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Multiple-object tracking while driving: the multiple-vehicle tracking task

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Abstract Many contend that driving an automobile involves multiple-object tracking. At this point, no one has tested this idea, and it is unclear how multiple-object tracking would coordinate with the other activities involved in driving. To address some of the initial and most basic questions about multiple-object tracking while driving, we modified the tracking task for use in a driving simulator, creating the multiple-vehicle tracking task. In Experiment 1, we employed a dual-task methodology to determine whether there was interference between tracking and driving. Findings suggest that although it is possible to track multiple vehicles while driving, driving reduces tracking performance, and tracking compromises headway and lane position maintenance while driving. Modified change-detection paradigms were used to assess whether there were change localization advantages for tracked targets in multiple-vehicle tracking. When changes occurred during a blanking interval, drivers were more accurate (Experiment 2a) and ~250 ms faster (Experiment 2b) at locating the vehicle that changed when it was a target rather than a distractor in tracking. In a more realistic driving task where drivers had to brake in response to the sudden onset of brake lights in one of the lead vehicles, drivers were more accurate at localizing the vehicle that braked if it was a tracking target, although there was no advantage in terms of braking response time. Overall, results suggest that multiple-object tracking is possible while driving and perhaps even advantageous in some situations, but further research is required to determine whether multiple-object tracking is actually used in day-to-day driving.

Keywords Object-based attention · Perception and action · Dual-task performance · Driving · Multiple-object tracking

The multiple-object tracking task (Pylyshyn, 1989; Pylyshyn & Storm, 1988) was originally devised to test a hypothetical mechanism purported to select a small number of visual items at once (targets) and monitor their independent positions as they moved among other identical items (distractors). This tracking mechanism was thought to be integral to visual–motor coordination (Pylyshyn, 2009), and in the basic research, many have argued that multiple-object tracking is critical to driving an automobile (e.g., Feria, 2008; Horowitz et al., 2007; Kunar, Carter, Cohen, & Horowitz, 2008; Trick, Enns, Mills, & Vavrik, 2004). However, although tracking has been studied for over 25 years, there has never been much interest in multiple-object tracking among those who actually do driving research, and there are no investigations of the topic in that literature. In fact, it is not even clear whether it is possible to perform multiple-object tracking while driving or whether there are any advantages or disadvantages to tracking while driving. In this article, we present a series of experiments that investigate multiple-object tracking in the context of a driving task. In the sections that follow, we will begin with a brief summary of the tracking literature as it relates to driving and then go on to describe the experiments.

When multiple-object tracking was first studied, Pylyshyn and Storm (1988) proposed that it relied on a mechanism that assigned mental indices or tags to a small number of target objects at once (three to five in most adults). This mechanism allowed people to refer to and thus track a small number of moving objects (targets) among others with similar properties, even if the objects' properties and positions changed from

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moment to moment. This reference mechanism was thought to be fundamental for visual–motor coordination, insofar as it was necessary for selecting potential target items so that the eye, the hand, or the attentional focus could be accurately directed to specific items among others even if the items were moving and changing. Pylyshyn (1989) took pains to distinguish between the mental indices or tags used in multiple-object tracking and the focus of visual attention: The attentional focus is thought to be unitary, and participants seemed to be able to track three to five independent noncontiguous target items at once with a higher level of accuracy than would be expected if they were simply shifting a unitary focus rapidly between targets. Furthermore, even if there were some way of dividing up the attentional focus, attention is thought to provide detailed perceptual information about attended objects, and this sort of information does not seem to be available for tracked objects in multiple-object tracking (Pylyshyn, 2004; Scholl, Pylyshyn, & Franconeri, 1999).

Multiple-object tracking has turned out to be more complex than initially proposed. For one, there is now controversy about whether multiple-object tracking can really take place without the use of higher-level resources such as spatial attention or working memory (e.g., Oksama & Hyönä, 2004; Scholl, 2009). There is evidence that it may require inhibiting the distractors as well as tracking the targets (Pylyshyn, Haladjian, King, & Reilly, 2008). Furthermore, a large number of different brain areas have been implicated, including the anterior cingulate, frontal eye fields, inferior precentral sulcus, anterior interparietal sulcus, posterior interparietal sulcus, transverse parietal lobule, superior parietal lobule, human motion area (MT+), lateral occipital cortex, cerebellum, and the early vision areas V1–V3 in the cortex (e.g., Culham, Cavanagh, & Kanwisher, 2001; Howe, Horowitz, Morocz, Wolfe, & Livingstone, 2009; Jovicich et al., 2001; Störmer, Winther, Li, & Andersen, 2013). Tracking performance is influenced by a variety of factors, including object spacing and speed (Drew, Horowitz, & Vogel, 2013), and it may involve hemisphere-specific resources (e.g., Chen, Howe, & Holcombe, 2013). Performance changes when participants are required to track unique objects instead of identical ones (Horowitz et al., 2007), which may indicate that tracking unique items requires additional mechanisms for storing object features/identities (Cohen, Pinto, Howe, & Horowitz, 2011; Oksama & Hyönä, 2008). Nonetheless, among those who do basic research, multiple-object tracking is still considered to be an important component of visual–motor coordination and thus integral to tasks such as driving.

However, although tracking has been studied for many years, it has never been a focus of study among those who actually do research on driving. This may be because there are a host of situational factors that distinguish tracking tasks as carried out in a laboratory from the activities that take place while driving a vehicle. For one, in a standard multiple-object tracking task, objects can typically move independently at a variety of different speeds, and in the classic task, their rate and direction of movement could change randomly and unpredictably from moment to moment. In contrast, road users (vehicles, cyclists, pedestrians) are limited in terms of the maneuvers they can perform and the directions in which and rates at which that they can travel. Often, the potential conflict points—the points where road users might come into each other's paths—are carefully controlled (sometimes with traffic lights), and the durations of these potential conflict periods are minimized. Consequently, there is typically no need to track multiple independent road users over extended periods of time. It may be enough to use a spatial strategy of focusing on certain "danger areas" around the potential conflict points, rather than tracking the independent trajectories of all the relevant road users while simultaneously ignoring the others. Moreover, the classic multiple-object tracking task often involves a number of identical abstract figures where there is no reason to expect any given object would move in any specific way. In contrast, road users differ in appearance, and drivers may access a lifetime's worth of experience in making predictions about how different types of road users move on the road. Finally, by its nature, driving requires multitasking insofar as drivers must simultaneously steer, control the vehicle speed (using the gas and brake pedals), and monitor the environment for hazards. Multiple-object tracking tasks are typically carried out alone or while doing one other task at most. Therefore, as a result of all these factors, to this point there has been little interest in studying tracking among driving researchers, perhaps because there seems to be more differences than similarities between the tracking task as carried out in a laboratory and the activities carried out when actually driving.

The only support for the importance of multiple-object tracking in driving comes from the individual-difference tradition, where the focus is on identifying the characteristics of drivers at risk. Older drivers are at disproportionate risk for certain types of collision (Hauer, 1988; McGwin & Brown, 1999; Preusser, Williams, Ferguson, Ulmer, & Weinstein, 1998; Skyving, Berg, & Laflamme, 2009). Multiple-object tracking performance decreases with age (Trick, Perl, & Sethi, 2005), and a recent study, the first and only study to link tracking and driving directly, showed that multiple-object tracking predicts road-test performance in older drivers (Bowers et al., 2013).

Unfortunately, at this point, it is not clear whether this correlation occurs because multiple-object tracking is a critical part of driving or because tracking performance is correlated with other abilities that are important for driving. Test banks are usually employed when identifying older drivers at risk (e.g., the *Driver Health Inventory*; Staplin, Gish, & Wagner, 2003) because a variety of measures predict driving performance, including contrast sensitivity (high and low contrast acuity), peripheral motion contrast thresholds (Henderson, Gagnon, Collin, Tabone, & Stinchcombe, 2013), working memory, visual search, and processing speed (e.g., the *Useful Field of View;* Owsley & McGwin, 2010), and so forth. Given the number and variety of individual predictors, it is not clear whether the correlation between tracking and driving indicates that tracking is a part of driving or whether it indicates that measures of multiple-object tracking tap some of the basic capacities tapped by these other measures. No test is a pure measure of a single ability, and surprising relationships between variables can emerge in correlational studies. For example, in healthy older drivers over the age of 60, the *Pelli–Robson* contrast sensitivity test predicts some of the variability in tracking performance (Trick, Hollinsworth, & Brodeur, 2009). That may be because to track things, you need to be able to see them, and for older adults, a variety of age-related disorders compromise vision (cf. Spence & Feng, 2010, re: manipulations that affect both contrast sensitivity and attentional measures such as multiple-object tracking in young adults).

Thus, although many assume that multiple-object tracking is integral to driving, at this point, it not even clear whether tracking is possible while driving. In the following experiments, we investigate this issue using a driving simulator. The first experiment investigates whether the need to actively control vehicle position interferes with tracking (and vice versa). Later experiments explore whether there are any advantages to tracking while driving—that is, whether drivers are better at monitoring changes in tracked, as compared with untracked, vehicles. The results of this research may have ramifications for both basic and applied research. In particular, if tracking while driving proves impossible or if it yields no advantage, it calls into question the allegation that multiple-object tracking is critical to visual–motor coordination in general, insofar as driving is a classic example of a task that requires visual–motor coordination. This result would have important ramifications for theory. Conversely, if tracking is possible during driving, and tracking while driving facilitates driving performance, it is possible that deficits in tracking may be a factor in some types of collision. This would be a useful finding from the perspective of those doing applied research.

Experiment 1: multiple-vehicle tracking

In this experiment, we adapted the standard multiple-object tracking task to a simulated driving environment where participants had to keep track of multiple moving vehicles among a cohort of vehicles on the road ahead. Although this task was somewhat exotic in terms of day-to-day driving, it enabled us to address some of the most basic questions about how tracking and driving (specifically, controlling the vehicle's position) might be coordinated within a driving task. The multiple-vehicle tracking task allowed us to ensure that drivers were truly tracking multiple objects at once, while investigating the impact on the drivers' ability to maintain a consistent vehicle position on the road over time.

The primary goal was to determine whether there was interference between driving and tracking. Given this goal, Thomas and Seiffert's (2010) study of the effects of observer motion on tracking is of special relevance. In this study, participants tracked generic objects (three-dimensional spheres) as viewed through virtual reality goggles. There were four conditions: active move (participants walked around objects), passive move (participants were pushed in a wheelchair around objects), active stay (participants walked in place next to the objects), and passive stay (participants sat in wheelchair next to the objects). Tracking performance was significantly poorer when participants were moving while tracking, but there was no significant difference between the active and passive move conditions. Consequently, the tracking decrement was attributed to observer motion and not to the requirements of actively performing movements. However, it is possible that this study underestimated the impact of active motion. Walking performance was not measured and if participants put more emphasis on tracking than on walking, it is possible that the interference may have manifested itself in terms of deficits in positional control while walking.

By testing tracking performance in a driving simulator, it became possible to measure subtle differences in longitudinal and lateral control, insofar as the simulator routinely measures longitudinal variability (variations in headway to lead vehicles as it relates to velocity control) and lateral variability (variations in vehicle position within the lane as it relates to steering). Furthermore, because we used a fixed-base simulator, it was possible to test participants without them experiencing the complicating effects of the vestibular and somato-sensory stimulation produced by actual movements through space. The use of a fixed-base simulator allows us to separate out the effects of visual interference from those produced by other sensory modalities. Given that multiple-object tracking has been shown to interfere with other spatial tasks (e.g., Trick, Guindon, & Vallis, 2006; Zhang, Xuan, Fu, & Pylyshyn, 2010) and seems to correlate with other spatial measures in young adults (Trick, Mutreja, & Hunt, 2012), we hypothesized that multiple-object tracking performance would decrease when the participant had to control the vehicle's position on the road while tracking. Conversely, we predicted that the longitudinal and lateral control (headway and lane position maintenance) would deteriorate when participants were tracking while driving.

Method

Design

There were two sets of analyses: the within-subjects analyses and the between-subjects analyses. Within-subjects analyses assessed tracking performance as a function of the number of vehicles to be tracked (only one, three, or four) and task load: single task (baseline tracking only; no steering or headway control required) and dual task (tracking while steering and controlling headway). Tracking performance was measured using a full-report methodology, where the participants had to identify all of the cued targets. The dependent variable was the percentage of target vehicles that were correctly identified (e.g., 3/4 targets = 75 % accuracy). Presentation order was blocked and counterbalanced for the task load factor, and both tracking and driving performance were measured. Within-subjects analyses were also used to assess the effect of the number of targets (one, three, and four) on driving performance. There were three measures of driving performance. Two addressed longitudinal (speed) control: *average headway distance* (mean distance between the participant's vehicle and the nearest leading vehicle) and *standard deviation of headway distance* (standard deviation of the distance between the participant's vehicle and the lead vehicles ahead, measured across time). A third assessed lateral control (steering): *Standard deviation of lateral position* (SDLP) was the standard deviation of the distance between the center of the lane and the participant's vehicle, measured across time.

A number of factors went into determining the appropriate sample size for the within-subjects analyses. Sample sizes are typically determined via power analyses: a priori calculations that make use of effect sizes gleaned from the literature involving the experimental paradigm in question. However, in this study, we were proposing a new paradigm (the multiple-vehicle tracking task), and given the number of modifications that had to be made to make the tracking task fit into a driving context, it was not clear whether performance in the multiple-vehicle tracking would be similar to that in standard multiple-object tracking. Moreover, power analyses assume that there is a single dependent variable, but in this case, there were four dependent measures, all of about equal importance to the theoretical conclusions (one measure of tracking performance and three different indices of driving). The power of a design depends on both sample size and the variance in the measure, and variance differences between different dependent measures are to be expected; it possible to have a sample size that might be adequate for one variable while too small for another, for example. Given these complications, we used the strategy of using both the tracking and driving literatures to choose a sample size, aiming for samples that were as large or larger. For tracking, we observed that many of the commonly cited multiple-object tracking studies that had within-subjects manipulations used sample sizes of 8–12 (e.g., Cohen et al., 2011; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008). As for the driving metrics, simulators vary in terms of how indices of driving performance are measured and calculated, and consequently, the safest route was to survey studies involving the same simulator as was to be used in the present investigations (n = 16–26; Reed Jones, Trick, & Matthews, 2008; Trick, Brandigampola, & Enns, 2012; Trick, Toxopeus, & Wilson, 2010). Thus, after consulting the relevant driving and tracking literatures, we chose a sample size that would have an adequate number of participants for the primary dependent measures. Although this process was not without problems, based on *G*Power3* sensitivity analysis (Faul, Erdfelder, Lang, & Buchner, 2007), the samples had at least enough sensitivity to identify moderate- to large-sized effects with adequate power ($1 - \beta = .8$) in the tracking data, and small- to medium-sized effects for the three measures of driving performance (by convention, small f = .10, medium = .25, large = .40; see Faul et al., 2007).

In contrast, the between-subjects analyses focused solely on measuring indices of driving performance (average headway, standard deviation of headway, standard deviation of lateral position) as a function of task load (driving while tracking, baseline driving). These analyses compared driving in the 28 participants who drove while tracking with that in the 25 participants who only had to drive. It is important to note that both groups saw identical visual displays (the shifting lead vehicles of the multiple-vehicle tracking task). The only thing that differentiated the groups was their instructions. We tested two different sets of drivers because we were concerned about differential carryover effects. Specifically, we were worried that if participants did both dual-task (driving while tracking) and single-task (baseline) conditions, it would be difficult for participants in the baseline condition to ignore the target vehicles as required if they had already done the dual-task condition first. Sensitivity analysis using G*Power 3 indicated that the between-subjects analyses had more than enough sensitivity to identify large-sized effects.

Participants

As is typical in studies that involve driving simulation, in this and all the following experiments, participants were pretested to ensure that they were at low risk for simulator adaptation syndrome (virtual-reality-induced dizziness, nausea, and eye strain). A standard screening test was used (Kennedy, Fowlkes, Berbaum, & Lilienthal, 1992), and only those who passed were invited to participate. (As it turns out, the screening test was effective; none of the participants had to withdraw due to simulator adaptation syndrome.) A total of 53 individuals were invited to participate. All were recruited from the University of Guelph participant pool and paid in course credit. The participants were licensed drivers 18–25 years of age with normal or corrected-to-normal vision (38 females). Of the 53 drivers, 28 were randomly assigned to do the tracking alone and tracking while driving portions of the study. The remaining 25 did baseline driving only (driving without tracking).

Apparatus and stimuli

This study used a DriveSafety DS600c fixed-base driving simulator: a modified Saturn sedan (the full car body) that measured driver performance at a temporal resolution of 60 Hz. Driving simulators permit participants to experience some of the sights, sounds, and sensations of driving (force-feedback/vibration on the steering wheel, gas and brake pedals) without experiencing the risks of actually driving. As well, through the induced self-motion illusion, they also experience some of the "feelings" of driving (vection: see Riecke, 2010, for a review). The illusion was created through images projected onto a 300° wrap-around viewing screen (250° in the front and 50° in the back) that immersed drivers in a virtual-reality driving environment. In this experiment, the environment involved a straight section on a three-lane freeway where a 3 × 3 grid of nine identical blue cars appeared in front of the participant's vehicle (see Fig. 1). The vehicles' visual angle would vary on the basis of how far they were from the driver, but drivers were encouraged to keep the same headway that they had at the beginning of the trial. If they did so, vehicles in the row closest to the driver (row 1) subtended an average visual angle of 2.97°, ranging from a high of 3.44° for those in the center of the road (immediately in front of where the driver was stationed throughout the drive) to 2.01° at the most distant position at the left and right. In rows 2 and 3, the vehicles subtended an average of 2.1° (range: 2.3º–1.9º) and 1.86° (range: 2º–1.72º). When vehicles moved, they shifted lanes at a rate of approximately one change per second, moving at a natural pace across the screen. Each change involved two identical vehicles trading positions on the roadway, and several such changes took place at once. The goal in this experiment was to create as challenging a tracking task as possible within the highway-driving environment, one that could take place over an extended period of time. There was a large number of densely packed vehicles, and the changes took place in such a way that the vehicles appeared to briefly overlap one another. This was seen as an acceptable solution to the challenge of packing as many vehicles as possible into the display, given that object tracking has previously been shown to be robust to occlusions (Horowitz, Birnkrant, Fencsik, Tran, & Wolfe, 2006), and our accuracy results bear this out. (In subsequent experiments, these occlusions were less common; the vehicles where "staggered" so that lane changes could occur without overlap.)

Procedure

In this and all following experiments, the experimental session began with the consent process, where participants were informed about the risk of simulator adaptation syndrome and were educated about symptoms so that they could recognize them should they develop. (Symptoms include dizziness, nausea, eye strain, headache, excessive sweating or swallowing.) As is standard in simulation studies, participants were told to inform the experimenter immediately if symptoms developed so that the experimental session could be terminated. After an initial introduction to the task, participants took their place in the driver's seat of the simulator. They all began with a warm-up where they were allowed to become familiar with driving in the simulator without any tracking requirements. This warm-up lasted until the participants indicated that they were comfortable driving the simulator (typically, around 2 min). After that, the procedure varied by condition. The 28 participants who did the single-and dual-task tracking conditions were instructed in the tracking task. The task had a number of phases. Participants began each trial "parked" behind nine static lead vehicles on the freeway. The participant's vehicle was placed between the left and middle highway lanes, directly on top of the dotted line, in order to maximize visibility for all nine lead vehicles. Participants in the dual-task (tracking and driving) condition were instructed to maintain the vehicle position directly on top of the dotted line, and this position was held automatically in the single-task (tracking-only) condition.

To begin, participants pressed a button on the steering wheel, after which, as a group, the lead vehicles accelerated to 60 kph. Next, the targets revealed themselves by flashing five times (there were one, three, or four target vehicles). Once the flashing stopped, the nine lead vehicles became identical again and started shifting positions within the cohort. This continued for 30 s, during which the vehicles progressed through a random ordering of all possible vehicle locations. The simulation paused, and the participants circled the

Fig. 1 *DS600c* simulator (left); multiple-vehicle tracking stimuli viewed from driver's (center) and isometric (right) view angles for Experiment 1. Vehicles in the front row, center photo, are changing lanes

locations of the target vehicles on a response sheet. (The sheet had a 3 × 3 matrix with the nine possible vehicle positions.) Once finished, the participant initiated the next trial by pushing a button.

Condition dictated the amount of control the participant had over the vehicle. In the single-task tracking condition, when the lead vehicles automatically accelerated to 60 kph, the participant's vehicle did as well (participants did not use the steering wheel or accelerator). However, in the dual-task condition, when the lead vehicles accelerated to 60 kph, the participants had to accelerate and steer to keep up, maintaining their vehicle's lane position and headway. Each tracking trial took approximately 55 s, including 5 s to cue the target vehicles, 30 s of tracking, ~15 s to report, and 5 s to reset the vehicle positions for the next trial. In each condition, participants were given 5 trials of tracking practice (1 for one target and 2 each for three and four targets) before the experimental trials in that condition began. There were 30 experimental trials for each of the single- and dual-task conditions (both tracking and driving performance were measured in the latter).

The 25 participants in the baseline (single-task) driving condition experienced exactly the same displays as those in the other conditions (the same trials, the same flashing and shifting lead vehicles). However, they were not told about the tracking task and were told only that they had to follow the lead vehicles at a fixed distance during each trial. As in the dual-task condition, when the lead vehicles started moving, the participants had to keep up and maintain their position. The baseline driving group did 5 trials of practice and 30 experimental trials.

Results

This section will begin with a discussion of the within-subjects analyses, where both the tracking and the driving data were analyzed as a function of the number of objects to be tracked. The between-subjects analyses follow, where driving performance was analyzed as a function of whether participants only had to drive (baseline driving) or drove while tracking (dual task).

Tracking accuracy

Tracking performance was measured as a function of task load (tracking alone, tracking while driving) and number of targets (one, three, or four) in a factorial repeated measures ANOVA. Response sheets for 5 participants were lost, so the final sample size was 23 rather than 28 for this analysis. Results are presented in Fig. 2. The main effect of number of targets was significant at $F(2, 44) = 28.676$, $p = .000$, partial $\eta^2 = .566$, with tracking accuracy significantly lower when there were more targets to track. Dual-task performance was significantly worse than that for the single task, $F(1, 22) = 37.543$, $p = .000$, partial $\eta^2 = .631$. There was also a task load × number of targets interaction, $F(2, 44) = 3.781$, $p = .031$, partial $\eta^2 = .147$, whereby the performance difference between tracking alone and tracking while driving became larger with the number of items to be tracked.

Simple main effects for the accuracy data were analyzed using multiple pairwise comparisons. Accuracy when tracking and driving (dual task) versus tracking without driving (single task) was compared for the one-, three-, and four-target conditions. When there was one target to track, accuracy was only marginally better in the single task condition as compared to the dual task condition, $t = 1.921$, $p = .068$. However, when there were three or four targets to track, accuracy was significantly better in the single-task condition ($t = 4.169$, $p = .000$, and $t = 7.514$, $p = .000$ for three and four targets, respectively).

Driving metrics

Two sets of analyses were performed. The first involved within-subjects comparisons that investigated how driving performance was influenced by the number of targets to be tracked (one, three, or four) in the 28 participants who did the multiple-vehicle tracking task while driving. The second compared driving performance between the 28 participants who tracked while driving and the 25 who only had to drive. To ensure that effects were not due to atypical performance in individual trials, for both analyses, outlier screening was carried out. Specifically, for each participant and condition, trials where measures were in excess of 2.5 standard deviations from the participant's respective mean for that condition were removed. In the dual-task group, this resulted in the removal of 1.2 % of the data for average headway distance, 2.3 % of the data for standard deviation of headway, and 4.5 % of the data for SDLP. In the baseline driving group, this resulted in the removal of 1.7 % of the data for average headway distance, 2.3 % of the data for standard deviation of headway, and 0.8 % of the data for SDLP.

Within-subjects analyses: effect of the number of targets on driving performance

For the drivers who were tracking while operating the vehicle (dual task), a one-factor repeated measures ANOVA was conducted measuring driving performance as a function of the number of targets to be tracked (one, three, or four). Results are presented in Fig. 3. There were no statistically reliable differences in the average headway distance for drivers tracking different numbers of targets ($p > .1$). However, as was predicted, the standard deviation of headway distance increased significantly with the number of tracking targets, $F(2, 54) = 4.096$, $p = .022$, partial $\eta^2 = .132$, indicating

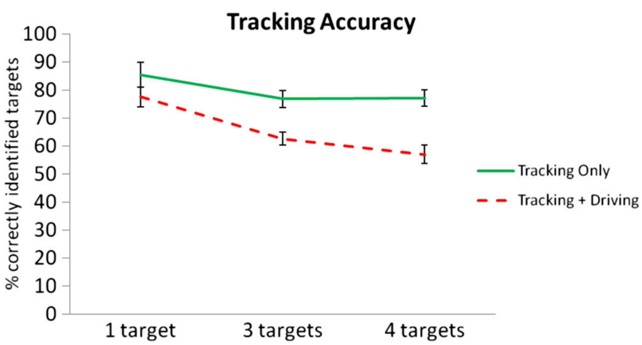

Fig. 2 Percentages of correctly identified targets in tracking in the single- (tracking only) and dual-task (tracking + driving) conditions. Standard error bars are included

that increases in the number of vehicles to track compromised the ability to maintain a consistent headway while driving. Pairwise comparisons revealed that the *SD* of headway distance was significantly larger when participants were tracking four targets as compared with when they were tracking one or three targets ($t = -2.091$, $p = .046$, and $t = -2.751$, $p = .010$, respectively), although there was no significant difference between one and three targets ($p > .05$). SDLP increased with the number of tracking targets in the same way, $F(2, 54) = 4.851$, $p = .012$, partial $\eta^2 = .152$. This indicated that the ability to maintain a consistent straight course while driving was reduced as the number of items to be tracked increased. Once again, pairwise comparisons revealed that SDLP was significantly larger when participants were tracking four targets as compared with when they were tracking one or three targets, ($t = -2.062$, $p = .049$, and $t = -2.704$, $p = .012$ respectively), while there was no significant difference between one and three targets ($p > .05$).

Between-subjects analyses: comparison of dual-task and baseline driving performance

Between subjects ANOVAs were carried out comparing dual-task and baseline driving in terms of average headway, *SD* of headway, and *SD* of lateral position (SDLP). Even when only tracking a single target, drivers in the dual-task condition maintained significantly shorter headways than those in the baseline driving condition, $F(1, 24) = 8.758$, $p = .007$, partial $\eta^2 = .267$. Drivers in the dual-task condition may have maintained a shorter headway to better see the lead vehicles they had to track. Conversely, the baseline drivers may have chosen to give the lead vehicles a wider berth given that this strategy would put them at lower risk of rear-end collision if one of the lead vehicles suddenly braked. Although there was no difference between the baseline and dual-task *SD* of headway when drivers were tracking a single target while driving, significant differences emerged once there were four targets, $F(1, 24) = 7.647$, $p = .012$, partial $\eta^2 = .277$. Finally, there was significantly higher variability in lane position (SDLP) in drivers who were tracking while driving as compared with those who were only driving, even when drivers were tracking only a single target, $F(1, 24) = 35.674$, $p = .000$, partial $\eta^2 = .641$.

Discussion

Experiment 1 showed that though multiple-object tracking is possible while driving, the demands of maintaining vehicle position compromise tracking performance. These differences were most evident when participants were closer to the upper limit of their tracking range (3 and 4 items). On the basis of Hulleman's (2005) *k* statistic, participants were performing as if they were capable of tracking up to 2.88 items at once in the four-target condition when they only had to track (single task), as compared with 1.39 items when they were tracking while driving (dual task). Conversely, tracking interfered with driving. Increases in the number of targets were associated with increases in variability in headway and steering variability (SDLP). Furthermore, lateral and longitudinal variability was lower when participants were simply driving behind a platoon of rapidly shifting vehicles as compared to when they were required to track some of those vehicles in the same context. It is important to note that the tracking task was reasonably demanding in terms of the both the number of items in the display and the duration of the tracking interval.

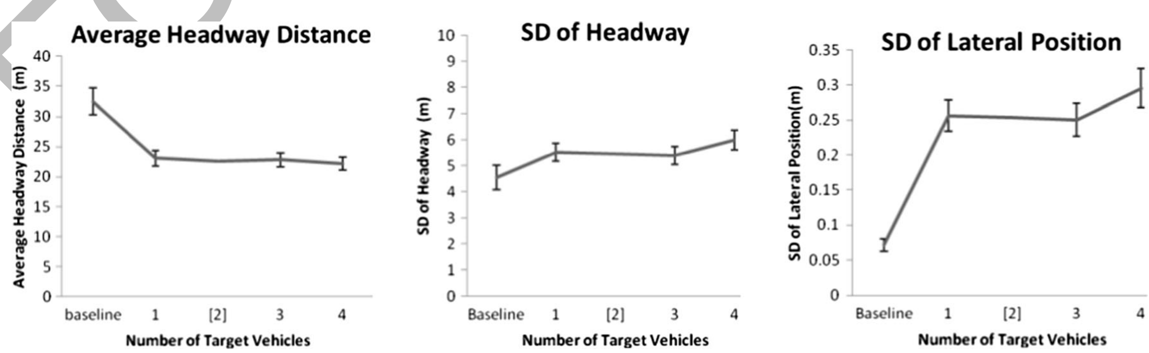

Fig. 3 Driving metrics for Experiment 1: average headway distance (left), standard deviation of headway (center), and standard deviation of lateral position (right), all measured in meters. Standard error bars are included. The [2] is a placeholder only: no two-target condition was tested

There are a number of factors that may contribute to this interference between tracking and course maintenance while driving. For one, the deficit may emerge due to the need to divide some general resource between several deliberate tasks—whether it is called cognitive effort, concentration, general working memory, or whatever is necessary for "paying attention." Alternatively, perhaps the source of the interference is more spatial in nature—for example, if the demands of the tracking task produced cognitive tunneling (a progressive narrowing of the peripheral field with effort or stress) that could compromise steering, given that skilled drivers use peripheral vision to steer (Smiley, Reid, & Fraser, 1980; Summala, Lamble, & Laakso, 1998; Summala, Nieminen, & Punto, 1996) and reductions in the peripheral field impair steering performance (Owens & Tyrrell, 1999). However, to our knowledge, at this point no one has investigated how reductions in peripheral field affect headway maintenance. It is also possible that the interference between tracking and driving might occur because some aspects of positional control require the same spatial indices that are used for individuation in tracking. Nonetheless, overall, this study revealed that in a complex visual environment that simulated movement in depth, participants had an impressive ability to track the positions of a small number of specific vehicles within a larger cohort of leading vehicles, even though the vehicles frequently occluded one another.

Experiment 2: change detection and hazard response in multiple-vehicle tracking

Multiple-object tracking may be possible while driving, but is there any benefit to tracking while driving? Consider the following situation. A police officer is driving down the road on patrol and suddenly spots some street racers. They try to make their escape, weaving through high-speed traffic, and the officer follows, trying to keep track of their various positions simultaneously so that he or she can move his or her eyes from one vehicle to the next and report as many details about each of the vehicles as possible (colors, vehicle models, maybe even bits of the license plates). Would there be any advantage to the officer trying to perform multiple-object tracking in this situation? Are drivers more efficient at reporting the properties of tracked, as compared with untracked, vehicles? One way to get at this question is to look at the ability to notice property changes in vehicles that are targets as opposed to distractors in multiple object tracking.

The tracking literature suggests that there should be an advantage for tracked vehicles—at least, if the tracking that occurs while driving works the same as the tracking in the classic multiple-object tracking task. Pylyshyn (1989, 2009) proposed that the indexes in multiple-object tracking operate at a relatively early stage in visual processing, before the operation of the one-area-at-a-time attentional focus used in detailed perceptual analysis. Although Pylyshyn argued that the indexes in his theory are not attention per se, he maintained that these pointers enable the attentional focus (and then the eyes) to be directed rapidly to the indexed locations, so that object properties can be reported more efficiently. This means property changes should be perceived more quickly and more accurately in targets than in distractors.

The remainder of this article focuses on the advantages for tracked (and thus indexed) vehicles, as compared with distractor (nonindexed) vehicles in the multiple-vehicle tracking task. In Experiment 2a, we investigated the ability to locate changes in the target as compare with distractor vehicles using a modification of the classic "one-shot" change detection paradigm (cf. Sears & Pylyshyn, 2000). In Experiment 2b, we adjusted the procedure so that response times (RTs) could be measured and used a more demanding (vehicle switch) change detection task. Finally, in Experiment 2c, we investigated how drivers perform in a more ecologically valid change-detection task: hazard response to brake light onsets in target versus distractor vehicles.

For the following three experiments, the choice of sample size was complicated given that they involved a novel combination of driving, tracking, and change detection tasks, and there was a variety of different dependent measures. It was impossible to use standard a priori power analysis. However, in this case, some measures were of more theoretical importance than others. We focused primarily on change localization and detection speed, using within-subjects manipulations. Among the change detection studies, the one most similar to ours is one that combines change detection and multiple-object tracking (Bahrami, 2003, $n = 7$). Other, more standard change detection studies used sample sizes of 10–16 participants for within-subjects manipulations (e.g., Cole, Kentridge, Gellatly, & Heywood, 2003; Spotorno, Tatler, & Faure, 2013). We chose slightly larger samples because we were unsure about how variable performance would be. As it turns out, on the basis of G*Power3 sensitivity analyses, the experiments described in the following sections used sample sizes that provided enough sensitivity to identify moderate-sized effects with adequate power ($1 - \beta = .8$) for all measures of change detection performance (moderate sized effects: $f = .25$).

Experiment 2a: "one-shot" change detection in a multiple-vehicle tracking task

Sears and Pylyshyn (2000) showed that participants were faster at determining the shape of an object that changed when it was a target as compared with a distractor in a standard multiple-object tracking task. In the present experiment, we measured change detection localization accuracy (the ability to indicate the location of the vehicle that changed) for target versus nontarget vehicles in multiple-vehicle tracking, comparing the performance of passive observers (single task: tracking only) and active drivers (dual-task: driving while tracking). In this case, one of the vehicles (either a target or a distractor) changed color in a modified version of the "one shot" change detection paradigm (e.g., Simons, 1996; Velichkovsky, Dornhoefer, Kopf, Helmer, & Joos, 2002), where a change occurs during a blanking interval that serves to disguise the local onset produced by the change. Participants were informed that changes would occur on most trials. Their task was to indicate whether there was a change and, if there was, the identity of the vehicle that changed (its current location). The prediction was that because target items are indexed to allow for tracking and indexed items have facilitated access to focused attention, participants should be more accurate at indicating the vehicle that changed if it was a target as compared with a distractor.

Several modifications were made to make the multiple-vehicle tracking task more appropriate for change detection analysis. Given that the goal of the experiment was to compare change detection in targets versus distractor vehicles, it was vital that we create a version of the multiple-vehicle tracking task where tracking accuracy was very high so that we could be as certain as possible that the participants were tracking the items that we thought they were. Consequently, only trials where participants correctly reported the locations of 100 % of the targets could be used in analysis. In this experiment, the total number of vehicles was reduced because tracking accuracy improves as the number of items in the display decreases (e.g., Trick, Jaspers-Fayer, & Sethi, 2005). As well, because the change detection task involved changes in vehicle color, it was important to have vehicles in a variety of different colors and shapes, or the change detection task would be trivially easy. In standard tracking studies, item heterogeneity has been shown to improve tracking performance (e.g., Makovski & Jiang, 2009). If the difficulty of the tracking task has an effect on dual-task driving performance, these modifications should also improve driving headway and lane position maintenance while tracking because they make the tracking task easier. Consequently, longitudinal (headway) and lateral (steering) vehicle control while tracking three target vehicles should be better in Experiment 2a than in Experiment 1.

The main prediction was that drivers should be more accurate at reporting the current location (i.e., the identity) of the vehicle that changed if it was a target, as opposed to a distractor, in tracking.

Method

Design

The percentage of trials on which participants correctly identified the location of the vehicle that changed was analyzed as a function of *task load* (tracking alone, tracking while driving), *number of targets* (one, three), and *change type* (target, distractor).

Participants

Twenty licensed drivers (15 females), 18–24 years of age, were recruited from the university participant pool and were paid in course credit (M age = 18.9 years, SD = 1.7). All reported normal color vision and normal or corrected-to-normal visual acuity.

Apparatus and stimuli

The driving simulations used in this study were similar to those in Experiment 1, except that the total number of vehicles was reduced to six and there was a maximum of three targets to be tracked. As well, there was more heterogeneity among the lead vehicles (see Fig. 4). There were nine possible vehicle colors (green, purple, red, white, light blue, yellow, gray, tan, and dark blue) and different types of car (Grand Prix, Celica, Lexus, Volkswagen), but all were mid-size sedans of about the same size.

On 80 % of the trials, there was a change in one of the vehicles (16, 18, or 20 s after the onset of the trial). During the change, one of the six vehicles would be replaced by one of a different color that did not duplicate any of the existing cars. In order to ensure that local transients did not attract attention, the change was made during a global transient (blank screen). For the 80 % of the trials on which there was a change, 40 % of the trials involved changes to target vehicles, and the other 40 % involved changes to distractors. For the remaining 20 % of the trials, the same vehicles were shown before and after the blanking interval.

Procedure

As in Experiment 1, participants were given 2 min to get used to driving in the simulator without tracking requirements before the study began. They were then given instructions for the multiple-vehicle tracking and change detection tasks. Participants were told that there would be changes on most trials (80 % of the trials), and they were shown how to fill out response sheets, first indicating the location of the target vehicles (one or three) and then the location of the vehicle that changed (if any). Participants were *strongly* encouraged to guess locations if they were unsure. The sequence of events in each trial is shown in Fig. 5. Each trial began by cuing the target vehicles, after which the six lead vehicles started randomly shifting positions. These movements continued for 16, 18, or 20 s, and then there was a 60-ms blanking interval (a blank

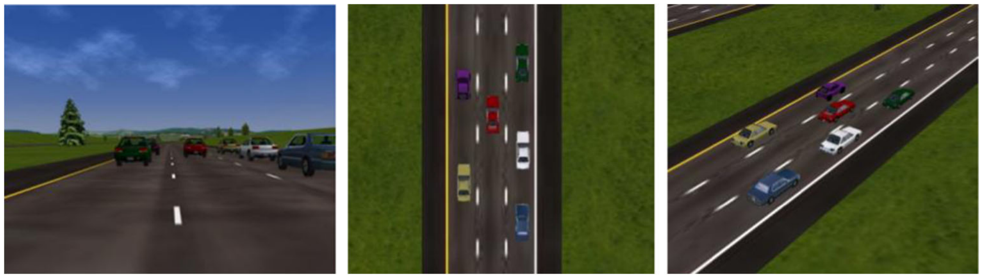

Fig. 4 Experiment 2a vehicle tracking stimuli from driver's (left), "birds eye" (center), and isometric (right) views

screen). After that, participants were presented with a static screen shot of the driving scene either as it was before the blanking interval (on 20 % of the trials) or with a change in one of the vehicles (on 80 % of the trials). At that point, participants filled in response sheets indicating the locations of the target vehicles in tracking and the vehicle that changed (if any). Participants were given 5 practice trials before they began the 60 experimental trials.

Results

The goal of this experiment was to determine how change detection performance varies as a function of the type of item that changes (tracked vs. untracked) and task load (tracking alone/single task, tracking while driving/dual task). However, before these analyses could be carried out, three preliminary analyses were required. One was needed to document performance in the tracking task. A second investigated driving performance as compared with that in Experiment 1. A third was performed to ensure that there were no between-condition differences in the number of false positives in change detection (cases where drivers falsely indicated that there was a change when there was none). The main analyses appear at the end of the section (the analyses that determine whether participants were better at identifying the vehicle that changed when it was a target as compared with a distractor).

Preliminary analyses

Tracking accuracy Participants correctly identified the locations of about 93 % of the targets, and neither the number of targets to be tracked (one, three) nor the task load (driving while tracking, driving alone) had significant effects. When participants were driving, tracking accuracy was 92.5 % for one target (SD = 16.08) and 92.83 % for three targets (SD = 10.13). When participants were not required to drive the vehicle, tracking accuracy was 95.06 % for one target (SD = 13.27) and 93.12 % for three targets (SD = 14.23). There was no significant interaction (p > .05 for all).

Driving metrics Average headway distance, SD of headway, and SDLP were analyzed. Outlier trials were screened out using the same technique described in Experiment 1. This resulted in the removal of 1.3 % of the data for average headway distance, 2.4 % of the data for SD of headway, and 3.2 % of the data for SDLP.

Because it was useful to find out whether driving performance improved as the tracking task was made easier, driving metrics were analyzed as a function of experiment (1, 2a) and number of targets (one, three) for trials on which participants were required to track while driving. Mixed factorial ANOVAs were carried out with experiment (1, 2a) as the between-subjects factor. To facilitate comparison, the data

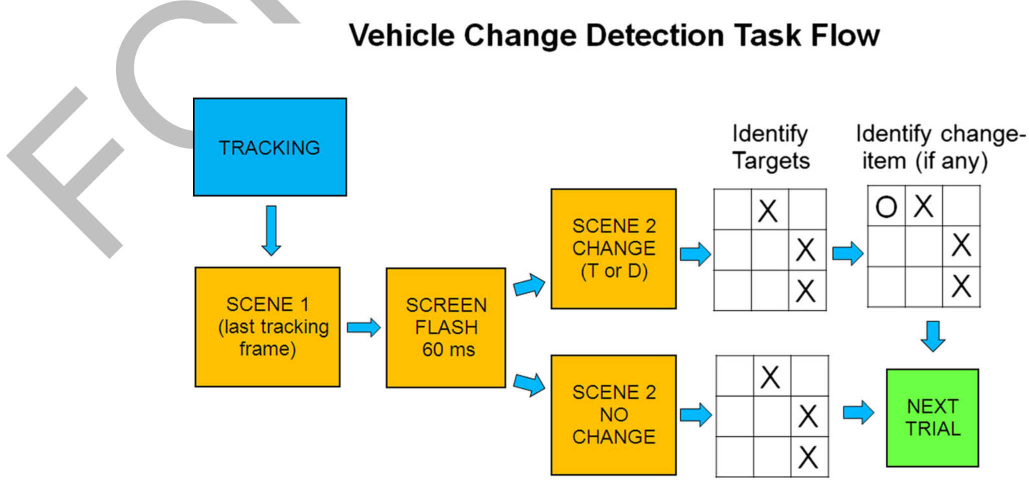

Fig. 5 Task-flow diagram of procedure for Experiment 2a (T = target; D = distractor)

from Experiment 2a were collapsed across the *change location* variable (target, distractor, none); furthermore, the four-target condition of Experiment 1 was omitted, since it did not have a counterpart in Experiment 2a. Comparisons between Experiment 1 and Experiment 2a revealed no significant differences in average headway (M = 23.34 m, SD = 5.53, and M = 22.18 m, SD = 5.54, for Experiments 1 and 2a, respectively). However, SD of headway distance was lower in Experiment 2a, as would be expected if the tracking task was easier and interfered less with driving, although this difference was not large enough to be statistically significant in the required between-subjects comparisons (M = 5.36 m, SD = 0.185, and M = 4.7 m, SD = 0.185, for Experiments 1 and 2a, respectively; $p > .05$). The predicted effect was statistically significant for steering variability though; SDLP was significantly lower in Experiment 2a than in Experiment 1, as would be expected if tracking while driving was better because of the easier tracking task (M = 0.253 m, SD = 0.095, and M = 0.108 m, SD = 0.098), $F(1, 46) = 160.957$, $p = .000$, partial $\eta^2 = .778$. Overall, there was some support for the idea that driving performance was slightly better in Experiment 2a, but there was no evidence of an experiment × number of targets interaction for any of the driving measures ($F < 1$).

When driving performance from the dual-task (tracking while driving) trials in Experiment 2a were examined in isolation, the number of targets (one, three) had no significant effect on average headway, although on average, the headway was slightly shorter with more targets (22.6 vs. 22.1 m for one and three targets, respectively). Surprisingly, for the SD of headway distance, the effect of the number of targets was opposite to what was expected, with slightly less variability in headway when there were more targets, $F(1, 19) = 5.836$, $p = .026$, partial η^2 = .235 (M = 4.84 and 4.57 m for one and three targets, respectively). The number of targets did not have a significant effect on steering variability (SDLP); there was only a very small increase in variability with the number of targets (0.105 and 0.108 m for one and three targets, respectively). This pattern of results suggests that in this experiment, the tracking task was not as demanding as in the first experiment, insofar as increasing the number of targets did not have as notable an effect.

Change detection

False positives in change detection Participants were told to expect changes on most trials; they were also strongly encouraged to guess the locations of the vehicles that changed if they were not sure. Given those instructions, there was good reason to expect few misses (trials where the participants indicated that there was no change when there was one) and large numbers of false positives (performance on the trials on which participants indicated that there was a change when there was none). As was predicted, misses were very rare, but to our surprise, the average false positive rate was only 10.4 %. False positives did not vary significantly with task load (tracking alone, tracking while driving) or the number of targets tracked (one, three). There was also no interaction ($p > .05$). The mean percentages of false alarms in the single-task condition for one and three targets were 11.2 % (SD = 22.1) and 12.5 % (SD = 26.2). For the dual-task condition, they were 13 % (SD = 13.4) and 5 % (SD = 12.2) for one and three targets, respectively (between-subjects variability may have obscured any effects). It is possible that the change detection task was too easy, given that both misses and false alarms were relatively uncommon. This may be because the change detection portion of the task occurred at a predictable time, at the end of the trial, 16 s or more after the onset of item movement. Participants may have developed the strategy of devoting all of their efforts to tracking in the initial phases of the trial, and then focusing their energies on change detection after 16 s. As well, they may have used a strategy of looking for a novel color when determining whether a change occurred (as described later).

Main analyses: were changes in targets (tracked vehicles) localized better than changes in distractors (untracked vehicles)? The main analyses involved looking at the accuracy with which drivers could localize the vehicle that changed when there was a change. The factors were trial type (target change, distractor change), number of targets (one, three), and task load (single task, dual task). Results are presented in Fig. 6. As was predicted, participants were more accurate at identifying the vehicle that changed when it was a target rather than a distractor in tracking. Participants correctly identified the vehicle that changed on 96.1 % of the target change trials as compared with 80.4 % on the distractor change trials, $F(1, 19) = 7.843$, $p = .011$, partial $\eta^2 = .292$).

If participants were truly distinguishing targets from distractors, and there was reason to expect that they were, given that only trials where participants reported 100 % of the tracking targets were analyzed, then increasing the number of

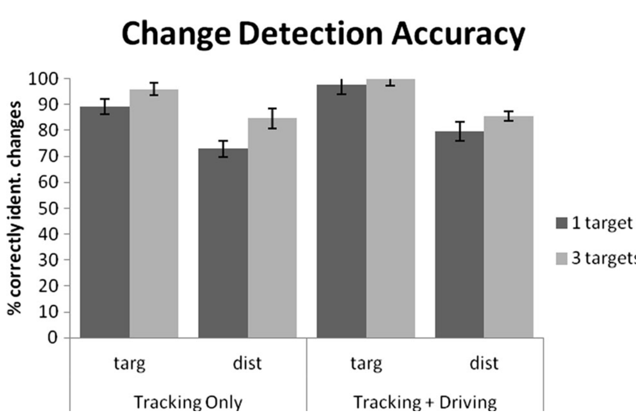

Fig. 6 Percentages of trials on which the participant correctly indicated the vehicle that changed in Experiment 2a. (Targ = change occured in a target vehicle; Dist = change occurred in a distractor vehicle.) Standard error bars are included

targets should have opposite effects on the difficulty of the change localization task, depending on whether it was a target change or a distractor change. As a result, planned comparisons were performed analyzing the target change and distractor change trials separately. Specifically, for target change trials, increasing the numbers of target vehicles to track should make change localization more difficult, because there are more target vehicles to choose from. When the target change trials were analyzed separately, there was little difference in change localization performance between one and three target trials ($F < 1$), although performance was very good in both conditions (approaching ceiling). Surprisingly, localization performance was significantly better for dual- than for single-task trials, $F(1, 19) = 18.6$, $p = .000$, partial $\eta^2 = .495$. Although this result is counterintuitive, it may be an indication that the tracking task was so easy that participants were not fully engaged in the single-task condition. This would explain why performance was at its worst in the easiest condition of all, when participants were tracking a single target and tracking was the sole task (the task load × number of targets interaction did not achieve statistical significance though, $F < 1$).

As for the distractor change trials, change localization should improve with increases in the number of targets to track, because increasing the number of target vehicles meant decreases in the number of nontarget (distractor) vehicles to choose from when determining the vehicle that changed. The predicted increase in change localization with increases in the number of targets emerged, $F(1, 19) = 4.695$, $p = .043$, partial $\eta^2 = .198$. The other effects were not significant (task, task × number of targets: $F < 1$).

Discussion

For trials on which there was a change, participants were about 16 % more accurate at localizing the vehicle that changed when the vehicle was a target, as compared with a distractor. This provides some support for the notion that tracking a visual object provides the visual system with facilitated access to it (Pylyshyn, 2004, 2009). However, overall, the performance in this experiment was surprisingly and perhaps even suspiciously good, given other studies of change detection during tracking (e.g., Bahrami, 2003). It is difficult to make direct comparisons due to methodological differences between studies, but given that the changes in this experiment involved the introduction of a new vehicle color, it is possible that performance may have been better than expected because some of the participants used a strategy of memorizing vehicle colors at the beginning of the trial and then choosing the vehicle with a novel color. Consequently, a second experiment was performed using a more difficult localization task.

Experiment 2b: detection and localization of "vehicle switch" events

Although the "one-shot" change detection paradigm used in Experiment 2a was useful, it had drawbacks. First, the change occurred at the end of the task when the vehicles had stopped moving, and participants had to first report target identities and then the location of the changed vehicles. This made it impossible to gather RTs. Second, change localization performance may have been better than it should be because the changes introduced a new vehicle color into the display.

As a result, the methodology was modified to make change localization more difficult. In this study, changes involved vehicles that switched locations—either two targets or two distractors (this avoided the introduction of new vehicle colors). Participants were required to report the locations of both vehicles involved in the switch, making this task much more difficult than most change detection studies, which typically only require participants to identify the location of one change. Latencies were gathered by changing the procedure so that the change occurred midtrial rather than at the end. Participants were required to hit a button as soon as they knew the identity of the vehicles that switched positions. RTs were measured, and participants indicated the identity of the vehicles that changed; then the animation resumed, and participants continued tracking until the end of the trial.

Method

Participants

Thirty licensed drivers (15 females) between the ages of 18 and 28 years took part in this experiment for course credit (*M* age = 20 years, *SD* = 2.8). All reported normal color vision and acuity.

Apparatus and stimuli

The apparatus and stimuli were basically the same as those used in Experiment 2a, although the experiment was simplified so that there were always three targets and there was no task load manipulation. As well, changes did not involve the addition of a new color into the display but, rather, came about because two vehicles switched positions (either two target vehicles or two distractor vehicles) during the blanking interval. There were also no catch trials (trials on which no change occurred).

Procedure

The procedure is summarized in Fig. 7. As before, participants began each trial parked behind a group of lead vehicles. After the six lead vehicles and the driver began moving, three

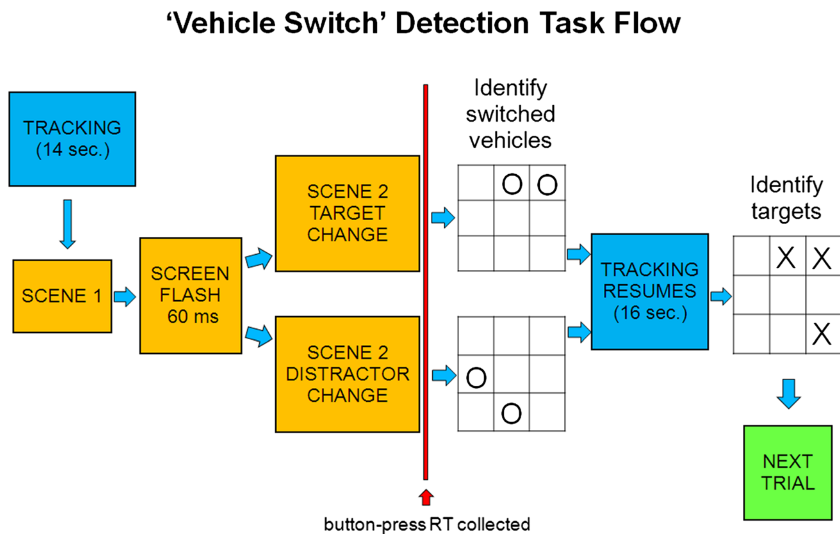

Fig. 7 Task-flow diagram of procedure for Experiment 2b

vehicles flashed to indicate that they were targets. Once the flashing stopped, the six lead vehicles began switching positions. At a randomly selected interval of 16, 18, or 20 s, a global transient (a 60-ms screen flash) occurred, and the simulation paused. When the driving scene resumed, either two of the target or two of the distractor vehicles had switched places. The participants were instructed to push a button on the steering wheel once they had decided which of the two vehicles switched and then mark the locations on a response sheet. (Participants were informed that only target–target and distractor–distractor switches would occur.) The animation resumed and continued until the end of the trial, at which point the participant indicated the location of the three target vehicles. The experiment began with 2 min of familiarization with the simulator and 5 min of practice at the tracking/change localization task. There were 40 experimental trials.

Results and discussion

The effect of the type of switch (target, distractor) was investigated using a repeated measures ANOVA. However, to begin, preliminary analyses were carried out to assess tracking performance. Overall, performance was good, although not quite as good as in Experiment 2a, which may have been due to the midtrial interruption produced by the change detection task. On average, participants correctly identified the positions of 88.23 % of the targets (Hulleman's k = 2.65 for three targets). There was no evidence that the type of switch that occurred midtrial (target switch, distractor switch) had an effect on the number of correctly identified target locations in tracking (M = 87.9 % and 88.57 % correctly identified targets for trials on which there were midtrial target and distractor switches, respectively; $p > .05$).

Only trials on which 100 % of the targets were correctly tracked were included in change detection analysis. On each trial, change localization scores were calculated such that correctly indicating both locations that changed resulted in a score of 100 %. If participants indicated the location of only one of the two that switched, their score was 50 %. Results are shown in Fig. 8. The ANOVA revealed no significant differences in change localization scores between target and distractor switches (66.21 % and 65.79 %, respectively; $p > .05$). In both cases, the expected outcome is about what would be expected if the participants were generally capable of distinguishing targets from distractors, but they confused targets with targets and distractors with distractors when indicating the location of the change. Specifically, given that there were three targets and three distractors, their localization scores approximated the expected outcome given random successive sampling without replacement from three items (expected outcome score: 66.7 % = [((2/3 × ½ × (score of 100)) + (2/3 × 1/2 × (score of 50)) + (1/3 × 2/2 × (score of 50))]/100) for each condition; one sample t-test expected versus observed accuracies, $p > .05$ for both target and distractor change conditions). There was also no significant difference between this expected outcome and the obtained outcome score even if trials on which there was a tracking error were included in the analysis, although in this case, the accuracies were lower (62.57 % and 61.81 % for targets and distractors, respectively), as might be expected if participants were occasionally confusing targets for distractors. Thus, the difference in localization accuracy between target and distractor change trials was not evident with this more difficult vehicle-switch /dual-response methodology. This may be because although the indices contained enough information for participants to be able to determine the location of the target vehicles (and thus, conversely, the distractors), these location indices have little information about the specific properties that were initially associated with each target or distractor (cf. Pylyshyn, 2004; Scholl et al., 1999), as might be predicted if location and property information employ independent or semi-

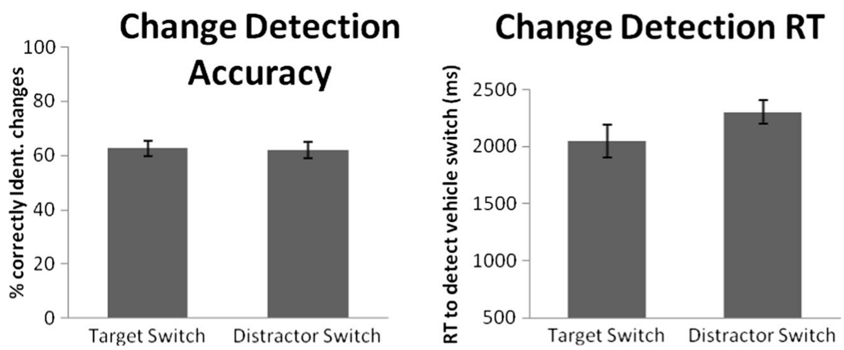

Fig. 8 Change detection localization scores (left) and response times (RTs; right) for the change detection task in Experiment 2b. Change localization scores were calculated such that participants who correctly identified the location of both the changes (indicating the two vehicles that switched) were given a score of 100 %. Those who identified the location of only one of the vehicles that switched were given 50 %. Change detection RT indicates the RT to indicate that there was a change (a buttonpress response). Standard error bars are included

independent mechanisms when people track heterogeneous items (see Cohen et al., 2011; Horowitz et al., 2007; Oksama, & Hyönä, 2008; cf. Makovski & Jiang, 2009, as it relates to the role of visual working memory when tracking heterogeneous as compared with homogeneous items).

Although there was little difference between target and distractor change trials in localization accuracy, there were marked differences in RTs. As is typical in RT studies, only latencies for correct trials were analyzed. Then RTs were screened using a standard procedure whereby, for each subject and condition, trials on which RT's were further than 2.5 standard deviations from that participant's mean for that specific condition were removed. (This resulted in the loss of 1.7 % of the trials.) The screened data were analyzed, and the predicted results emerged with a large (~250-ms) difference between conditions. Participants were significantly faster at determining the positions of two vehicles that switched when they were targets as compared with distractor vehicles, $F(1, 29) = 4.550$, $p < .05$, partial $\eta^2 = .136$. Thus, although participants had trouble distinguishing targets from other targets when making judgments about the vehicles that switched properties, they were much faster at change localization decisions when they were target vehicles, rather than distractor vehicles in tracking.

Experiment 2c: brake event detection and localization

Experiment 2c also investigated change detection for tracked and untracked vehicles, but the task was modified so that it was more like a natural driving task. Drivers are rarely faced with leading vehicles that change color, and there would be few safety implications for failing to notice such changes. There are important implications when a driver fails to notice brake light onsets in lead vehicles though, insofar as lapses such as these lead to rear-end collisions. In the original study by Sears and Pylyshyn (2000), changes that involved sudden onsets were avoided because of the danger that they would trigger rapid automatic reassignments of the attentional focus and possibly even saccades (e.g., Yantis & Jonides, 1984). Instead, Sears and Pylyshyn used changes that involved an offset (the loss of an item segment). There are a variety of change detection paradigms (see Rensink, 2002, for a review), but a number of studies use blanking intervals or random mud splashes. At present, there is considerable controversy about the exact conditions under which onsets will produce automatic attentional reassignments and eye movements (e.g., Ludwig, Ranson, & Gilchrist, 2008). However, if the question of whether multiple-object tracking would be advantageous in day-to-day driving is to be fully addressed, the idea that tracked items are given priority needs to be examined in the context of a more realistic driving task, and in daily driving, lead vehicle braking is signaled by the sudden onset of brake lights.

The second procedural modification involved the nature of the response. Typically, when drivers notice sudden braking in a lead vehicle, the appropriate reaction is to brake. Consequently, in this experiment, participants were instructed to brake when they saw brake light onsets in any of the lead vehicles. Braking RTs were measured, although participants were also asked to indicate the location of the vehicle that braked. If tracked items receive privileged access to the attentional focus, this advantage should be apparent in braking RT and localization accuracy to brake light onsets.

Method

Participants

Nineteen licensed drivers participated in the experiment for course credit (7 females; *M* age = 20.1 years, *SD* = 1.1). All had normal color vision and normal or corrected-to-normal visual acuity.

Apparatus and stimuli

In this experiment, there was no blanking interval and the change was the onset of brake lights in one of the lead vehicles (the brake lights went on, but the vehicle's speed did not truly change).

Procedure

Drivers had to steer and control the vehicle accelerator in this study. There were always three targets and three distractors in the tracking task, but in this case, for change detection, participants had to brake as soon as they saw brake light onsets in any of the lead vehicles. Each trial began with target acquisition (vehicles flashed off and on 5 times to indicate that they were targets), and after this, all the vehicles began switching positions. After 16, 20, or 24 s, the brakes light were activated for 500 ms in one of the vehicles (either a target or a distractor). Participants were instructed to brake as soon as they observed brake lights in any of the lead vehicles. The tracking display continued without pausing until the end of the trial, at which point the animation stopped and participants were required to indicate on a response sheet the position of the targets and the location of the vehicle that had braked. As in the other experiments, participants were initially given 2 min to become accustomed to the simulator and then had 5 practice trials with the tracking/change-detection task. After that, the participant completed 40 randomly ordered experimental trials.

Results

Three measures were assessed: tracking accuracy, change localization accuracy, and braking RT. Overall tracking accuracy for the three targets was high (93 % correctly identified targets, Hulleman's $k = 2.77$). This was important because only trials on which 100 % of the targets were correctly identified were included in change detection analysis. (There was no difference in tracking accuracy based on whether the subsequent brake light onset occurred in a target or distractor, $p > .05$.)

The measures of change detection performance are presented in Fig. 9. Change localization accuracy was measured as the percentage of times that participants correctly indicated the location of the vehicle that braked. Participants were more accurate at identifying the vehicle that braked if it was a target as opposed to a distractor in multiple-object tracking, $F(1, 18) = 16.318$, $p = .001$, partial $\eta^2 = .475$.

Braking RTs were calculated on the basis of the time between the onset of the brake lights in a lead vehicle and when the driver's foot contacted the brake pedal. RT analyses were performed for the trials on which participants were correct about the location of the change, and outlier RTs were screened using the same procedures described in previous experiments (3.9 % of the trials were dropped in screening). For the trials on which participants correctly identified the location of the braking vehicle, there were no significant differences in braking RT between targets and distractors (M = 1,018 and 1,024 ms, respectively; $p > .05$), as might be expected if the sudden onsets produced by the brake lights allowed the items to be detected automatically.

Discussion

Participants were 14 % more accurate at identifying the location of the braking vehicle if it was a target rather than a distractor in tracking. This finding runs counter to the prediction that the change detection advantage for tracked versus untracked items would disappear for sudden onset changes. (This prediction was based on the idea that sudden onsets would rapidly and automatically attract the attentional focus to the locus of the change, possibly even initiating eye movements.) These results suggest that the proposed indexing mechanism for tracked items is robust enough to provide localization advantages in this situation (drivers were primed to look for onsets, but the onset did not signal the presence of new objects). However, although localization performance was better when the lead vehicle that changed (braked) was tracked, it did not speed response to the detection of the brake light onsets. This suggests that when there is a transient such as a brake onset, at first the onset is not perfectly localized. This would permit rapid braking regardless of the location of

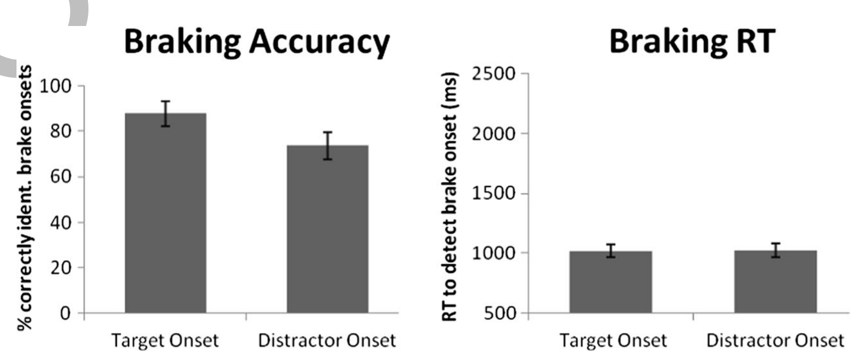

Fig. 9 Percentages of trials on which participants correctly indicated the vehicle that braked (left) and the braking response time (RT; right) for the brake light onset detection task (Experiment 2c). A brake onset was accurately localized if the participant was able to indicate the location of the vehicle that braked. Standard error bars are included

the transient but would, nonetheless, give target locations an advantage when it came to determining the identity of the vehicle that braked. This localization advantage may be of practical importance insofar as drivers need to know the position of a braking vehicle if evasive steering maneuvers are required. (In this experiment, there was no need for evasive steering; the brake light onsets were of brief duration, and the associated vehicle did not actually change speed.)

General discussion

This is the first study to investigate multiple-object tracking in the context of driving. A novel implementation of the multiple-object tracking task was developed for this purpose: a task that involved tracking multiple moving vehicles in a driving scenario where a cohort of vehicles shifted and moved on the road ahead of the driver. The retinal projection for each individual vehicle changed frequently as the cars jostled for position, and vehicles frequently occluded one another. This study showed that tracking was possible despite these occlusions, as would be expected given the research that shows that tracking is relatively robust to object occlusion in the classic multiple-object tracking task (e.g., Horowitz et al., 2006).

However, the present experiments also showed that both tracking and driving performance suffered when drivers tried to carry out the two tasks simultaneously. Tracking interfered with driving insofar as it compromised the ability to maintain a consistent course both longitudinally (*SD* headway: speed control) and laterally (SDLP: steering). These results show that *self-directed* motion diminishes tracking performance over and above the reductions produced by movement per se (Thomas & Seiffert, 2010). The interference between tracking and driving may indicate that they share a cognitive resource, general working memory, cognitive effort, or whatever is necessary for "paying attention," for example. Nonetheless, given that spatial tasks interfere more with tracking than do nonspatial tasks (e.g., Trick et al., 2006; Zhang et al., 2010), it seems likely that at least some of this interference may be specifically spatial.

It is interesting to consider these results in light of Wickens's (1984, 2002) distinction between focal and ambient attention. Focal attention is useful for reading words or picking out fine details in a scene; it typically requires the fovea and, thus, eye movements. In contrast, ambient attention is associated with ego motion (directing oneself through physical space), and it does not necessarily require the fovea. Wickens considers steering (maintaining the lateral position of a vehicle) to be a classic example of an ambient attention task. Skilled drivers do not make eye movements toward lane boundaries to maintain their lane position; they seem to use their peripheral vision to steer (Smiley et al., 1980; Summala et al., 1998; Summala et al., 1996). Similarly, steering does not seem to benefit much from the high levels of detail provided by foveation. In fact, when drivers wore goggles that reduced their visual acuity to 20/200, they managed to maintain their steering performance (Higgins, Wood, & Tait, 1998); hazard detection is another matter (hazard detection is typically measured in terms of braking RT). Given the interference between multiple-object tracking and steering, perhaps Wickens's "ambient attention" involves some of the same basic mechanisms involved in multiple-object tracking. Pylyshyn (1989, 2009) initially stressed the importance of spatial indices for focal attention, insofar as these indices were to be used to individuate potential targets for the attentional focus (and then the eye) so that observers could foveate a specific item among others. However, although these indices were presumed to be necessary for eye movements, multiple-object tracking by itself does not require eye movements, and in fact, they can be disruptive (Fehd & Seiffert, 2010). Perhaps the spatial indices used in tracking are used in ambient attention as well, even though eye movements are typically not required. Alternatively, it is possible that the relationship between tracking and steering is an artifact of cognitive tunneling, which occurs when the size of the peripheral field of view decreases with cognitive effort, given that reductions in the peripheral field compromise steering (Owens & Tyrrell, 1999), although this would not necessarily explain dual-task reductions in headway control.

Thus, this study contributed to the literature insofar as it showed that multiple-object tracking was possible in the context of a driving task, but the later experiments went on to investigate whether there was a benefit to tracking while driving. The results of these experiments suggest that there is an advantage to tracking a lead vehicle's position while driving, at least in some situations. Generally, the notion that indexed items have facilitated access to visual attention was upheld. In Experiment 2a, we demonstrated that change localization accuracy in a "one-shot" change detection task was better for tracked than for untracked vehicles. This interpretation was further supported by the results of Experiment 2b, which showed that drivers were 250 ms faster in making a decision about which two vehicles switched properties when the vehicles were targets, as compared with distractors, in tracking. This indicates that there is at least some attentional facilitation for detecting changes at indexed locations.

However, complexities emerged. In Experiment 2b, the tracking advantage was not evident in change localization accuracy, despite the advantage in detection latencies. In this experiment, the localization task was more difficult than in Experiment 2a, insofar as the vehicle switches involved changes in two locations at once (either two targets or two distractors) and participants had to identify both locations to get a 100 % score (50 % was awarded if only one was correctly identified). For both the target and distractor changes, the accuracy scores approximated the expected outcomes if the participants could distinguish targets from distractors but could not distinguish one target from another or one distractor from another. This represents a floor effect of sorts, but it is consistent with studies that indicate that the properties of individual tracked targets are not represented in multiple-object tracking (e.g., Pylyshyn, 2004; Scholl et al., 1999). Nonetheless, it is also important to note that the change detection task in this study was much more difficult than standard change detection tasks insofar as it involved reporting the locations of two changes, which would increase the memory load. Moreover, the displays were much more vast and complex than is typical in either change detection or tracking experiments, and furthermore, the participants were also exposed to the sounds and vibrations of driving. Consequently, it is possible that had there been less competing stimulation, there would have been more evidence that properties of individual targets were stored, as might be expected from the research on multiple-identity tracking (e.g., Cohen et al., 2011; Horowitz et al., 2007; Makovski & Jiang, 2009; Oksama & Hyönä, 2008).

In Experiment 2c, the task was modified so that it would be more similar to something that might occur in normal driving. Drivers were required to brake in response to the onset of brake lights in one of the lead vehicles. Braking RTs were measured, and participants were also required to indicate which of the six lead vehicles braked. There was no difference in braking latencies, but drivers were 14 % more accurate at locating the individual vehicle that braked when it was a target as compared with a distractor. Localization information such as this would be necessary if evasive steering maneuvers were required (e.g., lane changes).

Thus, these experiments were the first to show that it is possible to track specific lead vehicles among others in complex, dynamic visual environments that "slip by" as the driver travels in depth. They also showed that there may be some benefits to tracking specific vehicles, insofar as drivers can more quickly localize a braking vehicle if it is a target rather than a distractor. However, there is a cost to tracking while driving in terms of spatial stability, and it remains to be seen whether the benefit is worth this cost. In these experiments, the vehicles were not traveling very fast, and the steering task was extremely easy; steering conditions were optimal, and the road was straight. It is not clear whether drivers could safely negotiate a winding road while tracking or, for that matter, even deal with the steering challenges engendered by destabilizing lateral gusts of wind that push the vehicle one direction or the other on the road.

Furthermore, although the multiple-vehicle tracking task enabled us to ask some of the most basic questions about tracking and driving, it was quite exotic. Typically, there is no need to keep track of several vehicles at once among a lead cohort ("Follow those cars!"). These studies used a highway following task because it made it possible to present drivers with a relatively large number of vehicles that could be tracked over extended periods of time. However, in day-to-day driving, the best argument for the need for multiple-object tracking is at intersections, where drivers have to cross into the paths of other road users (automobile drivers, cyclists, motorcyclists, pedestrians, skateboarders). In countries where vehicles travel on the right side of the road, a classic example would be a left-hand turn across busy traffic. This is indeed an area of risk, and in the driving literature, a great deal of energy is now focused on evaluating the effectiveness of various in-vehicle technologies designed help drivers to negotiate intersections (e.g., Chang, Lin, Hsu, Fung, & Hwang, 2009; Chen, Cao, & Logan, 2011; Dotzauer, Caljouw, de Waard, & Brouwer, 2013; Moussa, Radwan, & Hussain, 2012).

Intersections are riskier for some drivers than for others though. For example, novice drivers are at higher risk, but their problems seem to be relatively easy to understand and alleviate. Lack of driving experience leaves novice drivers unprepared for covert hazards that occur at intersections, such as pedestrians emerging from behind parked vehicles. With simulator training, these expectations can be changed (Vlakveld et al., 2011). However, the group with the highest risk of collision at intersections is drivers over the age of 65 (e.g., Hauer, 1988; McGwin & Brown, 1999; Preusser et al., 1998; Skyving et al., 2009), and their problems are not as simple to explain or remedy. These drivers typically have many decades of driving experience and, thus, have well-developed expectations about the events that occur at intersections. They are, if anything, more concerned with safety than the other age groups and more likely to adopt driving practices that minimize their risks and compensate for driving challenges and their own attentional shortcomings (at least as measured by the *Useful Field of View*; see Trick et al., 2010). Many older drivers are acutely aware that they have problems with intersections (e.g., Eck & Winn, 2002), and yet this knowledge is not enough to reduce their risks.

Although there are a variety of age-related changes that may be a factor in intersection collisions, including restrictions in neck mobility (e.g., Isler, Parsonson, & Hansson, 1997), declines in the rate at which information can be extracted from an image (Ball, Edwards, & Ross, 2007), and reductions in the speed and breadth of eye movements (e.g., Maltz & Shinar, 1999), most recent studies emphasize eye movements. Several studies suggest that younger and older adults differ in their eye movement patterns at intersections (e.g., Dukic & Broberg, 2012; Romoser, Pollatsek, Fisher, & Williams, 2013). Eye movements are relevant because they permit objects of interest to be projected in the foveal area of the retina (the area with the best acuity).

However, although eye movements are important, it has long been known that people may attend to objects that they are not foveating, as occurs in covert orienting (e.g., Posner, 1980); conversely, they may foveate objects and yet fail to attend them, as shown by the notorious "looked-but-failed-to-see" collision (e.g., Clabaux, Brenac, & Perrin, 2012; Strayer, Drews, & Johnston, 2003; Treat et al., 1979; White & Caird, 2010). More worrying, there seems to be no difference in the eye movement patterns between those who make correct and incorrect decisions about when they can safely cross at multilane intersections (Hardiess, Hansmann-Roth, & Mallot, 2013), leading the authors to conclude that driver safety may be more related to the ability to represent the positions of multiple vehicles at once in working memory rather than to eye movements per se. There may be more to differential collision risk than varying patterns of eye movements.

If making good decisions about when to turn left at an intersection requires the ability to represent the positions of multiple positions at once, there is reason to expect a role for multiple-object tracking. If multiple-object tracking is important at intersections, the observed age-related deficits in multiple-object tracking may partially explain the larger collision risk that older drivers face (Trick et al., 2009; Trick, Perl, & Sethi, 2005). For that matter, these deficits may also be a factor in age differences in eye movement patterns if Pylyshyn is correct in asserting that the individuation mechanism used in tracking is critical for selecting future targets for eye movements (Pylyshyn, 2009). Nonetheless, it also seems plausible that crossing decisions require extra information that the tracking mechanism does not in itself provide. At least, this mechanism does not seem to use very much information about projected speeds and trajectories when research participants are required to determine the location of targets after occlusion (Fencsik, Klieger, & Horowitz, 2007). At this point, it is clear that more research is required.

Although the specific role of multiple-object tracking at intersections is yet to be determined, this study is the first to show that multiple-object tracking is at least possible while driving. Moreover, this study demonstrates that there are both disadvantages and advantages to tracking while driving. Tracking seems to reduce a driver's ability to maintain a stable position on the road (compromising steering and speed control) but it enhances the driver's ability to respond to changes in tracked vehicles, including safety-related changes. This study is only a preliminary investigation, but it adds a new technique to the tracking literature (a methodological contribution) and provides a strong test to Pylyshyn's (2009) prediction that the mechanisms used in multiple-object tracking are in visual–motor coordination and explores how tracking interacts with other perceptual–motor behaviors (theoretical contributions). The hope is that this study may also encourage more interaction between those who do basic and applied research.

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