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Attentional costs in multiple-object tracking

Michael Tombu* and Adriane E. Seiffert

Department of Psychology, Vanderbilt University, 418A Wilson Hall, 111 21st Avenue South,
Nashville, TN 37203, USA

Abstract

Attentional demands of multiple-object tracking were demonstrated using a dual-task paradigm. Participants were asked to make speeded responses based on the pitch of a tone, while at the same time tracking four of eight identical dots. Tracking difficulty was manipulated either concurrent with or after the tone task. If increasing tracking difficulty increases attentional demands, its effect should be larger when it occurs concurrent with the tone. In Experiment 1, tracking difficulty was manipulated by having all dots briefly attract one another on some trials, causing a transient increase in dot proximity and speed. Results showed that increasing proximity and speed had a significantly larger effect when it occurred at the same time as the tone task. Experiments 2 and 3 showed that manipulating either proximity or speed independently was sufficient to produce this pattern of results. Experiment 4 manipulated object contrast, which affected tracking performance equally whether it occurred concurrent with or after the tone task. Overall, results support the view that the moment-to-moment tracking of multiple objects demands attention. Understanding what factors increase the attentional demands of tracking may help to explain why tracking is sometimes successful and at other times fails.

Keywords

Multiple-object tracking; Attention; Dual-task; Proximity; Speed; Motion

1. Introduction

Imagine a primitive hunting party on the savannah stalking four weak gazelle amongst a larger herd. While the hunters get into position they must track these targets, which can be an easy task if the herd is sparsely distributed and moving slowly, but may become more difficult as the herd becomes more dense and the animals move amongst each other at a faster rate. Tracking difficulty, as assessed by the multiple-object tracking paradigm in the laboratory, also appears to depend upon the proximity of targets to distractors (Pylyshyn, 2004) and the speed at which the objects are moving (Liu et al., 2005). Though tracking has been hypothesized to be attentionally demanding (Cavanagh & Alvarez, 2005; Scholl, 2001), it is unclear how and when attention is used in this task. The goal of this study was to examine whether or not attention is required during the moment-to-moment tracking of multiple objects and whether increases in proximity and speed exacerbate attentional demands.

1.1. The role of attention in multiple-object tracking

Several lines of research converge on the conclusion that the human brain is resource limited such that it is incapable of processing all incoming stimuli in parallel (Lennie, 2003; Tsotsos, 1990). To overcome this shortcoming, stimuli of importance are selected for additional

* Corresponding author. Tel.: +1 6157157069. E-mail address: mike.tombu@vanderbilt.edu (M. Tombu).

processing with attention. Attention is limited in capacity, as well as spatial (Gobell, Tseng, & Sperling, 2004; Intriligator & Cavanagh, 2001) and temporal resolution (Duncan, Ward, & Shapiro, 1994; Nakayama & Mackeben, 1989; Verstraten, Cavanagh, & Labianca, 2000). In accounting for people's ability to track four or five independent objects simultaneously, theories differ in the role ascribed to attention. The mere fact that there is a maximum number of objects that can be tracked suggests that tracking relies on some limited resource (Allen, McGeorge, Pearson, & Milne, 2006; Alvarez & Cavanagh, 2005; Alvarez, Horowitz, Arsenio, DiMase, & Wolfe, 2005; Pylyshyn 2004, 2006; Sears & Pylyshyn, 2000) and this may very well be attentional in nature. Some researchers make a distinction between visual (or input) attention and more general central attention (Johnston, McCann, & Remington, 1995). In the present paper, we are explicitly interested in central attention that is not specific to a particular input or output modality. Is the limited resource that defines multiple-object tracking due to central attention or is it not attentional in nature?

Pylyshyn and Storm (1988), who introduced the multiple-object tracking task, proposed that tracking is accomplished via a limited number of visual indexes that are preattentive. Visual indexes, or FINSTs ("FINgers of INSTantiation"), individuate objects with visual mechanisms and track the locations of objects without attention. These indexes act like addresses or pointers, similar to a demonstrative reference in language such as the words "this" or "that" (Pylyshyn, 2001). They give a reliable reference for the object; yet do not include the object's semantic category or its visual properties beyond location. To acquire additional information about an object, attention is allocated. Therefore, according to this theory, attention would be important for many of the cognitive components of a typical multiple-object tracking task, such as interpreting the cues used to initially define targets and accessing information about targets for the purpose of response (Sears & Pylyshyn, 2000). Attention would not, however, be required for the moment-to-moment tracking of objects. Having said that, observers may choose to attend to the objects that are visually indexed at any time during tracking, though attention is not necessary for targets to be tracked per se (Pylyshyn, 2001). In addition, distractor inhibition during multiple-object tracking may be attentional in nature (Pylyshyn, 2006). According to the visual indexing theory, target tracking is accomplished preattentively, but accessing information about targets and inhibiting distractors requires attention.

Alternative theories have proposed a more central role for attention in multiple object tracking (Cavanagh & Alvarez, 2005; Scholl, 2001; Yantis, 1992). The unitary attention-switching theory posits that something akin to an attentional spotlight must visit the corresponding position of each target to update its position information. Simulation results based on unitary attention-switching models fail to achieve the high levels of performance of which observers are capable (Pylyshyn & Storm, 1988); a result that is problematic for this theory. Also problematic are the recent findings by Alvarez and Cavanagh (2005) indicating that tracking capacity is not only limited by the total number of targets, but also by visual hemifield. One way to salvage the theory is to allow for multiple attentional foci. According to a multifocal attention account, attention is a resource that can be subdivided and spread across numerous loci in parallel (Cavanagh & Alvarez, 2005). Multiple foci eliminate the need for attention switching and ascribe a limit to the attentional resource as the basis for the limits in multiple-object tracking performance.

When is attention required during tracking and what exactly is it doing? Is it used for the initial acquisition of targets, to follow them as they move about, to select them for report at the end of the trial, or some combination of these functions? Is attention involved with targets at all or only used to inhibit distractors? Is attention necessarily allocated to the targets during object motion at all, continuously or only during critical times? In this paper, we focus on the role of attention during the moment-to-moment tracking of multiple objects and the parameters that modulate the demand for attentional resources.

1.2. Does moment-to-moment tracking demand attention?

Previous work has provided support for the notion that the moment-to-moment tracking of multiple objects requires attention. Allen and colleagues (2004, 2006) have shown that performance on a multiple-object tracking task suffers when performed concurrent with a secondary task that demands attention. In the first few experiments (Allen, McGeorge, Pearson, & Milne, 2004), the participant's secondary task was to verbally classify visually presented digits as being less than or greater than five. Allen and colleagues found that tracking performance was hindered by the secondary task relative to a single-task baseline. This result has been taken as evidence that tracking requires attention (Cavanagh & Alvarez, 2005).

As an alternative to an attentional account, it is conceivable that the dual-task interference observed by Allen et al. (2004) may have resulted from working memory and task-switching demands present in the dual-task condition, but absent from the single-task condition. In addition, given that both tasks were visual in nature, the observed interference may have resulted from competition at a sensory level (Meyer & Kieras, 1997; 1999). This line of argument is consistent with the visual indexing theory (Sears & Pylyshyn, 2000), which would ascribe the observed dual-task interference to a common reliance on capacity limited *preattentive* resources as opposed to attention.

Recently, Allen and colleagues (2006) performed an additional dual-task experiment that employed a range of secondary tasks to parcel out interference arising from different sources (including sensory sources). Of particular interest for our purpose is the condition in which tracking was paired with the auditory-verbal secondary task, because this task demands attention and does not overlap with tracking in terms of sensory modality. Results were mixed. While one measure indicated that more interference was observed when tracking was paired with the auditory-verbal task than either the articulatory suppression or the spatial tapping task, other measures did not. Based on these results it is difficult to determine whether moment-to-moment tracking demands attention.

Two other published studies have used dual-task procedures to make conclusions about attention during tracking. Alvarez and colleagues (2005) examined the involvement of attention by pairing a multiple-object tracking task with either a visual search or an auditory discrimination task. Dual-task costs, as measured relative to a single-task baseline, were approximately the same in both cases. They concluded that tracking and the auditory task rely upon common central attentional resources. While this is one interpretation, alternative accounts exist that do not require that tracking be attentionally demanding. Because dual-task interference was measured relative to a single-task baseline, the observed performance decrement in the dual-task condition may arise from either the need for a task switch or the additional working memory load associated with holding two task instructions concurrently. Additionally, participants were required to delay their auditory task response until after they made their tracking responses. If accessing targets during the tracking response phase is attentionally demanding (as proposed by Pylyshyn, 2004), the observed interference could result from holding the auditory response in memory while making the tracking responses. By this interpretation moment-to-moment tracking does not require attentional resources, but target recovery does. Fougner and Marois (2006) observed dual-task interference between a visual working memory task and a multiple-object tracking task and concluded that tracking and visual working memory rely upon common amodal central attentional resources. However, their design also allows for the alternative interpretation that the locus of interference was at the stage of target acquisition or recovery and not during moment-to-moment tracking.

In the present experiments, we endeavored to demonstrate that moment-to-moment tracking has attentional demands that can be measured with dual-task procedures. We manipulated tracking difficulty either concurrent with or isolated from an auditory secondary task. If these

tracking manipulations increase the attentional demands of tracking, their effects should be larger when manipulated concurrent with a secondary task than when manipulated in isolation. Because our design contrasts two dual-task conditions (tracking manipulated concurrent with, or isolated from a secondary task) and employs tasks that do not share a sensory modality, our results should demonstrate central attention demands of tracking.

1.3. What might increase the attentional demands of tracking?

If keeping track of multiple targets does require attention, it should be possible to manipulate the attentional demands of tracking by manipulating tracking difficulty. In the present study we have chosen to manipulate tracking difficulty by varying target proximity and speed. Target-distractor confusions are more likely to occur the more proximal distractors get to targets (Pylyshyn, 2004), a result that is reminiscent of crowding (Bouma, 1970; Pelli, Palomares, & Majaj, 2004; Strasburger, 2005). Crowding may result from a failure of attention to individuate targets from distractors (He, Cavanagh, & Intriligator, 1996; Strasburger, 2005; but see also Nandy & Tjan, 2007; Pelli et al., 2004). If the attentional demands of target individuation in crowding increase with increased target-distractor proximity, it may also be the case that tracking becomes more attentionally demanding when targets and distractors are closer together. We explore this hypothesis in Experiments 1 and 2.

The speed at which objects move can strongly influence the difficulty of tracking. Any sampling algorithm that attempts to predict the position of an object as it moves will have more error when the object moves quickly and changes direction often (Blake & Isard, 1998; Kurien 1990). Pylyshyn and Storm (1988) applied this principle to multiple-object tracking tasks by modeling a single serial tracker that had the characteristics of attention. As the speed of objects increase, the probability that the model will lose the targets also increases because targets move too far from the predicted location to be differentiated reliably from distractors. In practice, Liu et al. (2005) have shown that participants do indeed produce more errors in tracking when the speed of objects in a display is increased from 1°/s to 6°/s. Though sensitivity to speed is an attribute of serial mechanisms, it would also be an attribute of parallel mechanisms with limited spatial or temporal capacity. Regardless of the model, increasing the speed of objects should increase the difficulty of tracking. If tracking is accomplished with attentional resources, increasing the speed of the objects in the display should increase the attentional demands of tracking. We explore this hypothesis in Experiments 1 and 3.

1.4. The present experiments

To assess whether increasing speed and proximity increase the attentional demands of moment-to-moment tracking, a dual-task multiple-object tracking paradigm was employed. Participants were required to track four of eight identical dots as they moved about the screen (see Fig. 1). At some point during tracking, a secondary task was performed. We selected as a secondary task one requiring a speeded, pitch discrimination. This task was chosen so that it would interfere with tracking by consuming attentional resources without also interfering with tracking on a peripheral input or output level (Meyer & Kieras, 1997, 1999). Two tasks that both rely on visual input can interfere with one another because of visual processing interactions, but a visual and auditory task will only commonly require central resources. Likewise, if two tasks both require manual responses, interference can be observed at the level of the motor action that is unrelated to the attentional demands of the tasks (DeJong, 1993). Responses to the tracking task were not required until the end of the trial; well after tone responses were executed thereby avoiding response interference.

Similar tone discrimination tasks have been used extensively in previous investigations of the psychological refractory period (DeJong, 1993; McCann & Johnston, 1992; Pashler, 1994; Tombu & Jolicoeur, 2005). Typically, participants in these experiments are presented with a

tone followed in close temporal proximity by a visual stimulus, both of which require a speeded judgment. Reaction times to the visual task increase as the stimulus onset asynchrony (SOA) between the two stimuli decrease. Pashler (1994) suggested that the slower reaction times result from postponement caused by a central attentional bottleneck in information processing. Alternative accounts posit that when the two tasks demand attention concurrently, limited attentional resources must be shared between the two tasks (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Regardless of the theoretical perspective, this previous research has shown that the tone discrimination task is useful for assessing attentional demands of concurrent tasks.

We used the tone discrimination task to temporarily reduce the availability of attention in order to assess the attentional demands of multiple-object tracking. Tracking difficulty was manipulated by increasing proximity and speed. Difficulty increased transiently either concurrent with or after processing of the tone task. If increased tracking difficulty increases the attentional demands of the tracking task, more tracking failures should occur when the demand cannot be met. Therefore, a larger effect of tracking difficulty should be observed when the manipulation occurs concurrent with the tone task, than when the tracking manipulation occurs separate from the tone task. One of the strengths of this paradigm is that we are not left in a position comparing dual-task performance to single-task performance. In addition to dual-task interference, dual- and single-task conditions differ in terms of their need for a task switch and differences in working memory load. By comparing performance in two dual-task conditions that differ only in the degree of overlap between tone processing and a tracking difficulty manipulation, our results are not contaminated by possible differences in task demands between conditions.

2. Experiment 1: Proximity and speed

Attentional demands of tracking are most likely to be revealed by a manipulation that increases both speed and proximity concurrently. In the current experiment, this was accomplished by making all of the dots in the display briefly attract one another, such that all the dots sped towards one another for a few hundred milliseconds. If the attraction manipulation increases the attentional demands of tracking, its effect should be larger at the short SOA when the tone task is concurrent with the attraction, than at the long SOA where the tone task is finished before the attraction occurs.

2.1. Methods

2.1.1. Participants—Eleven undergraduates (five female, aged 18–20), reporting normal or corrected to normal vision and hearing participated in this experiment in exchange for partial fulfillment of course credit. In all the experiments reported herein, participants were tested in accordance with the Vanderbilt University Human Subjects Protection Policy and APA 2002 Code of Ethics. For Experiment 1, the data for two participants were excluded from analysis due to poor performance on the tone task, which was less than 80% overall.

2.1.2. Apparatus and stimuli—The experiment was performed on a Mac PowerPC G4 computer using OSX running Matlab 7 and the Psychophysics toolbox version 1.0.0.5 (Brainard, 1997; Pelli, 1997). The screen refresh rate was 89 Hz. Viewing distance was approximately 57 cm.

2.1.2.1. Visual displays: A central box, 15.7° by 16.4° height by width, outlined by a 0.12° wide white border was shown on a black screen. Inside the box in pseudo-random locations, eight red dots with a radius of 0.3° were displayed for 2 s. Then, four of the dots were cued as targets for 2 s by green rings (outer radius of 0.45°). The cues were removed and the dots remained stationary for another two seconds before all of the dots began to move. At this point, target and distractor dots were identical.

2.1.2.2. Dot motion: All dots moved about the box in a pseudo-random manner, constrained such that dots did not overlap one another and did not move out of the box. The initial direction of motion for each dot was randomly chosen from 0° to 360°, in 5° steps, with the constraint that no more than two dots began with the same direction of motion. Dot velocity was calculated on each subsequent frame depending on three factors. The first factor was used to keep dots within the box. When a dot was within 0.6° of an edge of the box, its direction of motion was set to be perpendicular to that edge plus a random variation of 0–20°. Likewise if a dot was within 1.05° of a corner, its direction of motion was set to the bisection of the 90° angle formed by the corner. For the second factor, a new direction of motion was calculated on each frame to produce the pseudo-random motion. For the dots that were not close to the edges of the box, the new direction of motion was the same as the previous direction of motion changed by a random angle that varied from –20° to +20° in 5° steps. To avoid dots overlapping one another, a third factor caused each dot to be slightly repelled by all other dots. Each dot moved away from all the other dots in a direction that was weighted by dot proximity. The initial speed of each dot was set to 0.11° per frame (9.8°/s), but as a result of this repulsion, small variations in speed were produced.

2.1.2.3. Attraction manipulation: On half of the trials, inter-dot repulsion was briefly replaced by inter-dot attraction. During this period that was a maximum of 1.124 s, instead of repulsing each other, the dots attracted one another, with a similar algorithm except that attraction was twice as strong as repulsion. When attraction occurred, it always began between 2.247 and 3.371 s from motion onset (Fig. 1). In addition, if two dots closed to a distance of less than 2.4° or began at a distance of less than 1.2°, attraction for this dot pair was replaced by repulsion. This attraction manipulation had two consequences: dot speeds increased and dots became more proximal. To assess the magnitude of the manipulation, a simulation was performed to calculate the average inter-dot distance and speed for each dot for each frame. There were 120 simulated trials performed to determine the average dot proximity and speed. Results are plotted in Fig. 2A and B. The attraction manipulation resulted in a transient increase in dot speed of about 60% and a transient decrease in inter-dot distance of about 45%.

2.1.2.4. Tones: The high, medium and low tones were pure tones presented at a frequency of 3520, 880 and 220 Hz, respectively. Duration of each tone was 80 ms.

2.1.3. Procedure—The experiment was divided into two parts: a short practice session followed immediately by the experimental session. In the practice session, only the tone discrimination task was performed, whereas in the experimental session both the tracking and tone tasks were performed concurrently.

2.1.3.1. Practice session: The practice session was intended to familiarize participants with two aspects of the tone task. Each tone was demonstrated three times for 80 ms each time. Participants then performed two blocks of 12 pitch discrimination trials. A high, medium or low tone was presented for 80 ms and participants responded by pressing the Z, X or C keys, respectively. Feedback was provided. In the second block of trials, participants were required to respond to the tone within 1 s. To indicate the end of the response window, a composite tone was sounded, that consisted of the high, medium and low tones played simultaneously. If participants failed to respond within the response window, the trial was scored as incorrect.

2.1.3.2. Experimental session: In the experimental session, participants were required to do the tracking task and the tone task concurrently. Participants tracked four target dots among four distractor dots for 6.742 s (600 frames). At some point during the tracking task, a tone sounded followed by the composite tone indicating the end of the response window. Attraction occurred on half of the trials. At the end of the trial, all dots stopped moving and the mouse

pointer appeared. Participants selected four dots by pointing with the mouse and pressing a key. This tracking response was unspeeded and feedback was provided for each choice. Participants were instructed to guess if unsure. Each participant performed six blocks of experimental trials. The first block of 12 trials was practice and was not analyzed. In subsequent blocks, each combination of tone frequency, SOA, and tracking difficulty was presented twice per block for a total of 24 trials per block.

2.1.3.3. Tone task and SOA manipulation: The tone task in the experimental session was the same as it was in the last block of practice. The stimulus-onset asynchrony (SOA) between the tone and the beginning of the attraction manipulation was either short or long on each trial. When the SOA was long, the tone was presented one second prior to the beginning of the attraction period. Because tone responses had to be made within one second of the onset of the tone, tone processing must have been completed before the initialization of the attraction manipulation. On short SOA trials, the tone was presented simultaneously with the beginning of the attraction period. On trials in which attraction did not occur, the tone was presented relative to when attraction would have begun had the attraction occurred.

2.2. Results and discussion

Analysis of variance (ANOVA) was performed on accuracy results for both the tone and the tracking task. SOA and attraction were included as within-subject variables. Tracking performance is plotted in Fig. 3. Tone results are presented in Table 1.

2.2.1. Tone accuracy—Attraction impaired tone performance to a larger degree at the short SOA, than at the long SOA, $F(1, 8) = 5.4$, $MSe = 0.0070$, $p < .05$. The main effects of attraction and SOA were both significant, $F(1, 8) = 10.6$, $MSe = 0.0059$, $p < .05$, $F(1, 8) = 6.5$, $MSe = 0.0052$, $p < .05$, respectively. Tone responses were more accurate when there was no attraction during the tracking task and when the SOA was long (Table 1).

The large effect of attraction observed in tone discrimination performance at the short SOA could have resulted from one of two sources of errors: an increase in tone misidentifications or an increase in the number of tone responses that occurred outside of the 1-s response window. To tease apart these two factors, we performed a second ANOVA in which tone responses made outside of the one-second response window were excluded. Results are shown on the rightmost columns of Table 1. Examining only tone identifications that were incorrect revealed no significant effects or interactions, although the main effect of attraction approached significance, $F(1, 8) = 4.1$, $MSe = 0.0780$, $p < .08$. Overall, the SOA by attraction interaction observed when examining both sources of tone errors appears to result from a disproportionately high number of responses made too slowly when the SOA was short and attraction occurred. This result is consistent with the notion that the attraction manipulation interfered with tone processing when they occurred at about the same time.

2.2.2. Tracking accuracy—In this and all other experiments reported here, only trials where the tone response was correct and made within the 1-s response window were included in the analysis of the tracking task. Of greatest interest for our purposes, the effect of attraction was larger at the short SOA than at the long SOA, $F(1, 8) = 11.5$, $MSe = 0.0007$, $p < .01$. When the tone task was completed before the attraction commenced, tracking accuracy was only impaired by 9.3% from the increase in proximity and speed of the dots. When the tone and attraction occurred simultaneously, tracking performance was impaired by 15.2%. This magnification of the effect of attraction is consistent with the notion that the attentional demands of tracking were increased when the tone task was performed during inter-dot attraction.

Other effects also follow predictions. The main effect of attraction showed that more errors were made when attraction occurred, $F(1, 8) = 70.0$, $MSe = 0.0019$, $p < .01$, confirming that our attraction manipulation did, in fact, increase the difficulty of tracking. The main effect of SOA was not significant, $F(1, 8) = 1.7$, $MSe = 0.0032$, $p > .22$. This null effect is somewhat different from that observed in more traditional dual-task experiments employing a SOA manipulation (e.g. Pashler, 1994). Traditional dual-task experiments predict worse performance at short SOAs because two tasks occur together, whereas at long SOAs the tasks do not overlap. However, in the current paradigm the tone task is performed at times relative to a tracking difficulty manipulation, but always concurrent with the tracking task. As a result, some interference is expected regardless of the SOA. On trials where no attraction occurs, long and short SOA trials are essentially identical (tone presentation occurs somewhat earlier on long SOA trials) and performance in these two conditions should be similar. Results support this prediction.

It might be possible that the observed interaction between SOA and attraction results from a need to make eye movements and not by a concurrent demand for attentional resources. The observed interaction could be accounted for if more eye movements are required during inter-dot attraction and tone processing interferes with the execution of eye movements. To rule out this possibility, a control experiment was performed which was identical to Experiment 1 except that subjects were required to maintain fixation at the center of the display during tracking. Eye position was monitored with an ASL video-based eye tracker. Only trials were analyzed in which no eye movements occurred (5.1% rejected). Results from this control experiment replicated those of Experiment 1 showing an interaction between SOA and attraction in tracking performance ($F(1, 9) = 6.5$, $p < .05$; 3.9% attraction effect at the long SOA, 9.2% effect at the short SOA). This result indicates that the observed interaction was not being driven by any confound of eye movements.

The results of Experiment 1 indicate that increases in proximity and dot speed, such as those that occurred during inter-dot attraction, increase the attentional demands of tracking. This finding is in line with the hypothesis that tracking requires attentional resources. The increase in the demand for attentional resources may have resulted from the increase in proximity, in dot speed, or both of these manipulations in combination. Experiments 2 and 3 aim to disentangle the attentional contributions of proximity and dot speed.

3. Experiment 2: Proximity alone

Experiment 1 demonstrated that causing the dots in the tracking display to attract one another increased the attentional demand of tracking. However, it is unclear whether increases in speed, proximity or their combination caused this increase in attentional demands. Although both proximity and speed were expected to make tracking more difficult, the two factors may not necessarily interact (Bex, Dakin, & Simmers, 2003). Experiment 2 examined the effect of proximity while holding speed constant.

3.1. Methods

Methods were the same as in Experiment 1 with the following exceptions.

3.1.1. Participants—Twenty-one new undergraduates (15 female 18–21 years of age) reporting normal or corrected to normal vision and hearing participated in this experiment in exchange for partial fulfillment of course credit. The data for two participants were excluded due to poor performance on the tone task that was less than 80% correct overall. The data for one participant was excluded because performance was at ceiling in the tracking task at 96% correct or greater in all conditions.

3.1.2. Procedure—Attraction and repulsion were calculated as in Experiment 1, except that to determine dot position, a fourth factor was included that kept each dot's speed at 8°/s. To do so, on each frame each dot was always displaced 0.09°. As in Experiment 1, simulations were performed to calculate the mean proximity over the time course of the tracking period. Results are displayed in Fig. 4. As can be seen, transient proximity decreases during the attraction period were approximately 40%.

3.2. Results and discussion

Accuracy results for both tasks were subjected to ANOVA with SOA and attraction as within-subjects variables. Tracking performance as a function of SOA and attraction is plotted in Fig. 5. Tone results are presented in Table 1.

3.2.1. Tone accuracy—Only the main effect of SOA approached significance, $F(1, 17) = 2.9$, $MSe = 0.0018$, $p < .11$. Participants responded to the tone marginally more accurately when the SOA was short (89.9%) than when the SOA was long (88.2%). Neither the main effect of attraction, nor the interaction between SOA and attraction approached significance ($F_s < 1$). A separate ANOVA was again conducted excluding tone responses that were made outside of the one-second response window. Only the interaction between SOA and attraction approached significance, $F(1, 17) = 2.7$, $MSe = 0.0016$, $p < .13$. At the short SOA, participants made marginally more tone response misidentifications when the dots in the display attracted one another (6.3% vs. 3.7% error). At the long SOA, tone performance was roughly equal regardless of whether or not the dots in the display attracted one another (5% errors for both). This result is consistent with the notion that tone processing and the attraction manipulation increased attentional demand when they occurred at about the same time.

3.2.2. Tracking accuracy—Results from Experiment 1 were replicated. An interaction between SOA and inter-dot attraction was found, such that the effect of attraction was larger at the short SOA than at the long SOA, $F(1, 17) = 4.5$, $MSe = 0.0010$, $p < .05$. When the tone task was completed before the attraction commenced, tracking accuracy was only impaired by 1.8% by the increase in proximity. When the tone and attraction occurred simultaneously, tracking performance was impaired by 5.1%. This interaction indicates that increasing dot proximity increases the attentional demands of tracking. As in Experiment 1, the main effect of attraction showed that participants made more tracking errors when attraction occurred, $F(1, 17) = 15.7$, $MSe = 0.0014$, $p < .01$. This confirms that increasing the proximity of the dots in the display increases the difficulty of the tracking task. Also as in Experiment 1, the main effect of SOA was not significant ($F < 1$). The results of Experiment 2 show that the effect of manipulating proximity is larger when implemented concurrent with the tone. This result suggests that decreases in proximity modulate the attentional demands of tracking.

4. Experiment 3: Speed alone

The purpose of Experiment 3 was to examine whether increasing the speed of the dots in the tracking display increases the attentional demands of tracking, independent of increasing proximity. Experiment 3 is similar to Experiment 2 except that dots did not briefly attract one another, but instead, the dots briefly sped up on half of the trials. In addition, pilot data suggested that the increase in speed attracted attention to the multiple-object tracking task. As a result, difficulty effects were being observed primarily on the tone task. To avoid this, in the present experiment additional stress was placed upon the tone task and the change in speed was made gradual to avoid sudden onsets in acceleration. We predicted that tracking would be more attentionally demanding when the dots increased speed relative to when their speed remained constant.

4.1. Methods

Methods were the same as in Experiment 2 with the following exceptions.

4.1.1. Participants—Seventeen new undergraduates (six female, 18–21 years of age), reporting normal or corrected to normal vision and hearing participated in this experiment in exchange for partial fulfillment of course credit. The data for one participant were excluded due to poor performance on the multiple-object tracking task, which was at chance performance. The data for five participants were excluded due to poor tone task performance, which was less than 80%, correct overall.

4.1.2. Procedure—Instead of implementing an attraction manipulation as in Experiment 2, on half of the trials the speed of all dots in the display changed from a base rate of 6.7°/s towards a maximum speed of 20°/s. The speed manipulation increased dot speeds gradually at a rate of 47.5°/s². The duration of the speed up period was approximately 506 ms. The short SOA in this experiment was shifted by roughly 50 ms in order to ensure that tone processing began before the speed manipulation began. The short SOA was 56 ms, whereas the long SOA remained 1000 ms. To emphasize the tone task, performance feedback was provided at the end of the tracking period prior to participants' multiple-object tracking responses. Feedback was provided by changing the color of the display background to green for correct and red for incorrect.

4.2. Results and discussion

Accuracy results for both tasks were subjected to ANOVA with SOA and speed as within-subjects variables. Tracking performance as a function of SOA and speed is plotted in Fig. 6. Tone results are presented in Table 1.

4.2.1. Tone accuracy—Neither the main effects of SOA, speed, nor their interaction approached significance ($F_s < 1.9$). As in Experiments 1 and 2, a secondary analysis excluding trials in which tone responses were made too slowly was performed. Neither effect nor their interaction approached significance ($F_s < 1$).

4.2.2. Tracking accuracy—Results from Experiment 1 were replicated. An interaction between SOA and inter-dot attraction was found, such that the effect of speed was significantly larger at the short SOA than it was at the long SOA, $F(1, 10) = 6.9$, $MSe = 0.0011$, $p < .05$. When the tone task was completed before the speed manipulation (the long SOA), tracking accuracy was only impaired by 5.6% by the increase in speed. When the tone and speed change occurred simultaneously (the short SOA), tracking performance was impaired by 10.9%. This result is consistent with the notion that increasing the speed of the dots in the display increases the attentional demands of tracking. The main effect of speed showed that participants were better able to track when the speed of the dots in the display remained constant (78% correct) compared to when they sped up (70%), $F(1, 10) = 57.5$, $MSe = 0.0013$, $p < .01$, confirming that our manipulation had the desired effect. The main effect of SOA was not significant ($F = 2.8$, $p > .12$). The results of Experiment 3 show that the effect of manipulating speed is larger when implemented concurrent with the tone. This result suggests that, like proximity, changes in speed also modulate the attentional demands of tracking.

5. Experiment 4: Contrast

In Experiments 1–3, we manipulated tracking difficulty by varying proximity, speed or their combination. For each experiment, an interaction with SOA was observed, suggesting an increase in the attentional demands of tracking caused by the manipulation. To rule out the possibility that all tracking difficulty manipulations increase the attentional demands of

tracking, we set out to find a manipulation that increased tracking difficulty without increasing its attentional demands. Results from the psychological refractory period paradigm indicate that decreasing the contrast of a visual display impairs task performance without increasing the attentional demands of the task (DeJong, 1993; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2005). This manipulation is believed to affect early perceptual stages that can be carried out prior to processing requiring central attentional resources (DeJong, 1993). Experiment 4 was similar to Experiment 1, except that the contrast of the tracking display was briefly increased or decreased. If this contrast manipulation does not increase the attentional demands of tracking, the effect of contrast should be the same at both short and long SOAs. The lack of interaction between contrast and SOA would also rule out the possibility that the interactions observed in the first three experiments resulted from some methodological artifact of the paradigm we employed, such as the requirement that participants respond to the tone while tracking was underway.

5.1. Methods

Methods were the same as in Experiment 1 with following exceptions.

5.1.1. Participants—Twenty-four new undergraduates (16 female, 18–21 years of age), reporting normal or corrected to normal vision and hearing participated in this experiment in exchange for partial fulfillment of course credit. The data for six participants were excluded due to poor performance on the pitch discrimination task, which was less than 80% correct overall.

5.1.2. Procedure—Dots were presented in light gray (43.5 cd/m²) on a dark gray background (26 cd/m²). The contrast of the display was manipulated by increasing (49.0 cd/m²) or decreasing (28.2 cd/m²) the luminance of all of the dots for one second. As in Experiment 3, at the short SOA the tracking manipulation was delayed so that it occurred after tone presentation. The short and long SOAs were approximately 135 and 1135 ms, respectively.

5.2. Results and discussion

Accuracy results for both tasks were subjected to ANOVA with SOA and contrast as within-subjects variables. Tracking performance as a function of SOA and contrast is plotted in Fig. 7. Tone results are presented in Table 1.

5.2.1. Tone accuracy—The only effect on tone accuracy that approached significance was the interaction between contrast and SOA, $F(1, 17) = 3.1$, $MSe = 0.0031$, $p > .09$.

Participants were marginally poorer at the tone task when the SOA was short and the dots became dimmer (89% correct) than in any other condition (average 92%). Neither the main effect of SOA nor contrast approached significance ($F_s < 1$). As in previous experiments, a secondary analysis was performed excluding trials in which tone responses were made too slowly. Neither effect nor their interaction approached significance in this secondary analysis ($F_s < 1$).

5.2.2. Tracking accuracy—The interaction between contrast and SOA did not pass the statistical test ($F(1, 17) = 0.17$, $p > .68$). When the tone task was completed before the contrast manipulation, tracking accuracy was impaired by 2.4%. When the tone and contrast change occurred simultaneously, tracking performance was impaired by 3.3%. Changing the contrast of the dots did, however, reliably affect tracking performance, $F(1, 17) = 8.9$, $MSe = 0.0016$, $p < .01$. Participants were more accurate when the dots got brighter (79% correct) than when they got dimmer (76% correct). It is worth noting that the effect of contrast in Experiment 4 (2.4% at the long SOA) is slightly larger than the effect of attraction in Experiment 2 (1.8% at

the long SOA). In Experiment 2, a significant interaction between SOA and attraction was detected with 18 participants. Experiment 4 employed the same number of participants as in Experiment 2. Had contrast and SOA interacted in Experiment 4, we should have been able to detect this interaction. However, the statistic for the interaction did not approach statistical significance ($F(1, 17) = 0.17, p > .68$). Therefore, we conclude that contrast does not interact SOA. Briefly reducing the contrast of the dots in the tracking display impaired tracking performance equally regardless of whether the manipulation coincided with tone processing. The results of Experiment 4 demonstrate that it is possible to increase the difficulty of moment-to-moment tracking without increasing the attentional demands of tracking.

6. General discussion

In the first three experiments, we demonstrated manipulations that increased the attentional demands of multiple-object tracking, thus providing support for the view that moment-to-moment tracking requires attention. In Experiment 1, we showed that an attraction manipulation, that increased both the speed and the proximity of dots, had a larger effect when executed concurrent with an attentionally demanding auditory task than when it was executed in isolation. Experiments 2 and 3 showed that both proximity and speed manipulations were sufficient on their own to produce this pattern of task interference. In Experiment 4, we showed that stimulus contrast increased tracking difficulty in a manner independent of whether the manipulation was executed concurrent with or in isolation from the auditory task. These results suggest that the attentional demands of multiple-object tracking were transiently increased by increases in speed and proximity, but not contrast. Moreover, the type of attentional resources that these manipulations rely upon must be general enough to also be required by a task based in a different sensory modality. These results show that attention plays a central role in our ability to track multiple objects. In addition, they show that proximity and the speed of the items in the display exacerbate these attentional demands.

6.1. Using dual-task techniques to assess multiple-object tracking

Dual-task experiments have been used extensively to determine the locus of specific mental processes (Carrier & Pashler, 1995; Johnston et al., 1995; McCann & Johnston, 1992; Oriet, Tombu, & Jolicoeur, 2005; Pashler & Johnston, 1989; Richards, Tombu, Stolz, & Jolicoeur, 2004; Tombu & Jolicoeur, 2002). This technique takes advantage of the limits in the human ability to process information in parallel. Theories of dual-task interference generally posit that interference arises from a central, attentional stage of processing that is limited in capacity. Stages of processing before and after this central stage can be carried out in parallel, but central processing for more than one task must either proceed serially (Pashler, 1994) or in parallel, but share a limited pool of processing resources (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). The present results show that multiple-object tracking is also subject to this capacity limitation.

The current work goes beyond previous work by specifically demonstrating that the moment-to-moment tracking of multiple objects demands attention. In addition, the current results show that proximity and the speed of the dots mediate the attentional demand. More attentional resources must be deployed to objects that are more proximal to other objects or are moving more quickly. In traditional crowding experiments, individuation is believed to require attention when distractors crowd objects (He et al., 1996; Strasburger, 2005; but see also Nandy & Tjan, 2007; Pelli et al., 2004). This may also be the case in the present experiments. Target losses are also more likely as the speed of the objects increases (our Experiment 3; Liu et al., 2005). Our results show that increases in speed also increase the attentional demands, which suggest that attention may be important for keeping an up to date representation of target locations.

6.2. Implications for theories of attentional deployment in dual-tasks

That tracking requires central attention may also be able to tell us something about central attention. There is currently a debate within the dual-task interference literature as to the nature of dual-task interference (Navon & Miller, 2002; Ruthruff, Pashler, & Hazeltine, 2003; Tombu & Jolicoeur, 2003, 2005). According to some accounts (Pashler, 1994), information processing is subject to a central capacity limitation in the form of a serial processing bottleneck. While central operations for one task are being carried out, central operations for a second task must be put on hold. According to resource models (Navon & Miller, 2002; Tombu & Jolicoeur, 2003), information processing can be carried out in parallel, but is subject to a central capacity limitation in the form of a limited pool of attentional resources. When two tasks demand central attentional resources simultaneously, this pool of resources must be shared between them. Simulation results by Pylyshyn and Storm (1988) ruled out a tracking mechanism that operated by serially updating targets in turn in favor of a mechanism that operates at multiple locations in parallel. Our findings indicate that the mechanism responsible for our ability to track multiple objects relies upon central attention. In combination, these conclusions imply that attention can be subdivided and operate at multiple foci in parallel. While it still may be possible to explain these results with a more sophisticated mechanism of serial attention, it is clear that these results are consistent with distributed capacity-sharing models of central attention (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Further experimentation using the multiple-object tracking paradigm, and other tasks that require attention to multiple locations, may prove useful in the ongoing debate regarding the nature of capacity limits in information processing.

One of the traditional problems with using a dual-task approach to investigate the attentional demands of a continuous task is that continuous tasks may not rely upon attention continuously. If attention is only required by the continuous task intermittently, it is possible that the attentional demands of the secondary task can be interleaved into these lulls in attentional demands. Alvarez and colleagues (2005) used an argument akin to this to explain why tracking and visual search did not interfere with one another to the same degree as two tracking tasks. This is one reason why short, punctate tasks are generally employed in dual-task experiments investigating attentional demand. The use of brief tasks ensures that attentional processing of the two tasks overlap at short SOAs, and not at long SOAs.

In the present experiments, we were interested in the attentional demands of a continuous operation, namely multiple-object tracking, but we used a brief manipulation of difficulty to assess task load. The procedure time-locked the insertion of the tone task to a brief, discrete manipulation of the tracking task and used a response window to ensure that tone processing was completed within the desired time frame. This allowed us to be confident that any change in attentional demands caused by the manipulation would be occurring while tone processing was under way. Our observation that the effects of proximity, speed and their combination were larger when the SOA was short, suggests two conclusions. First, these manipulations increased the attentional demands of tracking. Second, tracking itself demands attention. Though it remains possible that tracking only requires attention when it is made more difficult, this interpretation seems unlikely given that we manipulated components of the tracking display that commonly vary. Using this procedure, we successfully provided evidence strongly supporting the idea that attention is important for efficient performance in the moment-to-moment tracking of multiple objects.

6.3. Implications for theories of multiple-object tracking

How do existing models of multiple-object tracking fair at accounting for these findings? Theories that have proposed that tracking is accomplished via preattentive visual indexes (Pylyshyn, 2001; Pylyshyn & Storm, 1988) are not supported by our results. Passive registration of location that updates effortlessly during tracking would not require attentional

resources common to a pitch discrimination task. Similarly, any theory that ascribes a role for attention only at the stages of target acquisition and/or response would also not be supported by the current results. Theories that account for tracking ability must include a role for a central resource in the moment-to-moment analysis of visual information for the purpose of tracking.

Multifocal attention models can easily accommodate the present findings. The requirement that each target be attended continuously for tracking to occur, necessitates a decline in performance when attention to the visual display is reduced due to a concurrent tone task. Even a multifocal attention model that posits intermittent attention to targets would be consistent with the current results. Interestingly, the observation that proximity and speed specifically increase attentional demands suggests that attention may be deployed more frequently or longer when target localization is exacerbated in space or time. This suggests some degree of intelligence to the mechanism responsible for tracking. The more that there is a threat of loss, the more frequently or the longer attention will be applied. This interesting hypothesis deserves additional examination that goes beyond the scope of the present study.

Demand on central attentional resources is not sufficient to account for previous results testing multiple-object tracking with dual-tasks. The mutual exclusivity of two multiple-object tracking tasks, but partial independence of multiple-object tracking and other attention-demanding tasks (Alvarez et al., 2005; Fougner & Marois, 2006) suggests that a second source of interference must also exist. This second source of interference may stem from a number of different possible sources. One intriguing possibility is a process that inhibits distractors. The updated visual index model proposed that attention is necessary during tracking specifically for the inhibition of distractors (Pylyshyn, 2006). The model could accommodate the current results if it were assumed that attentional demands of this inhibitory process would also increase transiently with increasing dot speed and proximity. One could easily imagine that increases in proximity and speed make target-distractor confusions more likely, thus increasing the demand for distractor inhibition. The idea that inhibition plays a role in attentional processing is in line with other views of attention that posit inhibitory surrounds around the locus of attention (Desimone & Duncan, 1995; Tsotsos et al., 1995). It is important to note that the idea of distractor inhibition is not inconsistent with the multi-focal attention model and has been suggested to account for recent observations (Alvarez & Cavanagh, 2006). Perhaps the best model will incorporate components of both approaches, with attentional resources used in distractor inhibition and updating of target location, but preattentive visual indexes for maintaining a representation of important locations.

7. Conclusions

The results of the present experiments firmly establish that attention is involved in the moment-to-moment tracking of objects. More specifically, they establish that tracking involves central attentional resources common to a tone discrimination task and that speed and proximity modulate the demand for these resources. While there appear to be sources in addition to central attention that play a role in tracking, attentional limits may play a central role in our limited ability to track multiple objects. Understanding what factors increase the attentional demands of tracking may help to explain why tracking is sometimes successful and at other times fails. This knowledge will lead to the development of better human-machine interface design as well as help explain the mental processes involved in more complex activities, such as when hunters on the savannah pursue their dinner.

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Fig. 1.

Depiction of visual displays used in Experiment 1. At the beginning of each trial, 8 static red dots appeared on the screen. Four dots were cued with green rings to indicate them as targets. Cues disappeared and all the dots started to move, initiating the tracking period of 6.7 s. At some point during tracking between 2.247 and 3.371 s from motion onset, the attraction manipulation was applied for 1 s that resulted in dots speeding up and moving closer together. After the attraction period, dots moved normally until the end of the trial. Static dots were displayed until participants selected four dots with the computer mouse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2.

Mean dot proximity (A) and speed (B) as a function of time and attraction condition for 120 simulated trials from Experiment 1. For both proximity and speed, the effects of the attraction manipulation have subsided approximately 1 second following their implementation.

Fig. 3.

Results of Experiment 1. Multiple-object tracking performance as a function of SOA and inter-dot attraction. Open symbols represent performance for trials where attraction did not occur; closed symbols represent performance for trials where attraction did occur. The effect of attraction was significantly larger when the SOA was short than when it was long.

Fig. 4.

Mean dot proximity as a function of time and attraction condition for 120 simulated trials from Experiment 2. The effects of attraction have largely subsided after approximately 1 s from its onset. The amplitude of the effect on proximity is slightly smaller in Experiment 2 than in Experiment 1.

Fig. 5. Results of Experiment 2. Multiple-object tracking performance as a function of SOA and attraction. Open symbols represent performance for trials where attraction did not occur; closed symbols represent performance for trials where attraction did occur. The effect of attraction was significantly larger when the SOA was short than when it was long.

Fig. 6. Results of Experiment 3. Multiple-object tracking as a function of SOA and speed. Open symbols represent performance for trials where the speed of display items remained constant; closed symbols represent performance for trials where display items briefly sped up. The effect of speed was significantly larger when the SOA was short than when it was long.

Fig. 7. Results of Experiment 4. Multiple-object tracking performance as a function of SOA and contrast. Open symbols represent performance for trials where the display items briefly got brighter; closed symbols represent performance for trials where the display items briefly got dimmer. The effect of contrast was not significantly larger when the SOA was short than when it was long.

Table 1

Tone performance in percentage correct

	Tracking Manipulation	All sources of errors		Excluding slow responses	
		SOA		SOA	
		Short	Long	Short	Long
Experiment 1	Attraction	80.0	92.6	93.3	97.2
Experiment 2	No attraction	94.8	94.4	98.0	97.7
	Attraction	89.5	88.6	93.7	95.3
Experiment 3	No attraction	90.3	87.8	96.3	94.8
	Faster	89.7	89.1	96.7	95.4
Experiment 4	No speed change	92.7	88.5	96.5	96.4
	Dimmer contrast	89.4	92.8	96.8	96.3
	Brighter contrast	92.4	91.1	97.3	96.1