Tracking by location and features: Object correspondence across spatiotemporal discontinuities during multiple object tracking

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Abstract

We examined whether surface feature information is utilized to track the locations of multiple objects. In particular, we tested whether surface features and spatiotemporal information are weighted according to their availability and reliability. Accordingly, we hypothesized that surface features should affect location tracking across spatiotemporal discontinuities. Three kinds of spatiotemporal discontinuities were implemented across five experiments: abrupt scene rotations, abrupt zooms, and a reduced presentation frame rate. Objects were briefly colored across the spatiotemporal discontinuity. Distinct coloring that matched spatiotemporal information across the discontinuity improved tracking performance as compared with homogeneous coloring. Swapping distinct colors across the discontinuity impaired performance. Correspondence by color was further demonstrated by more mis-selected distractors appearing in a former target color than distractors appearing in a former distractor color in the swap condition. This was true even when color never supported tracking and when participants were instructed to ignore color. Furthermore, effects of object color on tracking occurred with unreliable spatiotemporal information but not with reliable spatiotemporal information. Our results demonstrate that surface feature information can be utilized to track the locations of multiple objects. This is in contrast to theories stating that objects are tracked based on spatiotemporal information only. We introduce a flexible-weighting tracking account stating that spatiotemporal information and surface features are both utilized by the location tracking mechanism. The two sources of information are weighted according to their availability and reliability. Surface feature effects on tracking are particularly likely when distinct surface feature information is available and spatiotemporal information is unreliable.

Keywords: multiple-object tracking, object correspondence, surface features, object color, visual attention

While playing or watching team sports, driving a car, or watching children on playgrounds, human observers need to track multiple moving objects simultaneously. Observers are fairly good at this task even when only spatiotemporal information is available as has been repeatedly shown using the multiple object tracking paradigm (MOT; Pylyshyn & Storm, 1988). During MOT, observers usually track a number of targets among indistinguishable distractors. In the daily environment, however, objects have more distinguishing features than spatiotemporal information only, such as color, shape, or size. With the present research we examined to what extent and under which conditions tracking might also utilize feature information, more specifically object color, in addition to spatiotemporal information.

Since the first demonstration that observers can track up to four or five independently moving target objects among indistinguishable distractor objects (Pylyshyn & Storm, 1988), many studies have examined the nature of the mechanism underlying this ability. Because of the nature of this task, many studies focused on the spatiotemporal information present in the tracking display instead of object features. Typical results show that the tracking ability is influenced by object speed (Alvarez & Franconeri, 2007; Feria, 2013; Holcombe & Chen, 2012; Huff, Papenmeier, Jahn, & Hesse, 2010; Tombu & Seiffert, 2011), inter-object spacing (Franconeri, Jonathan, & Scimeca, 2010; Franconeri, Lin, Pylyshyn, Fischer, & Enns, 2008; Shim, Alvarez, & Jiang, 2008), the spatiotemporal stability of the tracking display (Huff, Jahn, & Schwan, 2009; Jahn, Papenmeier, Meyerhoff, & Huff, 2012; Meyerhoff, Huff, Papenmeier, Jahn, & Schwan, 2011), motion information (Fencsik, Klieger, & Horowitz, 2007; Huff & Papenmeier, 2013; Iordanescu, Grabowecky, & Suzuki, 2009; St.Clair, Huff, & Seiffert, 2010), or concurrent task demands (Allen, McGeorge, Pearson, & Milne, 2006; Huff, Papenmeier, & Zacks, 2012; Tombu & Seiffert, 2008). This strong focus on spatiotemporal information is also reflected in explanations of MOT. Tracking is either described as a limited number of *feature-blind* visual indices sticking to target objects (e.g., Pylyshyn, 1989, 2007), or a single (Oksama & Hyönä, 2008) or multiple attentional spotlights (Cavanagh & Alvarez, 2005) directed towards the *locations* of tracked objects with the spotlight locations updated as needed.

There is an increasing amount of research considering the role of surface features during tracking. Whereas some studies focused on individual differences when tracking locations or identities (Oksama & Hyönä, 2004), other studies focused on identity-location bindings during tracking and showed that observers are better at tracking object locations than object identities (Horowitz et al., 2007; Pylyshyn, 2004). This coincides with studies showing that the maintenance of feature-location bindings through object motion is effortful and error-prone (Cohen, Pinto, Howe, & Horowitz, 2011; Oksama & Hyönä, 2008; Pinto, Howe, Cohen, & Horowitz, 2010; Saiki, 2003a, 2003b). These results have been taken as evidence that spatiotemporal and identity information of tracked objects might be processed by two separate systems (Botterill, Allen, & McGeorge, 2011; Horowitz et al., 2007).

Other studies, however, have shown that feature information can influence the ability to track multiple objects (Bae & Flombaum, 2012; Cohen et al., 2011; Drew, Horowitz & Vogel, 2013; Horowitz et al., 2007; Howe & Holcombe, 2012; Liu & Chen, 2012; Makovski & Jiang, 2009a, 2009b; Ren, Chen, Liu, & Fu, 2009). For example, tracking multiple objects that are separated by distinct surface features is easier than tracking indistinguishable objects (Bae & Flombaum, 2012; Drew et al., 2013; Horowitz et al., 2007; Makovski & Jiang, 2009a, 2009b). This tracking benefit is explained by an effortful target recovery process. Whenever a target object is lost, it can be recovered based on the color information stored in visual working memory (Makovski & Jiang, 2009b). This suggests that surface features contribute to tracking in a strategic fashion. However, a recent study suggests that the processing of surface features of tracked objects draws on the same resource as processing the spatiotemporal information of tracked objects during difficult tracking tasks (Cohen et al., 2011). This suggests that location tracking that has so far been considered to have access to spatiotemporal information only might also be able to access surface features when needed. With the present work, we investigate whether surface features are utilized to track the locations of multiple objects in a non-strategic way.

In order to study whether location tracking draws on feature information in addition to spatiotemporal information, we conceptualized MOT as a correspondence problem (Pylyshyn, 2004) and successful tracking as the establishment of object correspondence over time. Studying the literature on the correspondence problem and the role of spatiotemporal information and surface feature information in solving it shows an interesting analogy to the MOT literature. Whereas earlier research focused on spatiotemporal information (e.g., Kahneman, Treisman, & Gibbs, 1992), recent literature provided evidence for surface feature effects (e.g., Hollingworth & Franconeri, 2009; Moore, Stephens, & Hein, 2010).

One paradigm for studying object correspondence is the object reviewing paradigm (Kahneman et al., 1992). During a preview phase, letters are presented on objects. The letters disappear and the objects move. When a matching test letter appears on an object, faster naming of this letter demonstrates object correspondence by motion, which is correspondence by spatiotemporal information. There are studies suggesting that surface features might be insufficient to establish object correspondence in such situations (Mitroff & Alvarez, 2007). These results are qualified by recent findings showing that surface features and spatiotemporal information are both used to establish correspondence across brief occlusions (Hollingworth &

Franconeri, 2009) or eye movements (Richard, Luck, & Hollingworth, 2008). In some experiments, correspondence by object color was found even when it contradicted spatiotemporal information (Hollingworth & Franconeri, 2009; Moore et al., 2010). Interestingly, most experiments used object displacements in order to study the effects of surface features on object correspondence.

A whole line of research studying object correspondence across object displacements concerns apparent motion and related phenomena. Stimuli are shown at different locations with varying distances and timings of onsets and offsets leading to the perception of either distinct stimuli or motion between the two stimulus locations (e.g., Kahneman & Wolman, 1970; Lappin & Bell, 1976). The perception of motion indicates the successful establishment of object correspondence across the two stimulus locations. Besides spatiotemporal properties, surface feature information has been found to influence the perception of apparent motion too (Shechter, Hochstein, & Hillman, 1988). The manipulation of surface features can also disambiguate displays with ambiguous spatiotemporal information, for example changing the perception of two objects as either bouncing or not while they briefly disappear behind an occluder (Feldman & Tremoulet, 2006).

Recently, the role of surface features for correspondence in apparent motion was again examined using the Ternus display (Hein & Cavanagh, 2012; Hein & Moore, 2012; Petersik & Rice, 2008). The Ternus display (Ternus, 1926) consists of three horizontally aligned objects. One of the outer objects alternates between two positions to the left and right of the other two static objects. Between any two states a blank is shown. Depending on the timing of the blank (e.g., Hein & Moore, 2012), correspondence can be established in two distinct ways resulting in differing perceived apparent motion. Either the outer object might be perceived as jumping between the two outer positions resulting in so called element motion; or the whole pattern may be perceived as shifting back and forth horizontally, the so called group motion. Using these displays it has been shown that varying the distribution of object features across objects and the two alternating display states can have a strong influence on the perception of either element motion or group motion and therefore the underlying process determining correspondence (Hein & Cavanagh, 2012; Hein & Moore, 2012; Petersik & Rice, 2008).

A fine grained analysis of the influence of different object features on the perceived apparent motion was done by Hein and Moore (2012). Besides showing a strong effect of surface features on perceived apparent motion and therefore the establishment of object correspondence, they showed that correspondence can also be established based on similar instead of identical surface features. Most important to our present experiments, Hein and Moore (2012) suggest a *flexible-weighting view* for the use of spatiotemporal information and feature information for object correspondence. That is, both sources of information are used to establish object correspondence and are weighted according to the kind of information available. The less similar the features of an object between two states are, the less it is used to establish correspondence. The same is true for spatiotemporal information. Because the Ternus display is ambiguous as to whether correspondence based on spatiotemporal information is due to group motion or element motion, surface features are used to establish object correspondence resulting in strong feature effects.

Applying this flexible-weighting view (Hein & Moore, 2012) to MOT leads to the interesting prediction that object correspondence and therefore tracking should be particularly influenced by surface features when spatiotemporal information is unreliable, thus receiving a lower weight by the correspondence mechanism. First evidence that this might be true for MOT can be derived from previous research studying surface feature effects across varying target-distractor distances. Whenever targets get close to distractors, spatiotemporal information is a less reliable source of information for distinguishing targets from distractors. In line with the flexible-weighting view, tracking targets is facilitated by uniquely colored distractor objects whenever targets get close to distractors and the color can help distinguish the targets from the nontargets (Bae & Flombaum, 2011). Furthermore, the effect of higher tracking performance with distinct object colors than homogeneous object colors is more pronounced in trials with a lower minimal target-distractor distance (Makovski & Jiang, 2009b). However, the former experiments were particularly concerned with distractor features and the later experiments with a strategic recovery of targets based on visual short-term memory.

With the present set of experiments, we designed three different tracking displays to test the hypothesis that surface features might be utilized to track the locations of multiple objects in situations of weaker spatiotemporal information. In particular, we designed tracking displays that introduced abrupt spatiotemporal discontinuities in a way that still allowed for solving the tracking task based on spatiotemporal information. The critical manipulation was whether objects were colored in a way that either matched with or differed from the spatiotemporal solution of the correspondence problem. Tracking performance was evaluated regarding the spatiotemporal solution of object correspondence across the spatiotemporal discontinuity. We hypothesized that tracking performance should be higher when the coloring matches with the spatiotemporal information and that it should be lower when it differs from the spatiotemporal information as compared with a control condition with homogeneous colors. In addition, specific tracking errors should occur with differing color information. We should observe a reliable number of responses that are based on the target color information instead of the targets' spatiotemporal information.

Experiment 1

In Experiments 1 and 2 we used abrupt scene rotations as spatiotemporal discontinuities. Abrupt scene rotations impair tracking performance as has been shown in multiple studies (e.g., Huff et al., 2009; Jahn et al., 2012). If tracking multiple locations utilizes surface features in addition to spatiotemporal information across spatiotemporal discontinuities, the brief presentation of object colors around the rotation should influence tracking performance. In particular, tracking performance should be higher with distinct object colors matching with spatiotemporal information across the rotation than homogeneous color. Furthermore, distinct colors that swap between objects across the rotation conflict with spatiotemporal information and should therefore impair tracking performance. When distinct colors are swapped, correspondence by color should cause a bias of responses towards selecting more distractor objects appearing in a former target color than distractor objects appearing in a former distractor color.

Method

Participants

Twenty students from the Knowledge Media Research Center's participants pool took part in exchange for monetary compensation or course credit. All participants reported normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were presented on a 15.4" HP EliteBook 8530p with an ATI Mobility Radeon HD 3650 graphics card. Stimuli were generated using the Blender Game Engine and custom software written in Python. Nine white spheres with black outlines moved on a gray floor plane (see Figure 1; see also http://www.iwm-kmrc.de/cybermedia/mot-features/). The spheres had a diameter of 0.6 to 1.1 degrees of visual angle (deg) on the screen depending on their position on the floor plane. The floor plane (13.2 to 23.1 deg horizontally; 6.3 deg vertically) was presented against a black background from a viewpoint of 20 degrees above the floor plane. Spheres moved at a speed of 2 deg/s when moving horizontally in the middle of the floor plane. Speed on screen varied depending on the spheres' positions on the floor plane. Spheres moved at linear trajectories. Colors were selected from the HSV color space. Saturation and value were set to 1.0 and hue varied between 0 and 320 degrees in steps of 40 degrees resulting in nine colors. The viewing distance was 55 cm.

Procedure and Design

Trials began with three targets being designated by flashing red four times within 1.6 s and remaining red for another two seconds. Thereafter, targets turned to white and all objects began to move. Participants tracked the target objects among indistinguishable distractor objects for six seconds. At the end of each trial, they marked the three targets with the mouse and guessed when uncertain. Participants received feedback on their performance after every trial.

An abrupt scene rotation occurred three seconds after motion onset. The scene rotated 30 degrees around the axis that is perpendicular to the floor plane at the center of the floor plane (left vs. right direction counter-balanced). All objects were colored for 500 ms before and 500 ms after the scene rotation. Coloring was smooth with the color fading in or out by increasing or decreasing its saturation value from 0.0 to 1.0 for 150 ms before and after the color change. There were three coloring conditions. In the *homogeneous* condition, all objects were colored with the same color. The color was randomly selected from the list of possible distinct color values. In the *distinct match* condition, each object was colored with a distinct color and stayed the same across the scene rotation. In the *distinct swap* condition, each object was colored with a distinct color. However, objects swapped their colors across the scene rotation with the following restrictions: Objects did not receive their former color and targets did not receive a former target color. Participants were instructed to track the initially marked target objects as they moved and to ignore object color. They were informed that the scene would abruptly rotate during object motion and that objects could change their color.

This resulted in a one-factorial (object color: homogeneous, distinct match, distinct swap) within-subjects design with 20 repetitions per condition. Participants performed 18 practice trials before performing the 60 experimental trials. All conditions were presented in random order throughout the experiment and the conditions in the practice trials were balanced according to the experimental design.

Results and Discussion

Tracking performance was measured as the proportion of correctly identified targets as defined by the allocentric coordinate system that was preserved across the scene rotation. In order to account for the fact that tracking performance was analyzed as proportional data, all analyses on tracking performance reported in the present manuscript were performed after applying an arcsine transformation to the proportion correct values.

Distinct color matching across the scene rotation improved tracking performance (see Figure 2). Swapping the distinct colors after rotation impaired tracking performance. This was confirmed by a repeated-measures ANOVA including the factor object color. Tracking performance varied significantly across object color conditions, $F(1.48, 28.12) = 52.24$, $p < .001$, $\eta_p^2 = .73$ (Greenhouse–Geisser corrected degrees of freedom due to deviance from sphericity).

Planned contrasts using paired *t*-tests confirmed that all three object color conditions differed significantly from one another, all ps < .001.

Analyzing the distinct swap condition showed that participants marked more distractors appearing in a former target color (M = 0.99, SE = 0.10) than distractors appearing in a former distractor color (M = 0.57, SE = 0.04) as confirmed by a paired *t*-test, $t(19) = 4.88$, $p < .001$. This indicates that participants established correspondence based on object color across the scene rotation.

The results of Experiment 1 demonstrate that the brief presentation of object colors around a scene rotation influences tracking performance. This is in contrast to the view that tracking multiple objects is based on spatiotemporal information only. Although this provides first evidence that location tracking might utilize object color in situations of unreliable spatiotemporal information, an alternative explanation remains possible. That is, object color might have been used in a strategic manner. A strategy of always relying on object color would result in a mean performance of about 50 percent correct because there was an equal number of distinct match trials and distinct swap trials in Experiment 1. Because 50 percent correct is above chance, relying on object color was not against the observer's interest and could have produced the observed pattern of results. In order to exclude this alternative explanation, we removed the distinct match trials in Experiment 2.

Experiment 2

Results of Experiment 1 provide first evidence that location tracking might utilize object color in situations of unreliable spatiotemporal information. In order to exclude the possibility that object color was used in a strategic fashion only, we removed the distinct match condition in the present experiment. Therefore, relying on distinct color information did never support tracking and was harmful to tracking on half of the trials. Additionally, we instructed participants to ignore object color and participants received feedback about their performance at the end of each trial. If we still observe effects of object color on location tracking performance this would provide evidence that surface features are used in a non-strategic way in our displays.

Method

Participants

Twenty new students were recruited.

Procedure and Design

The same procedure as in Experiment 1 was used unless noted otherwise. The distinct match condition was removed. Participants were instructed to ignore object color changes and that objects would swap colors or be homogeneous after the scene rotation. Thus, participants were informed that considering color information would impair performance.

These changes resulted in a one-factorial (object color: homogeneous, distinct swap) within-subjects design with 20 repetitions per condition. Participants performed 12 practice trials before performing 40 experimental trials.

Results and Discussion

Object color was manipulated such that relying on object color would be harmful to location tracking performance in half of the trials and that it did not support tracking in any trial. Furthermore, participants received feedback on their performance after every trial as in all other experiments. This should prevent any strategic use of object color. Furthermore, participants were instructed to ignore object color. Nonetheless, tracking performance was lower with distinct swapped colors than homogeneous color (see Figure 3) as confirmed by a repeated-measures ANOVA including the factor object color, $F(1, 19) = 36.96$, $p < .001$, $\eta_p^2 = .66$. Analyzing the distinct swap condition showed that participants marked more distractors appearing in a former target color (M = 0.84, SE = 0.06) than distractors appearing in a former distractor color (M = 0.57, SE = 0.05) as confirmed by a paired t-test, $t(19) = 4.12$, $p = .001$. The present results replicate Experiment 1 and provide evidence that surface feature information is used in a non-strategic way when tracking across spatiotemporal discontinuities.

In Experiments 1 and 2, objects were colored just before the scene rotation. Therefore, it might be possible that the utilization of object color is restricted to brief intervals following color onsets. We ran a control experiment that was identical to the present experiment with the exception that color onset occurred at the beginning of each trial such that the objects were colored for three seconds before the scene rotation occurred. The pattern of results was identical to the present experiment suggesting that object color is available to the tracking mechanism throughout a trial and not only immediately after color onset.

Experiment 3

In Experiments 1 and 2, we used abrupt scene rotations in order to create spatiotemporal discontinuities. This kind of manipulation does not only create spatiotemporal uncertainty but also changes the spatial configuration of the objects on the screen. In order to control for changes in spatial configurations on the screen, we used abrupt zooms in Experiment 3 instead. The spatial configuration of the targets on the screen remains intact across zooms. Nonetheless, zooming creates spatiotemporal discontinuities. According to the flexible-weighting view, we should observe a similar pattern of color effects as in Experiment 1.

Method

Participants

Twenty new students were recruited.

Apparatus and Stimuli

Abrupt zooms were used instead of abrupt scene rotations. The first zoom level was identical to Experiment 1. Object speed was set to 8 deg/s when moving horizontally in the middle of the floor plane. Object speed was set to a value that we expected to produce neither floor effects nor ceiling effects on tracking performance. At the second zoom level, the scene was presented further distant and therefore smaller (sphere diameter: 0.4 to 0.6 deg; floor plane: 8.6 to 11.9 deg horizontally, 3.5 deg vertically; object speed: 4.7 deg/s when moving horizontally in the middle of the floor plane; see Figure 4).

Procedure and Design

The same procedure as in Experiment 1 was used unless noted otherwise. The scene started either in the zoomed in state or zoomed out state (counter-balanced across trials) and abruptly changed its zoom level to the other state three seconds after motion onset. Participants were instructed that object color was irrelevant for their task. Object color was manipulated at three levels as in Experiment 1 resulting in a one-factorial (object color: homogeneous, distinct match, distinct swap) within-subjects design with 40 repetitions per condition. Participants performed 18 practice trials before performing 120 experimental trials.

Results and Discussion

The results replicated our findings from Experiments 1 and 2. Furthermore, they showed color effects with abrupt changes that did not change the spatial configuration of the objects on the screen. As in Experiment 1, distinct color matching across the zoom improved tracking performance and swapping the distinct colors after the zoom impaired tracking performance (see Figure 5). This was confirmed by a repeated-measures ANOVA including the factor object color. Tracking performance varied significantly across object color conditions, $F(2, 38) = 25.84$, $p <$

.001, $\eta_p^2 = .58$. Planned contrasts using paired *t*-tests confirmed that all three object color conditions differed significantly from one another, all $ps \leq .026$.

Analyzing the distinct swap condition showed that participants marked more distractors appearing in a former target color ($M = 0.71$, $SE = 0.04$) than distractors appearing in a former distractor color ($M = 0.58$, $SE = 0.04$) as confirmed by a paired *t*-test, $t(19) = 3.96$, $p = .001$. This confirms that participants established correspondence based on object color across the abrupt zoom.

Experiment 4

Experiment 4 was designed to investigate two questions. First, we investigated whether the color effects on tracking can also be observed with spatiotemporal discontinuities that do not change the reference frame. Abrupt rotations used in Experiments 1 and 2 changed the orientation of the tracking display and abrupt zooms used in Experiment 3 changed the size of the tracking display. Second, we investigated whether color conditions that had previously been shown not to influence tracking could be modified to influence tracking nonetheless. According to the flexible-weighting view this should be possible by reducing the precision of the spatiotemporal information in the tracking display and thereby increasing the relative weight of surface features.

According to previous findings, participants show a higher tracking performance with distinct object colors than homogeneous object colors only when objects keep their same color throughout a trial (Makovski & Jiang, 2009b). When objects had changed their colors every 500 ms in a way that still kept them distinct from one another at any point in time, the effect of object color had disappeared. Makovski & Jiang (2009b) argued that color information is used in a strategic manner based on visual short-term memory. When objects change their colors every 500 ms, the use of this effortful strategy might be abandoned.

In Experiment 4, objects changed their color every 500 ms. In addition, we introduced spatiotemporal discontinuities every 500 ms. Color information changed either at the time of the discontinuities or between two discontinuities. If introducing spatiotemporal discontinuities results in the use of surface features as predicted by the flexible-weighting view, we should observe color effects. In particular, color changes at the time of spatiotemporal discontinuities should impair tracking because object color and spatiotemporal information provide conflicting information. Improved tracking performance should be observed with color changes between two discontinuities because color information stays intact across the spatiotemporal discontinuity and matches with spatiotemporal information.

Method

Participants

Twenty new students were recruited.

Apparatus and Stimuli

The same stimuli as in Experiment 1 were used. The viewpoint on the scene was the same as in Experiment 1 before the scene rotation. It remained fixed throughout the present experiment. Object speed was set to 3 deg/s when moving horizontally in the middle of the floor plane. Object speed was set to a value that we expected to produce neither floor effects nor ceiling effects on tracking performance.

Procedure and Design

The target designation phase and response phase were the same as in Experiment 1. In contrast to Experiments 1 to 3, object motion was manipulated. It was smooth at 60 frames per second within the first 500 ms and last 1000 ms of the movement phase. In between, a reduced presentation frame rate of 2 frames per second was simulated. Participants saw a sequence of alternation between objects remaining stationary at their present position for 500 ms then being abruptly displayed at their next position resulting from their speed and linear trajectory, being stationary for 500 ms again, and so on (for a movie, see http://www.iwm-kmrc.de/cybermedia/mot-features/). The abrupt jumps introduced spatiotemporal discontinuities within a tracking task not including any changes in viewpoint nor to the reference frame.

We manipulated color changes such that they occurred either at the time of spatiotemporal discontinuities or between the discontinuities (see Figure 6), and such that object color was either homogeneous or distinct. In the condition with *color changes at the time of spatiotemporal discontinuities*, objects were colored in white for the first 500 ms and last 500 ms of the movement phase. In between, objects were colored at 500 ms intervals changing their color abruptly from one to the next interval. With *distinct* colors, colors were assigned to the objects in the following manner: At the beginning of each trial, three color sets containing three colors each were randomly drawn from the nine possible color values without replacement. In addition, three groups of objects were formed, three target objects, three distractor objects being assigned the target colors after each color change, and three distractor objects being assigned the colors of the other distractors after each color change. In the first color interval, the three sets of colors were randomly assigned to the target object group and two distractor groups. At each of the following color changes, the color sets were swapped across object groups. The former target colors were assigned to the distractor group that always received the target colors, the former colors of this distractor group were assigned to the other distractor group, and the former colors of that distractor group were assigned to the target group. Within each object group, the colors of the assigned color set were randomly assigned to the individual objects without replacement. This ensured that objects did not have the same color after every third interval. When object color was *homogeneous* instead of distinct, the underlying color sets were generated and changed in the same manner with the exception that participants did not see these color sets but were presented with all objects being colored in the object color of one randomly chosen target object.

In the condition with *color changes between the spatiotemporal discontinuities*, color sets were generated and changed in the same manner with the exception that all coloring actions occurred 250 ms further to the end of the trial. This caused color changes to occur right between the spatiotemporal discontinuities, thus objects maintained their color across the discontinuities.

Three levels of tracking duration were used (5.5 s, 6.0 s, 6.5 s) and balanced within each condition. Using these three durations ensured that targets were colored equally often in one of the three color sets at the end of a trial. This was employed to render a possible memorizing strategy ineffective that would involve trying to memorize the target colors at the beginning of the trial and recover targets based on these colors at the end of a trial. Participants were instructed to ignore object color and that attending to object color was detrimental to their performance.

This resulted in a two-factorial (object color: homogeneous, distinct; color change time: color change at discontinuities, color change between discontinuities) within-subjects design with 30 repetitions per condition such that the experiment lasted about one hour. Participants performed 12 practice trials before performing 120 experimental trials.

Results and Discussion

Our results show that object color is also utilized to support location tracking in tracking displays without changes to the reference frame. Furthermore, we found color effects under coloring conditions that had previously been shown to be ineffective. This was achieved by reducing the precision of spatiotemporal information with a reduced presentation frame rate.

We analyzed our data using a repeated-measures ANOVA including the factors object color and change time and the dependent measure proportion correct (see Figure 7). The non-significant main effect of object color, $F < 1$, and significant main effect of change time, $F(1, 19) = 10.61$, $p = .004$, $\eta_p^2 = .36$, were qualified by a significant interaction of object color and change time, $F(1, 19) = 16.89$, $p < .001$, $\eta_p^2 = .47$. Two planned paired *t*-tests were calculated to compare tracking performance between the object color conditions for color changes at the discontinuities and for color changes between the discontinuities. When color changed at the time of the spatiotemporal discontinuities, tracking performance was impaired with distinct colors as compared with homogeneous colors, $t(19) = -2.58$, $p = .018$. The reverse pattern emerged with color changes between the discontinuities: Tracking performance was higher with distinct than homogeneous colors, $t(19) = 2.95$, $p = .008$. This demonstrates that location tracking performance was influenced by object color in both change time conditions. Color changes that occurred at the time of the spatiotemporal discontinuities swapped target colors onto distractors thus causing an impaired tracking performance due to a mismatch of spatiotemporal information and object color. The reverse was true for the color changes between discontinuities because object color stayed the same across the spatiotemporal discontinuity thus matching with the spatiotemporal information.

In the distinct color condition with color changes between spatiotemporal discontinuities, two opposing processes might have affected tracking performance. First, object color matched with spatiotemporal information across the spatiotemporal discontinuities and could have *improved* tracking performance. Second, target colors were swapped onto distractor objects which could have *impaired* tracking performance. However, those swaps took place with continuous spatiotemporal information and therefore should not have influenced tracking according to the flexible-weighting view. The pattern of results is in line with this prediction. The influence of the first process was far stronger than the influence of the second process. The second process of impaired tracking performance due to swapped colors with continuous spatiotemporal information might even be non-existent. This also replicates previous findings showing that object color changing every 500 ms in displays with continuous spatiotemporal information does not influence tracking performance (Makovski & Jiang, 2009b).

Experiment 5

The flexible-weighting view predicts that the use of surface features in tracking depends on the reliability of the spatiotemporal information. Whereas tracking does not utilize surface features in a non-strategic way in situations of reliable spatiotemporal information (Makovski & Jiang, 2009b), our results of Experiments 1 to 4 provide first evidence that object color is utilized for tracking in a non-strategic way in situations of unreliable spatiotemporal information. Although this provides some evidence that the utilization of surface features for tracking is related to the reliability of spatiotemporal information, a stronger conclusion could be drawn if the reliability of spatiotemporal information was manipulated within one experiment. Therefore, we directly manipulated the reliability of spatiotemporal information in Experiment 5. In trials with unreliable spatiotemporal information we presented an abrupt scene rotation as in Experiments 1 and 2. Trials with reliable spatiotemporal information did not contain a scene rotation. In addition, we manipulated object color as in Experiment 2. According to the flexible-weighting view, swapping object colors should impair tracking performance more with unreliable spatiotemporal information than with reliable spatiotemporal information. With reliable spatiotemporal information, swapping object color might not impair tracking performance at all (Makovski & Jiang, 2009b).

Method

Participants

Twenty new students were recruited.

Procedure and Design

The same procedure as in Experiment 2 was used unless noted otherwise. A new factor was included to the design: scene rotation. In half of the trials there was an abrupt scene rotation as used in Experiments 1 and 2. In the other half of trials no scene rotation occurred. Object speed was set to 4 deg/s when moving horizontally in the middle of the floor plane. Object speed was set to a value that we expected to produce neither a floor effect in trials with an abrupt scene rotation nor a ceiling effect in trials without an abrupt scene rotation. Participants were instructed to ignore object color and that scene rotations occur in some of the trials.

These changes resulted in a two-factorial (scene rotation: with, without; object color: homogeneous, distinct swap) within-subjects design with 20 repetitions per condition. Participants performed 16 practice trials before performing 80 experimental trials.

Results and Discussion

We analyzed our data using a repeated-measures ANOVA including the factors scene rotation and object color and the dependent measure proportion correct (see Figure 8). The influence of object color on tracking performance was stronger with unreliable spatiotemporal information than with reliable spatiotemporal information as indicated by the significant interaction of object color and scene rotation, $F(1, 19) = 5.74$, $p = .027$, $\eta_p^2 = .23$. Two planned paired *t*-tests showed that tracking performance was impaired by swapping colors as compared to homogeneous colors with abrupt scene rotations, $t(19) = 3.88$, $p = .001$, but not without scene rotations, $t(19) = 1.26$, $p = .224$. This replicates both, the effect of object color on tracking in situations of unreliable spatiotemporal information (Experiments 1 to 4) and the finding that color changes do not affect tracking performance in situations of reliable spatiotemporal information (Makovski & Jiang, 2009b). Furthermore, this is the first study to show in one experiment that the effect of surface features on tracking performance depends on the reliability of spatiotemporal information. This provides further evidence that surface features are flexibly used during tracking depending on the reliability of spatiotemporal information. Furthermore, there was also a significant main effect of object color, $F(1, 19) = 13.34$, $p = .002$, $\eta_p^2 = .41$, and scene rotation, $F(1, 19) = 156.57$, $p < .001$, $\eta_p^2 = .89$. The main effect of scene rotation replicates previous work showing that abrupt scene rotations impair tracking performance (Huff et al., 2009).

We ran a second analysis on tracking errors in the distinct swap condition. We analyzed the dependent measure *number of marked distractors* using a repeated-measures ANOVA including the factors *distractor color* (former target color vs. former distractor color) and *scene rotation* (with vs. without). There were more correspondence errors based on object color with scene rotations than without scene rotations as indicated by a significant interaction of distractor color and scene rotation, $F(1, 19) = 11.56$, $p = .003$, $\eta_p^2 = .38$. We used two planned paired *t*-tests to further investigate the interaction. With scene rotations, participants marked more distractors appearing in a former target color ($M = 1.00$, $SE = 0.05$) than distractors appearing in a former distractor color ($M = 0.74$, $SE = 0.05$), $t(19) = 3.91$, $p = .001$. In accordance with our main analysis on tracking performance above, no such bias was observed without scene rotations. That is, the number of marked distractors appearing in a former target color ($M = 0.28$, $SE = 0.03$) did not differ significantly from the number of marked distractors appearing in a former distractor color (M = 0.25, SE = 0.03), $t(19) = 0.94$, $p = .358$. Furthermore, there was also a significant main effect of distractor color, $F(1, 19) = 14.96$, $p = .001$, $\eta_p^2 = .44$, and scene rotation, $F(1, 19) = 153.42$, $p < .001$, $\eta_p^2 = .89$.

The results of the present experiment were obtained even though there was no distinct match condition in the present experiment. That is, color information did not support tracking in any trial and relying on color information was even harmful for tracking in half of the trials. Nevertheless, object color was utilized for tracking in trials with unreliable spatiotemporal information. This replicates our results of Experiment 2 and provides further evidence that object color is used in a non-strategic way in our displays.

General Discussion

To date, research on attentive tracking is dominated by studies on objects' spatiotemporal features (e.g., Franconeri et al., 2010; St.Clair et al., 2010). Whereas some studies addressed the influence of surface features on tracking (e.g., Bae & Flombaum, 2012; Howe & Holcombe, 2012; Makovski & Jiang, 2009a, 2009b), the conditions under which tracking might utilize objects' surface features in addition to their spatiotemporal information are not yet understood. We studied this question by conceptualizing tracking as a continuous establishment of object correspondence over time. In particular, we tested the predictions of the flexible-weighting view stemming from research on object correspondence (Hein & Moore, 2012) with multiple object tracking displays. According to the flexible-weighting view, spatiotemporal information and surface features are both used to establish object correspondence and weighted according to the reliability of available information. Applying this idea to tracking, spatiotemporal information should receive a high weight in situations of continuous spatiotemporal information because the tracking task can be easily solved in these situations. If spatiotemporal information is unreliable, however, the relative weight of surface features should increase. These predictions are contrasted by the view that location tracking has no access to surface feature information. If this was true, effects of surface features should never be observed.

We report five experiments implementing three different kinds of spatiotemporal discontinuities in order to test whether surface feature effects occur during tracking in situations of unreliable spatiotemporal information. In particular, we manipulated object color across spatiotemporal discontinuities. In all experiments, location tracking performance was improved when surface feature information matched with spatiotemporal information across the spatiotemporal discontinuity. When target colors were swapped onto distractors, however, tracking performance was impaired and responses were biased towards the distractors receiving the former target colors. These results demonstrate that location tracking utilizes object color in situations of unreliable spatiotemporal information. Consistent with the idea that the relative weight of surface features is low with reliable spatiotemporal information at times of continuous spatiotemporal information, results of Experiment 4 suggest weak to no impairment when target colors were swapped onto distractors in between two spatiotemporal discontinuities. Furthermore, object color influenced tracking in situations of unreliable spatiotemporal information but not in situations of reliable spatiotemporal information in Experiment 5.

Our results challenge the view that only spatiotemporal information is utilized to track multiple objects as predicted by the use of feature-blind visual indices (e.g., Pylyshyn, 1989, 2007). Instead, we propose that location tracking operates by a flexible weighting mechanism analogous to object correspondence (Hein & Moore, 2012). That is, locations of multiple objects are tracked by spatiotemporal information and surface feature information weighted according to the reliability of available information. When objects move in continuous ways and in uncrowded situations, spatiotemporal information is a highly reliable source of information for tracking with a high relative weight. Surface features do, therefore, not influence tracking in such situations. If spatiotemporal information is less reliable, the relative weight of surface features increases thus being utilized to track the locations of multiple objects. However, the observation of surface feature effects on tracking does not only depend on the kind of spatiotemporal information available. It also depends on the kind of surface feature information available in the display. If the similarity of surface features between two points in time is reduced, surface features are less likely utilized by the correspondence process. Furthermore, the distinctiveness of surface features might influence their weight.

This flexible-weighting tracking account fits well with earlier findings on surface features during tracking. In accordance with the predictions of this account, the relative weight of surface features increases with decreasing inter-object spacing (Bae & Flombaum, 2012, Makovski & Jiang, 2009b). Furthermore, the distinctiveness of surface features influences tracking performance (Howe & Holcombe, 2012; Makovski & Jiang, 2009a, 2009b). However, it is possible that those studies examined two processes in combination. First, location tracking might utilize object color according to the flexible-weighting tracking account as described above. Second, object color might be utilized during a strategic recovery of lost objects by means of an effortful use of visual short-term memory contents (Makovski & Jiang, 2009b). In those experiments, the occurrence of the strategic recovery process was particularly likely because object color usually matched with spatiotemporal information. With our present set of experiments, we tried to eliminate the strategic and effortful use of object color by including trials, in which target colors were swapped onto distractors. Furthermore, we explicitly instructed participants to ignore color in some experiments. In Experiments 2 and 5, there was even no single trial where distinct object color information could be used to support tracking. Although participants received feedback about their performance at the end of each trial and using object color information was against the observers interest in Experiments 2 and 5, we still observed color effects as is in line with the flexible-weighting tracking account.

The flexible-weighting tracking account can also be used to refine the conclusions of previous experiments on the relation of location tracking and identity tracking (Cohen et al., 2011). According to these previous findings based on a combination of MOT and multiple identity tracking (MIT), tracking multiple object locations and tracking multiple identities share a common process. According to the flexible-weighting tracking account, this common process could be the processing of surface features. This could also explain why identity tracking impaired location tracking more at increased object speed (Cohen et al., 2011). Because the increased speed reduced the reliability of the spatiotemporal information, the relative weight of surface features was increased.

The flexible-weighting tracking account suggests that the weights given to spatiotemporal information and surface features change according to the reliability of the spatiotemporal information. The idea that location tracking allocates resources according to task demands is supported by previous research. However, previous research has studied the flexible allocation of attention towards spatiotemporal information (Alvarez & Franconeri, 2007). This flexible allocation also occurs within a tracking display with more attentional resources available to targets in crowded situations (Iordanescu et al., 2009), and more rescue saccades to crowded targets (Zelinsky & Todor, 2010). Concerning the flexible-weighting tracking account, future research needs to specify the characteristics and temporal constraints by which the weights given to spatiotemporal information and surface features are adjusted during location tracking.

More empirical work is also needed to examine the exact mechanism by which surface features support location tracking. Based on the framework that tracking is the establishment of correspondence over time we concluded that it is the tracking (correspondence) mechanism that utilizes both spatiotemporal and surface features. This is different from explicit working memory strategies studied by previous work (Makovski & Jiang, 2009b). The flexible-weighting view tested in the present set of experiments stems from research on apparent motion (Hein & Moore, 2012). Recent research suggests a close link between such correspondence processes of apparent motion and correspondence processes studied within the object file framework (Odic, Roth, & Flombaum, 2012). Therefore, our present results can also be linked to object files (Kahneman et al., 1992). Within the object file framework, feature information is represented within an object file. Object files are primarily addressed by spatiotemporal information. Therefore, it is spatiotemporal information but not the object file contents that are used to establish object correspondence across object motion. This is similar to the idea of feature-blind visual indices sticking to targets as they move (e.g., Pylyshyn, 1989, 2007). Our results suggest that the maintenance of the relation between an object file and the corresponding object in the visual scene is not supported by spatiotemporal information alone but also supported by the object file contents whenever spatiotemporal information is unreliable. This is in line with recent research questioning the spatiotemporal dominance within the object file framework (Hollingworth & Franconeri, 2009; Moore et al., 2010; Richard et al., 2008). It remains an open question, however, whether object file contents are used to maintain the relation between the object file and the external object the same way spatiotemporal information is. It is also reasonable to conceptualize this process as a fast recovery of a lost object based on object file contents, possibly based on processes similar to visual search.

So far, when considering the mechanism responsible for feature effects with unreliable spatiotemporal information it was assumed implicitly that features support tracking in an object-based manner, be it by correspondence processes utilizing spatiotemporal and feature information, or by object file representations. As an alternative one could assume that coloring targets enhances the representation strength of the target colors on a representation layer detached from and not bound to the spatiotemporal information (Wheeler & Treisman, 2002). When changes in the display occur, attention might be aligned by the spatiotemporal information and feature information in parallel and thereafter quickly withdrawn from the objects identified as nontargets (Kiss, Grubert, & Eimer, 2013). With reliable spatiotemporal information, post-change attentional selections based on color are identified as selecting nontargets and withdrawn, otherwise they are retained. This results in the hypothesis that the number of tracked (attentionally selected) objects should be increased for a short time following color swaps, which could be tested using electrophysiological measures (Drew et al., 2013; Drew, Horowitz, Wolfe, & Vogel, 2012; Drew & Vogel, 2008).

Our results demonstrate that surface features, in particular object color, can support tracking in a flexible manner. Although we studied object color only, our results are likely to generalize to other features because feature effects on tracking have been found not only with object color (Bae & Flombaum, 2012; Howe & Holcombe, 2012; Makovski & Jiang, 2009a, 2009b), but also with cartoon animals (Cohen et al., 2011; Drew et al., 2013; Horowitz et al., 2007), object size (Howe & Holcombe, 2012), object texture (Huff & Papenmeier, 2013; Meyerhoff, Papenmeier, & Huff, 2013; St.Clair et al., 2010), faces (Liu & Chen, 2012; Ren, Chen, Liu, & Fu, 2009), and digit identity (Makovski & Jiang, 2009a). Furthermore, tracking is also influenced by spatiotemporal features such as heading, motion information, and trajectory (Fencsik et al., 2007; Iordanescu et al., 2009; Jardine & Seiffert, 2011; Ogawa, Watanabe, & Yagi, 2009; St.Clair et al., 2010). Whether or not such spatiotemporal features should be conceptualized as spatiotemporal information or features in the sense of object file representations is to be explored by future research.

In the present set of experiments, tracking load was fixed at three targets. Future studies should investigate conditions with higher tracking loads in order to investigate whether the results hold when observers are deploying their full tracking capacity. Although we have never run an experiment containing a distinct swap condition at higher tracking loads, we predict that the qualitative pattern of results remains the same. This prediction is based on a preliminary study conducted in our lab that only included distinct match and homogeneous trials at tracking loads of three, four, and five targets. In that experiment, we observed a higher tracking performance with distinct match than homogeneous colors across a scene rotation at all three tracking load conditions. Based on these results we decided to use three target objects for the present set of experiments. This allowed us to run the present experimental design with nine distinct colors. Whether increasing the number of colors or reducing the distinctiveness of colors affects the utilization of object color as predicted by the flexible-weighting view should be investigated by future research.

The demonstration of the importance of surface features for location tracking adds to a growing body of research concerned with the role of spatiotemporal information and surface features for object correspondence. Our findings are in line with recent reports suggesting that the role of surface feature information might have been underestimated in the past (Hein &

Cavanagh, 2012; Hein & Moore, 2012; Hollingworth & Franconeri, 2009; Moore et al., 2010; Petersik & Rice, 2008; Richard et al., 2008).

An interesting conclusion that our results afford is that surface features are automatically processed during attentive tracking. This was particularly evident in Experiments 2 and 5 in which surface features never supported tracking. Nonetheless, we observed effects of object color on tracking. Thus, object color must have been processed in the first place. Interestingly, the maintenance of feature-location bindings through object motion is effortful on the one hand (Oksama & Hyönä, 2008; Pinto et al., 2010; Saiki, 2003a, 2003b) but on the other hand surface features are automatically processed during tracking. The processing of features during motion does, therefore, not seem to be the source of the impaired maintenance of feature-location bindings through object motion.

Conclusion

We introduced spatiotemporal discontinuities in order to study the role of surface features during tracking. Across three different kinds of such spatiotemporal discontinuities we obtained a reliable effect of surface features on location tracking performance. We suggest a flexible-weighting tracking account stating that spatiotemporal information and surface feature information are both utilized to track the locations of multiple objects. The two sources of information are weighted according to their availability and reliability. Surface feature effects on tracking are particularly likely when distinct surface feature information is available and spatiotemporal information is unreliable.

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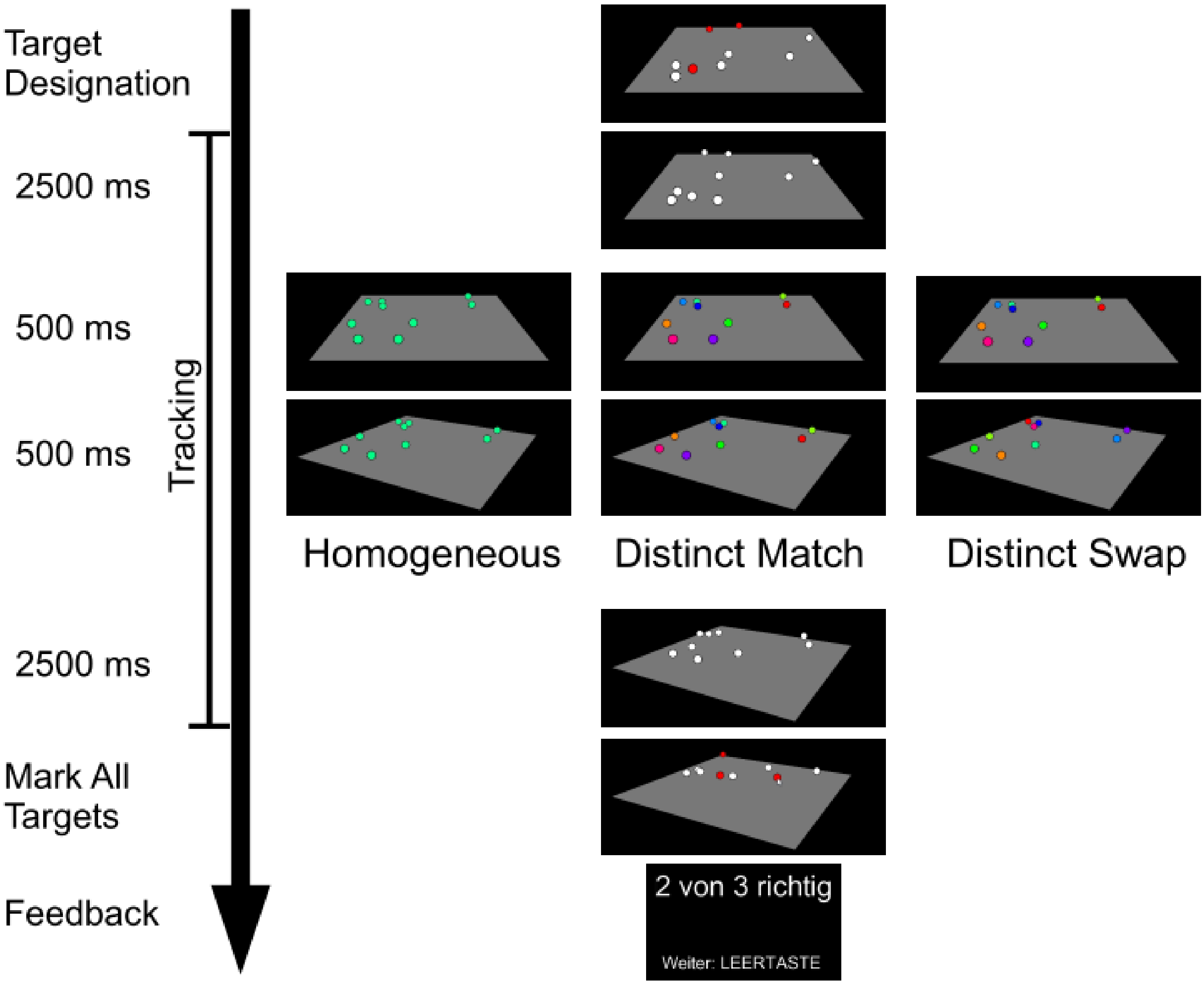

Figure 1. Three target objects are tracked among indistinguishable distractors. Around the instant of a scene rotation (spatiotemporal discontinuity), objects are colored homogeneously or distinctly, with the distinct colors matching or being swapped across the rotation. If surface features contribute to location tracking, distinct matched colors should improve and distinct swapped colors should impair tracking performance as compared with homogeneous coloring. Feedback was given at the end of each trial.

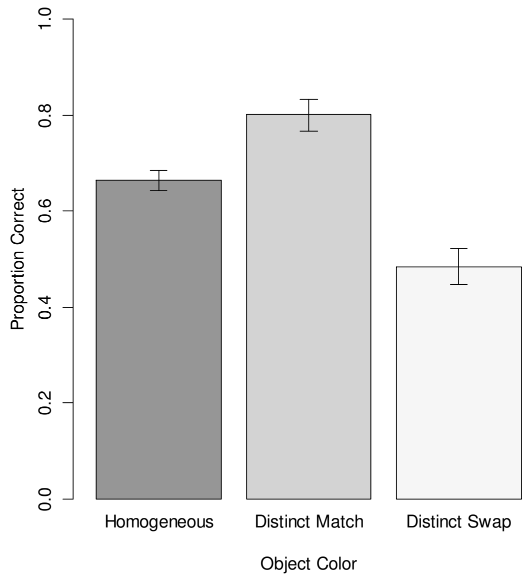

Figure 2. Results of Experiment 1. Location tracking performance was influenced by the color manipulation. Distinct object colors that matched with the spatiotemporal information across the discontinuity improved tracking performance. Distinct object colors that were swapped between objects across the discontinuity impaired tracking performance. Error bars indicate 95% within-subject confidence intervals (Baguley, 2012). Arcsine transformed values (see results section of Experiment 1) were converted back to proportion correct for easier interpretation.

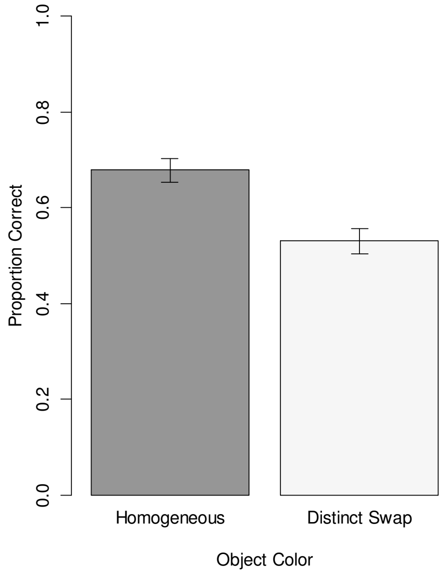

Figure 3. Results of Experiment 2. Error bars indicate 95% within-subject confidence intervals (Baguley, 2012). Arcsine transformed values (see results section of Experiment 1) were converted back to proportion correct for easier interpretation.

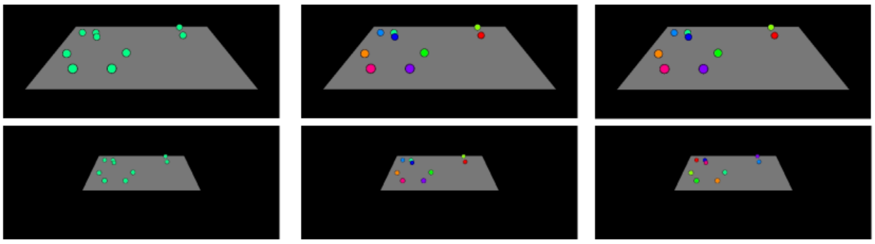

Figure 4: Abrupt zooms and color conditions used in Experiment 3. Order of the zoom states was counter-balanced.

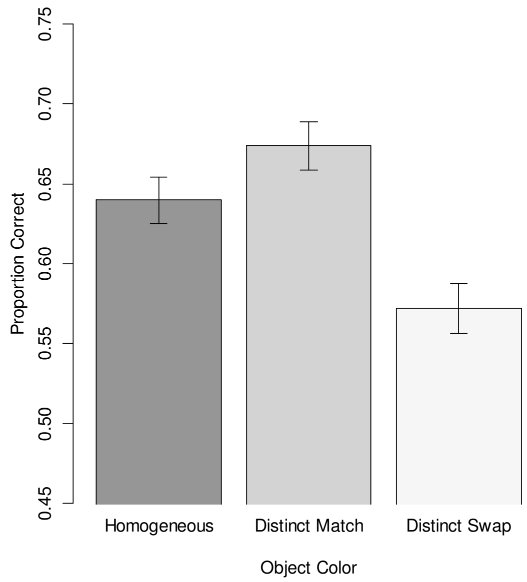

Figure 5: Results of Experiment 3. Error bars indicate 95% within-subject confidence intervals (Baguley, 2012). Arcsine transformed values (see results section of Experiment 1) were converted back to proportion correct for easier interpretation.

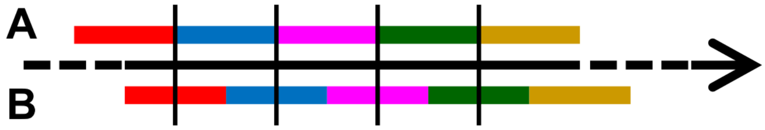

Figure 6: Timing of color changes in Experiment 4. Color changes occurred either at the time of the spatiotemporal discontinuities (A) or between the spatiotemporal discontinuities (B). Vertical lines represent the simulated video frame boundaries causing objects to be displayed at their next location based on their speed and trajectory. There were eight video frame boundaries in each trial.

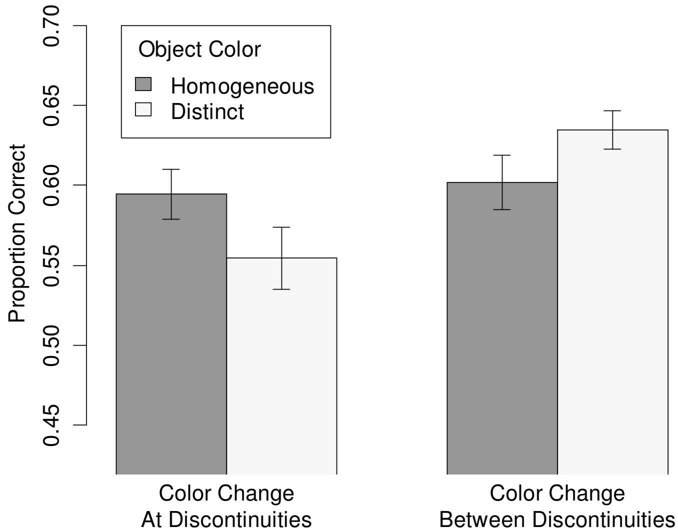

Figure 7: Results of Experiment 4. Error bars indicate 95% within-subject confidence intervals (Baguley, 2012). Arcsine transformed values (see results section of Experiment 1) were converted back to proportion correct for easier interpretation.

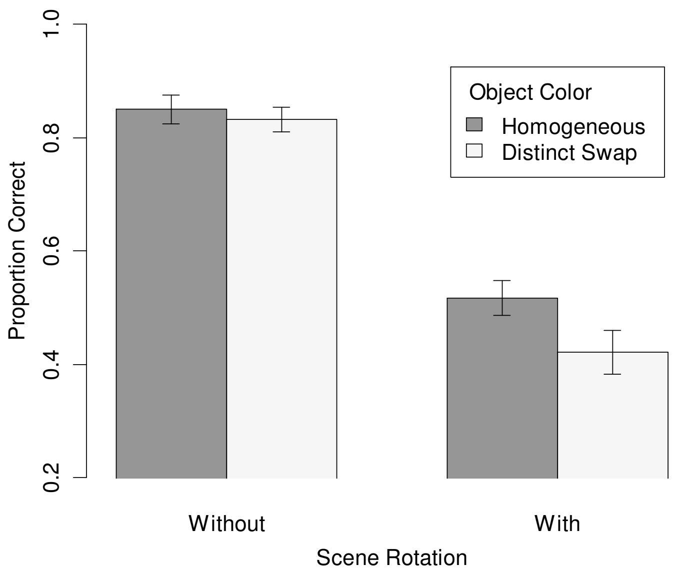

Figure 8: Results of Experiment 5. Error bars indicate 95% within-subject confidence intervals (Baguley, 2012). Arcsine transformed values (see results section of Experiment 1) were converted back to proportion correct for easier interpretation.