Not FLEXible enough: Exploring the temporal dynamics of attentional reallocations with the multiple object tracking paradigm

Meyerhoff, H. S., Papenmeier, F., Jahn, G., & Huff, M. (in press). Not FLEXible enough: Exploring the temporal dynamics of attentional reallocations with the multiple object tracking paradigm. *Journal of Experimental Psychology: Human Perception and Performance.* doi:10.1037/xhp0000187

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Running Head : Dynamic reallocation of attention
Keywords : Multiple object tracking, varying speed, interobject spacing, flexible allocation of attention, FLEX, spatial interference

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Word count : 7548

Abstract

The dynamic environment of human observers requires continuous reallocations of visual attention in order to compensate for location changes of the attended objects. Particularly, situations with reduced spatial distance between targets and other objects in the display are crucial for keeping track of the target objects. In the present experiments, we explored how the temporal dynamics of such moments of reduced spacing affects the reallocation of visual attention. We asked participants to track four targets among indistinguishable distractors. Hereby, we manipulated whether target and distractor objects moved at a constant speed or whether their actual speed followed a sine wave profile. The variable speed oscillated around the constant speed thus maintaining average speed as well as travelled distance and average spatial proximity. We observed inferior tracking performance with variable speed profiles relative to constant speed profiles (Experiments 1a and 1b). When we increased the number of pairs of targets and distractors moving with a variable speed profile (Experiment 2), performance declined continuously. Remarkably, tracking performance also declined when only distractors moved at variable speeds, suggesting that the dynamic changes in inter-object spacing rather than the variable speed impairs tracking (Experiment 3). In sum, our results provide evidence for a flexible allocation of the attentional resource toward targets suffering spatial interference by demonstrating the temporal constraints of the reallocation process.

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Attending and navigating within the natural environment frequently requires keeping track of the current locations of several objects. For instance, there is evidence that tracking other vehicles during driving increases the probability of detecting safety-related events (Lochner & Tick, 2014). In laboratory experiments, the ability to track the locations of a set of objects can be studied with the multiple object tracking paradigm (Pylyshyn & Storm, 1988). In this paradigm, participants are asked to identify a subset of targets among indistinguishable distractors after several seconds of object motion. Previous research has identified the number of close interactions among the moving objects to be the major limiting factor during tracking (Franconeri, Jonathan, & Scimeca, 2010). In the present study, we manipulate whether the objects move at a constant speed or at a variable speed that on average matches the constant speed. While this manipulation maintains the average spatial proximity between the moving objects, it alters the temporal dynamics of events of spatial proximity. We show that these changes in the temporal dynamics of spatial interference impair tracking performance.

Dynamic changes due to self- and object-motion frequently occur during natural perception. Adequately compensating for these dynamic changes is a crucial ability for maintaining a meaningful representation of the outside environment. To achieve this, visual attention cannot only be allocated to spatial locations, but also to visual objects (see Chen, 2012, for a recent review). Evidence for the allocation of attention toward objects results from experiments showing that visual attention spreads faster within an object than between objects (Duncan, 1984; Egly, Driver, & Rafal, 1994; Hollingworth, Maxcey-Richard, & Vecera, 2012; see also Scholl, Pylyshyn, & Feldman, 2001). Importantly, excitatory as well as inhibitory attentional processes remain attached to objects (e.g., Kahneman, Treisman, &

Gibbs, 1992; Tipper, Driver, and Weaver, 1991) or their frame of reference (Gibson & Egeth, 1994; Meyerhoff, Huff, Papenmeier, Jahn, & Schwan, 2011) when they move over time.

In contrast to most paradigms from research on visual attention, dynamic changes are an inherent property of the multiple object tracking paradigm. Therefore, this paradigm has fruitfully contributed to exploring the dynamics of visual attention. Indeed, there is convincing evidence that multiple object tracking draws upon attentional processes. First, individual differences are highly correlated between the multiple object tracking task and other tasks that typically explore visual attention such as visual search and inattentional blindness (Huang, Mo, & Li, 2012). Second, the detrimental influence of reduced inter-object spacing on tracking performance is more pronounced with an attention-demanding auditory dual task, but unaffected by a perceptual manipulation of the contrast (Tombu & Seiffert, 2008). This suggests that at least moments of increased tracking difficulty draw upon the same attentional resource as the attention-demanding auditory task. Third, results from neuroimaging studies (Doran & Hoffman, 2010; Drew, Horowitz, Wolfe, & Vogel, 2012; Störmer, Winther, Li, & Andersen, 2013) also indicate the involvement of attentional processes in tracking. To be more specific, tracking mainly affects spatiotemporal aspects of visual attention. Although feature information can be assessed during tracking (e.g., Horowitz et al., 2007; Oksama & Hyönä, 2008), it is typically irrelevant for object tracking (Pylyshyn, 2004; see also Makovski & Jiang, 2009) unless spatiotemporal information decreases in reliability (Bae & Flombaum, 2012; Papenmeier, Meyerhoff, Jahn, & Huff, 2014).

Several further theoretical approaches have been made in order to explain the role of visual attention in multiple object tracking. First, Cavanagh and Alvarez (2005) suggested that multifocal attention covers several independent objects simultaneously (see also Müller, Malinowski, Gruber, & Hillyard, 2003). An alternative framework was provided by Alvarez and Franconeri (2007). In their study, Alvarez and Franconeri observed that the speed rather than the number of objects limited tracking performance. When the moving objects were slow, their participants were able to track up to eight objects. Furthermore, decreasing inter-object spacing was more harmful for tracking performance at high object speeds than at slow object speeds (see also Chen, Howe, & Holcombe, 2013). From these results, Alvarez and Franconeri proposed the FLEX model according to which a limited attentional resource (see also Franconeri, Alvarez, & Cavanagh, 2013) is allocated flexibly toward objects being tracked. The allocation of the flexible resource is supposed to increase the local attentional resolution thus fostering tracking performance.

Further evidence in favor of the FLEX account was provided by a study by Iordanescu, Grabowecky, and Suzuki (2009) who observed that the accuracy of participants in reporting the location of targets increased with a decreasing distance to the nearest distractor. Because target-distractor relations continuously changed across the trials, these results demonstrate that the allocation of attention toward the individual target objects dynamically changes during tracking. Based on the momentary demands, more of the attentional resource is allocated toward objects close to distractors because the increase in spatial resolution by the allocation of attention reduces the probability of confusing target and distractor. It is currently unclear whether the shifts in visual attention that accompany the reallocation of the attentional resource during tracking draw upon the same resource as tracking itself. Although selecting and deselecting objects during an ongoing tracking task hardly affects tracking performance (Ericsen & Christensen, 2012; Wolfe, Place, & Horowitz, 2007), allocating the attentional resource toward multiple objects does not only reduce the local spatial resolution but also the local temporal resolution (see Holcombe & Chen, 2013).

An alternative to a flexible allocation of visual attention during tracking was provided by Franconeri, Jonathan, and Scimeca (2010) who suggested that the spatial interference from close objects is the only limiting factor of multiple object tracking performance. Franconeri et al. argued that all targets being tracked receive attentional enhancement that is accompanied by an inhibitory surround (see Hopf et al., 2006; Müller, Mollenhauer, Rösler, &

Kleinschmidt, 2005). Within this framework, tracking performance declines when distractor objects break through the inhibitory surrounds of targets. In line with this suggestion, Franconeri et al. (2010) demonstrated that the number of spatial intersections rather than the absolute duration of the tracking interval determines tracking accuracy. An important argument in favor of this spatial interference account is that other factors that have been observed to impair tracking performance, such as an increasing number of targets (e.g., Alvarez & Franconeri, 2007; Pylyshyn & Storm, 1988) and distractors (e.g., Bettencourt & Somers, 2009), or increased object speed (e.g., Alvarez & Franconeri, 2007) also increase the number of intersections between target and distractor objects (see also Franconeri, Lin, Pylyshyn, Fischer, & Enns, 2008). Because the inhibitory surround of one target also might interfere with the enhancement of another target, this approach explains further why spatial proximity between targets decreases tracking performance (Shim, Alvarez, & Jiang, 2008). Indeed, the spatial interference account provides a parsimonious explanation for tracking performance without additional assumptions such as the continuous reallocation of visual attention.

Responding to the work of Franconeri et al. (2010), several researchers have challenged the view that interobject spacing indeed is the only limiting factor of multiple object tracking as suggested by the spatial interference account. For instance, Tombu and Seiffert (2011) asked participants to track objects that rotated around each other on orbital paths. Despite constant interobject spacing across the trials, Tombu and Seiffert observed that increasing object speed decreased tracking performance. Further, Holcombe and Chen (2012) demonstrated that a fast-moving single object is capable of exhausting the attentional tracking resource. Also, tracking additional objects at large interobject distances impairs tracking performance although there should be no spatial interference (Holcombe, Chen, & Howe, 2014).

Beyond these models of tracking performance, recent computational models have conceptualized tracking errors as a result of probabilistic processes and their summations across trials (Zhong, Ma, Wilson, Liu, & Flombaum, 2014, see also Vul, Frank, Tenenbaum, & Alvarez, 2009). A core element of these models is that the mental representation of the locations of objects is noisy and does not match their actual locations perfectly. According to these models, tracking errors arise when the noisy representation of the target locations is ambiguous with respect to the actual locations of targets and distractors on the display. With an increasing amount of ambiguity, the probability of confusing distinct objects increases as well. For instance, reduced spacing between a target and a distractor is a typical situation for such an increasing amount of ambiguity. In line with the prediction of the models mentioned above, an increasing number of close interactions among the objects decreases tracking performance due to a summation of independent confusion probabilities (see also Bae & Flombaum, 2012, for matching behavioral data).

As outlined above, most models on multiple object tracking agree that reduced spacing between the moving objects increases the likelihood of tracking errors, but they differ in their explanation for such effects of spatial interference. Further, the models differ in whether they allow an influence of object speed that is independent of modulations of interobject spacing. A central challenge in previous research was to manipulate object speed without also varying other factors such as the distance travelled and subsequently inter-object spacing. Our critical manipulation is whether target and distractor objects move at a constant speed or continuously change their speed following a sine wave profile. This manipulation alters the dynamics of events of spatial interference. Importantly, however, the average speed of each object with a varying speed profile is identical to the speed of the objects with a constant speed profile. This ensures that travelled distance as well as average spatial proximity also does not vary between objects with differing speed profiles (see General Method section for details). Due to the matched spatial proximity, resolving an effect of variable speed profiles on tracking performance would require some further specifications of the spatial interference account, such as a space-based zone of inhibition that needs to be updated based on the actual task demands (see Tombu and Seiffert, 2011). Effects of the variability of object speed, however, can be explained within the FLEX framework. Because FLEX proposes continuous reallocations of the attentional resource due to changes in spatial proximity, we argue that more dynamically changing inter-object spacing should impair tracking performance. The reason for this is because some objects temporarily require a faster reallocation of the attentional resource than in the control condition, whereas slower reallocations would be temporarily sufficient for other objects. These dynamics would increase the probability of an inappropriate allocation of the attentional resource and subsequently the probability of tracking errors.

To anticipate our results, Experiments 1a and 1b show that varying speed profiles impair tracking performance. This decline in performance increases with the number of objects with a varying speed profile (Experiment 2). This is even true when only the number of distractors that move with a varying speed profile is manipulated, but all targets move at a constant speed (Experiment 3). Taken together, these results show that object tracking performance is vulnerable to dynamic changes in the object speed even when potentially confounding aspects of inter-object spacing are controlled for.

General Method

All stimuli were presented on a 15.4’’ HP EliteBook 8530p with an ATI Mobility Radeon HD3650 video card at an unrestricted viewing distance of approximately 60 cm under laboratory conditions. The experiments were programmed in Python using the PsychoPy libraries (Pierce, 2007).

Stimuli were eight identical white discs (1.3 deg in diameter; ~176 cd/m^2) moving inside a gray (~32 cd/m^2) square frame (20 x 20 deg) that appeared against a black (~0.2

cd/m^2) background. Each trial began with the presentation of the empty frame. After 500 ms the discs were positioned inside the frame. Four of them were designated as targets by flashing on and off in red (~7 cd/m^2) four times in 200 ms intervals and subsequently remained red for 400 ms before they turned back to white. Thereafter, all objects started to move for eight seconds (see Figure 1a). The speed of the individual objects was either constant at 8 deg/s or oscillated between 2 and 14 deg/s in a sine wave pattern with an average of 8 deg/s[1].

Each object completed exactly four cycles through this speed profile (i.e., 2 s per cycle; see Figure 1b). Therefore, the average speed and travelled distance were identical for

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[1] A prerequisite for this manipulation is that 8 deg/s reflects the middle between 2 deg/s and 14 deg/s in terms of tracking difficulty. Indeed, if tracking performance declines faster with object speeds above 8 deg/s than tracking performance increases with object speeds below 8 deg/s, any decrease in performance in conditions with variable speed could be attributed to such a skewed distribution of tracking difficulties. To rule out this possibility, we ran an additional experiment with 20 participants in which all objects moved at a constant speed varying from 2 deg/s to 14 deg/s in steps of 2 deg/s (please see Figure S1 in the electronic supplementary materials for detailed results). We then tested pairs of conditions with an average speed of 8 deg/s against the control condition with a constant speed of 8 deg/s. None of these pairs of conditions (2 and 14 deg/s: *M* = 3.07, *SD* = 0.16; 4 and 12 deg/s: *M* = 3.04, *SD* = 0.22; 6 and 10 deg/s: *M* = 3.02, *SD* = 0.24) differed from the condition with 8 deg/s (*M* = 2.99, *SD* = 0.29), *F*(3, 57) = 1.68, *p* = .182. If anything, performance was numerically better in the combined conditions with an average speed of 8 deg/s than in the constant speed condition with 8 deg/s. We therefore conclude that within the range of our speed values, 8 deg/s reflects an appropriate control condition for our conditions with variable speed profiles.

all objects in the display. In order to provide full details, we further analyzed and compared the trials of the constant speed and the variable speed conditions of Experiments 1a and 1b. The full details of these analyses are available in Table 1. In the first step of this analysis, we averaged different spacing parameters across all 481 frames of individual trials (note that we created a new set of trials for each participant). Most importantly, a series of Welch *t*-tests (to correct for unequal variances) confirmed that neither the average spacing across all objects, nor the average spacing between targets and distractors, nor the distance for each target to the closest distractor, or the closest other target in the display differed between the conditions. In a second step, we defined an inter-object distance of less than three object diameters (3.9 deg; center-to-center) to reflect spatial interference (see also Bae & Flombaum, 2012) and repeated the analysis reported above for such events. Again, neither the average number of close objects to each target (other targets as well as distractors) nor the average number of close distractors to each target varied between the conditions with constant and variable object speed. The same analysis also confirmed that the number of actual overlaps between the discs (i.e., a center-to-center distance of less than 1.3 deg) did not differ between the conditions. In the third and final step of the analysis of our stimuli, we analyzed the dynamics of the spatial interference events within the trials. Therefore, we focused on the individual events of spatial interference. For the purpose of this analysis, an individual event of spatial interference began when the distance between a distractor and a target decreased below three object diameters. The event then lasted until the distance rose above the same threshold. In line with the analyses above, the sum of the duration of the individual events of interference were nearly identical across the experimental conditions. However, due to the speed manipulation, the objects in the condition with variable speed crossed this border more frequently than those in the condition with constant speed. In reverse, however, the events in the variable speed condition were slightly shorter than the events in the constant speed condition. Most remarkably, a Levene’s Test for homogeneity of variances confirmed that the variability of the duration of events in the condition with the constant speed profiles was significantly smaller than in the condition with the variable speed profiles even when we analyzed the logarithmic durations in order to compensate for the skewed distributions of the durations.

Please note that the increase in the frequency of the events of spatial interference results from the fixed definition of the threshold of spatial interference because accelerating and decelerating objects might cross this fixed border multiple times within an interval that one intuitively would classify as a single event of spatial interference. What is most important is that on average, inter-object spacing as well as the overall duration of events of interference were identical between our conditions. In Experiment 1b, all objects had the same sine-wave pattern and thus accelerated simultaneously. In contrast to Experiment 1a, the number of moments of interference as well as their duration did not differ between the conditions with constant speed and variable speed even with a fixed definition of the border of an interference event. Importantly, the Levene-Test again confirmed that the variability of the (logarithmic) durations of the interference events was less pronounced with constant speed profiles than with variable speed profiles (please, see Table 1 for means and statistics). Further analyses of the full distributions of inter-object distances are reported within the electronic supplementary materials.

In sum, the analysis of our stimuli shows that the average spacing between the objects does not differ across the experimental conditions. Remarkably, however, the dynamics of the events of interference are modulated by the variable speed profiles. In Experiment 1a, the variable speed profiles induced more events of interference than constant speed profiles. On average, however, these events were shorter so that the sum of their duration was identical between the conditions. This came along with an increased variability of the duration of events of interference in the condition with variable speed profiles. In contrast, Experiment 1b controlled for the increasing number of events of interference. In this experiment, the only difference was in the variability of the durations of the events of spatial interference.

The exact combinations of objects with a constant speed and objects with a variable speed profile varied between the experiments and are described in the corresponding method sections. When an object hit the frame, its movement was reflected; however, objects streamed through each other in case of a collision event. At the end of the tracking period, all objects stopped moving and the mouse pointer appeared onscreen. Participants were instructed to mark all of the targets that they were able to track and to guess the remaining ones. After each trial, the participants received feedback regarding their accuracy. Each participant completed nine blocks of experimental trials. The first block was considered as practice and excluded from the analysis. In Experiments 1a and 1b, each block consisted of 16 trials allocated equally to two experimental conditions. In Experiments 2 and 3, each block consisted of 20 trials allocated equally to five experimental conditions. In these two experiments, we reduced the number of trials per condition in order to keep the duration of the experiments within one hour. Importantly, analyzing subsets of the data of Experiments 1a and 1b confirmed that this reduction did not affect the observed effect.

Experiments 1a and 1b

In Experiments 1a and 1b, we explored whether multiple object tracking performance is sensitive to varying speed profiles. In both experiments, all objects therefore either moved at a constant speed or with a varying speed profile. Importantly, the average speed of each object (across the trial) was identical thus equalizing the travelled distance as well as the average inter-object spacing. Therefore, if tracking errors stem only from average spatial proximity, varying speed profiles should have no influence on tracking performance. In contrast, if the temporal dynamics of the object motion overexert the reallocation of visual attention toward targets that approach distractor objects, tracking performance should decline with varying speed profiles.

In Experiment 1a, each object in the condition with varying speed profiles received an individual speed profile. Importantly, the average speed of all targets was identical at any time and matched the speed of the condition with constant speed. Despite the variable speed profiles, the average inter-object spacing was identical between the experimental conditions. The only differences between the conditions were within the dynamics of the events of interference. Due to accelerations and decelerations, the variability of the duration of the events of interference was larger in trials with variable object speeds than with constant object speed. There were more but shorter (i.e., the same sum) events of interference in the condition with variable speed profiles than in the condition with constant speed profiles. In Experiment 1b, we controlled for the number and average duration of the events of interference. In this experiment, all objects shared the same speed profile (i.e., they accelerate and decelerate simultaneously) in the condition with varying speed profiles. Therefore, the variability of the duration of the events of interference was the only difference between the experimental conditions in Experiment 1b. We will refer to this as differences in the dynamics of the events of interference. Furthermore, the initial speed of all objects was identical in this experiment in order to exclude the possibility that reduced performance with a variable speed profile results from an increased probability of losing objects with an especially fast initial speed (see Ma & Flombaum, 2013).

Methods

Participants

Twenty students of the University of Tübingen (17 females, 18-29 years) participated in Experiment 1a. A new sample of 20 students (14 females, 19-31 years) participated in Experiment 1b.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were as described in the General Method section with the following specifications. In Experiment 1a, each object received an individual speed profile. These speed profiles were arranged so that at any time, the average speed of the four target objects were identical to the speed in the condition with a constant speed profile (i.e., an accelerating target was compensated by a simultaneously decelerating target). For instance, if one target received the third speed profile from Figure 1, one of the other targets received the seventh speed profile. This ensured that on any frame the average speed of all targets was identical to the condition with constant speed profiles. Thus, no effect can be attributed to temporal peaks in the average target speed. In Experiment 1b, all targets and distractors received the same speed profile not only in the constant speed condition but also in the varying speed condition (i.e., simultaneous accelerations and decelerations) in order to exclude any influences from the number of differing speed profiles. Further, all objects started with a speed of 8 deg/s, identical to the condition with constant speed profiles.

Results

In both experiments, tracking accuracy was lower for objects with a variable speed profile than for objects with a constant speed profile (see Figure 2). For both experiments, we conducted a *t*-test for paired samples with the number of correctly identified objects as dependent variable and speed profile (constant vs. variable) as independent variables. The difference in tracking performance was significant for Experiment 1a, $M_{diff} = 0.165$, $SD = 0.105$, $t(19) = 7.03$, $p < .001$, $d = 1.57$, as well as for Experiment 1b, $M_{diff} = 0.152$, $SD = 0.126$, $t(19) = 5.39$, $p < .001$, $d = 1.21$. Although the numerical differences in the performance values were not large, this effect occurred highly reliably across participants as indicated by the huge effect sizes. In both experiments, 18 out of 20 participants showed impaired tracking performance with varying speed profiles relative to constant speed profiles. Because average inter-object spacing was identical between the experimental conditions, results of this experiment contradict the idea that spatial interference alone determines object tracking performance. Instead, the overall result pattern shows that the temporal dynamics of the events of interference (i.e., the variability in their duration) impaired multiple object tracking performance. This indicates that the process that compensate for decreasing inter-object spacing such as the reallocation of visual attention is sensitive to variations in the temporal profiles of events of interference.

Experiment 2

In Experiments 1a and 1b, we observed that tracking performance declined when all objects moved with a variable rather than a constant speed profile although spatial proximity was equated between the conditions (see General Method). This finding is consistent with the idea that a flexible reallocation of the attentional resource is sensitive to the temporal dynamics of our manipulation of the speed profiles. In Experiment 2, we aimed to provide further evidence for this interpretation by exploring the decline in tracking performance with a more fine-grained manipulation of the number of targets moving with a variable speed profile. Whereas either all or no objects moved with variable speed in Experiments 1a and 1b, zero, one, two, three, or four pairs of targets and distractors moved according to a variable speed profile in Experiment 2. In this experiment, temporal constraints of the reallocation process would predict declining tracking performance with an increasing number of targets that move with a variable speed profile.

Methods

Participants

Twenty new students (15 females, 19-32 years) participated in Experiment 2.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were as described in the General Method section with the following specifications. We varied the number of targets with a variable speed profile from zero to four. For each target that moved according to a variable speed profile, a matched distractor moved according to the same speed profile in order to prevent targets from being identified by their speed profile. All remaining targets and distractors moved at a constant speed that matched the average of the variable speed profiles.

Results

We analyzed tracking performance with linear mixed effect-models (lme; Baayen, 2008; Pinheiro, Bates, DebRoy, Sarkar, & R Development Core Team, 2011). This approach aims to explain results from a continuous independent variable with as few parameters (e.g., intercept, slope, etc.) as possible. Obviously, models that include more parameters always explain a set of results better than models with fewer parameters. Therefore, the model with the fewest parameters that does not explain the data worse than any model with more parameters provides the most suitable model to explain the data. In our case, a factorized model that includes one parameter per condition reflects the model with the most parameters, whereas a model with an intercept only reflects the model with the fewest parameters. In order to test whether tracking performance declines with an increasing number of pairs of targets and distractors that move with a variable speed profile, we tested whether a model that includes a slope (i.e., the decline) explains the data better than a model with an intercept only (i.e., no difference between the conditions) but not worse than the model with one parameter per condition (this would be equal to an ANOVA which ignores the order of the experimental conditions). All models treated the intercepts of individual participants as random effects.

The lme analysis confirmed that tracking performance declined with an increasing number of pairs of targets and distractors that moved with a variable speed profile (see Figure 3). The model with an intercept only, *df* = 3; AIC = 7.32 explained the data significantly worse than the model including an intercept and a slope, *df* = 4; AIC = -27.98, $\chi^2 = 37.30$, $p < .001$. Importantly, this model with intercept and slope did not explain the data worse than the model with one parameter per condition, *df* = 7; AIC = -22.3, $\chi^2 = 0.33$, $p = .954$. Therefore, the results of this experiment are consistent with our interpretation of the results of Experiments 1a and 1b. Increasing the temporal dynamics while maintaining the number of spatial interferences impairs tracking performance. As the results of the previous experiments have shown, this indicates temporal constraints in compensation for decreasing inter-object spacing.

Experiment 3

The results of Experiments 1a, 1b, and 2 show that tracking performance is lower when targets move at a variable speed than when they move at a constant speed even when the travelled distance and the average spatial interference are controlled for. However, it is not yet clear whether the temporal dynamics in spatial interference or the varying speed profiles themselves induce the impairment in tracking performance. In this experiment, we aimed to explore the influence of temporal dynamics in spatial interference independently of the speed profiles of the target objects. Therefore, all targets moved at a constant speed, but we varied the number of distractors that moved with a variable speed profile. If the decline in tracking performance in the previous experiments stems from the variable target speed itself, tracking performance should not be sensitive to the manipulation of the distractor speed in this experiment. In contrast, if the temporal dynamics of the events of interference (i.e., their variable durations), tracking performance should also decline when only distractors move at a variable speed.

Methods

Participants

Twenty new students (16 females, 19-28 years) participated in Experiment 3.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were as described in the General Method section with the following specifications. All targets moved at a constant speed. Depending on the experimental condition, zero, one, two, three, or four distractors moved with a variable speed profile. The instructions for this experiment mentioned that some objects may move at a variable speed, but we did not mention that variable speed profiles were unique for distractor objects.

Results

As in the previous experiment, we used lme analysis to assess our data. This analysis confirmed that tracking performance declined with an increasing number of distractors that moved with a variable speed profile (see Figure 4). The model with an intercept only, $df = 3$; AIC = -25.81, explained the data significantly worse than the model including an intercept and a slope, $df = 4$; AIC = -44.12, $\chi^2 = 12.49$, $p < .001$. Importantly, this model with intercept and slope did not explain the data worse than the model with one parameter per condition, $df = 7$; AIC = -41.44, $\chi^2 = 3.32$, $p = .344$. This result pattern shows that dynamics of changes in spatial interference affect tracking performance independently of the manipulation of target speeds. This result is even more remarkable when one considers that our manipulation allows for a strategic use of the speed profiles. With the exception of the condition in which all objects moved at a constant speed, objects with a variable speed could be rejected as potential targets. In principle, this would allow a (re-)identification of targets above chance level and should subsequently increase tracking performance. Nevertheless, these conditions exhibited declining tracking performance.

General Discussion

In our experiments, we explored how varying target and distractor speeds affects multiple object tracking performance. Importantly, we controlled for any influence from spatial interference in our experiments. The only difference between the experimental conditions was the presence of accelerations and decelerations as well as the higher variability of the durations of the events of interference in the condition with variable speed profiles. Nevertheless, variable speed profiles substantially impaired tracking performance, suggesting that the mechanism that compensates for spatial interference during tracking is sensitive to such a manipulation of the temporal dynamics of the events of interference. In line with this interpretation, tracking performance declined incrementally with an increasing number of pairs of targets and distractors that moved at varying speed (Experiment 2). The remarkable finding that variable speed profiles also affected tracking performance when only distractors obeyed variations in speed (Experiment 3) further emphasizes the role of the dynamics of spatial interference.

Across researchers, there is remarkable agreement that moments with increased spatial interference due to decreased inter-object spacing provide the major source for tracking errors (e.g., Alvarez & Franconeri, 2007; Bae & Flomblaum, 2012; Franconeri et al., 2010; Tombu and Seiffert, 2008). However, different explanations have been proposed for such effects of spatial interference. On the one hand, Franconeri et al. (2010) suggested that approaching distractors might break through the inhibitory surround of a target thus interfering with tracking. Within this assumption, tracking performance should decline with an increasing number of such interference events. On the other hand, the FLEX model (Alvarez and Franconeri, 2007) suggests that targets facing decreasing inter-object spacing require more attentional resources than targets without nearby other objects. Since the inter-object distances continuously vary across the duration of a tracking trial, the attentional resource also needs to be continuously reallocated. Within this framework, effects of spatial interference stem either from an insufficiently fast reallocation of the attentional resource or from a momentary depletion of the total amount of the attentional resource. Our observation that the tracking performance depends on the temporal dynamics rather than on the overall duration of interference events adds to the existing theories of object tracking by illustrating the temporal constraints of the mechanisms that allow for compensating for periods of reduced inter-object spacing.

With regard to the spatial interference account proposed by Franconeri et al. (2010), our results show that the dynamics rather than the distance travelled in close proximity determines tracking performance. According to this account, a zone of inhibition surrounds all individual targets. In order to facilitate the following argument, we consider this edge of the zone of inhibition as a fixed border rather than a continuous transition from no inhibition to full inhibition (but see Müller et al., 2005). Due to accelerations and decelerations, such a fixed border is crossed more often with variable speed profiles than with constant speed profiles (see also Bae & Flombaum, 2012); however, the total time spent inside the inhibition zone is identical between the two conditions because the increase in frequency comes along with shorter stays inside the inhibition zone (see the General Method section for details and statistics). Note, however, that Experiment 1b controls for the possibility that the detrimental effect of variable speed profiles exclusively stems from an increase in the number of events of interference independent of their overall duration. In this experiment, all objects accelerated and decelerated together thus keeping the number of interference events as well as their overall duration constant. A plausible interpretation for our pattern of results is that decreasing spacing between a target and another object triggers additional processes such as the allocation of attentional resources in order to avoid the confusion of targets. Because we did not control for eye-movements in our experiments, it is also possible that close encounters in our experiment attracted eye-movements. Typically, participants fixate on the center of the mass of all objects being tracked (Fehd & Seiffert, 2008); however, when target-distractor spacing becomes too small, so-called rescue saccades toward the location of the close pair of objects help to avoid confusing them (Zelinski & Todor, 2010). Such rescue saccades might be more reliable in the condition with constant object speed. Here, future research needs to disentangle attentional and oculomotor components of the detrimental effect of variable speed profiles. Independent of the exact mechanism, our results demonstrate that the process that compensates for decreasing inter-object spacing is vulnerable to the more dynamic and more variable changes in object spacing as induced by the variable speed profiles in our experiments.

A similar interpretation also holds true for the account suggesting that noisy mental representations of target locations cause tracking errors due to a summation of independent confusion probabilities (Vul et al., 2009; Zhong et al., 2014). Here, the key variable that modulates the effect of events of spatial interference is the noisiness of the mental representation of the object locations. Indeed, introducing variable speed profiles might increase this noisiness and in turn increase the probability of confusing targets and distractors when they are close to each other. Because these confusion probabilities cumulate across the duration of a trial, tracking performance consequently decreases. Such a probabilistic summation also nicely fits with the data of Experiment 2, which has revealed a decline in tracking performance with an increasing amount of objects moving with a variable speed profile. Again, what is important here is that it is the dynamic (in terms of the variability in duration) of the events of spatial interference that increases the probability of confusion because the other attributes of spatial interference such as average spacing, total duration of the interference events, as well as the exact number of events (Experiment 1b) are controlled for in our study.

With respect to the FLEX account of multiple object tracking, our study demonstrates limitations and costs of the flexible reallocation of attentional resources within the multiple object tracking paradigm. Whereas such limitations have been demonstrated in other experimental paradigms such as task switching (e.g., Monsell, 2003), a direct demonstration of the costs of attentional reallocation in tracking is still lacking. This is because most previous studies that have reported evidence in favor of FLEX were designed to disconfirm assumptions of alternative theoretical approaches. For instance, Alvarez and Franconeri (2007) showed that - in the case of slowly moving objects - the number of tracked objects exceeded the capacity limitations proposed by fixed-architecture models. In these terms, the FLEX model was underspecified thus allowing for an explanation of any results that violate the predictions of other models. Therefore, our study strengthens the FLEX account by finally demonstrating some of its limitations (see also Chen et al., 2013). Interestingly, although reallocations of the attentional resource seem to induce costs in tracking accuracy, adding to or subtracting objects from the set of tracked objects seems not to decrease tracking performance (Wolfe et al., 2007; see also Ericson & Christensen, 2012).

Several theoretical aspects are relevant when considering whether the spatial interference account or the FLEX account describe tracking performance more appropriately. On the one hand, the FLEX account includes a mechanism for the reallocation of attentional resources toward approaching objects, which would make tracking more vulnerable to dynamic changes in such events of interference. The major disadvantage of the FLEX account, however, is that it is not sufficiently specified to allow for concrete and testable predictions (see also Scimeca & Franconeri, 2015, for alternatives). Because we did not control for eye-movements in the present study, it also remains possible that parts of the lack of temporal flexibility of the attentional resource stem from a limited flexibility of eye-movements (see Franconeri, 2013; but see Luu & Howe, in press). On the other hand, the spatial interference account is a parsimonious theory that is capable of explaining a wide variety of findings in multiple object tracking. However, the idea of an inhibitory surround seems to suggest that everything that gets into this zone is inhibited irrespective of its dynamics. Previous research has identified the distance that distractors travel in proximity to targets as the key factor that determines tracking performance (Franconeri et al., 2010). Because average speed, average spacing, as well as the number of frames that distractors are at any specific distance to a target are constant in our experiments (see General Method), the travelled distance is constant, too. An interesting way to resolve the detrimental effect of our dynamic speed profiles within the spatial interference account comes from a study by Tombu and Seiffert (2011). Similar to our data, these authors observed that object speed and spatial proximity draw upon the same attentional resource. In order to explain their findings, Tombu and Seiffert suggested that the enhancement of target locations and the accompanying inhibitory surrounds arise in a space-based manner. Therefore, faster targets tend to leave the enhanced zone earlier than slower targets, thus increasing the probability of tracking errors. At the same time, reduced target-distractor spacing increases the probability that a distractor enters the enhanced zone, which also interferes with object tracking. Because target enhancement is an attentionally demanding process (Tombu and Seiffert, 2008) that needs to be updated continuously throughout a trial, both speed as well as spatial proximity impair tracking performance. Note that the same logic and conclusions hold true for our findings. Here, accelerating objects would also leave the enhanced zone earlier than would be expected based on their previous speed.

In agreement with previous research on object tracking performance, our results emphasize the role of events of spatial interference. With regard to a compensatory allocation of the attentional resource toward objects that are close to other objects, it is an intriguing question whether the reallocation process is reactive (i.e., reallocates resources based on the actual demands) or predictive (i.e., anticipates upcoming events of spatial interference). In contrast to a reactive allocation an anticipatory allocation of attention would require predicting upcoming events of spatial proximity from the motion paths of multiple objects. Here, a possible direction for future research is to explore whether the detrimental effect of variable speed profiles stems from accelerations and/or decelerations during epochs of spatial interference. Within a reactive system, tracking performance should decline with accelerations because this would require a faster reallocation, whereas tracking performance would benefit from decelerations because there is more time for the reallocation process. Within a predictive system, both accelerations as well as decelerations should impair tracking performance because the changes in object speed increase the difficulty of accurate predictions. With respect to such predictions in general, however, the empirical evidence is somewhat conflicting.

On the one hand, there is some support for the assumption that motion information is encoded in order to predict prospective object locations. For instance, when St.Clair, Huff, and Seiffert (2010) added texture information to the moving objects, they observed that texture motion that conflicted with the actual motion direction impaired tracking performance. These tracking errors occurred selectively on objects that actually revealed conflicting motion information (Meyerhoff, Papenmeier & Huff, 2013). However, because additional motion cues from texture motion only affect tracking with conflicting motion information but not with converging motion information, it remains possible that the texture effect results from the integration of conflicting motion information rather than from misdirected predictions (see Huff & Papenmeier, 2013). On the other hand, there is evidence that observers do not extrapolate the motion paths of multiple objects through brief intervals of occlusion (Franconeri, Pylyshyn & Scholl, 2012; Keane & Pylyshyn, 2006). If at all, such extrapolations seem to be limited to approximately two individual objects (Fencsik, Klieger & Horowitz, 2007).

The finding that predictions hardly affect tracking performance is also supported by a recent computational modeling approach (Zhong et al., 2014). In this study, the authors showed that even when participants would anticipate prospective object locations, the effect of these predictions would hardy influence the final measurement of tracking accuracy. Overall, it therefore seems unlikely that the dynamic reallocation of visual attention in displays such as ours (i.e., four targets and four distractors) rests on anticipatory processes. This suggestion is also consistent with the observation that the representation of an object's position lags behind its actual location (Howard & Holcombe, 2008; see also Howard, Masom, & Holcombe, 2011).

Our finding that varying distractor speed alone is sufficient to impair tracking performance leads to further questions regarding the representation of distractors during tracking. With respect to the question of distractor inhibition during tracking or part of the representation of the tracking trial, the empirical evidence is complex. On the one hand, there is evidence that distractor objects are inhibited during tracking. For instance, when participants perform a secondary probe detection task during tracking, probe detection performance on distractors is less reliable than on targets or the empty background (Pylyshyn, 2006; Pylyshyn, Haladjian, King, & Reilly, 2008; see also Doran & Hoffman, 2010; Huff, Papenmeier & Zacks, 2012). The idea of distractor inhibition during tracking is also consistent with the finding that an increasing number of distractors impairs tracking performance even when display density is compensated for by a simultaneous extension of the tracking area (Bettencourt & Somers, 2009). On the other hand, however, there are some findings that highlight the limitations of distractor inhibition. For instance, Alvarez and Oliva (2008) observed that the average location of all distractors is represented above chance level during tracking. Further, displacing distractors during tracking while controlling for spatial interference as well as for attentional capture impairs tracking performance (Meyerhoff, Papenmeier, Jahn, & Huff, 2015). Finally, in a multiple object tracking variant of the contextual cueing paradigm (see Chun & Jiang, 1998), Ogawa, Watanabe, and Yagi (2009) observed that repeating target and distractor paths across the experimental trials increased performance above the level of a pure repetition of target paths. These results suggest that the spatial configuration of targets and distractors is encoded in order to enhance the allocation of visual attention toward target objects. In line with the latter findings, our results indicate that distractor locations need to be represented at least to an extent that allows for the detection of approaching events in order to increase the amount of the attentional resource on the corresponding target (Iordanescu et al., 2009).

Conclusion

Our study shows that detrimental effects of increasing object speed on tracking performance cannot solely be attributed to an increase in the travelled distance, which in return increases average crowding. Across four experiments, we observed that dynamically changing object speeds decrease tracking performance even when average spacing, the total duration of events of spatial interference, as well as the number of close encounters are controlled for (see General Method, Experiment 1a and 1b). Our results therefore show that object speed can affect visual tracking beyond the detrimental effect of decreasing inter-object spacing during tracking.

Acknowledgement

We thank Sandra Hermann, Alexandra Zürn, Lotte Roessler, and Philipp Schröder for their help in conducting the experiments. This research was supported by German Research Foundation (DFG) Grants HU 1510/4-3 and JA 1761/5-3

Author Contributions

All authors developed the study concept and contributed to the study design. HSM programmed the experiments. Data collection was performed by student assistants under the supervision of HSM. Data analysis were performed by HSM. HSM drafted the manuscript and all authors provided critical revisions. All authors approved the final version of the manuscript for submission.

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Tables and Figures

Table 1. Detailed analysis of the experimental manipulation (constant vs. variable speed profiles) on different aspects of inter-object spacing. The reported statistics either refer to Welch *t*-Tests or to Levene-Tests of equality of variances. Please see main text for further explanations.

Figure 1. Illustration of the experimental stimuli and procedure. A: Participants tracked a subset of four previously designated targets across an interval of object motion. Afterwards, they identified the tracked objects and received feedback regarding their accuracy. B: Illustration of the experimental manipulation. The objects either moved at a constant speed of 8 deg/s (solid line) or their speed oscillated from 2 to 14 deg/s in a sine wave pattern. Depending on the experiment, there were up to eight distinct speed profiles within the same trial.

Figure 2. Tracking performance declined when all objects moved at a variable speed. A: Results of Experiment 1a. With variable speed profiles, each object received an individual speed profile. B: Results of Experiment 1b. With variable speed profiles, all objects received the same speed profile. All error bars indicate within-subject confidence intervals (Baguley, 2012).

Figure 3. Results of Experiment 2. Tracking performance declined with the number of targets that moved at a variable speed. For each target with a variable speed profile, there was a matched distractor. The dashed line reflects intercept and slope of the fitted model. Error bars indicate within-subject confidence intervals (Baguley, 2012).

Figure 4. Results of Experiment 3. Tracking performance declined with the number of distractors that moved at a variable speed. All target objects moved at a constant speed. The dashed line reflects intercept and slope of the fitted model. Error bars indicate within-subject confidence intervals (Baguley, 2012).

Table 1. Detailed analysis of the experimental manipulation (constant vs. variable speed profiles) on different aspects of inter-object spacing. The reported statistics either refer to Welch *t*-Tests or to Levene-Tests of equality of variances. Please see main text for further explanations.

		Experimental Condition		
	Level of Aggregation	Constant Speed	Variable Speed	Stats
Experiment 1a (distinct speed profiles)				
Mean Spacing	per target per frame	9.76 deg	9.75 deg	*t*(2877.92)=0.52, *p*= 606
Mean T-D-Spacing	per target per frame	9.75 deg	9.76 deg	*t*(2877.21) = 0.12, *p*=.904
Mean T distance to closest D	per target per frame	5.23 deg	5.23 deg	*t*(2875.50)=0.25, *p*=.803
Mean T distance to next T	per target per frame	6.06 deg	6.02 deg	*t*(2874.56)=1.36, =.174
Objects closer than 3 diameter	per target per frame	0.56 objects	0.56 objects	*t*(2858.76)=1.30, *p*=.192
Distractors closer than 3 diameter	per target per frame	0.32 objects	0.32 objects	*t*(2846.14)=1.04, p=.299
Objects closer than 1 diameter	per target per frame	0.07 objects	0.07 objects	*t*(2776.73)=1.55, *p*=.121
Distractors closer than 1 diameter	per target per frame	0.04 objects	0.04 objects	*t*(2748.73)=0.50, *p*=.619
Sum of event duration	per trial*	724.51 frames	727.49 frames	*t*(2851.94)=0.51, *p*=.609
Number of events	per trial	18.01 events	16.27 events	*t*(2877.65)=15.65, *p*<.001
Mean duration of events	per event of interference	44.54 frames	40.40 frames	*t*(43475.44)=10.95, *p*<.001
Variability of event durations (log)	per event of interference	0.63 log(frames)	0.65 log(frames)	*F*(1, 49350)=125.09, *p*<.001
Experiment 1b (same speed profile)				
Mean T-D-Spacing	per target per frame	9.74 deg	9.75 deg	*t*(2877.87)=0.33, *p*= .742
Mean T distance to closest D	per target per frame	9.73deg	9.76 deg	*t*(2877.682)=1.40, *p*=.161
Mean T distance to next T	per target per frame	6.00 deg	6.00 deg	*t*(2875.92)=1.44, *p*=.151
Objects closer than 3 diameter	per target per frame	0.56 objects	0.57 objects	*t*(2876.23)=0.52, *p*=.604
Distractors closer than 3 diameter	per target per frame	0.32 objects	0.32 objects	*t*(2876.49)=1.11, *p*=.265
Objects closer than 1 diameter	per target per frame	0.07 objects	0.07 objects	*t*(2876.66)=0.36, *p*=.717
Distractors closer than 1 diameter	per target per frame	0.04 objects	0.04 objects	*t*(2847.85)=0.46, *p*=.643
Sum of event duration	per trial*	731.60 frames	725.64 frames	*t*(2876.05)=0.99, *p*= 322
Number of events	per trial	16.37 events	16.17 events	*t*(2877.62)=1.77, *p*=.076
Mean duration of events	per event of interference	44.70 frames	44.87 frames	*t*(46719.49)=0.39, *p*=.701
Variability of event durations (log)	per event of interference	0.63 log(frames)	0.80 log(frames)	*F*(1, 46851)=851.42, *p*<.001

Notes: deg = degree of visual angle; T = Target; D = Distractor; *n events in parallel count n times

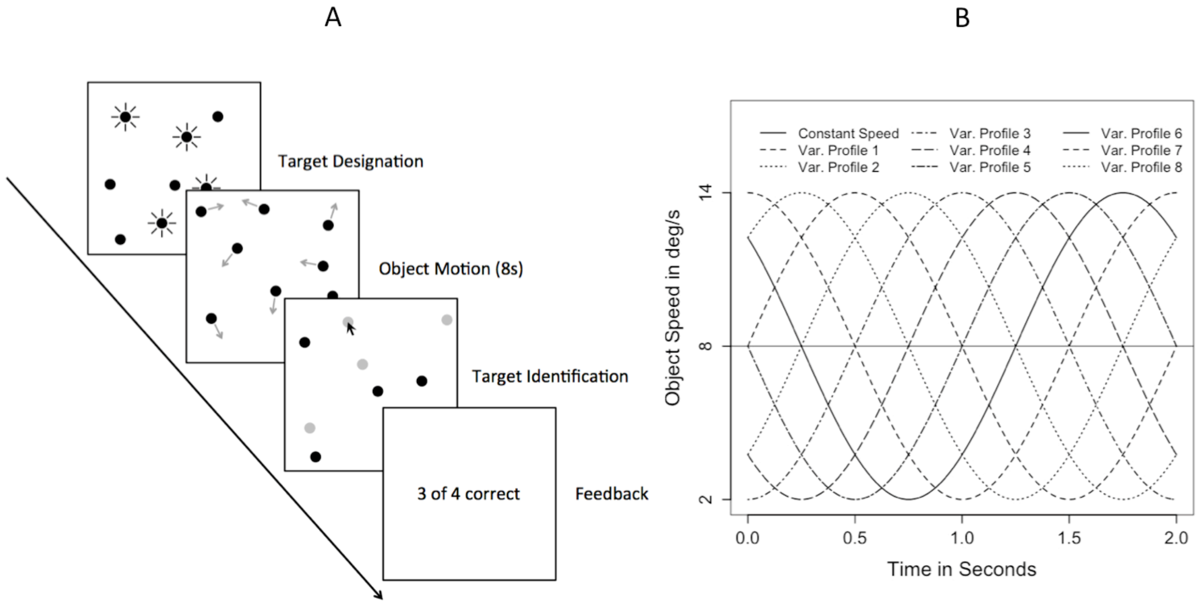

Figure 1. Illustration of the experimental stimuli and procedure. A: Participants tracked a subset of four previously designated targets across an interval of object motion. Afterwards, they identified the tracked objects and received feedback regarding their accuracy. B: Illustration of the experimental manipulation. The objects either moved at a constant speed of 8 deg/s (solid line) or their speed oscillated from 2 to 14 deg/s in a sine wave pattern. Depending on the experiment, there were up to 8 distinct speed profiles within the same trial.

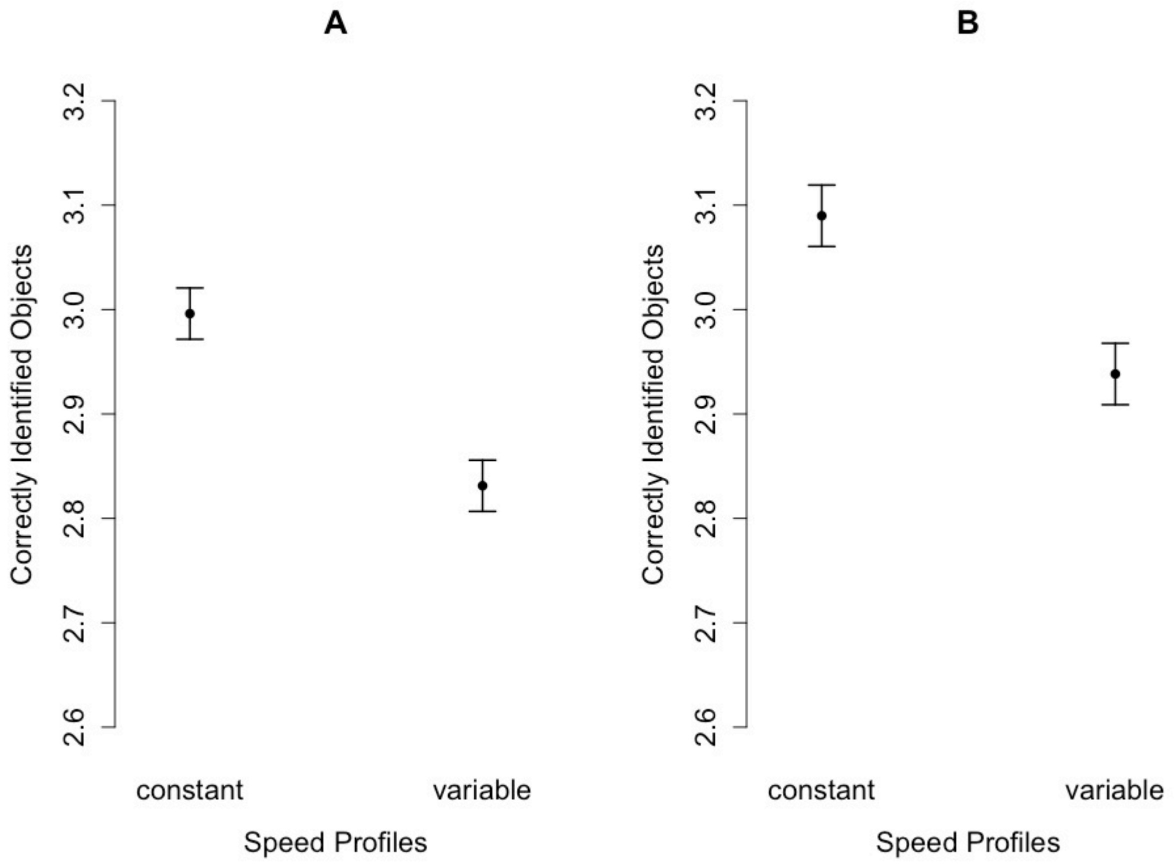

Figure 2. Tracking performance declined when all objects moved at a variable speed A: Results of Experiment 1a. With variable speed profiles, each object received an individual speed profile. B: Results of Experiment 1b. With variable speed profiles, all objects received the same speed profile. All error bars indicate within-subject confidence intervals (Baguley, 2012).

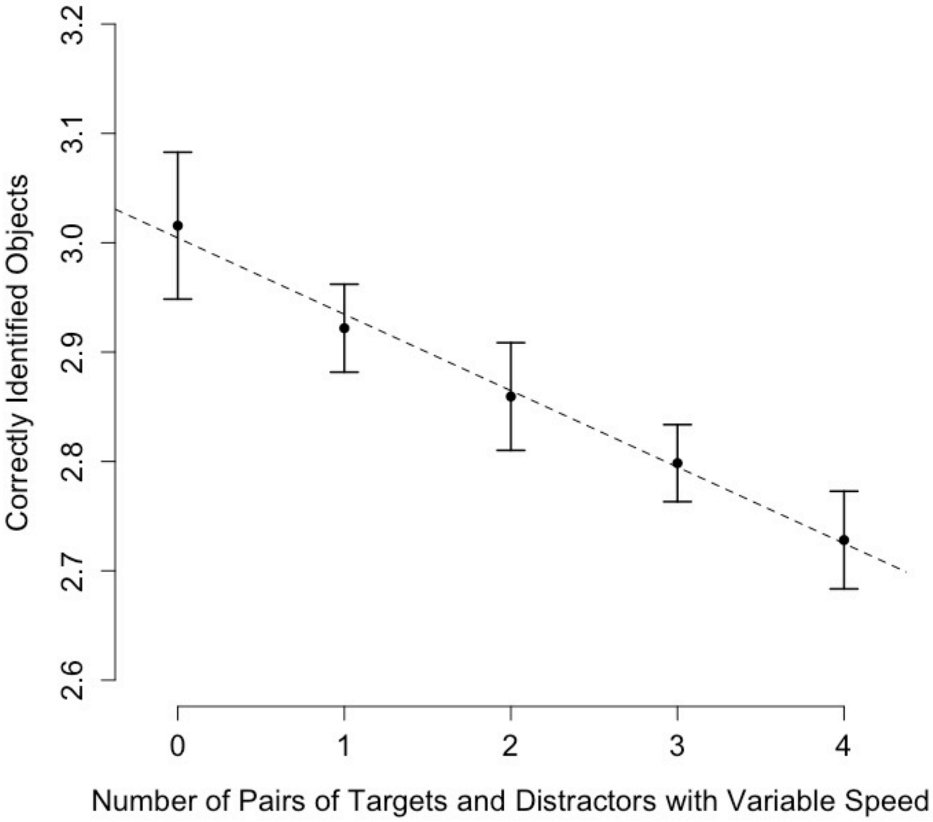

Figure 3. Results of Experiment 2. Tracking performance declined with the number of targets that moved at a variable speed. For each target with a variable speed profile, there was a matched distractor. The dashed line reflects intercept and slope of the fitted model. Error bars indicate within-subject confidence intervals (Baguley, 2012).

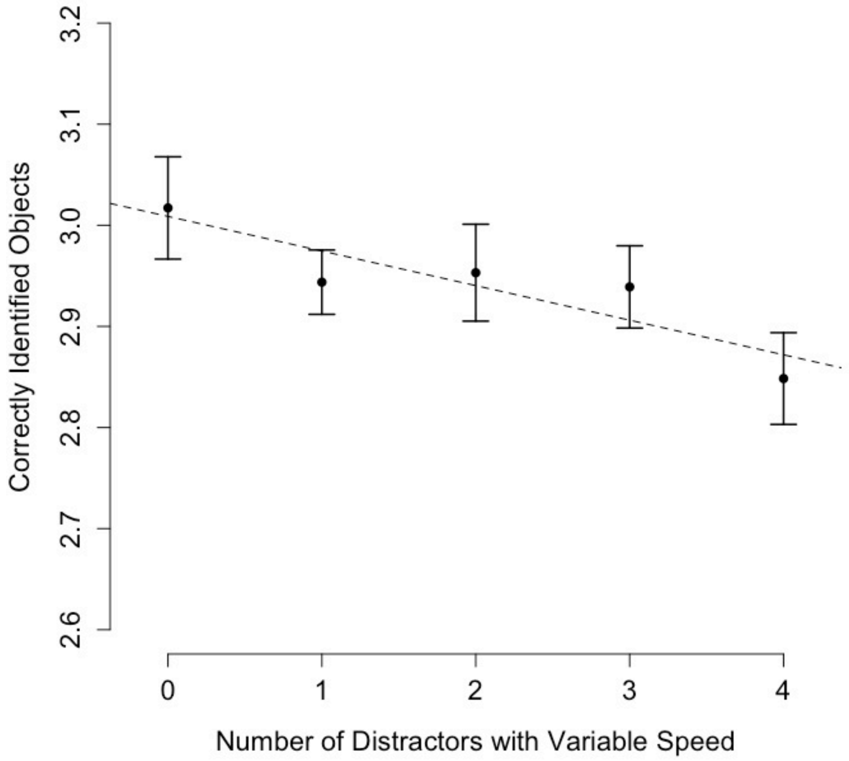

Figure 4. Results of Experiment 3. Tracking performance declined with the number of distractors that moved at a variable speed. All target objects moved at a constant speed. The dashed line reflects intercept and slope of the fitted model. Error bars indicate within-subject confidence intervals (Baguley, 2012).