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Self-motion impairs multiple-object tracking

Laura E. Thomas [*], Adriane E. Seiffert

Vanderbilt University, Department of Psychology, 111 21st Avenue South, Nashville, TN 37203, United States

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ABSTRACT

Investigations of multiple-object tracking aim to further our understanding of how people perform common activities such as driving in traffic. However, tracking tasks in the laboratory have overlooked a crucial component of much real-world object tracking: self-motion. We investigated the hypothesis that keeping track of one's own movement impairs the ability to keep track of other moving objects. Participants attempted to track multiple targets while either moving around the tracking area or remaining in a fixed location. Participants' tracking performance was impaired when they moved to a new location during tracking, even when they were passively moved and when they did not see a shift in viewpoint. Self-motion impaired multiple-object tracking in both an immersive virtual environment and a real-world analog, but did not interfere with a difficult non-spatial tracking task. These results suggest that people use a common mechanism to track changes both to the location of moving objects around them and to keep track of their own location.

1. Introduction

Imagine you are driving down a busy interstate and spot your exit up ahead. To successfully navigate to the off ramp, you must not only continually update a representation of your own location in space, but also simultaneously keep track of other moving cars. Vision research has shown that people can track a subset of objects moving on a computer screen, even when the targets are identical to distractors (Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988; Scholl, 2001). People no doubt take advantage of this ability while moving through the world—as they negotiate interstate traffic, play team sports, or even walk down a crowded sidewalk. However, to date there has been no research investigating the impact of self-motion on the ability to track multiple objects. When people move through the world, how do changes to their own location affect their ability to keep track of other moving objects?

In order to move through space successfully, people refer to internal representations of the environment and their own position within it. Research demonstrates that people update a representation of their own changing location in space not only rapidly, but also nearly inevitably. When participants must respond to questions about spatial layout, their responses immediately reflect experienced rotations or translations that they find difficult to ignore (Farrell & Robertson, 1998; Farrell & Thomson, 1998; May & Klatzky, 2000; Rieser, 1989). Although researchers have documented circumstances under which spatial updating of the self does not necessarily occur automatically, such as when observers are disoriented (Waller, Montello, Richardson, & Hegarty, 2002) or updating in an imagined environment (Wang, 2004), in many situations people do seem to update their position largely obligatorily (Farrell & Robertson, 1998; May & Klatzky, 2000). This evidence indicates that when you are driving down the interstate, you cannot help but keep track of your car, updating a representation of your location in space relative to other cars and landmarks such as off ramps.

Here, we consider how you keep track of other objects, such as cars sharing the road, when you are also moving. The ability to track multiple moving objects has a capacity limit (Allen, McGeorge, Pearson, & Milne, 2006; Alvarez & Franconeri, 2007; Cavanagh & Alvarez, 2005; Fougnie &

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[*] Corresponding author. Tel.: +1 615 870 2929; fax: +1 615 343 8449.
E-mail address: laura.e.thomas@vanderbilt.edu (L.E. Thomas).

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Marois, 2006; Pylyshyn & Storm, 1988; Tombu & Seiffert, 2008). We use the term tracking mechanism to encompass the necessary resources for dynamically updating a representation of objects' changing locations in space. If people use the same mechanism to track the changing locations of other moving objects as they do to keep track of their own changing location in space, we might expect that self-movement would interfere with multiple-object tracking. When a person can't help but keep track of her own changing location, perhaps she becomes less able to keep track of other moving objects.

We used immersive virtual reality to test the hypothesis that keeping track of one's own movement impairs the ability to track other moving objects. We asked participants to keep track of one or three moving balls—varying tracking load—while they either walked around the area in which the balls moved or walked in place maintaining a constant location (Fig. 1). In addition, we tested whether passive changes to participants' location would interfere with tracking performance by having an experimenter push them in a wheelchair. These conditions also allowed us to test for the possibility that performing any physical action impairs tracking, regardless of whether this action entails a change in location or not.

2. Experiment 1

2.1. Method

2.1.1. Participants

Sixteen volunteers from Vanderbilt University participated for course credit or a monetary compensation.

2.1.2. Apparatus

Participants viewed the virtual environment on an nVisor SX head mounted display (HMD; NVIS, Reston, VA), which presented stereoscopic images in a 60° diagonal field of view at a refresh rate of 60 Hz using Vizard software (WorldViz, Santa Barbara, CA) rendered graphics. A three-axis orientation sensor (InertiaCube2; Intersense, Bedford, MA) tracked head orientation and an optical tracking system (PPTX4; WorldViz, Santa Barbara, CA) tracked head position. The graphics displayed in the HMD were updated based on head position and orientation, leading participants' physical movements to translate into visual movements within the virtual world.

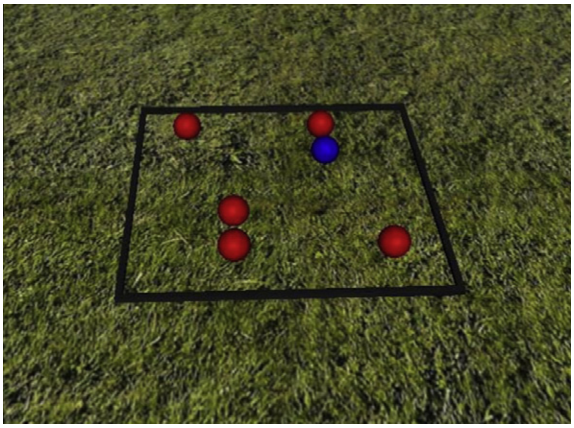

Fig. 1. Tracking balls as they appeared in the HMD during the cue period of a one-target trial. Target balls were cued by briefly changing color from red to blue. Following the cue period, all six red balls moved in straight paths inside the box while participants either walked around the tracking area, walked in place, were wheeled around the tracking area, or sat in the stationary wheelchair.

2.1.3. Stimuli, procedure, and design

Inside a virtual world consisting of blue sky and a field of grass, participants were placed 4.5 ft from the center of a 3×3 ft black outlined box on the ground. Inside the box were six red balls that subtended approximately 3.3° of visual angle when in the center of the box. Participants performed a multiple-object tracking task. At the start of each trial, the balls appeared in random positions inside the box for 500 ms. Either one or three of these balls changed color from red to blue for 1700 ms, designating them as targets, before returning to red (Fig. 1). All of the balls then moved in straight paths inside the box at approximately 19 deg/s, bouncing off of the box's edges and passing through each other. After 5 s of movement, the balls stopped and one ball changed color from red to blue. Participants verbally responded "yes" if they thought that the probed blue ball was the same as one of the targets and "no" otherwise. For half of trials, the cued ball was a target; for the other half of trials it was a distractor.

While engaged in the tracking task, participants performed in four different conditions that varied their movements. In the *active move condition*, participants walked an arc 90° around the box, moving from the center of one side of the box to an adjacent side. While walking, participants remained oriented so that their bodies faced the direction in which they moved and their heads remained turned toward the box. Participants initiated this walk at the same time that the tracking balls began to move and completed the walk when the balls stopped. To ensure that participants walked appropriately, an experimenter guided them by holding one end of a 4 ft stick while the participant held the other end. In the *active stay condition*, participants simply walked in place as the balls moved, oriented identically to the active move condition but maintaining a constant position. In the *passive move condition*, an experimenter pushed participants in a wheelchair through the same arc, facing the same direction, and with the same timing as in the active move condition. Finally, in the *passive stay condition*, participants sat in the stationary wheelchair throughout a trial with the box at their side and without making any sort of physical action. Note that throughout every trial and in all conditions, participants' heads remained in the same position relative to their bodies. At the end of each trial in which participants changed location, they turned 180° so that they could move in the opposite direction along the same arc on the next move trial.

Before putting on the HMD, participants spent approximately 5 min observing the testing area as they provided consent and listened to instructions. Participants then put on the HMD and were given the opportunity to familiarize themselves with the virtual environment before performing eight practice trials in the active conditions followed by four alternating blocks of 40 trials, two blocks of the active conditions and two blocks of the passive conditions. The order of conditions was counterbalanced across participants. In all blocks, the presence of self-motion (move or stay) was randomly intermixed, as were the number of targets (1 or 3) and the identity of the probe (target or distractor). Before each trial began, an experimenter announced whether the trial included motion of the participant.

2.2. Results and discussion

Fig. 2 shows the average proportion correct at the tracking task. Participants were better at tracking one ball than three ($F(1,15) = 133.73$, $p < 0.001$), a result in agreement with previous work showing target load effects (Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988). Participants also performed better when they walked in place than when they walked to another location (active stay vs. active move $F(1,15) = 8.59$, $p < 0.05$). This impairment was strongest when participants tracked three targets (interaction $F(1,15) = 17.30$, $p<.01$). These results show that self-motion interfered with multiple-object tracking. When tracking load was low, participants' movements did not strongly influence tracking performance, but when load was high, moving around the box hurt their performance. In addition, we found that even when participants were not responsible for planning and executing their own movements—passively moving in the wheelchair—their motion still interfered with tracking multiple objects (passive conditions interaction with set-size $F(1,15) = 8.97$, $p < 0.01$). Participants' performance did not vary as a function of whether they were or were not in the wheelchair (active vs. passive $F(1,15 = 3.42$, *ns*), regardless of whether they moved or stayed in the same location (interaction $F(1,15) = 1.62$, *ns*), suggesting that the physical action of walking in and of itself did not impair tracking. These results are consistent with our hypothesis that keeping track of one's own changing location impairs the ability to simultaneously keep track of other moving objects. People cannot help but keep track of their own changing location (e.g., Farrell & Robertson, 1998), and they seem to do so at the expense of tracking other targets, presumably because people employ the same resources for spatial updating of their own position and object tracking.

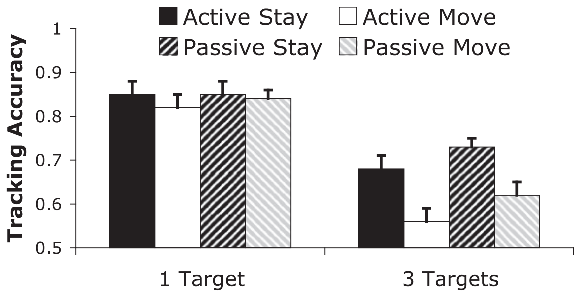

Fig. 2. Mean tracking accuracy in Experiment 1.

3. Experiment 2

The results of Experiment 1 suggest that self-motion impairs object tracking because of the participant's changing location. However, in both the active and passive move conditions of Experiment 1, participants experienced changes to both their location in space and their viewpoint as they moved. In Experiment 2, we dissociated viewpoint changes from self-motion to determine whether location changes without viewpoint changes would also cause impairment.

3.1. Method

Twelve volunteers from Vanderbilt University participated for monetary compensation. The stimuli, timings, and sequence of events were the same as in Experiment 1. There were four conditions. Two of these conditions, the *active move condition* and *active stay condition*, were replications of these conditions from Experiment 1. The two other conditions dissociated participants' movements from the visual information they received. In the *location change condition*, participants moved in exactly the same manner as they did in the active move condition, walking 90° around the box. However, participants' viewpoint remained constant, appearing as if they stayed in the same location. We locked the horizontal coordinates of the HMD display such that neither horizontal translations nor rotations affected the visual display. In the *viewpoint change condition*, participants walked in place just as they did in the active stay condition, but their viewpoint was translated 90°, appearing as if they walked around the box. We achieved this effect by recording the position of a person walking the 90° arc and storing the 3D position of the headset during the walk. We then fed the horizontal coordinates of this recorded motion to the HMD while participants walked in place, leading them to see a smooth change in position. In all of these conditions, the HMD display still reflected participants' real-time vertical coordinates to preserve the up-down shifts in viewpoint associated with the participant's actual stepping movements. Participants' head-body positioning was again kept constant across conditions. After practice trials, participants performed four blocks of 40 trials—two blocks intermixing active move and active stay conditions and two blocks intermixing location change and viewpoint change conditions.

3.2. Results and discussion

As Fig. 3 shows, participants again had more difficulty in tracking three targets than one ($F(1,11) = 83.2$, $p < 0.001$). Replicating Experiment 1, participants were worse at tracking when they walked around the box than when they walked in place ($F(1,11) = 23.90$, $p < 0.001$). This effect was larger when they had to track three targets instead of one (interaction $F(1,11) = 12.95$, $p < 0.01$), indicating that

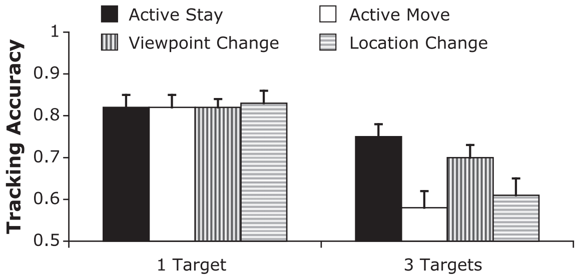

Fig. 3. Mean tracking accuracy in Experiment 2.

self-motion interferes with tracking multiple objects. Participants were also better at tracking three targets in the viewpoint change condition than the active move condition ($t(11) = -3.4$, $p < 0.05$). Although abrupt changes to viewpoint can disrupt tracking performance (Huff, Jahn, & Schwan, 2009), in the current experiment, smooth changes in viewpoint alone did not seem to impair multiple object tracking. Simulated optic flow in the absence of vestibular and proprioceptive self-motion cues can cause vection (e.g., Warren, 1995), but optic flow alone is not sufficient to induce spatial updating (Chance, Gaunet, Beall, & Loomis, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Peruch, May, & Wartenberg, 1997). Thus participants in the viewpoint change condition may not have received adequate information to perform spatial updating of the self, leading to no tracking impairments in this condition. Of more importance, participants were impaired at tracking three targets in the location change condition, relative to active stationary ($t(11) = 5.2$, $p < 0.01$). Multiple object tracking suffered when participants experienced a change in location as they tracked, regardless of whether or not their viewpoint reflected this location change. The results of Experiment 2 therefore support the hypothesis that self-motion impairs multiple object tracking because of the change in location this motion necessitates. By keeping track of their own changing location in space, people become less able to keep track of the changing locations of moving targets, supporting the notion that people use a common tracking mechanism for both spatial updating of their own location and multiple-object tracking.

4. Experiment 3

While the results of the first two experiments show that self-motion impairs multiple object tracking in a virtual environment, it is not clear whether this effect occurs only in the virtual environment or will also occur when people attempt to track objects in the real world. Moving in virtual environments can be dizzying and disorienting (Nichols & Patel, 2002). However, virtual and real environments have been shown to elicit similar spatial representations and learning patterns (Wan, Wang, & Crowell, 2009; Williams, Narasimham, Westerman, Rieser, & Bodenheimer, 2007). If spatial updating of the self draws upon the same resources as object tracking, then we would expect self-motion to impair tracking performance regardless of whether this motion occurs while a participant views a virtual display or simply looks at the real floor. We tested this hypothesis in Experiment 3 by running a real world version of the tracking task.

4.1. Method

Twelve volunteers from Vanderbilt University participated for monetary compensation. The timings and sequence of events were the same as in Experiment 1, and participants once again performed under *active move* and *active stay* conditions. However, instead of viewing red balls that rolled on the ground of a virtual environment, participants in Experiment 3 were asked to keep track of one or three (of six) white dots projected onto the physical floor of a dimly lit room. Target dots flashed yellow at the beginning of each trial. The dots moved in the same manner as in the previous experiments within a 4.5 × 4.5 ft box taped on the floor. Participants stood approximately 5 ft from the center of this box and either walked in place or walked in a 90 arc around the box as the tracking dots, each subtending approximately 1.5° of visual angle, moved. Because participants could see where they were going in the real world, there was no need for an experimenter to guide their movements. After eight practice trials, participants performed two blocks of 40 trials intermixing self-motion (move or stay), number of targets (one or three), and probe identity (target or distractor) conditions.

4.2. Results and discussion

As Fig. 4 shows, the results of Experiment 3 replicated the major findings of Experiments 1 and 2. Participants were worse at tracking three targets than one ($F(1,11) = 51.06$, $p < 0.001$), had more difficulty tracking while walking around the box than while walking in place ($F(1,11) = 8.32$, $p < 0.02$), and once again, the detrimental effects of self-motion on tracking performance were most pronounced when participants had to track three targets instead of one (interaction $F(1,11) = 7.93$, $p < 0.02$). These findings provide additional support to the claim that self-motion impairs multiple-object tracking and demonstrate that this influence of self-motion on tracking is not unique to a virtual reality setting.

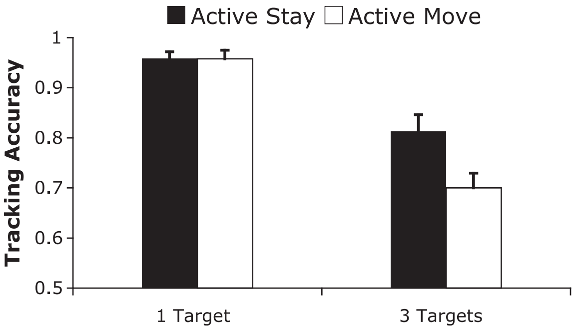

Fig. 4. Mean tracking accuracy in Experiment 3.

5. Experiment 4

We have shown that participants have more difficulty tracking objects—both in virtual reality and the real world—when they themselves are moving, presumably because spatial updating of one's own position and object tracking rely on the same mechanism. However, it is also possible that self-motion draws upon more general resources and that walking would impair any cognitive task. In Experiment 4, we investigated this possibility by asking participants to perform two different tracking tasks while walking in place or walking around the tracking area. The first of these tasks was the standard spatial multiple-object tracking task employed in the previous experiments. The second was a non-spatial task in which participants tracked a stationary object as it moved through feature space by gradually changing orientation and color (Blaser, Pylyshyn, & Holcombe, 2000). If self-motion impairs multiple-object tracking because of shared spatial resources, then participants' movement should affect spatial, but not non-spatial, tracking performance.

5.1. Method

Twelve volunteers from Vanderbilt University participated for monetary compensation. Participants performed two tracking tasks under *active move* and *active stay* conditions. The *location track* task was a direct replication of the three-target condition of Experiment 3 and required participants keep track of the changing spatial locations of moving target dots. In the *feature track* task, participants were presented with two colored, square-wave gratings that overlapped inside a circular aperture (similarly to Blaser et al., 2000). In each feature track trial, the target grating was presented stationary and alone at a random orientation and a random starting color for 1700 ms. The distractor grating was then superimposed over the same spatial location as the target at a starting orientation 45° from the target's starting orientation and a random starting color. Both did not change for 500 ms. Then, both the target and distractor randomly underwent smooth transformations of color and orientation, without changing spatial location, for 5 s. Both gratings maintained a constant red color number of 255, while the green and blue color values ranged from 0 to 255. The grating green and blue color values incremented or decremented by one each frame, with the direction of change varying randomly every 730 ms for the target grating and every 560 ms for the distractor grating. The gratings' orientations changed by one degree every two frames, with the direction of change varying randomly every 450 ms for the target grating and every 620 ms for the distractor grating. Under these conditions, the two gratings could completely cross in feature space in each trial. At the end of the trial, one of the gratings was removed and participants reported whether the remaining grating was or was not the target. The gratings subtended approximately 0.7° of visual angle, placing them beyond the limits of the resolution of spatial attention (Blaser et al., 2000; Eriksen & Hoffman, 1972; He, Cavanagh, & Intriligator, 1996) and therefore ensuring spatial information did not contribute to this tracking task. After four practice trials each for the feature and location tracking tasks, participants performed four blocks of twenty trials—two blocks of the feature task and two blocks of the location task. Order of blocks was counterbalanced across participants.

5.2. Results and discussion

Fig. 5 shows the average proportion correct at the tracking tasks under active stay and move conditions. Replicating the previous experiments, participants' performance in the location track task suffered when they moved as compared to when they stayed in the same location ($t(11) = 3.41$, $p < 0.01$), again showing that self-motion impairs a spatial tracking task. However, the movement manipulation did not affect performance in the feature track task ($t(11) = -0.47$, $p > 0.6$). Participants found the feature tracking task difficult, but were able to perform this task at an above-chance level ($t(11) = 2.79$, $p < 0.02$ for active stay; $t(11) = 5.56$, $p < 0.001$ for active move). Participants needed to attend to and dynamically update a representation of the color and orientation of the feature target, but moving around the display did not impair these non-spatial processes. These results support our hypothesis that the interference of self-motion on multiple-object tracking we have observed is specifically spatial: namely, that participants use a common spatial mechanism or representation to keep track of their own movements as well as the movements of other objects.

6. General discussion

Although you may feel like you have an accurate representation of the shifting locations of surrounding cars while you change lanes on a busy interstate, our results suggest you would be better at keeping track of moving objects if you aren't moving. We found that self-motion impairs multiple-object tracking. Self-motion did not strongly interfere when participants only had to track one target, presumably because the load on the tracking mechanism was low. However, participants consistently had more difficulty in keeping track of three moving targets when they themselves were also moving through space. This was true regardless of whether participants were responsible for their own movement or not (Experiment 1), whether they viewed

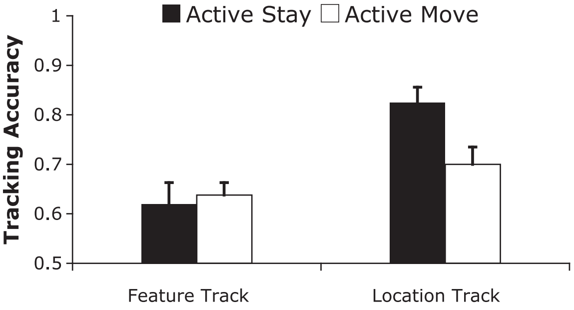

Fig. 5. Mean tracking accuracy in Experiment 4.

stimuli in virtual reality or the real world (Experiments 3 and 4), and did not occur because of the change in viewpoint associated with moving (Experiment 2). However, moving through space did not affect performance on a non-spatial tracking task (Experiment 4). Although participants in our experiments were not required to keep track of where they were, they likely had difficulty ignoring changes to their location. People tend to obligatorily update a representation of their own changing location when they make translational or rotational movements, even in the absence of vision (Farrell & Robertson, 1998; Farrell & Thomson, 1998). Our results suggest that the spatial updating associated with self-motion interferes with successful tracking of multiple objects. We propose that both object tracking and spatial updating tap common limited-capacity spatial resources.

The ability to track moving objects is supported by a limited-capacity mechanism that individuates and maintains object identities across changes in space. Previous work has demonstrated that people can track a limited number of targets, with that number dependent upon several visual characteristics, such as the speed of the objects, the size of the objects and the number of distractors (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Tombu & Seiffert, 2008). One prominent model of multiple-object tracking, the FINST (Fingers of INSTantiation) model, posits that observers track objects by attaching mobile indexes to each target that act as pointers, maintaining contact with the target locations without the need for attention (Pylyshyn, 2001; Pylyshyn & Storm, 1988). These indexes stick to targets as they move through space and allow attention rapid access to a target's location. According to another popular model of multiple-object tracking, the multifocal attention model, each target attracts an independent focus of attention that follows targets as they move through space (Cavanagh & Alvarez, 2005). While these models differ in the role they assign to attention in multiple-object tracking, both propose a need for some spatial resource that follows targets as they move.

Here we have observed that object tracking is compromised when participants change location, suggesting that the spatial resources people use to track moving objects are also employed to keep track of movements of the self. Expanding the domain of the tracking mechanism to self-motion opens new possibilities for understanding how people represent their location in space and their relationship to other objects. In both spatial updating of the self and object tracking, people continually update a representation of objects' locations in space. Judgments about trajectory, orientation, and heading of the self are subject to dual-task interference from both visuospatial and nonvisuospatial secondary tasks (Takei, Grasso, Amorim, & Berthoz, 1997; Talkowski, Redfern, Jennings, & Furman, 2005; Yardley, Gardner, Lavie, & Gresty, 1999; Yardley & Higgins, 1998). Spatial updating may therefore interfere with object tracking because keeping track of one's own location involves making judgments about trajectory that interfere with keeping track of other objects. Alternatively, shared representations of space may be taxed by self-motion and object tracking. If people keep track of self-location and the location of target objects through the same spatial representation, then self-motion may impair object tracking because the updating of any information in this representation may have a limited capacity.

What sort of common spatial representation might object tracking and self- motion share? One possible locus for the interference of self-motion on object tracking is an egocentric subsystem that represents object locations with respect to the body (e.g., Rump & McNamara, 2007; Sholl, 2001). There is behavioral evidence that people rely on egocentric representations to track objects (Huff et al., 2009; Seiffert, 2005). When observers attempt to track moving objects when they themselves are also moving, it is therefore possible that performance suffers because of the capacity limitations in the egocentric subsystem (Rump & McNamara, 2007; Wang et al., 2006). The FINST model of multiple-object tracking may be consistent with the use of an egocentric representation. Although the FINST model makes no specific claims about the frame of reference of the pointers that maintain contact with target locations, the idea lends itself well to an egocentric representation; these mental 'fingers' point to objects as they change locations, allowing observers to quickly access information about where an object is with respect to their own position. However, the multifocal attention model of tracking could also be consistent with a shared egocentric representation because it likewise does not specify the frame of reference that attentional foci adopt. Attentional foci could also act on egocentric representations, again potentially taxing an already engaged egocentric subsystem during self-motion.

Another possible spatial representation shared between self-motion and multiple-object tracking may be an allocentric representation of space. In addition to transient egocentric representations, observers also form more enduring representations of their surroundings using allocentric or object-to-object reference frames (Rump & McNamara, 2007; Sholl, 2001). People also can use an allocentric reference frame to track targets. Evidence shows that tracking accuracy is not affected by global scene changes that preserve allocentric coordinates, but is reduced by distortions in scene coherence that disrupt allocentric coordinates (Liu et al., 2005). The multifocal attention model of multiple-object tracking could be consistent with an allocentric account of our findings if attention to objects was paid to an allocentric representation of space. This would enable people to also represent their own position in the same representation, attending to and updating the location of the self in the same way that targets are attended. This would essentially add an additional target to the tracking task, increasing load and subsequently decreasing tracking performance. Of course, FINSTs could also be applied to an allocentric representation. Future research will be necessary to determine upon which spatial representations interference occurs and which model best accounts for the shared resources of self-motion and object tracking.

In addition to demonstrating shared cognitive resources across self-motion and object tracking, this study demonstrates the unique and powerful contribution that virtual environments can have in research on spatial cognition. These experiments help to bridge the gap between cognitive experiments testing tracking of multiple objects moving on a computer screen and the natural environment in which people track objects while moving in space. Extending this work to test object tracking during driving would further inform applied research looking for cognitive factors influencing car crashes. In addition, the use of the virtual display allowed for the independent manipulation of viewpoint and location change we employed in Experiment 2. While these conditions represented unnatural situations, their comparison revealed the importance of location change in impairing object tracking. The unique opportunities presented in working with a virtual environment will doubtlessly continue to contribute to future explorations of the mechanisms of spatial cognition.

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