15$), .55 ($SD = .11$), and .39 ($SD = .17$), respectively. This pattern is compatible with the strategy of using the visual angle subtended by the target at blanking time as a cue to contact time. On average, this angle was smallest on trials with the short presentation duration. Thus, an observer who adopted a strategy of responding *late* if the final size of the target object was small would produce the largest proportion of *late* responses if the presentation duration was short. As the interaction between distractor condition and presentation duration was not significant, however, it can be concluded that the effect of the distractor on $P(late)$ cannot be attributed to such a strategy. The main effect of scaling factor and the remaining two- and three-way interactions were not significant.

Sensitivity

On average, $P(C)$ was .66 ($SD = .045$, range = .59–.73). The frequencies of hits and false alarms were summed across target velocity, scaling factor, and presentation duration, such that in each distractor condition there were 144 trials per observer. Table 1 displays average sensitivity for the three distractor conditions. A univariate repeated-measures ANOVA showed no significant effect of distractor condition on d', $F(2, 36) = 0.01$.

Discrimination Thresholds

The mean of the smaller of the two ΔTTC_{Th} estimates was 740.4 ms ($SD = 309.2$ ms, range = 417–1,323 ms). For 7 observers, minimum ΔTTC_{Th} was larger than 800 ms, such that $\Delta TTC = 800$ ms was used in the main experiment. The average maximum ΔTTC_{Th} was 1,077.0 ms ($SD = 292.2$ ms). The grand mean was 900.5 ms ($SD = 272.6$ ms). A post hoc complex comparison showed that ΔTTC_{Th} in Experiment 4 was significantly larger than the average ΔTTC_{Th} in Experiments 1 to 3, $t(39.02) = 3.67$, $p = .001$ (two-tailed, equal variances not assumed). The thresholds thus indicate that the task was more difficult for the abstract geometric objects, presumably because only expanding size information was available.

Discussion

The presentation of abstract objects instead of vehicles did not remove the bias toward *early* responses in the condition with the late-arriving distractor. This result makes the complex safety strategy mentioned earlier even less likely. A distractor that does not resemble objects encountered in daily life should not make observers more cautious. As in Experiment 3, there was also a small decrease (see Figure 7) in average $P(late)$ in the condition with the early-arriving distractor, but this effect was not significant.

On trials presenting the target object only, observers produced a significant bias toward *late* responses. It remains unclear whether the bias was stronger than in the first three experiments because of the different type of stimuli or because of the variation of presentation duration.

Presentation duration had a strong effect on $P(late)$, which can be explained by the observers judging an object subtending a large angle at blanking time to arrive earlier than an object with a smaller final size. This result is compatible with previous reports that observers use simple pictorial cues, such as retinal size, in TTC estimation (DeLucia, 1991, 2005). As there was no interaction between presentation duration and distractor condition, however, the effects of the distractor objects cannot be attributed to the use of size information.

Experiment 5: PM Task

Experiments 1 to 4 established a stable pattern of effects caused by a moving distractor object. To rule out the possibility that the results were due to the particular psychophysical procedure, a PM task was used in Experiment 5. Observers viewed a target object in virtual reality approaching them on the mid-sagittal plane. At some point in time, the object disappeared from screen. The observers were asked to press a button at exactly the moment they thought the object would have arrived at their position had it continued its trajectory. As in the previous experiments, distractor objects with a TTP either earlier or later than target TTC were presented. As Tresilian (1995) has pointed out, in a PM task the observers are required to delay their response after the disappearance of the target from the screen, and thus "cognitive" mechanisms such as clocking or cognitive motion extrapolation are likely to play a role. In contrast, in the AI task, this type of cognitive influences is minimized (cf. DeLucia & Novak, 1997; Law et al., 1993). Thus, the two types of tasks differ in terms of the processing involved. Note that it could be argued that the AI task used in the previous four experiments is rather artificial, while the PM task is more intuitive. However, if one considers the real-world example of crossing a street, a pedestrian judges at a given point in time whether an approaching car will arrive at his or her position late (i.e., late enough for the pedestrian to safely cross the street) or early (i.e., too early for the pedestrian to proceed). Put differently, we frequently perform AI tasks in everyday life. At any rate, both tasks reflect TTC estimation capabilities more akin to "slow" judgments involving temporal estimation, such as street crossing, rather than to fast interceptive actions (cf. Tresilian, 1995) involving a direct perception–action coupling.

Also, a potential explanation for the effect of the late-arriving distractor being stronger than the effect of the early-arriving distractor should be addressed. The longer presence of this distractor between the target's disappearance from the screen and response could be responsible.[4] In fact, the late-arriving distractor was visible during at least 90% of the period between blanking of the target object and response in approximately 90% of all individual trials collected in Experiments 1 to 4. The early-arriving distractor, conversely, was visible for at least 90% of this period in only about 30% of the trials in Experiments 1 and 2 and in slightly more than 50% of all trials in Experiments 3 and 4. In Experiment 5, the target and the distractor object were blanked from the screen simultaneously. If the moving distractor object exerted its effect on TTC judgments mostly between blanking of the target object and response, neither the late-arriving nor the early-arriving distractor should have had an effect in the present experiment, as both distractors were completely absent during the extrapolation period.

Method

Observers

Twenty-one volunteers participated in the experiment. The data for 2 observers indicated that they had always pressed the response button at a constant time after the target object had disappeared from the screen, rather than judging TTC of the target. Because German was not their native language, it is possible that these observers did not understand the instructions correctly. Their data were excluded from the analyses. The remaining participants (6 women, 13 men) ranged in age from 20 to 33 years ($M = 24.5$, $SD = 3.0$). All reported normal or corrected-to-normal vision. The observers were uninformed about the hypotheses under test.

Stimuli and Apparatus

The same stimuli and apparatus as in Experiment 4 were used. Across conditions, the target object subtended a visual angle between 2.26° and 26.93° at the instant before it disappeared.

Procedure and Design

Three values of target TTC were factorially combined with three target velocities, three presentation durations, and three scaling factors. Target TTC was 3,636 ms, 4,000 ms, or 4,400 ms. Target velocity was 24.545 m/s, 27.0 m/s, or 29.7 m/s. For each velocity, we computed a starting distance to produce the designated TTC, which resulted in distances between 89.25 m and 130.69 m. The scaling factor was 0.6, 1.0, or 1.4. Target and distractor size were always scaled by the same factor. Presentation durations were 2,100 ms, 2,600 ms, and 3,100 ms. This selection of the parameters resulted in extrapolation intervals (i.e., the time between target disappearance and TTC) ranging from 536 ms to 2,300 ms. The same parameter values were used for each observer. Unlike in the previous experiments, the target and the distractor disappeared from the screen simultaneously.

The experiment started with a practice block in which only trials without distractor were presented, containing each of the 81 factorial combinations once. Visual trial-by-trial feedback was provided in the form of the deviation of the time of the observer's keypress from the actual target TTC. Observers were informed that the size, the speed, and the presentation duration of the target object would be varied and that none of these variables provided a reliable cue to contact time. They were instructed to mentally extrapolate the movement of the target object and to respond on this basis.[5]

In the main part of the experiment, no feedback was provided. Three distractor conditions were presented. Either the distractor arrived at the observer's eye plane earlier than the target (TTP = 3,500 ms), it arrived later than the target (TTP = 4,500 ms), or no distractor was presented. Observers were instructed to ignore the distractor object. Each observer received each of the 3 (target TTC) × 3 (target velocity) × 3 (presentation duration) × 3 (scaling factor) × 3 (distractor condition) combinations two times, which resulted in a total of 486 trials. Presentation order was randomized. No feedback was provided. The experimental session lasted approximately 75 min, with two short breaks.

Results and Discussion

The individual data were analyzed in terms of constant error (CE) and variable error (cf. Hartmann, 1983; Tresilian, 1994). CE denotes the signed difference between the observed response time (i.e., the time between the disappearance of the target object and the keypress) and the correct response time (i.e., the extrapolation interval). In all following analyses, we used the median rather than the arithmetic mean of the CE when aggregating across trials or conditions within an observer, to reduce the influence of long response times. Variable error denotes the standard deviation of the difference between the observed response time and the correct response time.

On trials without a distractor, the individual data could be accounted for reasonably well by a linear regression between extrapolation interval and response time, with the coefficient of determination ranging from .85 to .99 ($M = .94$, $SD = .04$). For 11 of the 19 observers, the estimated slope was significantly smaller than the ideal value of 1.0, compatible with findings from previous PM experiments (Cavallo & Laurent, 1988; DeLucia & Liddell, 1998; Heuer, 1993; McLeod & Ross, 1983; Schiff & Oldak, 1990). The intercept was significantly larger than the ideal value of 0 ms for 13 observers, unlike in most previous PM studies, in which the data could be accounted for by linear regression through the origin. A potential explanation for the larger intercepts observed in the present experiment is that the range of target TTCs was smaller than the range of extrapolation intervals. Therefore, it is conceivable that some observers adopted a strategy of timing the average target TTC (4,012 ms). In the extreme, such a strategy would result in the observer always pressing the response key 4,012 ms after the appearance of the object on the screen. In fact, the response times of 4 observers at the shorter presentation durations were roughly compatible with such a strategy. On average, however, observers adapted their response times to target TTC (see Figure 8, left panel). For the mean data, the best fitting linear regression line (the thick line in the left panel of Figure 8) had an intercept of 350 ms ($SD = 295$ ms) and a slope of 0.79 ($SD = 0.25$). Therefore, the CE (i.e., the average difference between the correct response time and

[4] We thank an anonymous reviewer for entertaining this explanation.

[5] For a discussion of whether observers in a prediction-motion task use motion extrapolation in the sense of visual imagery or estimate tau at the moment the object disappears from the screen and then use a timing mechanism to delay their response until the virtual collision time, see DeLucia and Liddell (1998).

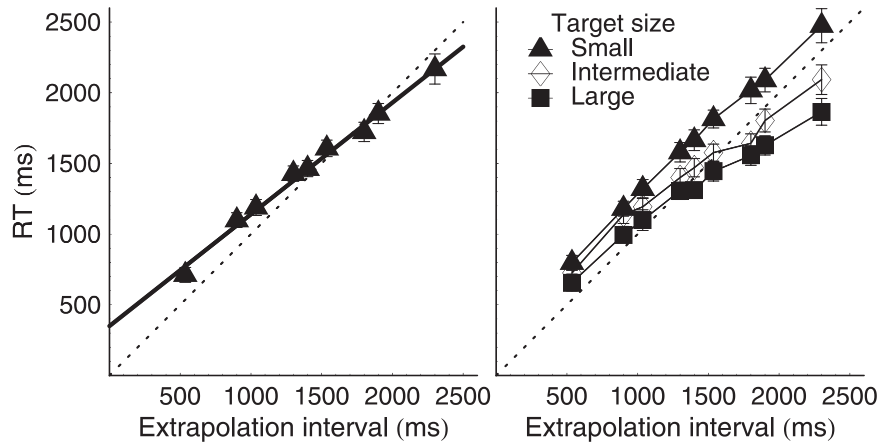

Figure 8. Experiment 5. Left panel: Mean response time (i.e., the time between the disappearance of the target object and the keypress) as a function of the extrapolation interval for the no-distractor condition. The thick line shows the best fitting linear regression line (y = 350 ms + 0.79 x). The dotted diagonal represents perfect performance. Right panel: Mean response time as a function of extrapolation interval and target size for the no-distractor condition. Error bars show plus and minus one standard error of the mean of the 19 individual median response times (RTs).

the observed response time) was positive for short extrapolation intervals. At long extrapolation intervals, the observers underestimated target TTC, evident by the negative CE.

An ANOVA with the within-subject factors extrapolation interval, target size, and target velocity conducted for the trials without a distractor showed a significant effect of extrapolation interval on the CE, $F(2, 36) = 11.5$, $\tilde{\varepsilon} = .23$, $p = .001$—the longer the interval was, the larger the underestimation of TTC was. The variation in target size due to the three scaling factors had a clear effect on the CE, $F(2, 36) = 126.1$, $\tilde{\varepsilon} = .74$, $p = .001$ (see Figure 8, right panel). For the smallest target size, TTC was consistently overestimated, and the CE changed only a little with the extrapolation interval. For the two larger target sizes, the CE changed from positive to negative values as the duration of the extrapolation interval increased. The increase of the effect of target size with extrapolation interval was confirmed by a significant Extrapolation Interval × Target Size interaction, $F(16, 288) = 6.19$, $\tilde{\varepsilon} = .91$, $p = .001$. It is compatible with data by DeLucia (1991). Target velocity had a small but significant effect on the CE, $F(2, 36) = 5.74$, $\tilde{\varepsilon} = 1.0$, $p = .007$. Means for the slow, intermediate, and fast velocities were −4.4 ms (SD = 239.5 ms), 32.3 ms (SD = 235.2 ms), and 53.3 ms (SD = 226.0 ms), respectively. The remaining main effects and interactions were not significant. The variable error—that is, the standard deviation of an observer's response times in a given condition—increased with the extrapolation interval, $F(8, 144) = 9.2$, $\tilde{\varepsilon} = .79$, $p = .001$ (see Figure 9). This pattern is compatible with results from Schiff and Detwiler (1979) and DeLucia and Lidell (1998). The main effects of target size and target velocity as well as all interactions were not significant.

To analyze the effects of the distractor object on the CE, we conducted an ANOVA with the within-subject factors target TTC, distractor condition, target velocity, presentation duration, and target size. There was a significant main effect of distractor condition on the CE, $F(2, 36) = 15.1$, $\tilde{\varepsilon} = 1.0$, $p = .001$. With both the early-arriving and the late-arriving distractor, observers estimated target TTC as being earlier than in the no-distractor condition (see Figure 10).

Post hoc analyses showed that the decrease in CE relative to the control condition was significant for the late-arriving distractor, $F(1, 18) = 11.4$, $p = .003$, as well as for the early-arriving distractor, $F(1, 18) = 25.4$, $p = .001$. Thus, the relative underestimation of target TTC caused by the late-arriving distractor was not restricted to the AI task used in Experiments 1 to 4. Note that in Experiments 3 and 4, the average data also indicated an underestimation of target TTC caused by the early-arriving distractor, but these effects were not significant. In the present experiment, estimated target TTC was even significantly smaller with the early-arriving distractor than with the late-arriving distractor, $F(1, 18) = 5.6$, $p = .03$.

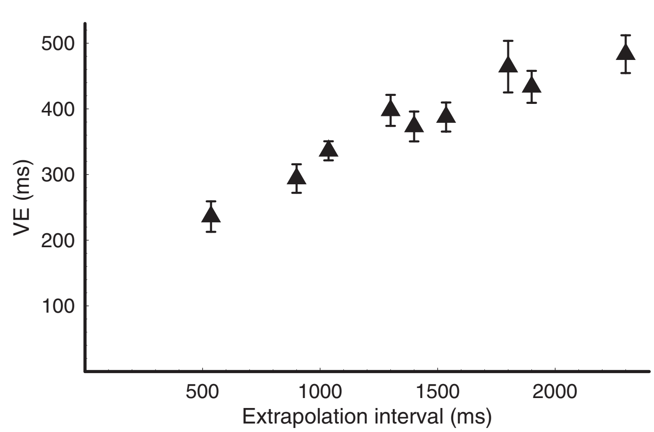

Figure 9. Experiment 5: Mean variable error (VE; i.e., the standard deviation of the individual response times) as a function of extrapolation interval for the no-distractor trials. Error bars show plus and minus one standard error of the mean of the 19 individual values.

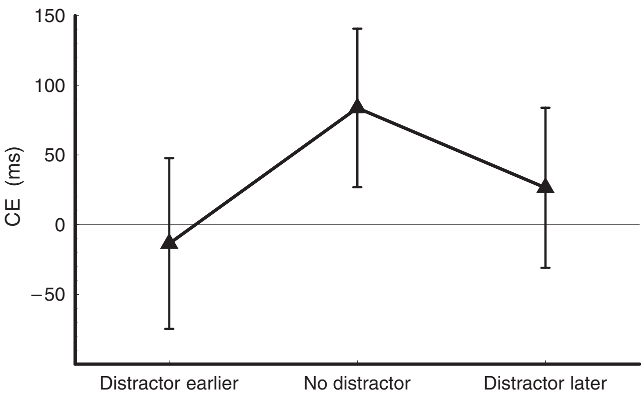

Figure 10. Experiment 5: Mean constant error (CE; i.e., the signed difference between the observed response time and the correct response time) observed in the three distractor conditions. Positive values indicate an overestimation of target time to contact. Error bars show plus and minus one standard error of the mean of the 19 individual values.

There was a high degree of interindividual consistency. Of the 19 observers, 15 underestimated target TTC with both types of distractor, relative to the no-distractor condition. For 11 of the latter 15 observers, the effect of the early-arriving distractor was larger than the effect of the late-arriving distractor. Taken together, the data collected in the PM task are compatible with the safety strategy discussed above, if we assume that the blanking of target and distractor always triggered the potential for action. It seems that the observers' strategy was (a) be cautious if there is an additional approaching object and (b) be even more cautious if this object will be here soon.

The data do not completely support the second component of the strategy, however. The underestimation of target TTC did not increase continually with the difference between target TTC and distractor TTP. As Figure 11 shows, the early-arriving distractor (triangles; TTP = 3,500 ms) caused a stronger effect shift in the CE relative to the no-distractor condition (open diamonds) if it was combined with the largest rather than with the smallest target TTC (i.e., distractor arriving 900 ms and 136 ms earlier than the target, respectively). A repeated-measures ANOVA conducted on the data obtained with no-distractor and early-arriving distractor trials showed a marginally significant Target TTC × Distractor Condition interaction, $F(2, 36) = 3.2$, $\tilde{\varepsilon} = .84$, $p = .061$. For the late-arriving distractor (see the boxes in Figure 11; TTP = 4,500 ms), however, the distractor-induced underestimation of target TTC did not systematically depend on whether the distractor arrived 864 ms, 500 ms, or only 100 ms later than the target; the Target TTC × Distractor Condition interaction was not significant, $F(2, 36) = 0.27$. In this respect, the data from Experiment 5 again suggest that the early-arriving distractor triggered a somewhat different mechanism than the late-arriving distractor.

The effect of the distractor was stronger at the shorter presentation durations (see Figure 12), confirmed by a significant Distractor Condition × Presentation Duration interaction, $F(4, 72) = 3.8$, $\tilde{\varepsilon} = .89$, $p = .01$. The effect of the distractor was thus largest at the longest extrapolation interval, because presentation duration was negatively correlated with the extrapolation interval. None of the remaining interactions involving distractor condition was significant.

Distractor condition had no significant effect on the variable error, $F(2, 36) = 0.9$. This finding parallels the observation made in the identification task (Experiments 1 to 4) that the distractor had an effect on response bias but not on sensitivity, according to the SDT terminology. There was a significant Distractor Condition × Target Velocity interaction, $F(4, 72) = 2.6$, $\tilde{\varepsilon} = 1.0$, $p = .041$, mainly due to the fact that for the smallest velocity, the variable error was smaller with the early-arriving distractor than in the control condition, while this pattern was reversed for the intermediate velocity. We have no explanation for this effect.

General Discussion

In five experiments, we studied TTC judgments for a target object in the presence of a single task-irrelevant moving distractor object, using an absolute identification task (Experiments 1 to 4) and a PM task (Experiment 5). We were surprised to find that the distractor influenced response bias by producing a contrast effect. Thus, the observers were unable to ignore the task-irrelevant

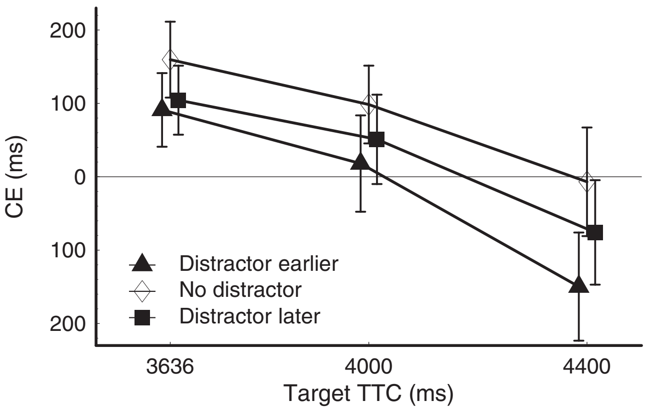

Figure 11. Experiment 5: Mean constant error (CE) as a function of distractor condition and target time to contact (TTC). The lines were shifted by 15 ms on the *x*-axis for clarity. Error bars show plus and minus one standard error of the mean of the 19 individual values.

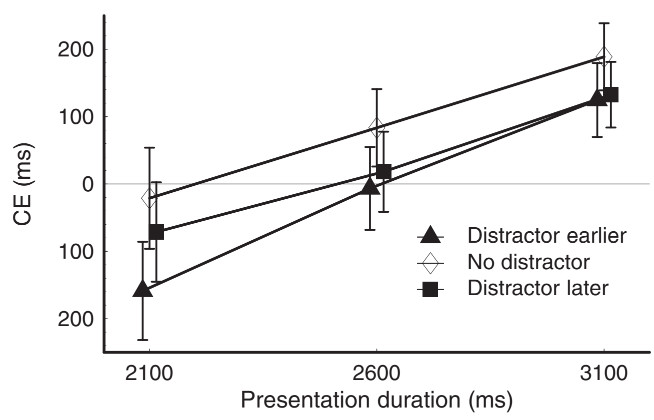

Figure 12. Experiment 5: Mean constant error (CE) as a function of distractor condition and presentation duration. Error bars show plus and minus one standard error of the mean of the 19 individual values.

distractor. Additionally, if some simple averaging of target and distractor TTC had occurred, a distractor arriving later than the target should have caused overestimation of target TTC. The opposite was the case: Distractors arriving at the observer's eye plane later than the target object consistently caused an underestimation of target TTC relative to the condition without a distractor, evident in a decrease in the proportion of *late* responses (Experiments 1 to 4) or shortened response times (Experiment 5). This contrast effect was observed in all five experiments, and within each experiment we found a high degree of interindividual consistency, with 79% to 100% of all observers showing the same pattern. The experiments thus firmly established a contrast effect caused by the late-arriving distractor, refuting potential assimilation or averaging effects between target TTC and distractor TTP.

When the distractor arrived at the observer earlier than the target, we found no significant change in the mean proportion of *late* responses in the AI task, although Experiments 3 and 4 showed the trend of a small decrease in *P*(*late*). Within each experiment, there was a rather large variability in the individual effects of the early-arriving distractor on *P*(*late*). In the PM task (Experiment 5), however, the early-arriving distractor also caused a significant underestimation of target TTC relative to the control condition that was even stronger than for the late-arriving distractor.

In Experiments 1 to 4, we did not alter the pattern of results by reducing the information provided by single visual cues, neither by varying size at blanking time (Experiments 2 to 4) nor by varying distance at blanking time (Experiment 4). In other words, while we found evidence for the use of final target size as a cue to contact time (Experiment 4), the effect of the distractor cannot be explained by such a strategy. The results from Experiment 3 demonstrate that the distractor produced the same effects, albeit less pronounced, if stereoscopic information was available.

A simple explanation for the effect of the distractor object on TTC judgments in the AI task is that the responses were influenced by judging target TTC relative to distractor TTP, a strategy that might have been promoted by the surface structure of the task requiring observers to respond *early* or *late*. It is obvious that the observers did not exclusively adopt this strategy, because in this case performance would have been at chance level ($d' = 0$). A response bias introduced by judging target TTC relative to distractor TTP would be compatible with the decrease in *P*(*late*) observed with the late-arriving distractor. However, a relative judgment would result in an increase in *P*(*late*) caused by the early-arriving distractor. This was clearly not the case, which thus speaks against this model of simply comparing target and distractor contact times. Above that, such a strategy principally cannot account for the effect of the distractor on absolute TTC estimates obtained in the PM task in Experiment 5.

An alternative explanation is that observers used a safety strategy, in the sense that the additional approaching object was identified as a potential threat, so that it made observers more cautious when they considered an action. According to this safety rule, observers should adopt a bias toward *early* responses. This explanation is compatible with the effect of the late-arriving distractor and with the slight but nonsignificant decrease in *P*(*late*) observed with the early-arriving distractor in Experiments 3 and 4. However, a simple safety strategy should result in an even stronger bias toward *early* responses introduced by the early-arriving compared to the late-arriving distractor, but this relation was observed in Experiment 5 only. A potential explanation for the absence of an effect of the early-arriving distractor is that the safety strategy was abandoned when the situation could be judged early on as not affording action. In Experiments 4 and 5, we presented abstract geometric objects approaching on a uniformly black background. It appears unlikely that these artificial stimuli were perceived as threatening, although this possibility cannot be ruled out completely. Still, we found essentially the same effect of the late-arriving distractor as in Experiments 1 to 3, which featured simulations of real-world vehicles. This finding questions even the flexible safety strategy hypothesis.

It should be noted that the distractor effects cannot be explained by adaptation to the range of TTCs presented during the experiment because the distractor TTPs were always placed symmetrically about mean target TTC. Moreover, as we randomly interleaved the trials without and with a distractor, adaptation should have influenced TTC judgments for both the target object presented in isolation and the target object presented together with the distractor. Thus, the observed differences between the two conditions cannot be explained by a simple adaptation effect.

Finally, we found a dissociation between the effects of the distractor on sensitivity and on response bias. While the significant effects of the distractor on the proportion of *late* responses and on the CEs clearly demonstrate that the observers were not successfully ignoring the distractor, we found no deterioration in sensitivity introduced by the additional moving object, neither in the AI task nor in the PM task. It thus can be concluded that the distractor introduced no additional variability (e.g., "memory noise"; Durlach & Braida, 1969) in the decision variable. In more general terms, neither memory capacity nor processing capacity seemed to be an issue, at early or late processing stages, compatible with findings by DeLucia and Novak (1997), who reported a decline in the efficiency for detecting the first-arriving object only if the set size was increased beyond six objects. Thus, the results demonstrate a lossless combination of TTC information from the different objects (Pattern c discussed in the introduction).

In conclusion, as different as existing hypotheses may be with respect to the complexity of the invariant information that a TTC processor may use, they are based on the common assumption that the visual system is able to single out the relevant target object and to ignore irrelevant objects. We have shown this not to be the case. In our experiments, a task-irrelevant object had an effect on response bias while leaving sensitivity unaltered. The contrast effect caused by the late-arriving distractor and the qualitative differences between the effects of the early and the late distractor speak against a simple averaging or low-level cross-talk between TTC detectors. Instead, the task-related significance of an object (task relevant vs. task irrelevant) seemed to determine how the TTC information from this object factored into the final TTC judgment. It remains to be shown at which stage of processing this dissociation between task-relevant and task-irrelevant objects takes place. A tentative answer is suggested by our finding that for the early-arriving distractor, the PM and the AI task yielded different results, although essentially the same stimulus configuration and thereby the same visual information were used. Thus, it seems likely that the effect of the distractor on the response bias is caused by mechanisms located at higher processing stages. At any rate, the sorely needed revision of TTC theory not only has to accommodate the capacity of estimating TTC for multiple objects without a loss in sensitivity but also has to consider whether an object has figure or ground status.

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