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Influencing the Allocation of Attentional Resources in Tracking: Evidence for a Combined Parallel and Serial Mechanism

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INFLUENCING THE ALLOCATION OF ATTENTIONAL RESOURCES IN TRACKING: EVIDENCE FOR A COMBINED PARALLEL AND SERIAL MECHANISM

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For my parents
Thomas and Jordeen

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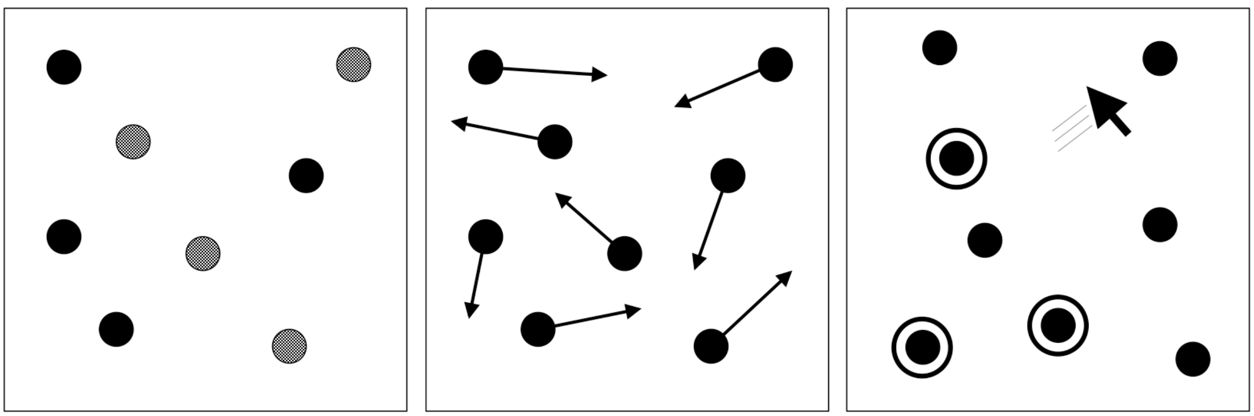
ABSTRACT

The ability to track multiple moving objects (e.g. cars on a roadway, players and/or balls in a sporting event, pedestrians in a crowded space) has been thought to be a parallel process, such that all the objects are tracked simultaneously (Howe et al., 2010). Others have asserted that some serial mechanism is involved in the tracking process, suggesting that there are shifts of attention from object to object in order to successfully track (Oksama & Hyönä, 2008). Subsequent research has demonstrated that changes in trajectory can attract attention (Howard & Holcombe, 2010) and that these localized changes in trajectory negatively affect tracking ability (Ericson & Beck, 2013). However, research has demonstrated that large global scene changes do not have an effect on tracking accuracy (Liu et al., 2005). Therefore, the current research investigated the attentional mechanisms that are used in object tracking. Specifically, this study investigated differences between global and localized changes in trajectory (Experiment 1), determined how long it takes temporally for shifts of attention to occur (Experiment 2), and investigated how parallel and serial mechanisms function together as a cohesive process (Experiment 3). Results from this study indicated that a parallel processing system for multiple object tracking is utilized. However, when two targets sequentially change trajectory abruptly within a specific temporal window tracking accuracy is reduced. This finding suggests that although tracking is primarily parallel, some attentional resources may be devoted or serially transferred towards specific target items. A hybrid resource model that uses both parallel and serial mechanism is discussed.

CHAPTER 1. INTRODUCTION

When navigating a busy street or walkway, you may catch yourself following multiple items simultaneously. For example, while driving a car down the road you need to attend to all the cars moving about you in order to avoid a collision. However, if a vehicle were to swerve or make some unexpected movement this would likely attract your attention towards this vehicle and away from the other vehicles on the roadway. During this time you are momentarily allocating your cognitive resources away from all the surrounding information and focusing the majority of your attention on this one swerving car. Thankfully, our cognitive resources adjust after these instances occur, such that attention is quickly redistributed back to the surrounding environment. Attention has been broadly defined as "taking possession of the mind, in clear and vivid form… it involves withdrawal of some things in order to deal effectively with others" (James, 1890); in this case the swerving car would represent the taking possession of the mind, as you attend to it, and away from the other surrounding information.

The laboratory task for the situation described above has been given the moniker Multiple-Object Tracking (MOT) and involves participants following a subset of identical moving objects (Pylyshyn & Storm, 1988). In a typical MOT experiment (see Figure 1) the targets are flashed or cued for a brief period of time, the cues are removed, and then the objects begin moving about the display. Following the end of the motion, participants are instructed to select the objects that were cued at the start of the trial. Using the MOT paradigm it has been found that participants can accurately track approximately four items simultaneously (Pylyshyn & Storm, 1988), but this limit on set size is based on individual differences (Alvarez & Franconeri, 2007). Therefore, the MOT task demonstrates that the attentional system is finite, and thus has a limited capacity for the amount of information (targets) that can be concurrently processed. Other than the number of objects to track, limitations to accurately performing the task have been attributed to occlusion (Scholl & Pylyshyn, 1999; Zelinsky & Todor, 2010), spatial proximity (Franconeri, Jonathan, & Scimeca, 2010; Franconeri 2013; Franconeri, Alvarez, Cavanagh 2013; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008; Pylyshyn, 2004), speed (Alvarez & Franconeri, 2007; Chen, Howe, & Holcombe, 2013; Feria, 2013; Holcombe & Chen, 2012; Liu et al., 2005), number of distractors (Bettencourt & Somers, 2009), and changes in trajectory (Ericson & Beck, 2013; Ericson, Goldstein, & Beck, *2013; 2014*).



a) **b)** **c)**

Figure 1
Sample Multiple-Object Tracking Sequence. a) Items are initially flashed or highlighted in order to indicate that these items are targets. b) All the items begin moving about the display independently and in some randomized fashion for a scheduled duration. c) The objects stop moving and the observer is then tasked with using a mouse cursor to identify the items that were initially designated as the target items. Ringed items are those targets that were already selected.

Various theories regarding the underlying attentional mechanisms involved in MOT have been proposed. In general, these theories can be divided into four groups: discrete sets (Pylyshyn, 2001), a flexible resource (Alvarez & Franconeri, 2007), spatial interference (Franconeri et al., 2010), and serial switching (Oksama & Hyönä, 2008). Interestingly, the spatial interference, discrete sets, and flexible resource theories share a parallel attentional component in order to track all the targets simultaneously. These theories posit that attention is deployed to the targets and then is maintained on all targets simultaneously throughout the duration of the tracking sequence. In contrast, the serial shifts theory implies that attention is moved between each target in order to update when and where the targets are located.

The discrete set account for object tracking is known as the FINST (Fingers of INSTantiation) theory, which explains tracking limitations in terms of a discrete set of indexes (Pylyshyn, 2000; Pylyshyn & Storm, 1988). The FINST theory asserts that attentional indexes, or “fingers”, are deployed in parallel to the target objects when they are cued at the start of a trial. These indexes are then maintained on the targets throughout the duration of the trial. These FINST indexes can serve as individual pointers or can be grouped together to form corners of a shape (Yantis, 1992). Accordingly, Yantis (1992) demonstrated that by adopting a grouping strategy, forming an imagined shape out of the vertices of the targets, tracking accuracy is improved. This grouping of items facilitates a parallel mechanism, as grouping does not lend itself to a serial strategy for object tracking. However, a notable limitation of grouping is that the imagery for the shape becomes difficult to maintain when the imagined shape begins to have more than 4-5 vertices (e.g. pentagon, hexagon or octagon). Regardless of whether this type of grouping mechanism is used or not, the FINST model assumes that attention works with a discrete set, or slots, with some limited capacity for the number of items to be tracked (approximately 4 targets). According to the FINST theory, it is assumed that tracking errors occur as a result of this limited indexing capacity (Pylyshyn, 2000).

The next theory to describe attention allocation during MOT has been coined the FLEX (FLEXibly allocated indexes), and uses a unified attentional resource rather than a fixed set (Alvarez & Franconeri, 2007). In the FLEX model, indexes are deployed in the same manner as a FINST, but differ in that as each FLEX is added it diminishes the attentional resources available for the to-be-tracked items. As an analogy to distinguish the two, the FINST model would assume that you have a set number of cups that can be filled, whereas the FLEX would suggest that you have an unlimited number of cups but only so much water to distribute within each cup. Therefore, the FLEX model suggests that tracking ability is not limited to the 4 or 5 items as suggested by FINST; instead it relies on a flexibly allocated attentional resource that can distribute load across multiple items simultaneously.

Spatial interference accounts for limitations in MOT have posited that attention can be deployed to multiple items simultaneously, but that the spatial resolution at which attention can represent the targets impacts tracking accuracy rather than some cognitive attentional resource (Franconeri, 2013; Franconeri et al., 2008, 2010). In this model, object tracking utilizes an on-target/off-surround spotlight mechanism, such that these spotlights may interfere with each other during tracking. Specifically, when targets come in close proximity of each other the suppression zone of one target may overlap with the attentional activation of another target negating the activation, causing the target to be lost. This theory posits that all targets are tracked in parallel and that only the spatial proximity drives performance. Therefore, it is possible to track as many targets as you want as long as there is no close spatial interference, which would result in failures of tracking accuracy. However, subsequent research has demonstrated that this is not necessarily the case and that tracking does rely on an attentional resource that is limited in ways other than spatial resolution. For example speed (Feria, 2013) and trajectory changes (Ericson & Beck, 2013) have been shown to affect tracking performance when target proximity is held constant.

Opposing these three parallel models is the serial explanation for attention allocation during MOT. According to serial theories, rather than multiple indexes that are maintained on the targets, a single attentional index is used to rapidly transfer between the targets (Oksama & Hyönä, 2008; Tripathy, Öğmen, & Narasimhan, 2011). Serial switching assumes that the observer must maintain a representation of the target objects as the attentional spotlight transfers from one item to the next. Errors occur in the tracking process when the items that are being observed get confused with one of the distractor objects (Holcombe & Chen, 2013; Howe et al., 2010). This confusion occurs because attention is not shifted rapidly enough and the representations of the target objects are not maintained accurately while attention is allocated to another target (Holcombe & Chen, 2013). By manipulating the rotational speed of the targets and the number of distractors, Holcombe and Chen (2013) argue that serial updating is based on the temporal resolution and the number of targets to accurately track. Thus, it appears that serial updating is dependent on how quickly targets are updated at the spatial locations of distractors. Accurate tracking for one target could occur at a positional updating of approximately 7Hz (7 spatial positions per second), but accurate tracking of three targets required fewer distractors or a slower rotational speed of 3Hz (3 spatial positions per second). This suggests that the number of targets in the display will ultimately determine how quickly an individual can update representations of the target objects.

A serial updating process suggests that the representation of the positional information for a target may lag behind the actual position of a target during the tracking process (Howard & Holcombe, 2008). To demonstrate this Howard and Holcombe (2008) removed the targets from the display while they were in motion and the participants' task was to report the location of the target when it disappeared. They found that participants reported the spatial positions of the objects in a location prior to where they had actually disappeared (Howard & Holcombe, 2008). This supports a serial mechanism because, if a parallel mechanism was being used, the reported location should be at the location where the target disappeared, not at a location that occurred prior to the disappearance.

The majority of attention accounts for MOT are consistent with a parallel account, with evidence against a serial attention mechanism in MOT. For example, Howe et al. (2010a) found that having targets move at independent times in a sequential order (i.e. moving and stopping the targets one by one) resulted in no benefit compared to when subsets of the targets moved and stopped simultaneously. Howe et al. (2010a) argued that performance should have been significantly better in the sequential movement condition if a serial updating mechanism were being utilized, as this spatial updating would not be taxed since the other targets were not moving. Instead, Howe et al. (2010a) assert that a parallel mechanism must be used since tracking performance was maintained during these simultaneous stops. In addition, research on probe detection tasks in MOT has demonstrated that probes appearing on targets are detected with little to no effort when compared to probes appearing on distractor items (Pylyshyn, 2006). Furthermore, it has been found that probe detection performance is improved when probes appear in the empty space around the targets. The ability to detect probes on both targets as well as the empty space around targets suggests the use of a parallel mechanism, as the updating process in a serial mechanism would not be fast enough to detect the probes appearing on each individual target (Pylyshyn, 2006).

One possible explanation for these differing patterns of results, either parallel or serial, is that positional information is derived from the current location and trajectory in order to predict where the target will be. Specifically, a Kalman type predictive filter may be employed in order to successfully complete the tracking task (Flombaum, Zhong, Ma, Wilson, & Liu *2013*; Rieth & Vul, *2013*). Kalman filters incorporate both the current location and trajectory of the targets while also implementing random variations of potential movement in order to predict the next most likely possible location of the targets. This predictive function, with predictions being determined at the current spatial position of a target, aids in tracking as the attentional mechanism can make an assumption about the next location of a target. The incorporation of such filters does not necessarily lend itself exclusively to either a serial or parallel account, as predictions may be needed for both processes. Despite these assumptions, neither a solely parallel nor a solely serial model seems to account for all the data, suggesting some other process may be utilized.

1.1 The Hybrid Resource Model of Attention

The majority of research suggests a parallel account for tracking (Franconeri et al., 2010; Pylyshyn & Storm, 1988; Yantis, 1992), however recent research has found support for a serial component (Ericson & Beck, 2013). An account of attention that uses both parallel and serial mechanisms for tracking may explain some of the inconsistencies in the data that have traditionally been forced into a mutually exclusive framework, such as grouping objects into an imagined shape for a parallel account (Yantis, 1992) or needing to maintain target identities while tracking for a serial account (Oksama & Hyönä, 2008). Recent findings suggest that abrupt changes in target trajectory can impact tracking performance (Ericson & Beck, 2013), which is consistent with a serial mechanism of attentional allocation. Using a Planets and Moons Tracking (PMT) paradigm (Tombu & Seiffert, 2011; see Figure 2), where each target object rotates in a circular manner in a pair with a distractor, Ericson and Beck (2013) had observers track the target objects while altering the number of times the objects abruptly changed direction during the tracking sequence. They found that as the number of changes in target trajectory increased, accuracy decreased. This finding suggests that attention is directed toward these abrupt changes and away from the other target items (Ericson & Beck, 2013; Howard & Holcombe, 2010). This is consistent with a serial mechanism being employed while tracking, however Ericson and Beck

(2013) suggest that a default parallel system is used that temporarily switches to a serial system when an item attracts attention due to a change in trajectory (Howard & Holcombe, 2010). Further support for a serial mechanism comes from eye movement data suggesting that brief fixations are found towards individual targets during the tracking sequence, even though for the majority of the task fixation is typically held between the targets (Fehd & Seiffert, 2010; Zelinsky & Todor, 2010). However, even though these fixation shifts occur, they do not suggest the allocation of the attentional resources at these times.

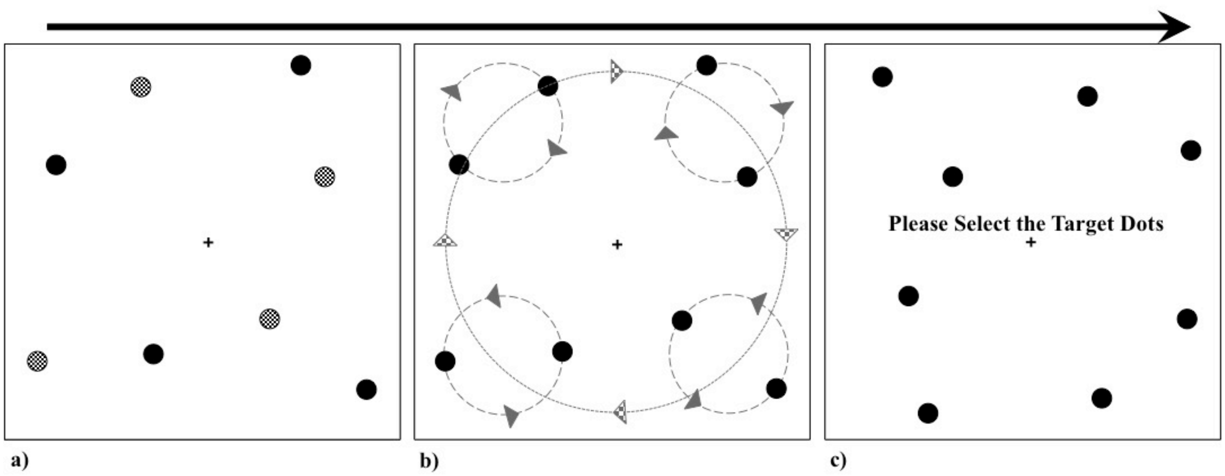


Figure 2
Example Trial Sequence. PMT example and sample trial sequence for all experiments in this study, a) Targets cued in red (depicted in grey here) for 2 s b) cues removed 1s, tone sounds and dot pairs begin rotational movement for both local rotation (small circle, solid arrows) and global rotation (large circle, checkered arrows), c) dots stop moving and participants use mouse and spacebar to select the targets, feedback given for “correct” and “incorrect” responses. Circles and arrows are displayed for demonstration purposes and were not on the screen during the experiment.

The concept of a resource model for attentional tracking is not novel, as many of the models with serial accounts describe some attentional resource limiting process to object tracking (Chen, Howe, & Holcombe, 2013; d’Avossa et al., 2005; Holcombe & Chen, 2012; Oksama & Hyönä, 2008). Although eye movement data has demonstrated that serial shifts can occur (Fehd & Seiffert, 2010; Zelinsky & Todor, 2010), it is still not known how parallel and serial mechanisms could work in conjunction. The result of Ericson and Beck (2013) coincides nicely with many of the other theories regarding attention and tracking ability, most notably the FLEX model proposed by Alvarez and Franconeri (2007). The primary difference, is that although the FLEX distributes attention equally to each visual index based solely on the number of items in the display to track, Ericson and Beck (2013) posit that the distribution of attention to each visual index is dependent on current task demands. That is, if one target needs more resources at a given moment because of an increase in speed or a change in direction, more attentional resources can be directed to that target.

The hybrid resource model suggests that over the course of a single trial, attention is in fluctuation as resources are constantly being distributed to and from target items via attentional attraction. This attentional attraction serves as the serial component in the hybrid resource model. However, when an attraction of attention occurs, attention is not necessarily devoted fully to one item, or rather that some of the attentional resource remains on the non-attracted targets. Following the attraction, attention is reallocated and distributed across all of the targets. This reallocation of attention to the targets is brief and is thought to be an efficient process (Ericson & Christensen, 2012; Wolfe et al., 2007). For instance, a change in trajectory for a target would require a quick allocation of attentional resources towards this object to update its representation; this is then followed by a redistribution of attention back to all of the targets simultaneously.

The proposed hybrid resource model for this research functions such that during target selection, visual indexes are assigned via an overall distribution of attention, much like the FLEX (Alvarez & Franconeri, 2007). However, the hybrid resource model does not consider the distribution of attention to be fixed throughout the duration of the trial. Instead, the hybrid resource model considers attention to be a pooled resource that is continuously changing its allocation depending on current task demand. During the maintenance portion of the trial, attention continues to be distributed to each index as an overall resource. This attention resource can be accumulated directly to one target item or over all of the target items, depending on current task demands. Task demands can lead to changes in the allocation range from speed, proximity, trajectory, occlusion or other situations that may require a greater demand of attentional resources to one or a subset of items. For example, if a target has recently changed direction, a greater dedication of attentional resources may be required to maintain the visual index on that target. The cost to this hybrid resource model is that when attention is more heavily devoted to a particular target, the representation to the remaining items is weakened. It is during these moments, when attention is prioritizing resources to one target and leaving a weaker representation for the remaining targets, that tracking errors are likely to occur on these items. In relation to the aforementioned cups and water example, it would be akin to having a set amount of water, but being able to continuously transfer water to and from each cup in order to make a cup more or less full as needed. This hybrid resource model encompasses both parallel and serial accounts for tracking, and provides a logical explanation of a system that could be used to effectively track multiple moving objects.

1.2 Current Study

The current study attempts to identify the processes in tracking that allow for a distribution of attention to all targets simultaneously and an allocation of attention to a specific target when needed. Localized changes in trajectory likely involve a serial process (Ericson & Beck, 2013), where as global changes (e.g., a change in trajectory for all items simultaneously) may be managed with a parallel process. Previous research on MOT has demonstrated that tracking performance can be maintained across large continuous scene changes (Liu et al., 2005), suggesting that the spatial positions of all the tracked items are held in parallel. Liu et al. (2005) used 3D environments to track object within a dynamic moving scene. Participants tracked targets within a Necker cube that turned and rotated continuously, thus the viewing angle of the targets was altered for the participant. They found that performance did not diminish during these dynamic scene translations, suggesting that scene changes have no effect on tracking accuracy. Additionally, Howe et al. (2010b) examined how scene attributes may also facilitate performance in object tracking. By adjusting the scene speed as well as the gaze location, Howe et al. (2010b) was able to determine that scene changes provide evidence for the parallel mechanism in tracking. The PMT design of Tombu and Seiffert (2011) uses large global rotations for the objects about a central point, while still having local trajectory information for each individual target item.

Based on the findings regarding scene changes (Howe et al., 2010b; Liu et al., 2005), it can be inferred that changes in trajectory to the global motion of the objects in a PMT design should have no effect on tracking performance and that all the objects are tracked in parallel during global motion. Assuming the hybrid model, following a global change in trajectory attention should be attracted equally to all items, so there should not be a preferential attraction to one item over the others. However, if a local change in trajectory occurs, tracking accuracy should suffer as attention is being attracted to the location of the change (Ericson & Beck, 2013; Howard & Holcombe, 2010). The roles of serial and parallel mechanisms will be tested by examining the effects of local versus global changes in trajectory in the first experiment of the current study. This will further the investigation of the presence of the hybrid resource model in MOT, by examining both parallel (global changes) and serial (local changes) mechanisms of object tracking in the same experimental design.

This study attempts to provide further evidence that, consistent with the FLEX model, 1) attentional resources are distributed and maintained across all objects and 2) there is some reallocation of attention via a serial updating mechanism to demanding targets (Experiment 1). In addition, this study will also examine the time frame for the serial switching and reallocation process (Experiment 2). Alvarez and Franconeri (2007) suggested that attention is distributed and allocated to the targets based on display and stimulus parameters, and then once this allocation has occurred it is maintained for the duration of the trial. However, Ericson and Beck (2013) have demonstrated that attention can be drawn towards specific target items based on immediate task demands. Ericson and Christensen (2012) found that attentional reallocation is quick and effortless, and often comes at little cost to the observer. However, it was not determined how quickly this process can take place.

Ericson and Beck (2013) have demonstrated that increasing the number of changes in trajectory negatively impacts tracking ability. Therefore, an examination of the effect of the time frame between targets changing trajectories can determine how fast, or how long it takes, for attention to allocate to a single target then redistribute across all targets. Theeuwes, Atchley, and Kramer (2000) suggested that a critical time period for attention to be redistributed following a distracting item was approximately 150 ms. This 150 ms timeframe is consistent with other research that has also demonstrated a critical time of 150 ms for the allocation of visual attention (Posner, 1980). Therefore, it is expected that during a MOT sequence when a serial shift in attentional allocation occurs for a changed target, if a second target changes trajectory within 150 ms, this second change may not be detected. Failure to detect this change would prevent parallel attention from being appropriately allocated back to this target. That is, when two changes in trajectory occur close in time, tracking performance should decline; thus a quantifiable measure of the allocation timeframe can be observed. In a purely parallel model of attention a decline in accuracy should not occur; specifically, if all the targets are held simultaneously even when changes in trajectory occur, then no decrease should be observed regardless of how temporally close the two targets change direction. Conversely, a decline in accuracy would comply with a serial account for tracking, as this temporal measure investigates the time course required in order to make a serial shift of attention to each target. However, tracking accuracy should decrease regardless of which target item changes trajectory, as serial shifting would require some systematic updating process.

Finally, an attempt was made to identify how attention may be allocated and distributed when local and global changes in trajectory occur (Experiment 3). When there is a local change in trajectory, are all of the attentional resources pulled away from everything else, or is there still enough of this resource available to update non-changing locations after a global motion change? An investigation was conducted to see how performance may be affected when observing a global change immediately followed by a local change, or when observing a local change immediately followed by a global change. If the hybrid resource model for attention functions as predicted, local changes should disrupt accuracy when closely followed by a global change in trajectory, as an attentional allocation should be occurring towards a single target for the local change, causing the loss of information for the global movement of items. Meanwhile, global changes should offer no interference when occurring prior to a local change, as the global changes should not disrupt the parallel allocation of attention such that when the local change occurs it should still afford the ability to conduct a serial attentional shift when a local change occurs.

Experiment 1 attempts to delineate the parallel and serial mechanisms in tracking and how these mechanisms are used by examining differences between two types of changes in trajectory, either global or local. For a summary of the results that each theory would predict refer to Table 1. A FINST model of MOT would predict no main effects for the type of change occurring or for the number of changes, as well as no interaction. This is due to the fact that FINST indexes are fixed; therefore any change on screen should not have an effect on performance (Pylyshyn, 2001; Pylyshyn & Storm, 1988). The FLEX would predict a main effect for the type of change but not for the number of changes, with no significant interaction. The FLEX would assume that once the task demands change, the attentional resources are adjusted and subsequently the items are lost; with the type of change in trajectory as the limiting factor and neither the number of changes or the latency between changes causing performance loss (Franconeri & Alvarez, 2007). Once a change in trajectory occurs and an item lost, attention is distributed across the remaining items with no attentional effort to attain the lost target. The spatial interference hypothesis would expect a significant effect for the number of changes and an interaction, but not for the type of change. This result would be expected based on the spatial positions of the targets. Performance in the global condition should be equal across all trials as the targets are constantly a set distance from each other. Meanwhile, the local changes would reduce performance since each trajectory change would theoretically place the targets within closer proximity to each other, thus resulting in the interaction (Franconeri et al. 2010; Franconeri, 2013). Finally, a serial updating account would expect no interaction, but would expect main effects for the type of change and the number of changes occurring. The effect between global and local stems from the idea that when all the targets change trajectory in the global condition multiple unattended targets should be lost at the same time. In this case performance in the global would possibly be *worse* than performance in the local. Meanwhile an effect from the number of changes should be found, because as the number of changes increases the less likely a correct update for the spatial locations of the targets would occur (Holcombe & Chen, 2013; Oksama & Hyönä, 2008).

Table 1
Potential Theoretical Outcomes. List of otential outcomes for each main effect and interaction based on each theory of tracking for Experiment 1 (✔ = Accept; ✗ = Reject).

Theory Type	**Parameter Manipulations Experiment 1**		
	Local vs. Global	*# Changes*	*Interaction*
Parallel			
FINST	✗	✗	✗
FLEX	✔	✗	✗
Spatial Interference	✗	✔	✔
Serial	✗*	✔	✗
Hybrid Resource	✔	✔	✔

Note: *Denotes possible significant difference but with local change performance better than global change performance.

To summarize, the current study investigates the hybrid resource model by examining MOT performance after global and local changes in trajectory (Experiment 1), to quantify how long an attentional shift after a localized change in trajectory lasts (Experiment 2), and then to examine how both parallel and serial mechanisms function together as a cohesive process (Experiment 3). If a hybrid resource model is not supported from the results, such that no differences appear to exist between the global or local changes in trajectory, this finding would contrast the FINST (Pylyshyn, 2000) and spatial interference (Franconeri et al., 2010) hypotheses on object tracking. On the other hand, better performance for local changes in trajectory compared to global changes would promote a serial mechanism for tracking.

CHAPTER 2. EXPERIMENT 1 – LOCAL VS. GLOBAL MOTION

Because abrupt changes in trajectory can attract attention (Howard & Holcombe, 2010), Experiment 1 is designed to test what types of changes, global and/or local, require attentional resources. Using a PMT design, this experiment compares unified global changes in trajectory to individual localized changes in trajectory. Based on the findings of Liu et al. (2005) MOT accuracy does not diminish when large scene based changes are present, which is consistent with a parallel tracking mechanism. Meanwhile, it has been shown that local changes in trajectory can impair tracking performance (Ericson & Beck, 2013; Howard & Holcombe, 2010), which is consistent with a serial allocation mechanism in which attention is attracted away from non-changing targets causing a decrement in performance. It was hypothesized 1) that tracking accuracy would be better for global changes in trajectory and 2) that as the number of changes increasing tracking accuracy would diminish. This experiment compares accuracy between the local changes in trajectory and the global changes in trajectory to examine the possibility of serial and parallel mechanisms occur concurrently within MOT.

The design for Experiment 1 consisted of a 4 (number of changes) x 2 (level of change: global or local) repeated-measures design. To assess the sample size to be used in this study a power analysis was performed using the software program *G*Power* (Faul, Erdfelder, Buchner, & Lang, 2009). To determine the appropriate effect size for this experiment a pilot run of data was conducted consisting of nine participants. Following an analysis of these participants the data from the interaction revealed a $\eta^2_p = .041$, therefore an effect size of $f = .207$ was used. In addition a modest assumption of power to detect a significant effect was utilized $(1-\beta) = .8$. Since the interaction term was being used to evaluate the sample size the number of groups was 1, while the number of measures equaled 8. An evaluation of the correlations between each of the measures revealed that the overall correlations among measures to be ~= .5 (Min cor. = .193, Max cor. = .946). Additionally preliminary analysis revealed no violation of sphericity. Based on the above parameters the power analysis revealed that a sample size of n = 22 would be sufficient for this experiment.

2.1 Method

2.1.1 Participants. Thirty participants were recruited for this study via the Louisiana State University psychology research participation pool, however one participant was removed from the dataset for failure to complete the entirety of the experiment within the allotted time. The resulting twenty-nine participants (7 males, 22 females) were then included in the data set with a mean age of 20.75 years (*SD* = 2.82 years). All participants reported having normal or corrected to normal vision without colorblindness.

2.1.2 Apparatus and Stimuli. Stimuli were presented on Apple iMac computers with LCD Displays set with a 20" diagonal and a resolution of 1680 x 1050. Stimuli were created and managed using MATLAB R2008b (The Mathworks Inc.; Natick, MA) and the Psychophysics Toolbox (Brainerd, 1997; Pelli, 1997). Participants were seated 57cm from the monitor, but were not managed using a chin rest or other restraining device. For each trial, eight black dots, each 0.5° visual angle in diameter (assuming a viewing distance of 57 cm), were presented on a white background. Four dots were targets and each target was paired with a corresponding distractor dot. These four target-distractor pairs were located around a cross in the center of the display; each pair rotated around a circle 2.8° in diameter and centered between the target and the distractor (local rotation), while the midpoint for each of these pairs is placed equidistant about a larger imaginary circle 15.6° in diameter that rotates around the central fixation point (global rotation). Each target-distractor pair completed eight revolutions in the local rotational movement, whereas, the global rotation consisted of only two rotations around the center point in the display. The motion sequence of each trial lasted approximately 15 seconds.

The experiment incorporated a 4 x 2 repeated-measures factorial design with four possible numbers of changes in trajectory (1, 2, 4, or 8) for each level of change (global or local). Within a trial, each target-distractor pair rotated at the same speed but independently of the other pairs (local motion); in addition the center axis of each target-distractor pair rotated in a large circle about the fixation point (global motion; see Figure 2). In the global change type trials, the global motion of all of the pairs changed direction. These large global changes abruptly switched direction of all objects on the screen simultaneously, but did not affect the direction of rotation of the individual target-distractor pairs (local motion). Global changes occurred randomly with the timing constraint that 217 ms must have passed between changes. In the local change type trials only one target-distractor pair changed trajectory at a time. Local changes occurred randomly throughout the trial and there was a minimum of 17 ms between two local changes. For a summary of the timing parameters for each condition please refer to Table 2. For the localized changes, the 1-change trials consisted of one change for each pair (4 total changes), the 2-change trials consisted of 2 changes for each pair (8 total changes), the 4-change trials consisted of 4 changes for each pair (16 total changes), and the 8-change trials consisted of 8 changes for each pair (32 total changes). During local change type trials, no global changes in trajectory occurred. On local change trials, the global motion was randomly chosen at the start of the trial to be either clockwise or counter-clockwise in direction and remained unidirectional for the duration of the entire trial. Regardless of change type, the timing of each change was randomly determined with the constraint that neither a global or a local change could occur within .10 revolutions of the start or end of a trial.

Table 2
Experiment 1 Average Time Between Trajectory Changes. Mean time (*SD*) between displayed trajectory changes based on condition type, as well as the range of observed times between changes.

	Number of Changes			
Change Type	*1 Change*	*2 Changes*	*4 Changes*	*8 Changes*
Global Change	N/A	3954 ms (2248)	2080 ms (610)	1130 ms (210)
Range	N/A	217-8020 ms	217-4010 ms	217-2005 ms
Local Change	3147 ms (1020)	1402 ms (292)	649 ms (94)	317 ms (29)
Range	17-12462 ms	17-7630 ms	17-3977 ms	17-2005 ms

Note: There are no timing parameters for the global 1-change trials since only one trajectory change occurred on each trial.

2.1.3 Procedure. At the start of the experiment demographic information was collected and then participants were verbally given instructions regarding the task, as well as having the instructions visually presented on the monitor. Participants were tasked with tracking four target dots, which were cued in red for two seconds at the start of each trial. Following the offset of the cues the dots remained stationary for one second and then a tone sounded indicating the start of the motion sequence for the trial. Following the motion sequence the dots remained in their final positions and participants selected one dot from each target-distractor pair by pointing at a dot with the mouse and pressing the spacebar. Black response circles appeared around each selected dot, and accurate feedback for each dot selected was provided after each choice with the word “Correct” or “Incorrect” presented at the center of the display. It was not expected that feedback would interfere with response choices, as all items presented remained in the same spatial location and were visible to the participant at all times. Trial conditions (type of change x number of trajectory changes) were randomly intermixed within 4 blocks, with each block containing 24 trials, resulting in 96 trials total for the experiment.

2.2 Results

The dependent measure for this experiment was the proportion of targets accurately tracked (see Figure 3). Arcsine transformations were performed prior to analysis in this experiment; the reported means and figures represent the nontransformed accuracies. Arcsine transformations were conducted in order to equalize the variance as well as normalize the proportional data from the tracking accuracy for each of the targets, as the observed accuracy (total $M = .85$, $SD = .12$) was not centered about chance performance (.5 proportion correct). A 2 (type of change) x 4 (number of changes in trajectory) repeated-measures analysis of variance (ANOVA) for the type of change (global or local) and number of changes in trajectory (one, two, four, or eight) was conducted. Analysis revealed no significant interaction, $F(3, 84) = 1.288$, $p = .284$, $\eta^2_p = .044$; a significant main effect for the type of change, $F(1, 28) = 35.758$, $p < .001$, $\eta^2_p = .561$ (global, $M = .88$, $SD = .08$; local, $M = .81$, $SD = .12$); and no main effect for the number of changes in trajectory, $F(3, 84) = .360$, $p = .782$, $\eta^2_p = .013$.

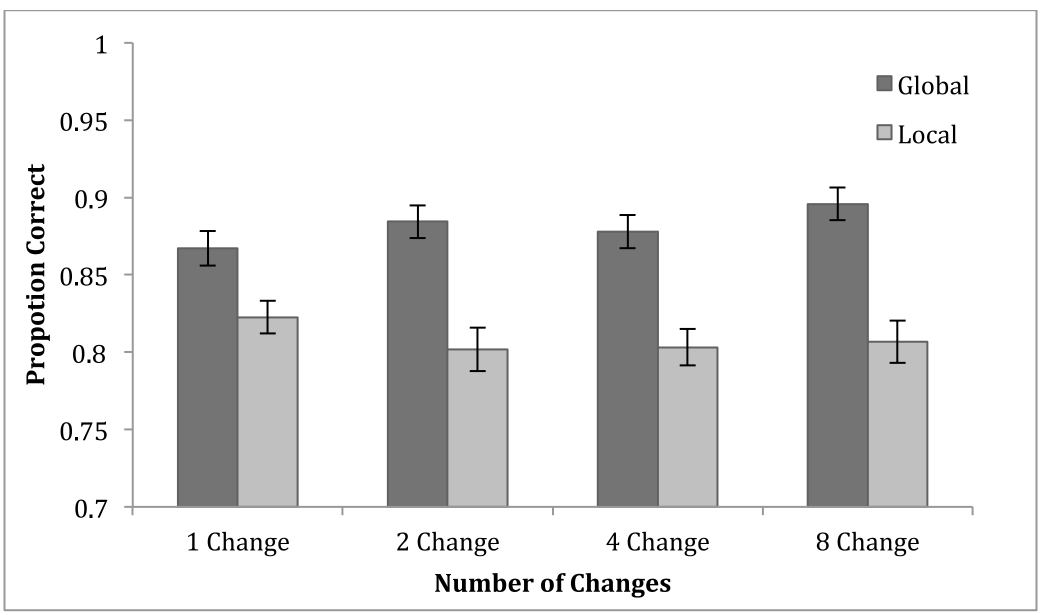


Figure 3
Experiment 1 Results. Mean proportion correct for the number of trajectory changes by the type of change. Error bars represent 95% Confidence Intervals.

To determine whether there was an effect of the total number of changes displayed, planned comparisons were conducted revealing a significant effect between the local 1-change and global 4-change trials $t(28) = 3.30$, $p = .003$; as well as the local 2-change and global 8-change trials $t(28) = 4.631$, $p < .001$. The main effect for type of change coupled with the result of the planned comparisons suggests that local changes are more likely to disrupt performance compared to global changes, and that this performance loss is not related to the cumulative total number of changes in trajectory that occur within the motion sequence for the targets.

2.3 Discussion

A main effect for type of change was observed, but there was no main effect for the number of changes in trajectory or an interaction (Figure 3). This main effect is consistent with previous findings demonstrating that the number of global scene changes do not negatively impact tracking ability (Liu et al., 2005). Furthermore, a higher proportion correct for trials with global changes in trajectory suggests that localized changes have more of a negative impact on performance, which is indicative of a potential attraction of attention (Howard & Holcombe, 2010). Meanwhile, the stable tracking performance as the number of changes in trajectory increases, particularly for the local changes, was surprising as this result contradicts the results of Ericson and Beck (2013).

The potential lack of a replication of Ericson and Beck (2013) for the number of changes in trajectory indicates a purely parallel model of object tracking, specifically the FLEX (Alvarez & Franconeri, 2007) as a loss in accuracy was still found for local changes compared to global changes. One possible reason for this occurrence is the incorporation of the global motion to the PMT design. Specifically, the previous studies (Ericson & Beck, 2013; Franconeri et al., 2010; Howe et al., 2010a) did not have the global motion in the display. Therefore, the globalized motion could have affected the motion percept of the to-be-tracked items, thus making the tracking task easier. When a change in trajectory occurs the perception of a brief pause occurs due to the congruency of motion associated between the local and global level. This perceptual pause could have negated the change in trajectory effect (Howard & Holcombe, 2010; Ericson & Beck, 2013), such that the appearance of pauses aided the participant, causing the lack of an effect for the number of changes in the local change trials. Alternatively, the global rotation now included in the display may have made the task more difficult than those from the previous findings. Performance for the local 1-change trials (M = .867) was lower compared to those of Ericson and Beck (2013; M ~= .90), which did not include the global rotation. This low performance may suggest a floor effect for the number of changes in trajectory manipulation.

Another possible explanation for the lack of a number of changes in trajectory effect could be the global rotation crossing each visual hemifield (Alvarez & Cavanagh, 2005; Hudson, Howe, & Little, 2012). An individual has two visual hemifields, meaning that information is initially processed within the visual field of each eye independently. Specifically, Alvarez and Cavanagh (2005) have demonstrated, when tracking, it is much more difficult to track a subset of targets that occur unilaterally within one visual hemifield when compared to tracking a subset of targets bilaterally across each hemifield. Since the global motion in the display allowed for the targets to cross over the hemifields consistently, this may have diminished the change in trajectory effect as the changes in trajectory may have been consistently occurring across hemifields or closer to where the hemifields cross near the midline of the display. However, in these previous studies (e.g. Alvarez & Cavanagh, 2005; Hudson et al., 2012) the participants were instructed to maintain fixation on the center of the screen, thus artificially creating the distinction of each hemifield, whereas in the current study participants were afforded the ability to view the display freely so no measure of hemifield crossover can be determined.

The post-hoc comparisons between the local 1-change and global 4-change, and the local 2-change and global 8-change demonstrated that the number of changes observed was not the driving influence on tracking performance. Specifically, since the total number of observed trajectory changes in the given conditions, 4 change and 8 changes respectively, was identical the total number of changes can be ruled out as a primary cause for a decrement in tracking ability. This finding instead suggests that the amount of time occurring between two changes in trajectory may be causing the negative impact on tracking ability. This potential temporal latency effect would contradict some of the underlying constructs of the FLEX (Alvarez & Franconeri, 2007), as an equal distribution of attention across all of the items would have remained since the number of changes in trajectory would have remained constant. Therefore, determining the latency required between trajectory changes to accurately track offers the most tangible solution for discovering any potential serial components to object tracking.

Since the global changes seemed to have little to no effect on tracking ability, a parallel processing mechanism for attention can be inferred. Although the FLEX model (Alvarez & Franconeri, 2007) offers the most tangible explanation, one explanation for the difference between accuracy for the local and global changes may be the incorporation of Kalman predictive filters (Flombaum et al., *2013*; Rieth & Vul, *2013*). As previously mentioned these models suggest that the current location and trajectory of each target is utilized to predict the next most likely location for the target to be positioned. This type of filter is conducive to the results found in Experiment 1, as a global change would facilitate the ability to predict the location of all the targets simultaneously, whereas a local change in trajectory only offers new information for a single target.

Experiment 1 successfully demonstrated that global changes do not negatively impact tracking accuracy compared to local changes in trajectory. This finding suggests that tracking may rely on a parallel process, but that local changes in trajectory can negatively impact tracking ability. This negative impact on tracking ability may be caused by an attraction of attention towards targets that have recently changed trajectory (Ericson & Beck, 2013; Howard & Holcombe, 2010). How quickly attention may be reallocated following a local change in trajectory has yet to be determined. This leaves the question unanswered regarding the utility of a purely parallel, purely serial, or a combination of both mechanism in order to successfully track multiple moving items.

CHAPTER 3. EXPERIMENT 2 – DELAYED VS. SIMULTANEOUS LOCAL CHANGES

A serial process in MOT is suggested by previous studies that have found that changes in trajectory attract attention (Ericson & Beck, 2013; Howard & Holcombe, 2010) and by the finding from Experiment 1 in which local changes impacted performance more than global changes. However, the lack of a number of changes effect in the local change condition suggests that the timing between changes rather than the number of changes may be important for revealing the serial attraction of attention after a local change in trajectory. As can be seen the average amount of time between changes in the 8 changes local trials (317 ms), the changes may not have been occurring close enough temporally to each other to demonstrate the number of changes in trajectory effect. If the effect of local changes on performance is caused by a serial component, then this effect should increase as the time between changes decreases. That is, there should be a window of time for which attention is attracted to the item that most recently changed and if another change occurs within this window performance should suffer.

Experiment 2 was designed to quantify the time needed for attention to be successfully reallocated to all of the targets after a change in trajectory in order to have the least potential for a loss in tracking accuracy. Theeuwes et al. (2000) demonstrated that attention is attracted by the onset of a distractor, but is then reallocated back to the target 150 ms following the display of a distractor item. This suggests that it takes approximately 150 ms to shift from a serial allocation of attention back to a parallel allocation. This experiment intended to see for how long an attraction of attention towards a target effectively diminishes tracking accuracy for the remaining targets. Specifically, if a serial attentional resource mechanism is used, when two targets change trajectory within 150 ms of each other, tracking performance should suffer for the second target to change trajectory. Meanwhile, it is possible that a simultaneous change (0 ms) in trajectory between two targets could actually facilitate processing, suggesting that the parallel mechanism is still active at the time of a trajectory change event and that a serial shift does not occur until after the change has been recognized. Thus, when a simultaneous change occurs both items are seen in unison, however, an attentional attraction (Howard & Holcombe, 2010; Ericson, Goldstein, & Beck, *2014*) still occurs, but to only one of the targets that changed trajectory. This would result in equal performance for both of the items that changed trajectory simultaneously.

Experiment 2 utilized a one-way repeated-measures design. Because performance will be evaluated across each of three types of targets (*pre-latency, post-latency,* and *no change*) a 5 (latency) x 3 (target type) repeated measures design was used to assess the needed sample size. Again *G*Power* (Faul et al., 2009) was used in order to complete the analysis. The effect size for this experiment was based on the interaction from Experiment 1, $\eta^2_p = .044$, therefore an effect size of $f = .215$ was used. A modest assumption of power to detect a significant effect was utilized $(1-\beta) = .8$. The interaction term was used to evaluate the sample size, thus the number of groups was 1, while the number of measures equaled 18. An assumption for the correlation among measures was set to $r = .5$, as well as assuming no violations of sphericity. Based on these parameters the analysis revealed a required sample size of n = 15.

3.1 Method

3.1.1 Participants. Thirty-six participants were recruited for this study via the Louisiana State University psychology research participation pool, however four participants were removed from the dataset due to a computer error and an unintentional data overwriting error from the experiment administrator. The resulting thirty-two participants (1 male, 30 females, 1 undisclosed) were then included in the data set with a mean age of 20.47 years (*SD* = 2.48 years). All participants reported having normal or corrected to normal vision without colorblindness.

3.1.2 Apparatus and Stimuli. The apparatus and stimuli are identical to those used in Experiment 1 except for the changes noted here. In the current experiment, no global changes in trajectory occurred, although global motion was still present in the display. Targets were limited to completing five and a half revolutions at the local level, thus the motion portion of each trial was approximately equal to 8.25 s. In addition, there were only two changes in trajectory on every trial. Via random selection, one of the targets was chosen to change trajectory during the trial and a second target would change trajectory either simultaneously (0 ms) or after a latency period (50 ms, 100 ms, 150 ms, 200 ms, or 250 ms) from when the first target changed trajectory. Latencies were selected to match the methodology of Theeuwes et al. (2000). Because only two different targets changed trajectory in each trial, accuracy was divided amongst the targets by the characteristics of each. This left three types of targets available: the *no change* targets, the *pre-latency* target, and the *post-latency* target. Therefore, the analysis focused on each of these target types for accuracy.

3.1.3 Procedure. The procedure was identical to that of Experiment 1 except there were no global change trials. There were 4 blocks, with 24 trials in each block, resulting in 96 trials for the experiment. This resulted in 16 observations per latency time for the experiment.

3.2 Results

The dependent measure for this experiment was the proportion of targets accurately tracked for each target type (see Figure 4). A preliminary analysis was conducted in order to determine if there were any differences between target types (*no change*, *pre-latency*, and *post-latency*) in the simultaneous condition (0 ms). Since the changes in trajectory occur concurrently, no differences should be observed for each target type. Therefore, a repeated-measures ANOVA was conducted on the simultaneous (0 ms), no latency trials, for each target type. This analysis revealed no significant main effect for the type of target (*no change: M* = .82, *SD* = .12*; pre-latency*: *M* = .82, *SD* = .16*;* and *post-latency: M* = .80, *SD* = .12) for the simultaneous trajectory trials $F(2, 62) = .319$, $p = .728$, $\eta^2_p = .010$. The simultaneous (0 ms) trials were thus excluded from all further analysis.

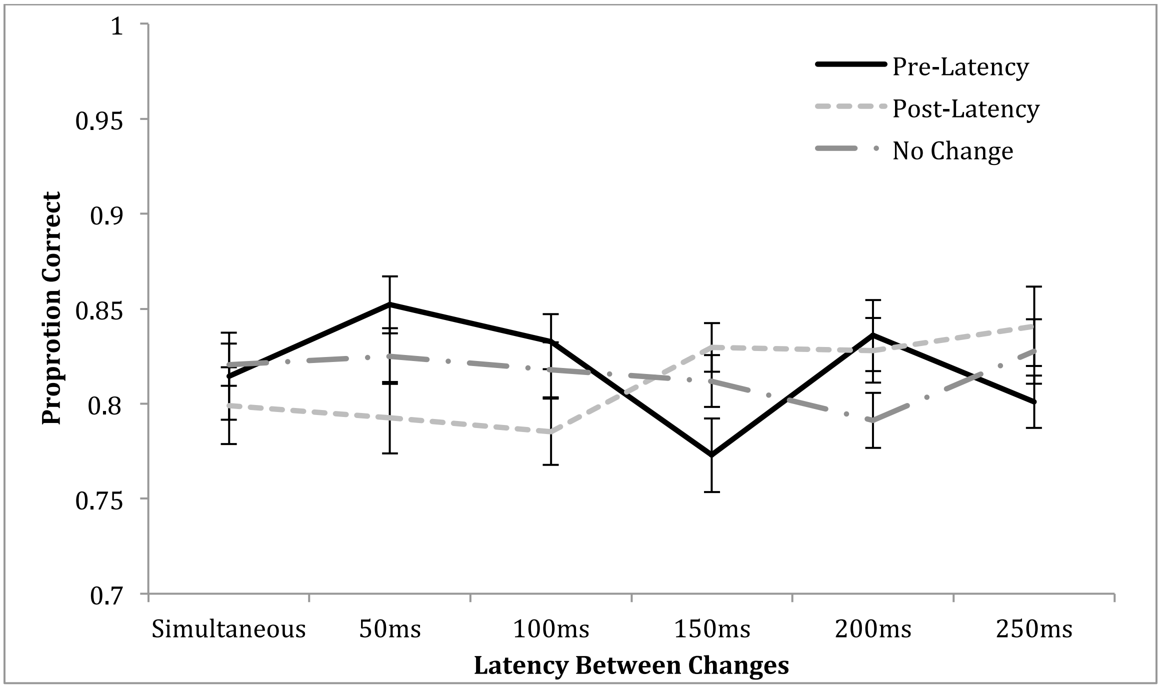


Figure 4
Experiment 2 Results. Proportion correct for each target type: no change, pre-latency, and post-latency targets. Error bars represent 95% confidence intervals.

Following the preliminary simultaneous analysis, five latencies between trajectory changes remained (50 ms, 100 ms, 150 ms, 200 ms, or 250 ms) for the three target types (*no change*, *pre-latency*, and *post-latency*). A 5 x 3 repeated-measures ANOVA was thus conducted on these variables. Analysis revealed a significant interaction, $F(8, 248) = 2.680$, $p = .008$, $\eta^2_p = .080$; but no main effect for target type, $F(2, 62) = .094$, $p = .910$, $\eta^2_p = .003$; and no main effect for latency between changes in trajectory, $F(4, 124) = .757$, $p = .555$, $\eta^2_p = .024$.

To further investigate the interaction a series of one-way repeated-measures ANOVA's for each target type across each latency were performed. Analyses revealed a significant effect for the *pre-latency* targets, $F(4, 124) = 3.437$, $p = .011$, $\eta^2_p = .100$; but not for either the *post-latency,* $F(4, 124) = 1.792$, $p = .135$, $\eta^2_p = .055$; and *no change* targets, $F(4, 124) = .928$, $p = .450$, $\eta^2_p = .029$. Post-hoc LSD for the *pre-latency* targets revealed that significant differences were occurring between the 50 ms ($M = .85$, $SD = .15$) and the 150 ms ($M = .77$, $SD = .15$) latencies, $p = .002$, the 50 ms and the 250 ms ($M = .80$, $SD = .15$) latencies, $p = .031$, and the 100 ms ($M = .83$, $SD = .14$) and the 150 ms latencies, $p = .034$. The results suggest that tracking accuracy is significantly decreasing for the *pre-latency* target at the 150 ms latency.

Additional planned post-hoc comparisons were conducted for the *pre-latency* and *post-latency* targets for all latencies between changes in trajectory. Significant effects were found at the 50 ms latency (*post-latency* target: $M = .79$, $SD = .13$), $t(31) = 2.188$, $p = .036$; and for the 150 ms latency (*post-latency* target: $M = .83$, $SD = .15$), $t(31) = 2.072$, $p = .047$. This result suggests that tracking accuracy is better for the *pre-latency* target when there is 50 ms between trajectory changes, and tracking accuracy is better for the *post-latency* target when there is 150 ms between trajectory changes.

3.3 Discussion

Previous findings on attentional attraction (e.g., Howard & Holcombe, 2010) indicated that attention can be attracted to a single target. Experiment 2 demonstrates the speed at which attention can be preferentially allocated to a target that has recently changed trajectory, and then reallocated back to the remaining items. Specifically, when a target (*pre-latency)* changes trajectory 50 ms before another target (*post-latency*), tracking accuracy is better for the target which changed trajectory first. Additionally, when the *pre-latency* target changes trajectory 150 ms before the *post-latency* target, accuracy becomes better for the second target that changed trajectory, as attention has now been attracted and allocated away from the first target (*pre-*

latency) and towards the second target to change trajectory (*post-latency*). This finding suggests that some attentional attraction is occurring in MOT when objects abruptly change direction.

In contrast to these results, a purely parallel model of object tracking would predict equal performance for all the targets for all latencies, whereas an entirely serial updating strategy would expect to find performance to be worse for *post-latency* targets as the serial updating would miss any updates to trajectory for non-attended items. Based on the serial updating prediction it could also be inferred that a loss would be seen in the *pre-latency* trials. These predictions arise from the lack of attentional attraction within the serial and parallel models for object tracking. Therefore, by ruling out either a pure serial model or a pure parallel model it becomes likely under the experimental conditions being utilized here that the suggested hybrid resource model of attention is being used for object tracking.

The results of the current experiment complement the literature on attentional capture, or rather an involuntary and mandatory deployment of attention towards a target or stimuli (Posner, 1980; Theeuwes et al., 2000). Specifically, the significant effect at the 150 ms latency is in line with the critical capture period found in these studies. The data from this experiment suggests that prior to a latency of 150 ms, such as at 50 ms, the *pre-latency* target is given some preferential resource in order to successfully track the object. This suggests that the initial attraction and allocation of attention to the *pre-latency* target misses any other potential attentional attractions that could occur, such as the *post-latency* target, as the attraction may still be occurring towards the *pre-latency* target. However, at 150 ms, it is likely that attention is attracted towards the *pre-latency* target, although the attentional shift to the target completes, the subsequent abrupt trajectory change of the *post-latency* target pulls attention towards this second trajectory change, and the spatial updating for the first *pre-latency* target was not completed.

This attraction of attention explains the reduction in accuracy for the *pre-latency* target and the improvement in accuracy for the *post-latency* target. This accuracy trade-off approximately mirrors one another, further suggesting that the reallocation of attention is quick and somewhat effortless (Ericson & Christensen, 2012). These performance decrements for target type from the attentional shifts may have been too small to be detected in previous studies. This temporal latency finding also explains the results of Ericson and Beck (2013), because as the number of changes in trajectory increased (4 – 36), the loss in performance, from the *pre-latency* to *post-latency* targets, began to manifest themselves because not only are more changes occurring but, they are likely occurring closer to each other in time.

The significant interaction from Experiment 2 supports the hypothesis that serial shifts of attention are needed in MOT, and that an allocation of attentional resources may be occurring at the moment of a trajectory change. This finding therefore supports the hybrid resource model of attentional attraction. These results suggest that tracking is not entirely a parallel process as has been previously suggested and, instead, implies that attentional resources are shifted to the target object with the most immediate need. The finding indicates that although parallel processes are used, the serial shifts of attention might not have been detected in previous research (Howe et al., 2010a) due to the trade-off in accuracy between the *pre-latency* and *post-latency* targets; with performance prior to 150 ms being improved for the *pre-latency* target while performance at 150 ms being better for the *post-latency* target. Therefore, examining accuracy for individual target types demonstrates the effect, whereas recording the total proportion of targets accurately tracked may have missed the effect.

CHAPTER 4. EXPERIMENT 3 – HYBRID MODEL OF ATTENIONAL ALLOCATION

Given evidence from previous research for both serial and parallel attention allocation during MOT (Howe et al., 2010; Oksama & Hyönä, 2008), it is important to understand how transitioning from a parallel allocation to a serial allocation or vice-versa affects performance. In Experiment 3, the global and local changes in motion from Experiment 1 were implemented in the same trial and a manipulation of the latency, similar to Experiment 2, but now between global changes and local changes, was also implemented. It was expected that a (parallel) distribution of attentional resources across all the items would occur during a global change, while a local change causes an allocation of attentional resources to a single item (serial). Therefore it was hypothesized that two changes in trajectory, where the first change is global and the second local, would have significantly better performance than a local change followed by a global change.

The design for Experiment 3 consisted of a repeated-measures design. However, since performance was evaluated across two types of change order, a 4 (latency) x 2 (change order) repeated measures design was used to assess the needed sample size. Again, *G*Power* (Faul et al., 2009) was used to complete the analysis. The effect size for this experiment was based on the interaction from Experiment 1, $\eta^2_p = .044$, therefore an effect size of $f = .215$ was used. Again, a modest assumption of power to detect as significant effect was utilized $(1-\beta) = .8$. The interaction term was used to evaluate the sample size, thus the number of groups was 1, while the number of measures equaled 8. An assumption for the correlation among measures was set to $r = .5$, as well as assuming no violations of sphericity. Based on these parameters the analysis revealed a required sample size of n = 21.

4.1 Method

4.1.1 Participants. Sixty participants were recruited for this study via the Louisiana State University psychology research participation pool. However, four participants were removed from the dataset for reporting non-normal vision and two others were removed for not performing above chance performance in the experiment. Therefore the final sample consisted of fifty-four participants (17 males, 34 females, 3 undisclosed) with a mean age of 19.81 years (*SD* = 1.30 years). All participants used in the sample reported having normal or corrected to normal vision without colorblindness.

4.1.2 Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 2 except for the changes noted here. In the current experiment a 2 (change order) x 5 (latency) factorial design was used with global changes incorporated into the design. Changes for Experiment 3 now occurred in one of three manners; the first of these was that a global change would occur simultaneously with a local change, resulting in a global/local simultaneous (0 ms latency) condition. The second manner was a global change followed by a local change after a given latency; *global-local* change order. The third alternative was that the local change preceded the global change; *local-global* change order. Based on the results of Experiment 2, the time latencies between changes used in this experiment were: 50 ms, 100 ms, 150 ms, or 200 ms.

4.1.3 Procedure. The procedure was identical to that of Experiment 2, except for the changes noted in the apparatus and stimuli. Again there were 4 blocks, but now with 30 trials in each block, resulting in 120 trials for the experiment. This resulted in 12 observations for each change type and latency across the entire experiment.

4.2 Results

The dependent variable for this experiment was the proportion of targets accurately tracked (see Figure 5). Arcsine transformations were performed prior to the analysis in this experiment; the reported means and figures represent the nontransformed accuracies. As before, arcsine transformations were conducted in order to equalize the variance and normalize the proportional data from the tracking accuracy for each of the targets, as the observed accuracy (total $M = .84$, $SD = .12$) was not centered about chance performance (.5 proportion correct). A 2 (change order) x 4 (latency) repeated-measures ANOVA was performed. The analysis revealed no main effect for change order, $F(1, 53) = .367$, $p = .547$, $\eta^2_p < .007$; no main effect for latency, $F(3, 159) = 2.370$, $p = .073$, $\eta^2_p = .043$; and no interaction, $F(3, 159) = 2.106$, $p = .102$, $\eta^2_p = .038$. These findings indicated that there were no differences in tracking accuracy between the different change orders for any of the time latencies when the changes occurred.

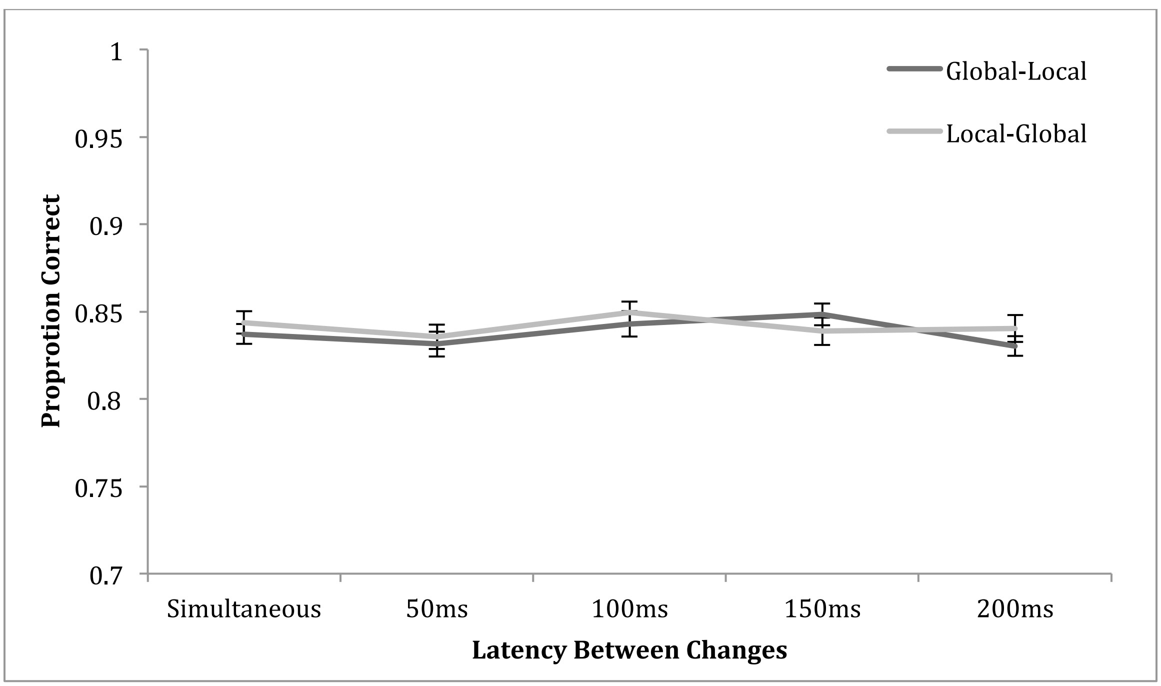


Figure 5
Experiment 3 Results. Average proportion correct for *global-local* (black line) and *local-global* (gray line) change orders for each latency. Error bars represent 95% confidence intervals.

A second analysis was conducted in order to investigate whether change order had an effect on each target type. Within each change order a single target changed trajectory at the local level, it was therefore important to investigate tracking accuracy solely for this local target for each change order. A summary of the data for each target type and change order at a given latency can be found in Figure 6. A 2 (target type) x 2 (change order) x 4 (latency) repeated-measures ANOVA was conducted. The analysis revealed no significant main effects: target type, $F(1, 53) = .438$, $p = .511$, $\eta^2_p = .008$; change order $F(1, 53) = .049$, $p = .826$, $\eta^2_p = .001$; and latency, $F(3, 159) = 1.150$, $p = .331$, $\eta^2_p = .021$. In addition there were no significant interactions: target type x change order x latency, $F(3, 159) = .827$, $p = .481$, $\eta^2_p = .015$; target type x change order, $F(1, 53) = .882$, $p = .352$, $\eta^2_p = .016$; target type x latency $F(3, 159) = 1.552$, $p = .203$, $\eta^2_p = .028$; and change order x latency, $F(3, 159) = 1.883$, $p = .135$, $\eta^2_p = .034$. This suggests that there are no differences for the type of target changing trajectory regardless of change order or latency in this experiment.

Planned comparisons were conducted for the local target types for each change order in the 50 ms and 150 ms latencies. These time latencies were chosen as planned comparisons since these were the latencies that demonstrated effects in Experiment 2. The analysis revealed that at the 50 ms latency for the local target type there was no significant difference between the *global-local* ($M = .84$, SD = .14) and *local-global* ($M = .85$, SD = .16) change order, $t(53) = .393$, $p = .696$. There was however a significant effect at the 150 ms latency for the local target between the *global-local* ($M = .86$, SD = .16) and *local-global* ($M = .83$, SD = .16) change order $t(53) = 2.337$, $p = .023$. This effect signifies that tracking accuracy is better for the target that changed its local trajectory following 150 ms latency from a global change.

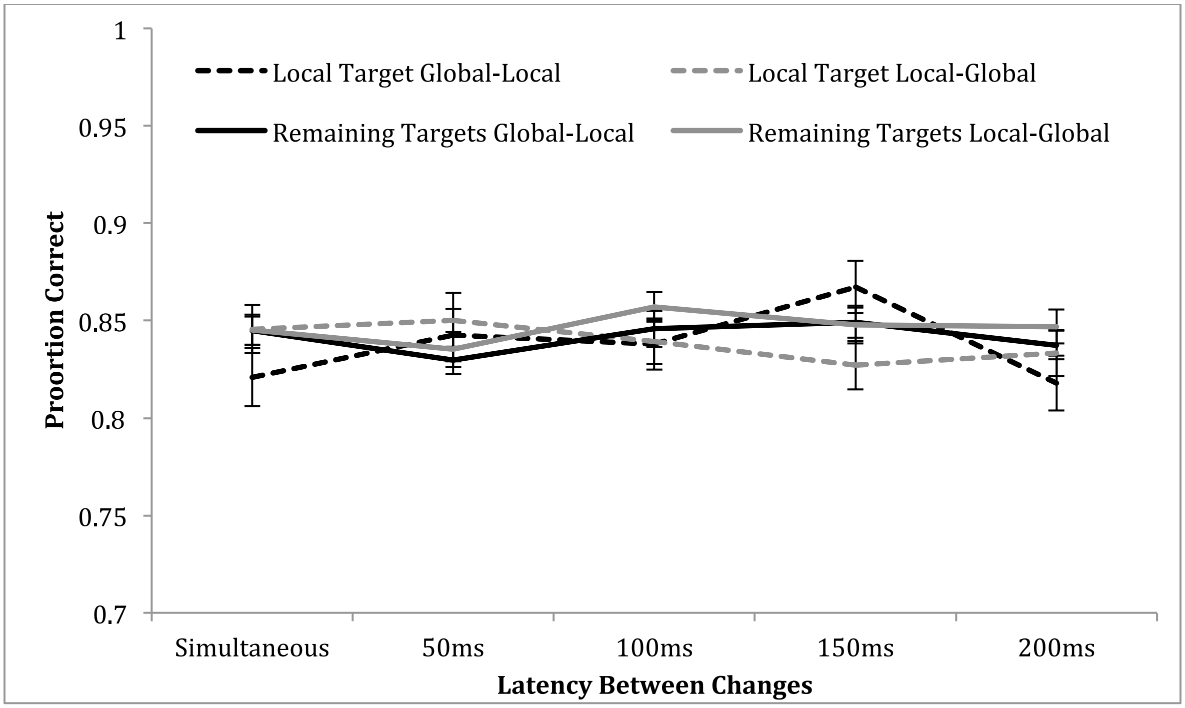


Figure 6:
Experiment 3 Target Type Results. Proportion correct for target type. Either the local target (dotted lines) that changed trajectory or the remaining targets (solid lines) that changed their global trajectory within the *global-local* (black lines) or *local-global* (gray lines) change order. Error bars represent 95% confidence intervals.

4.3 Discussion

The results of Experiment 3 demonstrate no effect of change order on tracking accuracy, *global-local* and *local-global*, regardless of how close in temporal proximity the abrupt changes occur. The lack of any main effects or interactions indicates that all the objects are held in parallel, and do not require a serial component via attentional attraction. It is possible that similar to the FLEX, the amount of attention still on the other items when a local change occurs is enough to detect a global change. This finding does not completely support the hybrid resource model of attentional resources, since no main effect demonstrated the lack of a serial process being used in MOT. Others have already speculated that MOT is solely a parallel process (Howe et al., 2010a); but this finding demonstrates that the allocation of resources occurs in parallel and does not require a serial component. This solely parallel component suggests that the spatial locations of the to-be-tracked objects are constantly being updated and held in working memory, or having the next location predicted via some filter mechanism (Flombaum et al., *2013*; Rieth & Vul, *2013*). However, this finding is inconsistent with other previous findings on temporal updating (Holcombe & Chen, 2013) and attentional attraction (Howard & Holcombe, 2010).

The planned comparisons revealed that a significant difference was present for the local items between the *global-local* and *local-global* change orders. This finding demonstrates that some attentional attraction may be occurring for the local changes in trajectory. Specifically, it demonstrates that the local item changing trajectory benefits when a latency of 150 ms occurs following a global change in trajectory, whereas, if the local change occurs 150 ms prior to the global change there is a loss in tracking accuracy for this particular item. This finding is consistent with the result of Experiment 2, in addition to previous literature on attentional capture (e.g., Posner, 1980; Theeuwes et al., 2000). What makes this finding novel, however, is the demonstration that the global changes can attract attention in a similar manner to a local change in trajectory. Therefore the local target item functions similar to the *pre-latency* target, while the global change is similar to the *post-latency* target of Experiment 2. This suggests that when all the remaining items are being held, they could be represented cognitively as a single unified object (Yantis, 1992), and still cause an attraction of attention. Although the main effect was not significant, the apparent allocation of attention at 150 ms either towards or away from the local trajectory change target still supports the hybrid resource model and the reallocation mechanism of attention. This effect may have just been noise within the data; therefore replication of this finding is needed in future replications.

It is possible that the global changes did not necessarily attract attention the same way that a local change in trajectory does, as seen by the result of Experiment 1. It may have been possible to still see, or even infer, the spatial position of the remaining targets following the global change. That is a global change does not require the same attentional attraction as a local change, or rather allocating attention to a single object, however this seems unlikely due to the lower accuracy for the local target in the *local-global* 150 ms latency condition compared to performance for this target in the *global-local* order. Therefore, another possible explanation could be that during the global change the local change in trajectory was masked, as seen by the lack of any local effect in the simultaneous (0 ms) trials. When a global change occurs it masks the attraction of attention towards the local change target. If this were indeed the case it would imply that when parallel attention is uniform across all the items from a global change that the subsequent local change in trajectory is updated in unison with all the remaining target items simultaneously.

CHAPTER 5. GENERAL DISCUSSION

It has been suggested that attention may be evenly distributed across all target objects in a MOT task, such that this attentional resource for target tracking is flexible based on current task demands (Alvarez & Franconeri, 2007). Meanwhile, others have demonstrated that attentional resources are capable of being reallocated to additional targets during the tracking sequence (Ericson & Christensen, 2012; Wolfe et al., 2007). Errors in tracking accuracy have been attributed to a variety of characteristics such as spatial proximity (Franconeri 2013; Franconeri et al., 2008; Franconeri et al., 2010, 2013), speed (Alvarez & Franconeri, 2007; Holcombe & Chen, 2012), number of distractors (Bettencourt & Somers, 2009), and changes in trajectory (Ericson & Beck, 2013; Ericson et al., *2013; 2014*). However, it is unknown in these dynamic MOT displays how attention may be allocated during potential lapses in tracking ability. The use of trajectory changes allows the capability to highlight single events during the MOT sequence and to pinpoint whether attention is being preferentially allocated to a target that has recently changed direction.

Across three experiments an attempt was made to identify both a global parallel attentional resource as well as a localized serial allocation of attentional resources when a single target changes trajectory. By isolating tracking performance to single events, tracking ability can be assessed and assumptions regarding the attentional mechanisms can be determined for the task. Results demonstrated that a parallel mechanism is being used to track multiple items simultaneously (Experiment 1), but that some serial allocation of resources is attracted during abrupt changes in trajectory (Experiment 2), and that attentional attraction does not occur for global changes in trajectory (Experiment 3).

5.1 A Combined Parallel and Serial Mechanism

The results of this study suggest the use of a hybrid resource model that tracks the targets in parallel until demands require some serial allocation. Experiment 1 confirmed the parallel mechanism in MOT, specifically the main effect demonstrating that global changes in trajectory do not negatively impact tracking ability the same way the local changes in trajectory do. This finding supports a parallel mechanism over a serial mechanism. If a serial mechanism were used a greater loss in performance should have been discovered for the global changes, since all the items changed direction uniformly the serial updating would not have been able to account for this mechanism. Additionally, Experiment 1 failed to replicate the number of changes in trajectory effect (Ericson & Beck, 2013), suggesting that the global motion included in the PMT was in some way negating the number of changes in trajectory effect. This lack of an interaction does not dismiss the hybrid resource model, but rather fails to dismiss other parallel models of attentional tracking, such as the FLEX (Alvarez & Franconeri, 2007).

The results of Experiment 2 demonstrated that an attentional updating mechanism was in play when local changes in trajectory occur within a specific temporal proximity of each other. Results of this experiment demonstrated that how close in time trajectory changes occur negatively influences tracking accuracy. Specifically, when an abrupt trajectory change happens and a subsequent change occurs on another target within 50 ms, tracking accuracy is significantly better for the target that changed trajectory first. This suggests that an attentional attraction occurred and the subsequent, *post-latency*, target was not seen or updated in its change of trajectory. Conversely if the abrupt change for a target happens and the subsequent change on the opposing target occurs at 150 ms, accuracy then suffers for the target that had changed trajectory first. This implies that the attentional attraction had occurred for the first target, but the second abrupt change also attracted attention away from the first target. This finding gives a template for the time frame in which attention can be allocated to a single target and then redistributed back to the remaining target items.

Although Experiment 1 provided evidence for a parallel process in order to successfully complete a MOT task, Experiment 2 demonstrated that some serial component must also be at play in the tracking task. Specifically, if an only parallel mechanism for object tracking were being utilized, performance should have remained equal for all latencies regardless of target type; whereas a serial only mechanism would be expected to lead to differences between each latency for the target type. Instead, the interaction effect suggested that it may be a combination of both processes. This then gives credence to the hybrid resource model. Accordingly, the assumption would be that all items are held in parallel, and that if an abrupt change occurs attention is attracted to this location; if no other change occurs prior to 200 ms from this change then performance would remain unaffected. If a second change occurs prior to 150 ms then attentional allocation remains on the first of the changed item, whereas a change at 150 ms would cause an attentional attraction to the newly changed item.

It is possible to speculate that the result of Experiment 2 was caused by a serial only mechanism. For instance, Holcombe and Chen (2013) found that the serial updating mechanism for tracking to a single target to be approximately 7 Hz, or rather 142 ms. This would coincide nicely with the result found in the current study, however; Holcombe and Chen (2013) found the update rate for three or more targets to be approximately 3 Hz, or rather 333 ms. Therefore the updating mechanism outlined by Holcombe and Chen (2013) would not be fast enough to account for the results found here. Specifically, the *pre-latency* target accuracy at 50 ms and the *post-latency* target accuracy at 150 ms could not be easily accounted for. Instead the predominantly parallel process with a fast allocation and redistribution of attention across all the targets as outlined in the hybrid resource model seems to be the likely mechanism.

The lack of a main effect for change order or latency in Experiment 3 calls into question the actual utility of the hybrid resource model. The hybrid resource model would have predicted some trade off between the *local-global* changes in trajectory, as the attentional resources would have been allocated preferentially to the local target. However, the result from this experiment instead suggests a parallel only model, most likely the FLEX (Alvarez & Franconeri, 2007). However, the significant effect at 150 ms of the local change trajectory item having a higher accuracy performance when the local change followed the global change in trajectory demonstrates that there is some serial attraction of attention. In addition, the lower local change performance at this latency when the local change preceded the global change demonstrates that the global, or parallel, change can also attract attention. This suggests that when held in parallel the items function as a unified whole (Yantis, 1992). It is possible that at higher tracking speeds, this effect would then exacerbate itself further, as the tradeoff from the change order would be more apparent. Therefore, although the main effect was not found, it would be premature to dismiss the hybrid resource model as a potential tracking mechanism, as other stimulus factors could have caused the lack of effect.

The findings from this study contradict several previous hypotheses regarding how tracking is performed. The results from Experiment 2 demonstrate that local changes in trajectory can disrupt tracking ability, which is problematic for the spatial interference hypothesis (Franconeri, 2013). Because the experimental design holds all the objects at a specific spatial proximity the spatial interference explanation is nullified. Second, results from Experiment 2 negate a parallel-only hypothesis (Howe et al., 2010) as the changes in trajectory attract attention, providing evidence towards a serial component to object tracking. In addition the results of Experiment 2 demonstrated that a serial shift may be occurring because tracking performance was affected by on the temporal proximity of two changes occurring near each other. Finally, the results found in Experiment 1 and Experiment 3 refute a serial-only account for tracking (Holcombe & Chen, 2013; Oksama & Hyönä, 2008; Tripathy et al. 2011) since the local change followed by global change, at 150 ms, demonstrated that attention was attracted back to the global items in unison.

5.2 Future Directions

There are several issues that should be addressed in future studies regarding this research. First, there is no clear evidence either for or against the proposed hybrid resource model. For instance, Experiments 1 and 3 provide support for a parallel process, while Experiment 2 seems more supportive of a serial updating mechanism. The cause for this is currently unknown; however one way to address this issue of the items held in parallel, and how to weaken the representation of each target, would be to increase the number of targets (for example, from four to six). By doing so the distribution of attention would be spread across more targets, thus when a change in trajectory occurs, the attraction of attention would weaken the representation of each object greater than when tracking fewer targets. This would result in overall lower tracking accuracy as the number of changes in trajectory increased. Another potential investigation would be to increase the rotational speed of the target items. As mentioned previously the global rotation and the local rotation give the perception of a brief pause when the rotational movements change and become congruent. By increasing the rotational speed it may be possible to alleviate this slowing-down perception, thus potentially finding the change in trajectory effect. This would then make the attraction tradeoff for the change order, from global to local and vice versa from Experiment 3 more apparent. Finally, one option, particularly with Experiment 1, would be to block trials by change type, either local or global changes. It is possible that the differing types of changes may require a specific attentional set. By eliminating expectations of the participant to either one attentional set, global or local, over another, it may be possible to identify the change in trajectory effect. Regardless of the suggestion or changes to methodology outlined here, there still remains uncertainty regarding the processes used in order to successfully track multiple moving targets simultaneously.

The contribution of this work is two-fold; first the applications extend themselves to many applied areas of the cognitive sciences. For instance, driving research could use this information to incorporate fewer localized changes in a driver's immediate area (speedometer, odometer, radio, etc.) to prevent shifts of attentional resources. Sports science can use this information in order to improve performance in ball sports, for both ball movement and for player/teammate movement, as the movement of a single object may pull attention away from the broader game plan. In addition, applications for current user interfaces and novel displays could be used such as website design, robotics tracking, or other various heads up displays; such that understanding how an individual can multi-task on tablets or other devices may help direct or influence task prioritization.

Second, this research lends itself to understanding the underlying mechanisms of attention. Specifically previous hypotheses have been proposed that attention towards tracked items is conducted in parallel and is limited by some fixed number of items (Pylyshyn, 2001) or that there is a distributed resource capacity limitation (Alvarez & Franconeri, 2007). This research extends the findings of the distributed resource, but implies that a hybrid resource mechanism is used such that serial shifts towards specific targets are accounted for via a redistribution process for attention. This dynamic resource reallocation of attention via a hybrid system represents a new step in understanding the cognitive underpinnings of attentional processes.

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APPENDIX. INSTITUTIONAL REVIEW BOARD APPORVAL FORMS

Application for Exemption from Institutional Oversight

Unless qualified as meeting the specific criteria for exemption from Institutional Review Board (IRB) oversight, ALL LSU research/projects using living humans as subjects, or samples or data obtained from humans, directly or indirectly, with or without their consent, must be approved or exempted in advance by the LSU IRB. This Form helps the PI determine if a project may be exempted, and is used to request an exemption.

Institutional Review Board
Dr. Robert Mathews, Chair
203 B-1 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.6792
irb@lsu.edu | lsu.edu/irb

➢ Applicant, Please fill out the application in its entirety and include the completed application as well as parts A-E, listed below, when submitting to the IRB. Once the application is completed, please submit two copies of the completed application to the IRB Office or to a member of the Human Subjects Screening Committee. Members of this committee can be found at http://www.lsu.edu/irb/screeningmembers.shtml

➢ A Complete Application Includes All of the Following:
- **(A)** Two copies of this completed form and two copies of parts B thru E.
- **(B)** A brief project description (adequate to evaluate risks to subjects and to explain your responses to Parts 1 & 2)
- **(C)** Copies of all instruments to be used.
  - •If this proposal is part of a grant proposal, include a copy of the proposal and all recruitment material.
- **(D)** The consent form that you will use in the study (see part 3 for more information.)
- **(E)** Certificate of Completion of Human Subjects Protection Training for all personnel involved in the project, including students who are involved with testing or handling data, unless already on file with the IRB. Training link: (http://phrp.nihtraining.com/users/login.php.)

1) Principal Investigator: Melissa R. Beck **Rank:** Assistant Professor **Student*? Y/N** N

Dept.: Psychology **Ph:** 578-7214 **E-mail:** mbeck@lsu.edu

2) Co Investigator(s): please include department, rank, phone and e-mail for each
* If student, please identify and name supervising professor in this space
Justin Ericson, Psychology, Grad Student, 36-6588, jerics1@lsu.edu

3) Project Title: Tracking Objects

4) LSU Proposal?(yes or no) N **If Yes, LSU Proposal Number** ______

Also, if YES, either ◯ **This application completely matches the scope of work in the grant**
OR
◯ **More IRB Applications will be filed later**

5) Subject pool (e.g. Psychology Students) Psychology Students in Subject Pool
•Circle any **"vulnerable populations" to be used**: (children <18; the mentally impaired, pregnant women, the aged, other). Projects with incarcerated persons cannot be exempted.

6) PI Signature M. R. Beck **** Date** 1/11/10 (no per signatures)
****I certify my responses are accurate and complete.** If the project scope or design is later changed I will resubmit for review. I will obtain written approval from the Authorized Representative of all non-LSU institutions in which the study is conducted. I also understand that it is my responsibility to maintain copies of all consent forms at LSU for three years after completion of the study. If I leave LSU before that time the consent forms should be preserved in the Departmental Office.

Study Exempted By:
Dr. Robert C. Mathews, Chairman
Institutional Review Board
Louisiana State University
203 B-1 David Boyd Hall
225-578-8692 | www.lsu.edu/irb
Exemption Expires: 1-10-2013

IRB# E4899 LSU Proposal# ______
☒ Complete Application
☒ Human Subjects Training

Screening Committee Action: Exempted ✓ Not Exempted ____ Category/Paragraph 2
Reviewer Mathews **Signature** Robert Mathews **Date** 1/11/10

Project Report and Continuation Application

(Complete and return to IRB, 131 David Boyd Hall, Direct questions go to IRB Chairman Robert Mathews 578-8692.)

Institutional Review Board
Dr. Robert Mathews, Chair
131 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
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IRB#: E4899 **Current Approval Expires On:** 1/10/2013

Review Type: Exempt **Risk Factor:** None

PI: Dr. Melissa R. Beck **Dept:** Psychology **Phone:** 578-7214

Student/Co-Investigator: Jusitn M. Ericson

Project Title: Tracking Objects

Number of Subjects Authorized: 300

Please read the entire application. Missing information will delay approval!

IRB Security of Data Agreement: http://research.lsu.edu/files/item26774.pdf

I. PROJECT FUNDED BY: ______ LSU Proposal #: ______

II. PROJECT STATUS: Check the appropriate blank(s) and complete the following:

- (●) 1. **Active,** subject **enrollment continuing;** # subjects enrolled: 150
- ( ) 2. **Active,** subject **enrollment complete;** # subjects enrolled: ______
- ( ) 3. **Active,** subject **enrollment complete;** work with subjects continues.
- ( ) 4. **Active, work with subjects complete;** data analysis in progress.
- ( ) 5. Project **start postponed;** date: ______
- ( ) 7. **Project cancelled:** no human subjects used.
- ( ) 6. **Project complete;** end date: ______

III. PROTOCOL: (Check one).

- (●) Protocol continues as previously approved
- ( ) Changes are requested*
  - --*List (on separate sheet) any changes to approved protocol.*

IV. UNEXPECTED PROBLEMS: (did anything occur that increased risks to participants):

--State number of events since study inception: 0 since last report: 0
--If such events occured, describe them and how they affect risks in your study, in an attached report
--Have there been any **previously unreported** events? Yes/No: No

V. CONSENT FORM AND RISK/BENEFIT RATIO:

Do new knowledge or adverse events change the risk/benefit ratio? Yes/No: No
Is a corresponding change in the consent form needed? Yes/No: No

VI. ATTACH A BRIEF, FACTUAL SUMMARY of project progress/results to show continued participation of subjects is justified; or to provide a final report on project findings.

VII. ATTACH CURRENT CONSENT FORM (only if subject enrollment is continuing); and check the appropriate blank;

- (●) 1. Form is unchanged since last approved
- ( ) 2. Approval of revision requested herewith: (identify changes)

Signature of Principle Investigator: [signature] **Date:** 1/7/13

IRB Action: ✓ Continuation approved; ___ Disapproved ___ File Closed **Approval Expires:** 1/7/16

Signed [signature] Date 1/8/13

Study Exempted By:
Dr. Robert C. Mathews, Chairman
Institutional Review Board
Louisiana State University
203 B-1 David Boyd Hall
225-578-8692 | www.lsu.edu/irb
Exemption Expires: 1/7/2016

Consent Form

1. Study Title: Tracking Objects

2. Performance Site: Louisiana State University and Agricultural and Mechanical College

3. Investigators: The following investigators are available for questions about this study, M-F, 8:00 a.m. - 4:30 p.m: Dr. Melissa Beck, 578-7214, mbeck@lsu.edu; Justin Ericson, jerics1@lsu.edu

4. Purpose of the Study: This study investigates how accurate participants are at tracking moving objects

5. Subject Inclusion: Individuals between the ages of 18 and 65 with normal or corrected to normal vision

6. Number of subjects: 150

7. Study Procedures: The study will take approximately 30 to 60 minutes to complete. Participants will be asked to look at a visual display and answer various questions about the items on the screen.

8. Benefits: This study will advance research on how individuals follow moving objects.

9. Risks: There are no foreseeable risks of participation.

10. Right to Refuse: Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.

11. Privacy: Results of the study may be published, but no names or identifying information will be included in the publication. Subject identity will remain confidential unless disclosure is required by law.

12. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Robert C. Mathews, Institutional Review Board, (225) 578-8692. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of this consent form.

Signature of Subject______________________________ Date_______________

VITA

Justin Merrill Ericson, a native of Dearborn, Michigan, received his bachelor's degree from Purdue University in May 2005. Upon graduation, Justin began work at Vanderbilt University, where his research interests in visual perception and attention began to develop. Justin later enrolled at the University of Dayton in order to attain his Master of Arts. While working on his thesis, Justin was also awarded a research fellowship working with the Air Force Research Laboratories at Wright-Patterson Air Force Base. Following his graduation from the University of Dayton in August 2009, Justin enrolled in the doctoral psychology program at Louisiana State University. Here he researched aspects of visual perception and attention, particularly multiple-object tracking, visual search, and global precedence. While studying at Louisiana State University, Justin was awarded a research fellowship with the Gulf Coast Center for Evacuation and Transportation Resiliency in order to investigate inattentional blindness while driving motor vehicles. Following his commencement from Louisiana State University, Justin is beginning a Post-Doctoral fellowship at Duke University.