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Changes in Color Guidance over the Course of a Complex Visual Search

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**CHANGES IN COLOR GUIDANCE OVER THE COURSE OF A COMPLEX
VISUAL SEARCH**

A Thesis Presented

by

RYAN PAPARGIRIS

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ABSTRACT

CHANGES IN COLOR GUIDANCE OVER THE COURSE OF A COMPLEX VISUAL SEARCH

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When searching for an object, we store a mental representation of the target, which guides our search through the use of attention. The effectiveness of this search guidance varies depending on the task and the relationship between target and distractors. With a better understanding of how search guidance changes over time within a trial, we can better compare the differences between experimental conditions. Eye tracking data from a variety of search tasks were analyzed to determine how color guidance varied over the course of the trial. Color guidance for a given fixation was evaluated based on the distance in color space between the nearest object and the target color. These color differences were averaged over all of the trials and plotted based on when the fixation occurred in the trial. The results indicate that color guidance does not begin working at maximum effectiveness immediately. As the trial progresses, the average color difference decreases. After this initial decrease, if the target is not present, guidance becomes less selective and target dissimilar distractors are increasingly fixated. The color distance graphs were compared between experiments to reveal significant differences arising from the experimental conditions.

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CHAPTER 1

CHANGES IN COLOR GUIDANCE OVER THE COURSE OF A COMPLEX VISUAL SEARCH

1.1 Introduction

In order to accomplish most tasks in life, we are required to focus our senses on a specific aspect of the world. The environment provides an endless stream of information and only certain parts are useful. It is imperative to be able to direct our mental resources towards the goal that is most beneficial for survival. Attention is the mental faculty that allows us to accomplish this by selecting the information that receives additional processing, while inhibiting the remaining information from interfering. Every aspect of cognition is influenced by attention, and developing a greater understanding of the underlying mechanisms that produce attention can offer insight into how our minds work.

Attention has been a topic of interest for psychologists and philosophers dating back centuries (McCallum, 2015). After all, we spend our waking hours attending to one thing after another. Furthermore, not all attentional systems are equal. Farone et al. (2003) has estimated that as many as 1 in 20 children have attentional deficits. In addition, many high-risk jobs, such as security, require the use of attention. Researching how attention operates can lead to advances in our ability to treat individuals with attentional deficits, as well as new methods that improve the performance of those who rely on attention for safety.

1.1.1 The Study of Visual Attention

Much of the research in the field of attention has focused on visual attention, which is the set of processes that direct the flow of information through the visual system. Humans are visual beings and a large portion of our brains are dedicated to vision. While the neural pathways visual information travels within the brain are well studied, we still don't understand visual attention at a mechanistic level. Visual search tasks are a useful tool in studying visual cognition and attention. A successful search requires remembering what the target is, directing the eyes towards target-like objects and deciding whether the object being fixated matches the target. This process requires the use of attention at each step. By observing search behaviors, researchers can infer the role of attention in directing search.

Search behaviors can be broadly defined as the visible actions performed during search. A fixation occurs when a participant pauses their gaze on a location in their visual field. If there is an object in that location, it is inferred that the participant is attending to that object. A saccade refers to a fast eye movement that takes place between fixations. Saccades are a measure of overt attention, as they are easily observed. Once a region of the visual field is fixated, attention can then select different spatial locations within that region, without making additional saccades. These shifts of attention within a fixation are not observable, and thus this selection process is described as covert attention. The internal nature of covert attention makes it difficult to study. Covert attention can be studied using behavioral measures such as reaction time and accuracy, as well as physiological measures obtained through EEG. With these measures, it can be difficult to investigate attentional changes during a trial, and for this reason we will focus on overt attention for this analysis. Through eye-tracking, overt attention can be recorded for the duration of a visual search task.

1.2 The Target Template in a Visual Search

In a typical search paradigm, information defining the target is presented before the task begins. During a simple search in which the distractors are markedly different from the target, the target object is very salient and is easily identified. This phenomenon has been demonstrated in studies that utilize simple search paradigms and show little increase in search time when the number of distractors increases (Egeth, Jonides & Wall, 1972; Treisman & Gelade, 1980). In a complex search, there is no simple feature difference that distinguishes the distractors from the target. A mental representation of the target properties must be formed to accomplish a complex search. This mental representation has been referred to as an attentional trace (Näätänen, 1982), or an attentional template, (Eimer, 2014) as well as a target template (Hout & Goldinger, 2014; Duncan & Humphreys, 1989).

1.2.1 Evidence for a Target Template in Search

Without a target template, performance would be at chance during a complex search. Our ability to successfully remember information specifying a target and select a matching target amongst distractors indicates that a target template is involved. The formation and maintenance of a target template has been revealed through single cell recordings as well as EEG studies. Recordings obtained from individual neurons in the inferior temporal cortex of macaques before the search array appeared have demonstrated greater activity in the neurons that encode the relevant features of the target (Chelazzi, Duncan, Miller & Desimone, 1998). This has led researchers to propose that the target template may be represented in IT cortex. However, recent studies that investigated

activity arising from populations of neurons implicate the parietal lobe in maintaining visual information.

The contralateral delay activity (CDA) is an ERP component that is responsive to the number of items stored in working memory, and it is measured from parietal electrodes (Luria, Balaban, Awh & Vogel, 2016). Woodman and colleagues have revealed an increase in the CDA amplitude following the presentation of a target-cue (Woodman, Carlisle & Reinhart, 2013). This has been interpreted to represent the participant loading the mental representation of the target into their working memory. In addition, the CDA amplitude has been shown to be positively correlated with search accuracy and negatively correlated with reaction time (Woodman et al., 2013). Further evidence for the parietal cortex's contribution to visual memory is found in the fMRI literature. Xu and Chun (2006) have shown parietal activation during the encoding and maintenance of visual information (See also Todd & Marois, 2004). Taken together, individual neurons in the inferior temporal cortex respond to particular features of the target template, while neurons in the parietal cortex maintain information stored in visual working memory, which includes the target template.

1.2.2 Search Guidance and the Influence of the Target Template

Stroud and colleagues have shown that participants fixate on objects that have similar features to the target template (Stroud, Menneer, Cave & Donnelly, 2012). This phenomenon is referred to as search guidance, which is a component of attention that is necessary for efficient search. When search is guided by color, search guidance is referred to as color guidance. Search guidance can interfere with search when a search is paired with a memory task (Hollingworth & Beck, 2016; Kuo & Chao, 2014; Olivers,

Meijer & Theeuwes, 2006). In these experiments, participants perform a visual search task while holding an item in working memory that is irrelevant to the search. In some of these experiments, participants saccaded to a singleton distractor that was similar to the working memory item, despite the fact that this was detrimental to search performance (Olivers et al., 2006).

During a visual search, the target template resides in visual working memory, readily accessible for the task at hand (Woodman et al., 2013). The target template is used to guide search towards target similar objects. Once a participant saccades to an object that they suspect may be the target, a comparison is made between the target template and the fixated object. These roles require the target template to be available to our mental faculties consistently throughout the experiment, as repeatedly retrieving the item from long term memory would be unnecessarily costly. Menneer, Cave, Stroud, Kaplan & Donnelly (2011) conducted a study to test the assumption that the target template is encoded in visual working memory. Participants performed a single target search in conjunction with a working memory task. Performance was measured by the rate of fixations to distractors that were dissimilar in color to the target; this measure is referred to as the unguided fixation rate. When holding an extra item in working memory, participants had a higher unguided fixation rate than when they performed only the single target search task. This decrease in performance was most dramatic when the WM item was a color. Interestingly, most of this performance deficit was not caused by an increase in fixations to the WM color, as one might expect based on previous studies that demonstrate attentional capture. The WM color interfered with the target template, resulting in less effective color guidance overall (Menneer, et al., 2011).

1.2.3 Evaluating the Effectiveness of Search Guidance

Fixations made during a search provide invaluable information regarding the effectiveness of search guidance. If a fixation rests on a target-similar object, it can be inferred that search guidance is effectively directing attention towards objects that may be the target. Conversely if the fixations fall on objects that are highly dissimilar to the target, it can be inferred that search guidance is not effective for that fixation. Overt attention can be monitored with eye tracking equipment that records the location and duration of each fixation, which can then be used to determine the properties of the fixated object and how similar it is to the target. Comparing the fixated object to the target allows researchers to gain insight into how attention affects search under different conditions.

1.3 Search Guidance and the Dual Target Cost

Experimental conditions can alter the degree to which search is guided. Testing participants in a variety of conditions allows us to examine the search factors that promote effective search guidance, as well as the factors that interfere. When searching for a single target defined by color and shape, participants are capable of effective search guidance (Menneer, Barrett, Philips, Donnelly & Cave, 2007). This is demonstrated in their ability to ignore objects that are dissimilar in color to the target (Stroud, Menneer, Cave & Donnelly, 2012).

A particular type of search task has two targets that the participant must search for: these tasks are referred to as dual-target searches. A dual target search is disjunctive if only one of the two targets can appear during a single trial. In some disjunctive dual target search tasks, search is not as effective as it would be during a single target search

(Menneer, Barrett, Philips, Donnelly & Cave, 2007; Menneer, Cave & Donnelly, 2009; Stroud, Menneer, Cave & Donnelly, 2012). This is revealed through decreased accuracy (Menneer et al., 2007), increased reaction time, and a greater rate of fixations to target-dissimilar distractors (Stroud et al., 2012). Maintaining an additional mental target representation interferes with our ability to utilize the target template to guide search. This decrease in search performance due to an additional target is referred to as the dual-target cost. A similar effect was observed in Menneer et al. (2011) when a color working memory task was added to a single target search, as discussed previously.

1.3.1 Dual Target Search Strategies

One question that arises in the context of dual-target search concerns the way search guidance exerts its influence. Evidence from reaction time data (Irons, Folk & Remington, 2012) and ERP studies (Grubert & Eimer, 2015) has suggested that in dual-target search, both targets guide search simultaneously. Alternatively, results from an eye tracking study has suggested that participants can voluntarily switch between two target templates during search (Beck, Hollingworth & Luck, 2012). Cave et al. (2017) conducted an analysis on data from a dual-target search experiment (Stroud et al., 2012) that determined the number of fixations guided by a single target before color guidance switched and began guiding by the other target. The results from this analysis suggest that there were too many consecutive fixations guided by a single target for color guidance to be purely simultaneous (Cave, Menneer, Nomani, Stroud, Donnelly, 2018). In addition, there were too many ‘switches’ in color guidance from one target template to the other for search guidance to be purely successive. Similar results have been obtained from foraging search studies in which participants search for multiple instances of

different types of targets (Wolfe, Aizenman, Boettcher & Cain, 2016). While foraging, participants will collect instances of a certain target while starting to search for a different target.

Early studies that investigated the dual-target cost utilized a search paradigm that allowed the participant to ignore color (Menneer, et al., 2011; Stroud et al., 2012).

Participants were able to identify the target based principally on shape. While searching without color guidance would require a serial search that is ultimately longer than color-guided search, subjects may have preferred unguided search because it requires less effort. Specifically, selecting each item in the array sequentially and checking its shape does not require the active maintenance of a target template to guide attention. Cave, Menneer, Kaplan, Chang & Stroud (in preparation) have shown that when they eliminated the usefulness of shape, participants effectively guided search using color. This is revealed by significantly lower fixation rates to target color-dissimilar distractors. This evidence also supports the hypothesis that participants store a target template. Without such a template, performance on this type of task would be at chance.

1.4 Aim of this Research

Much of the research in visual attention aims to develop a better understanding of the factors that influence search guidance. If we can identify how effective search guidance arises, we are one step closer to improving our search capabilities. Many high-risk careers involve search tasks in the day to day responsibilities. One aim of this research is to identify ways to improve search, regardless of the context. To investigate this, it is critical to understand how search guidance changes over time, for better or worse.

1.4.1 Previous Research Investigating Changes in Guidance

Chang (2017) assessed changes in search guidance over the course of an experimental testing session and found that color guidance can be shaped by previous experience with search tasks. Two subject groups were compared: the easy and the hard group. The easy group had all easy search trials with distractors that were dissimilar in color to the target. The hard group had half easy trials, and half hard trials, randomly intermixed. Many of the distractors in the hard trials were very similar in color to the target, rendering search more difficult overall. The easy trials were compared between the two groups. Participants in the hard group had poorer color guidance than the participants in the easy group. This result demonstrates that the experience of difficult search can alter a participants' search strategy. Specifically, experiencing difficult color discrimination between the target and the distractors made the participants less likely to rely on color, even when the discrimination was not difficult.

1.4.2 Research Questions

While Chang's study indicates that color guidance can change over the course of an experiment, this raises the question as to whether guidance can change within a single trial. If the effectiveness of color guidance can change within a trial, then perhaps improvement (or deterioration) in guidance occurs on a shorter time scale than the duration of an experiment. The ability to adjust guidance would be a useful search strategy as real-life searches vary in complexity and some searches may be better suited to search guidance than others. Accurate color guidance during search may be an unnecessary use of attentional resources if the target is very similar in color to the

distractors. While this may explain why participants in the hard discrimination condition in Chang's (2017) study demonstrated poorer color guidance, we would not expect it to influence guidance within a trial. If relying on guidance is not an effective strategy for the task, it is unlikely that they will be altering color guidance within the trial. It is more likely that they will have abandoned color guidance altogether.

Previous research has shown that search guidance does not begin immediately after the target is presented (Wolfe, Horowitz, Palmer, Michud and Van Wert, 2010). A brief period of several hundred milliseconds must elapse before the target stimuli can be utilized to guide search. From this it can be predicted that guidance may not be most effective at the start of a trial. However, whether the effectiveness of guidance changes as the trial progresses is not well established.

One model of search guidance that adequately predicts many aspects of reaction times and error rates is Guided Search 4.0 (GS4) (Wolfe, 2007). In GS4, search is guided to objects according to activation strength (Wolfe, 2007). The object that is most similar to the target template will be fixated first, followed by the item with the second highest activation. This proceeds until the target is found or search is terminated (Wolfe, 2007). Based on GS4, we predict that guidance would be most effective early in the trial when it is fixating objects with the highest activation. As a result, guidance would be worst towards the end of the trial before search is terminated when the items with lower activation are being fixated.

1.5 Present Analysis

The analysis proposed in this paper aims to investigate within-trial changes in color guidance. Each fixation is assigned to the nearest object in the search array, and the difference between the color of that object and the target color will inform us of the

effectiveness of color guidance during that fixation. These results will enhance our understanding of attentional control during visual search tasks by informing us of the conditions that promote the use of search guidance. In addition, understanding the time scale in which color guidance changes brings us one step closer to designing protocols to improve search performance. With a greater appreciation of how we search for objects, we can utilize the strengths and avoid the weaknesses of our attentional system to be more effective searchers.

CHAPTER 2

EXPERIMENTS

2.1 Methods

The data used in this analysis were collected at the University of Massachusetts Amherst and come from several experiments described in a series of papers, some of which have already been published (Stroud et al., 2012; Menneer et al., in press; Cave et al., in preparation).

2.1.1 Summary

In these studies, participants volunteered in exchange for class credit with no prior knowledge of the experiment. Researchers ensured that the participant had normal color vision by administering the Ishihara test prior to experimentation (Ishihara, 1917). A brief description of the search task was provided to the participant before they began the task. The participant placed their chin on a chin rest while the experimenter secured the eye tracking hardware to their head. Only the right eye was used for eye tracking purposes. After a nine-point calibration of the eye tracking equipment, the participant began their five practice trials to ensure that they understood the task. When a participant was ready to end a trial, they would indicate whether the target was present using a Microsoft game controller. The experiment concluded when the participant had completed all of the trials.

2.1.2 Design

The experiments presented here have two main factors that are relevant for the current analysis. The task-set factor refers to the items a participant must store in memory for the task and it contained three levels: single, dual and working memory (WM). Task-set was the only between-subject factor. In the single target condition, participants were presented with a single item to search for. Similarly, the dual-target level involved searching for either of two items. In the WM level, participants were presented with a color to store in their working memory before they performed a single target search (Menneer et al., 2011). After the participant completed a search trial in the WM condition, they were required to indicate what memory color they were presented with at the start of the trial.

The second main factor was target-presence. In the single and WM conditions, the target was either absent or present. In the dual-target condition, only one of the two targets could be present in each trial. An experiment consisted of 256 trials with a target present in 50% of trials.

2.1.3 Stimuli

The objects in the display consisted of “T’s” and “L’s”, each constructed from two rectangles. The T is composed of one rectangle bisecting the second rectangle (Figure 1A). Conversely, the rectangles that comprise the pseudo-L’s are adjoined with an offset rendering them a hybrid T/L shape that is difficult to discern from a T (Figure 1B).

2.1.4 Experiments

Three separate categories of search experiments will be presented in this analysis: color-T (Stroud et al., 2012), varied target (Menneer et al., in preparation) and pure color (Cave et al., in preparation).

Color-T search allows participants to utilize color and shape to guide search towards the target-T; however the presence of target-color pseudo-L's makes shape information necessary to identify targets. Participants are assigned a target color or pair of target colors depending on the task-set. In color-T search, the task-set is consistent over the course of the experiment. Conversely, varied target search is a color-T search with the task-set (the color or colors of the target) changing between trials. A pure color search includes only T's in the display; therefore participants must search by utilizing only color and not shape.

2.1.5 The Search Display

Each object in the display appeared as one of sixteen possible colors. The pool of colors was selected from CIExyY color space and were chosen to be noticeably different from one another while not being so different that a pop-out effect occurs (Figure 2) (Menneer, Barrett, Philips, Donnelly & Cave, 2007). The assignment of colors to distractors occurred independently. As a result, some arrays had more color variation than others. To assure that the target color did not confound results, each of the sixteen possible colors was used as a target for an equal number of the participants.

The search display consisted of ten items equally spaced in a circle against a white background (Figure 3). Each object was assigned a random orientation of 0°, 90°, 180° or 270°. When the target was present, a single T would be in the display that was a

target color. In the color-T and varied target experiments, distractors consisted of pseudo-L's. In pure color search, all the objects in the display were T's.

2.1.6 Apparatus

Eye movements were tracked using an SR Research Limited Eye-Link II while the participant searched the display presented on a 17-inch Vision Master Pro 514 iiyama CRT monitor. Participants were instructed to place their chin onto a chinrest to ensure that their heads did not move over the course of the experiment. The participant indicated whether the target was present in the search array using a Microsoft game controller. The output from the eye tracking program indicated where in the visual array each fixation rested, and for how long.

2.1.7 Procedure

The order of events for a single trial was consistent across all experiments (Figure 4). First a dot appeared at the center of the display. In the WM experiment, the color to store in WM was presented following the dot. After the dot or WM color, an image of the target T('s) that the participant would be searching for was presented. The target remained on the display for a full second and was then replaced by another central fixation dot. The fixation dot was then replaced by the ten-item search array (Figure 3), which remained on the monitor until the participant pressed one of two buttons on the game controller to indicate whether the target was present. In the working memory task, the sixteen-color ring (Figure 2) was presented following the search array. Participants fixated on the color that they believed to be the memory item.

2.2 Current analysis

The goal of this analysis is to understand how color guidance changes over the course of a trial. To gauge how effective color guidance is during a given fixation, we determine how different the color of the currently fixated object is to the more similar target color. The difference is quantified by the number of steps on the color ring between the target color and the fixated color. In Figure 5 for example, if a participant is fixated on a distractor that is violet (outlined with a red square), and the target is orange (black square), then that fixated color has a color-step of four. Color-step will be referred to as color-difference from here on. Color-difference is defined as the minimum number of steps on the sixteen-color ring between the color of the fixated object and a target color. In single target search, the target color that is more similar to the color of the fixated object will always be the one target color that the participant is given (Figure 6). In dual-target search, the addition of a second target decreases the maximum difference between the fixated color and the target color (Figure 6). For example, if the targets are orange and purple and the participant fixates yellow, the color step value for that fixation would be 3, because yellow is more similar to orange than it is to purple (Figure 5).

2.2.1 Bin Sorting Algorithm

To visualize the change in color guidance over the course of the trial, a graph is created by normalizing the lengths of trials and plotting the average color-difference values. The total number of fixations in a trial varies quite dramatically. Regardless of the number of fixations in a trial, each trial will be divided into 100 steps or timeslices, and the information about fixated colors in that trial will be distributed across 100 bins, with each bin or storage unit holding values representing one timeslice, or approximately 1%

of the search in that trial. Bins work well for this type of analysis because the number of fixations in a trial can determine the number of bins allocated to a single fixation. The color-difference values are placed in bins corresponding to the part of the trial when the fixation took place.

For this analysis, a vector of 100 bins was created. Within a trial, each fixation will be represented by approximately the same number of bins. To determine the number of bins filled for each fixation, 100 was divided by the number of fixations. For example, if a trial had five fixations, the first 20 bins would be filled with the color-difference value for the first fixation. The second 20 bins would be filled with the color-difference value obtained from the second fixation. Figure 7 demonstrates this process with five trials and ten bins. This would proceed until the end of the trial and would repeat again for the next trial (Figures 7 & 8). The values in each bin would be averaged over the number of trials and across participants. A graph of these bins reveals the average change in color-difference over the course of a trial.

Some fixations were removed prior to analysis depending on where and when they occurred. Fixations recorded before the stimulus array appeared are not informative and so these fixations were removed. Furthermore, fixations that were distant from the stimulus array were removed. This includes fixations that were greater than 50 pixels outside of the stimulus ring, as well as those 50 pixels or less from the center. These distant fixations were presumably not guided and therefore are not useful in studying color-guidance. Alternatively, incorrect trials were included in this analysis because participants could perform guided search prior to their incorrect response. An incorrect response simply means they did not correctly identify whether the target was present; it does not mean that color guided search did not happen during that trial.

2.3 Results

The effectiveness of guidance can be inferred from the curve produced when averaged color-difference values over the course of a trial are plotted. The averaged color-difference values will reflect the similarity between the color of the objects fixated at that point in the trial and the target color. If color-difference were to increase as the trial progressed, this would mean that guidance is more precise at the start and decays over time. This is because a greater value of color-difference reflects a larger number of steps between the color of the fixated object and the color of the nearest target on the color ring (Figure 5). According to Guided Search 4.0, search is guided to the most similar objects first (Wolfe, 2007). If the target is not found, progressively less similar objects are fixated. This pattern of search would produce a color-difference plot that increases as the trial progresses. Conversely if the values of color-difference decrease over the course of a trial, we can infer that search guidance improves. If the participants are receiving better color information as the trial progresses, then we would expect guidance to improve. The null hypothesis is that color guidance is not dynamic within a trial and this would be revealed by a flat line.

Presented below is a series of analyses, each comparing the average color difference between two experimental conditions to infer if there is a significant difference in color guidance. For each fixation, color difference was determined by quantifying the difference between the target color and the color of the fixated object. The color difference measure was used to assess the effectiveness of color guidance for that fixation. For each comparison across a pair of search conditions, the mean color

difference for each of the first six fixations in a trial was compared across conditions. Planned linear and quadratic contrasts were conducted on the average color differences for the first six fixations to detect general patterns in the data.

After that first analysis was completed, the trial lengths were then normalized to allow an additional comparison that compensated for the varying fixation totals across trials. The normalization was done by organizing each trial into a series of bins, each representing 1% of the total sequence of fixations for the trial. To test significance of the normalized color-difference values, t-tests were conducted on pairs of bins across experiments to determine if there was a significant difference for that portion of the trial.

Both approaches were used to answer whether the effectiveness of color guidance varies over time within a trial, and also to investigate how color guidance is influenced by the different experimental conditions.

The first result presented will be a comparison of the search behaviors employed when the target is present, and when it is absent. For this comparison, only the normalized analysis was conducted as it was sufficient in revealing the general search method that was implemented. After the absent versus present comparison, single target search results will be presented, followed by dual target search and finally varied target search.

2.3.1 Target Present and Absent Comparison

Target present trials generally end upon discovery of the target. A comparison of the target present and target absent conditions provides insight into what occurs when the participant cannot locate the target. Based on the normalized analysis, the average color

differences for the absent and present conditions are very similar for the first fixations (Figure 9). In target present trials, participants fixate on colors that are increasingly similar to the target color, and when the target is found, the participant ends the trial. For this reason, target present trials have fewer fixations, on average, than target absent trials. Target present trials produce a color difference curve that decreases for the entire trial (Figure 9, blue). The two conditions differ between twenty-five and fifty percent of the way through the trial. If the target has not been located, participants begin to fixate on colors that are increasingly dissimilar to the target color (Figure 9, red). This produces a color difference curve that decreases at the start and then increases for the remainder of the trial. This pattern is consistent across experiments. The remainder of the results discussed will focus strictly on target absent data.

2.3.2 Analysis of the Single Target Search Conditions

2.3.2.1 Summary of Single Target Experimental Conditions

The single target search task presented here involves a participant searching for a target “T” (Figure 1A) of a specific color and responding whether or not the target is present. The search display (Figure 3) is a ring of ten items with each item being one of sixteen possible colors (Figure 2). At the start of each trial the participant is presented with a color that informs them of their target-color, which remains constant throughout the experiment. In color-T search (Stroud et al., 2012), each distractor in the display is a pseudo-L (Figure 1B). This makes it possible for the target to be distinguished from the distractors by shape in addition to color. On some target-absent trials, one or more pseudo-L’s of the target color may be present in the display. In pure color search (Cave et

al., in preparation) all of the items in the display are “T”s and target colored distractors are not possible. For this reason, participants must solely rely on color to find and identify the target during pure color search.

2.3.2.2 Single Target Results

Comparing color-T and pure color search under different conditions provides an opportunity to evaluate how search performance changes when shape information is available. In order to compare pure color search with color-T search, fixations made in color-T search to target-colored distractors were removed from the analysis, because there are no target-color distractors (color step = 0) in pure color search. Including fixations to target-color distractors dramatically reduces the average color difference in color-T search, making it difficult to compare with pure color search. Figure 10 reveals the average color distance for each fixation, up until fixation six. Six was chosen as a cutoff point because most trials have at least six fixations, though some have more, and others have less. From Figure 10, we can see that the average color difference does not remain constant throughout a trial. Specifically, the first fixation has a greater average color difference than the second fixation. After the second fixation, the average color difference increases for the remaining fixations, ending at a value greater than the average color difference of the first fixation. Planned contrasts revealed a significant linear trend in color-T ($F = 29.235, p = 0.001$) indicating a significant linear increase in color difference as the trial progresses (Figure 2). The contrast did not reach significance in the pure color search condition ($F = 0.9579$). A significant quadratic effect was not demonstrated in either color-T ($F = 2.16$) nor pure color search ($F = 0.464$). While the

graph in Figure 10 provides a clear image of how color guidance changes between fixations, it fails to incorporate data from the final fixations on longer trials.

The fixations removed from the ends of some trials to produce the graph in Figure 10 contain valuable information regarding color guidance. In order to analyze color guidance over the course of the entire trial, a binning algorithm (section 2.2.1) was implemented that normalized the number of fixations in a trial to fill a set of bins with color difference values (Figures 7 & 8). This method of analysis made it possible to compare trials of varying fixation totals and eliminates the need to remove fixations. As with the fixation-by-fixation analysis (Figure 10), the normalized analysis (Figure 11) reveals changes in color guidance as the trial progresses. Specifically, in a pure color single target search, the average color difference decreases up until forty percent of the way through the trial before it begins to increase. The color difference for pure color is greater than the color difference for color-T at the start. The differences in these values did not reach significance for any of the time steps.

2.3.2.3 Summary of the Working Memory Condition

The working memory condition (Menneer et al., 2011) involves the addition of a simple working memory task to the standard single target search. The participant is presented with a memory color at the start of the trial. This color changes from trial to trial to ensure that the color remains in working memory. The working memory test appears after the participant submits a response to the search task. The search display is replaced by a display containing all the colors shown in Figure 2, and the participant is

instructed to fixate on the color that was presented at the start of the trial as the memory color.

2.3.2.4 Working Memory Results

The addition of a working memory task impairs search guidance. This is indicated by an increase in the color difference measure. When the single target condition is compared to the WM condition for each bin in the normalized analysis, the increase reaches significance for the entire trial in color-T search (Figure 12, left panel). However, in pure color search, only the bins at the start of the trial reveal a significant difference (Figure 12, center panel). A comparison of the two working memory conditions reveals a significant difference over the entire trial (Figure 12, right panel). As with the previous comparisons, fixations made to target-color distractors in color-T search were removed from the analysis comparing color-T search to pure color search.

The graphs in Figure 13 illustrate the non-normalized comparisons, which only include the first six fixations. It is evident that the color difference curves follow a similar pattern across conditions. Specifically, the first fixation is at a higher color difference than the subsequent fixation. After this initial drop in color difference, the average values for the remaining fixations increase. Planned contrasts of the data from the color-T WM experiment revealed a significant linear effect ($F = 6.541, p = 0.05$), in addition to a significant quadratic effect ($F = 18.880, p = 0.001$). These contrast results support the claim that the average color difference value decreases before increasing. Contrasts of the pure color WM task did not reveal significant effects in either the linear contrast ($F = 0.9068$), or the quadratic contrast ($F = 1.374, p = 0.2448$).

2.3.3 Analysis of Dual Target Search Conditions

2.3.3.1 Summary of Dual Target Search Conditions

The dual target search task follows the same procedure as the single target search task. The key difference between the two conditions involves the number of targets. As implied by the name, dual target search involves searching for two possible targets. At the start of each trial the participant is presented with their two target-colors. If the target is present, it will appear as one of the two possible target colors. As with single target search; color-T search includes pseudo-L distractors while pure color search strictly contains T's.

2.3.3.2 Dual Target Results

Color guidance in pure-color search has been shown to be more accurate than color guidance in color-T search (Cave et al., 2015). In pure color search, participants are unable to use shape to confirm whether an object is the target. Because they must hold the target colors in memory in order to identify a target, they are more likely to also use the target colors in memory to guide search. Also, because shape cannot be used to confirm target identification in pure color search, it is generally more difficult than color-T search, and that extra difficulty may promote the use of color guidance. Figure 14 supports previous findings in showing that the color difference was greater for color-T search, and less for pure color search. In the normalized graph (Figure 14, left) the average color difference in Color-T search is significantly greater than in pure-color search, specifically in the second half of the trial. An examination of the color differences

across each of the first six fixations (Figure 14, right) reveals that both curves follow a similar path. Furthermore, planned contrasts revealed a significant quadratic component in color-T ($F = 55.005$, $p = 0.001$), and pure color ($F = 34.607$, $p = 0.001$). From the graph on the right side of Figure 14, it is evident that the function follows a U-shaped pattern. A significant linear effect was not demonstrated in either color-T ($F = 2.848$) nor pure color search ($F = 0.4048$).

The differences observed between the two graphs in Figure 14 arise due to the methods of analysis used to produce each graph. As a reminder, the normalized graph (Figure 14, left) is produced using a binning algorithm (Figures 7 & 8) that allows the inclusion of all fixations. The alternative approach (Figure 14, right) only includes the first six fixations of each trial and does not utilize normalization.

2.3.4 Single Vs. Dual target

All single and dual comparisons revealed significant differences, with the dual target average difference being less than the single target. The dual-target experiments produce graphs with smaller average differences due to the way that the differences are mapped (Figure 5). With two targets, there are a greater number of target similar colors, decreasing the average difference overall. For this reason, dual and single comparisons cannot be meaningfully made using this method.

2.3.5 Analysis of the Varied Target Search Conditions

2.3.5.1 Summary of Varied Target Experimental Conditions

The varied target search condition is a variation on the traditional single and dual target color-T search. At this point, all the conditions discussed have had a consistent target or set of targets. As the name describes, in the varied target condition, the target color(s) changes from trial to trial. Like the color-T conditions previously described, varied target color-T search involves searching for a target-T amongst pseudo-L distractors.

2.3.5.2 Varied Target Results

Varying the target color from trial to trial produces a more difficult task as the participant cannot encode the target color into long term memory. The change in color guidance produced by this added difficulty can be seen when comparing the color differences between varied and consistent target search. Figure 15 reveals that the average color difference is greater in consistent target search; however the normalized analysis shows that this difference is only significant at the start and end of the trial. Furthermore, Figure 15 (right) indicates that a different search strategy may be employed during varied target searches. Specifically, in the nonnormalized analysis, participants appear to focus on target-similar distractors even towards the end of the trial in the varied condition. Contrasts of the single varied target data revealed a significant linear increase, ($F = 7.413, p = 0.01$) with no significant quadratic component ($F = 0.123$).

The varied single target condition may produce unexpectedly low color difference values because color guidance is very accurate in this condition, or there might instead be a stronger tendency in this condition to fixate a few items repeatedly. Perhaps participants are returning to target similar distractors multiple times before ending the trial due to the

added difficulty of a varying target. In Figure 16, the color difference values are plotted separately for refixations and for novel fixations (fixations to previously unfixated items). A refixation is defined as fixating on an item in the search display that has already been fixated in that trial. From Figure 16, it appears that in consistent target search, refixations are focused on objects that are more similar in color to the target than an average novel fixation. Conversely, in varied target search, refixations and novel fixations appear to have similar average color difference. Furthermore, refixations account for roughly the same proportion of total fixations both conditions, with 12.3% in varied target and 12.7% in consistent target. Based on these findings, it is unlikely that refixations are producing the low color difference in varied single target search.

A comparison of the dual varied target condition with the dual consistent target condition reveals minor differences in the average color difference values. Based on the graph in Figure 17 (left) that presents the normalized analysis, it appears that varying the targets in a dual target search does not significantly influence the average color difference. From the non-normalized analysis, planned contrasts of the first six fixations in the varied dual target condition reveal a significant linear effect ($F = 22.133, p = 0.001$), and a significant quadratic effect ($F = 28.415, p = 0.001$). The curve appears to be an amalgam of a straight line and a U-shaped function.

CHAPTER 3

DISCUSSION

The results presented above support previous findings that utilized the unguided fixation rate to infer the effectiveness of color guidance. This analysis has used the average color-difference of each fixation to evaluate color guidance over the course of a trial. Each experiment type will be discussed separately, followed by a general discussion of the patterns observed across experiments.

3.1 Target Present Vs. Target Absent

The general shape of functions showing changes in color difference through the course of a trial in both the target present and target absent conditions reflects the search habits of participants as well as the changing nature of color guidance. In both conditions, the participant begins fixating objects with colors several steps away from the target in color space (Figure 9). As the trial progresses, color guidance becomes more effective and participants fixate objects that are more like the target in color. In target present trials, the participant finds the target soon after guidance reaches maximum effectiveness and the trial is concluded (Figure 9). When the target is absent, color guidance becomes less selective as the trial progresses, allowing participants to fixate target dissimilar distractors until they ultimately conclude that the target is not present (Figure 9). This aspect of search is described in the Guided Search 4.0 model which states that when the

target is not identified, attention continues to sample items without replacement, and search guidance directs attention towards objects that are increasingly dissimilar to the target template (Wolfe, 2007).

3.2 Single Target

Participants have proven to be capable of effectively using color guidance to locate a single target. There were no significant differences in the average color difference values between pure color and color-T single target search (Figure 10). When participants perform a single target color-T search while holding a color in their working memory, they perform poorly and have many unguided fixations (Menneer et al., in press). Holding a color in WM severely interferes with a participant's ability to effectively guide search using their mental target representation. The color difference graphs comparing the single target color-T condition with the WM condition reveal how dramatically the addition of a color WM task can decrease the effectiveness of color guidance (Figures 12 & 13). The addition of a WM task to pure color search revealed a significant difference only at the start of the trial. Participants in the pure color search task had to rely on color to guide search, while participants in color-T could rely on shape.

Perhaps participants in color-T search are ignoring the color information on some trials and simply searching by shape. This leads to many unguided fixations, and that impairs performance because the participant is not directing their search towards objects similar in color to the target. The addition of a WM task forces the participant to store color information and this can interfere with their ability to effectively search by color.

Specifically, distractors similar in color to the WM color may capture the participants' attention, impairing their color guidance. Menneer et al. investigated this (in press) and concluded that the WM color does capture attention; however the attentional capture does not explain all the performance cost. Alternatively, in pure color search, participants are only able to identify a target by color, and thus they must retain the target color in memory. Given that they are holding the target in memory, they may be more likely to also use it to guide search. From Figures 12 and 13, the addition of a WM task impairs color guidance in pure color search. With no alternative to color, pure color searchers persevere with their impaired color guidance. In color-T search, the added difficulty may encourage participants to abandon color guidance and focus on shape. Disregarding color leads to a higher average color difference value as the participants are not focusing their search towards target-similar objects.

3.3 Dual Target

The addition of a second target to a search task produces a more difficult task with a greater number of unguided fixations (Stroud et al., 2012). Additionally, dual target pure-color search has been shown to produce more effective color guidance than color-T search. This analysis supports that finding, revealing that pure color dual target search produces significantly lower average color difference values compared to color-T search, specifically in the second half of the trial (Figure 14). Participants in color-T search have a higher rate of unguided fixations than in pure color search (Cave et al., 2015). This can be explained by the fact that pure-color participants are required to utilize their mental representation of the target colors in order to complete the task.

Alternatively, participants in color-T search have the option to abandon color and solely utilize shape for search and target identification.

3.4 Varied Target

Intuitively, varying the target makes the search task more difficult because the participant cannot encode the target template into long term memory; they can only maintain it in working memory. It is perhaps unexpected then that the average color difference is significantly different only between the varied and consistent single target experiments, and not the dual target experiments (Figure 15 & 17). Furthermore, the average color difference in the varied single target experiment was only significantly greater than the consistent at the start and end of the trial. One possible explanation is that the effectiveness of color guidance is not influenced by whether the target template is stored in WM or LTM. This proposed feature of color guidance would eliminate any advantage provided by having a consistent target.

Based on the color difference curves presented in Figure 8, it appears that participants in a single varied target color-T search have very effective color guidance. This is inferred from the low average color difference across all six fixations. In varied single target search, participants are not focusing on target dissimilar distractors in the same manner as when the target is consistent. One explanation for this is that the presentation of a novel target color at the beginning of each trial increases the likelihood that it will be encoded in WM and used to guide search, or that the extra difficulty with the varied targets induces participants to employ guidance more effectively. It is also possible that color guidance is similar across varied and consistent conditions, but that

participants in the varied condition are often refixating on target similar items and ending the trial before fixating on target dissimilar distractors. However, as seen in Figure 16, the proportion of refixations is similar in both conditions. Additional analyses investigating search behaviors in this condition will help to better understand what is promoting effective color guidance.

3.5 Single Vs. Dual Target Searches

All single and dual comparisons revealed significant differences, with the dual target average color differences being less than the single target color difference values. The dual-target experiments produce graphs with smaller average differences due to the way that the differences are mapped. With two targets, there are a greater number of target similar colors, decreasing the average difference overall. For this reason, dual and single comparisons cannot be meaningfully made using this method of analysis.

CHAPTER 4

CONCLUSION

Both the non-normalized and normalized analyses revealed that color guidance fluctuates over the course of a trial. Color guidance is not fully effective at the start of a trial. As the trial progresses, color guidance improves. In target absent trials, after color guidance reaches its maximum effectiveness for the trial, it becomes less selective and guides participants towards distractors that are colored more dissimilar to the target. Previous research has shown that the effectiveness of color guidance can change within an experiment (Chang, 2017). These analyses extend that result by demonstrating changes in color guidance within a trial.

Across experimental conditions, the average color difference for the first fixation is almost always greater than the second fixation. This is particularly fascinating when considering the varied and consistent target comparisons. Regardless of how familiar a participant is with the target, their color guidance does not reach full effectiveness until after the first fixation. One possible explanation is that the mental representation of the search display is not very accurate at the beginning of the trial, and thus color guidance cannot effectively guide search. Additionally, this indicates that the effectiveness of color guidance at the onset of search is not influenced by whether the target template is stored in WM or LTM. Furthermore, this finding supports the claim that color guidance is dynamic within a trial.

The results from these analyses support claims made previously regarding these experiments. Specifically, when participants must hold two colors in working memory, as in a dual target search or a WM search, they are less likely to rely on color guidance if an alternative approach is available. This is demonstrated in Figure 14, which compares performance across color-T and pure color dual target search. Color guidance is more effective in pure color search, even though it is a harder task. Participants have the option to search by shape in the color-T condition and the addition of a second target pushes participants away from using color guidance.

4.1 Future Directions

Further investigation into the factors that produce the differences seen in these color difference graphs will provide useful insight into the conditions that promote effective color guidance, especially in the single varied target search condition, in which color guidance is consistently accurate. Additional analyses designed to understand the search strategies employed in this condition could help to better understand how participants in that condition utilize color guidance so effectively.

Figures



Figure 1: Sample T (A) and pseudo-L (B) that are present in the display.

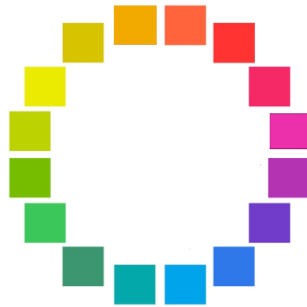


Figure 2: The sixteen possible colors arranged in a circle. This will be referred to as the color ring.

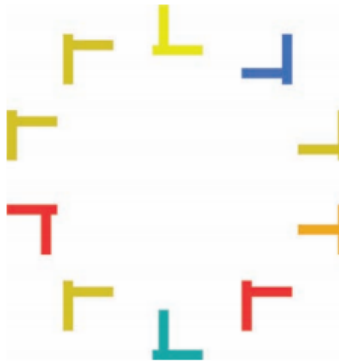


Figure 3: A sample search display from a color-T experiment with a target present.

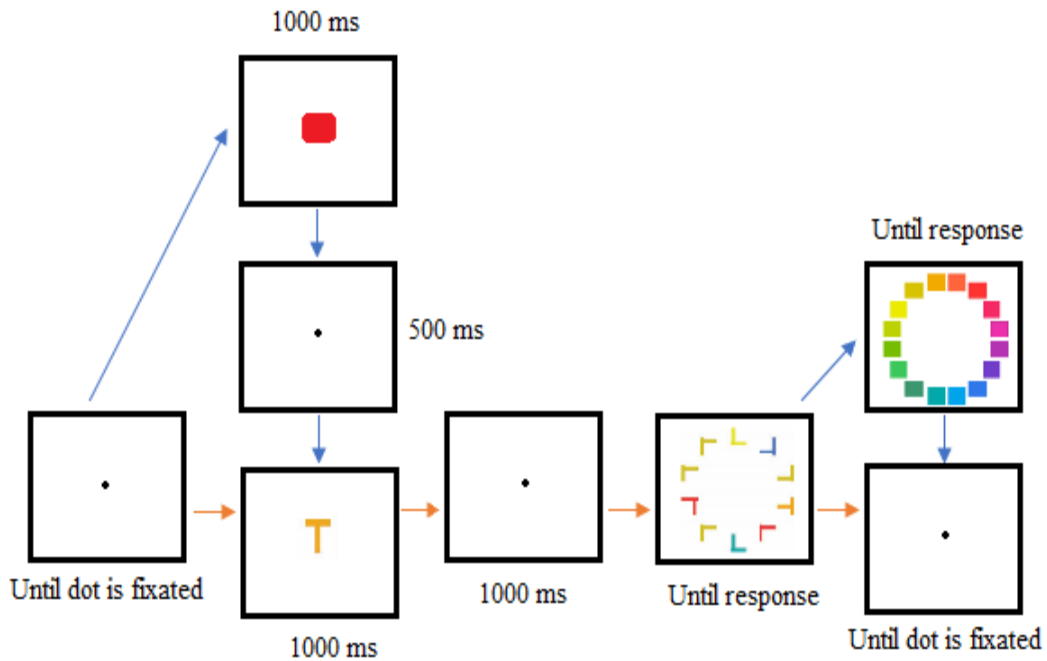


Figure 4: Diagram of experimental procedure. Orange arrows indicate the path followed in color-T, pure color and varied target experiments. Blue arrows indicate where the WM experiments differ.

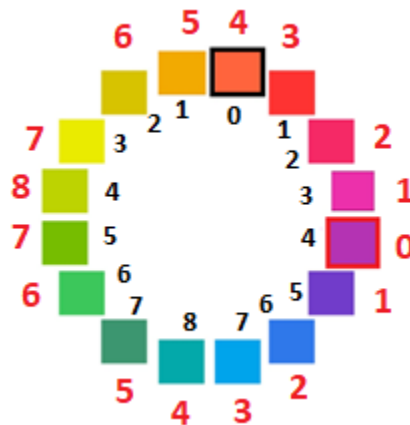


Figure 5: The sixteen possible colors arranged in a circle. The orange outlined in black is four steps away in color space from the violet outlined in red. The red numbers indicate the color-difference values of each color in relation to the purple target. The black numbers indicate the color difference values in relation to the orange target.

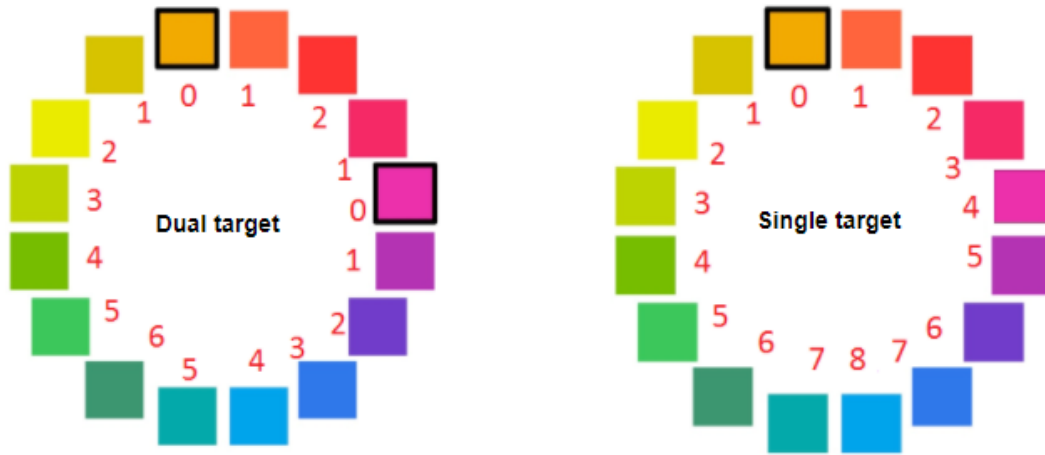


Figure 6: The color-difference mapping differs between dual and single-target search. Color-difference is determined by the number of color-steps on the sixteen-color ring between the color of the fixated object, and the nearer target.

Trial Number	Fixation Total	Color Differences	Bins											
1	1	3	3	3	3	3	3	3	3	3	3	3	3	3
2	2	2,1	2	2	2	2	2	1	1	1	1	1	1	1
3	3	1,3,2	1	1	1	3	3	3	3	2	2	2	2	2
4	4	4,2,3,1	4	4	2	2	2	3	3	1	1	1	1	1
5	5	2,1,3,4,3	2	2	1	1	3	3	4	4	3	3	3	3
Bin totals			12	12	10	11	13	13	14	11	10	10	10	10
Bin averages			2.4	2.4	2	2.2	2.6	2.6	2.8	2.2	2	2	2	2

Figure 7: The binning process for five trials of fixation totals 1,2,3,4 and 5. The bin total (10 in this example, 100 in the analysis) is divided by the fixation total to determine how many bins will be allocated to each fixation. The bin totals are divided by the total number of trials to get the average color difference value for each bin.

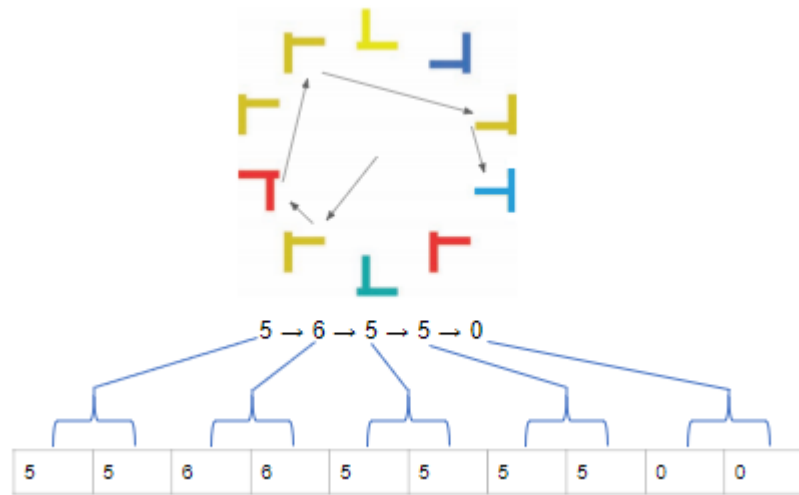


Figure 8: The gray arrows indicate the path that eyes follow during this sample trial. Each object fixated is given a color-difference value. The number of bins allocated to a single

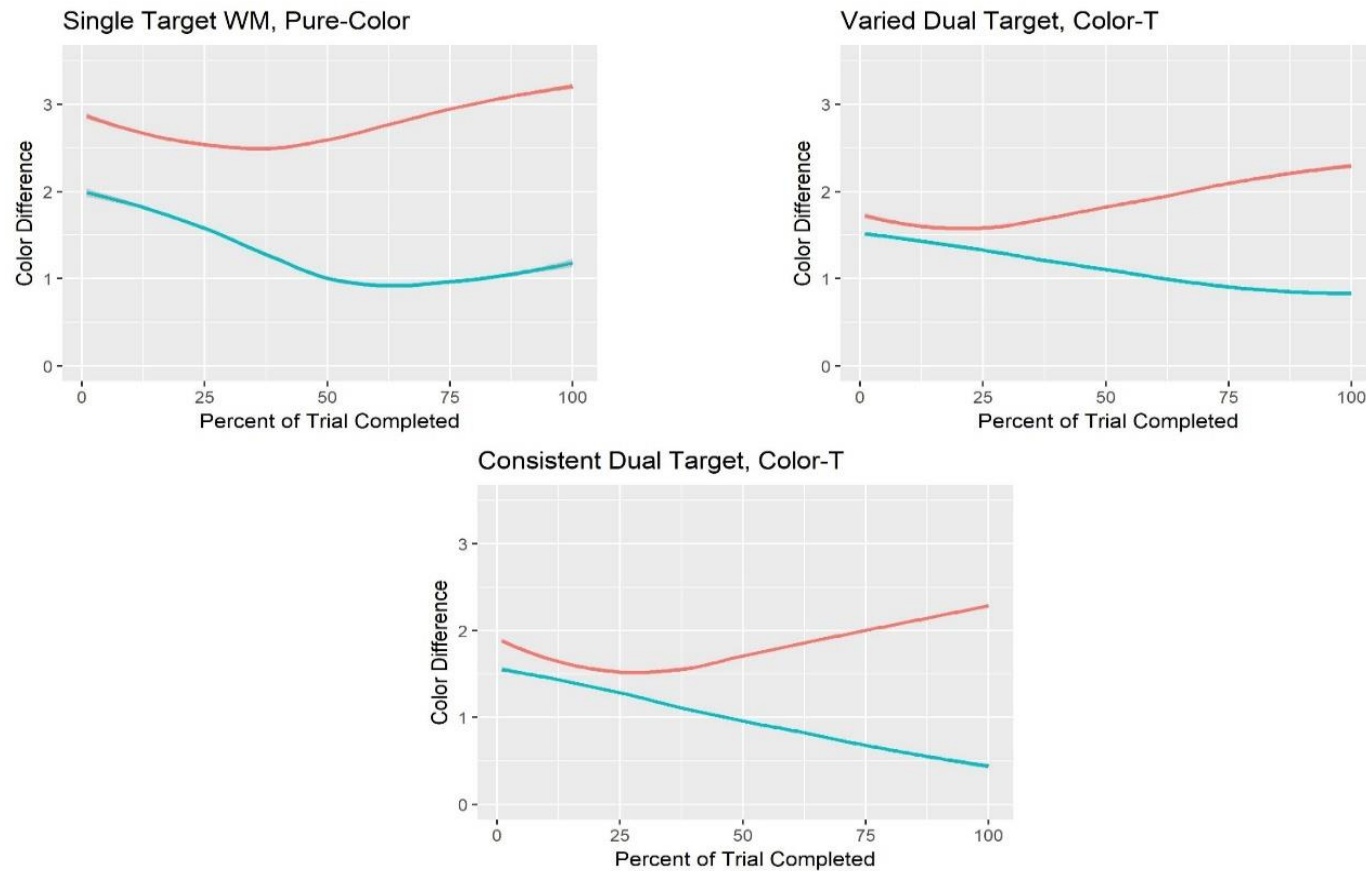


Figure 9: Color difference curves for target absent (red) and target present (blue) conditions for a variety of search conditions. (Left) Single target pure color search with a WM task. (Middle) Dual target color-T search. (Right) Dual varied target search. The curves in this graph have been smoothed to highlight the overall pattern. The y-axis represents the average color difference and the x-axis indicates the proportion of the trial that has been completed.

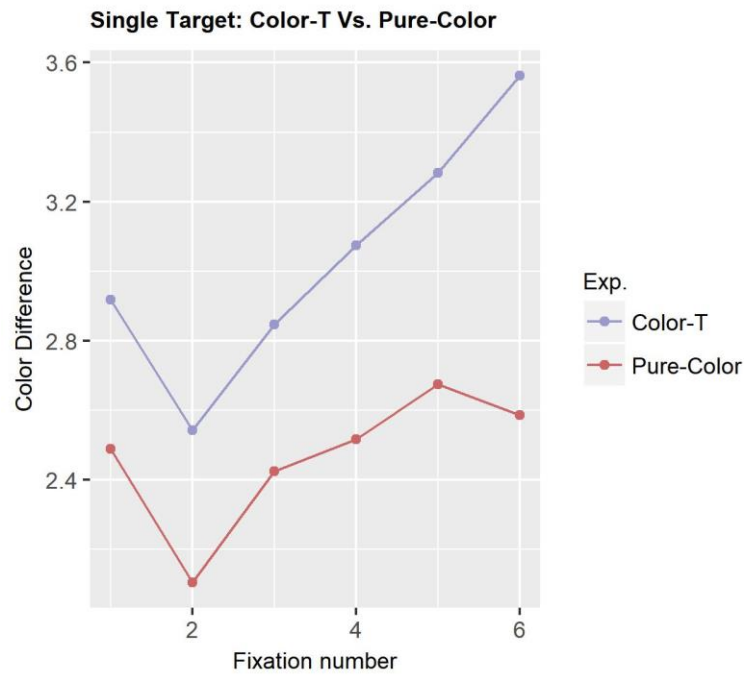


Figure 10: Average color difference values for fixations 1-6 in pure color (red) and color-T (blue) single target search. The y-axis represents the average color difference while the x-axis indicates the fixation number.

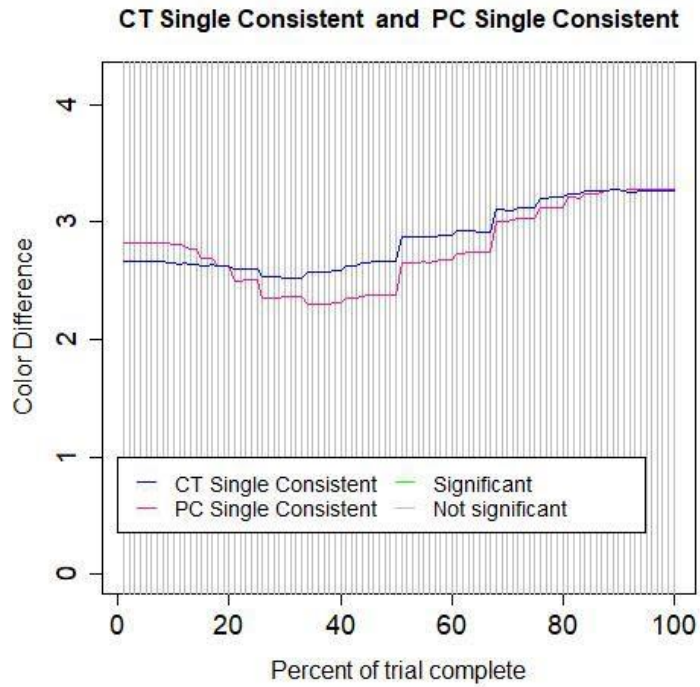


Figure 11: A comparison of single target pure color (red) and color-T (blue) search. A significant difference ($p < .05$) between the two lines is indicated by green bars. None of the time steps produced a significant difference. The y-axis indicates the average color difference (in color steps) from the target color. The x-axis represents the duration of the trial.

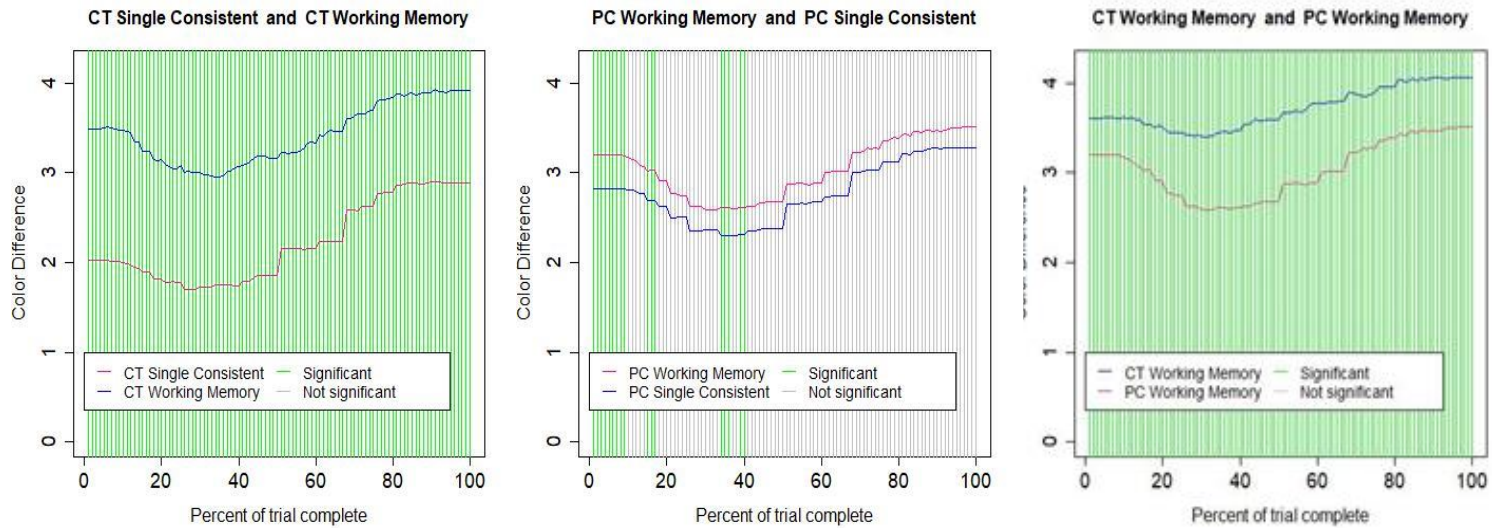


Figure 12: (Left) Average color differences for single target color-T search (red) and single target color-T search with the addition of a WM task (blue). (Center) Average color differences for single target pure-color search (blue) and single target pure-color search with the addition of a WM task (red). (Right) A comparison of the average color differences produced by the two working memory experiments. A significant difference ($p < .05$) between the two lines is indicated by the green bars. The y-axis indicates the average color difference (in color steps) from the target color. The x-axis represents the duration of the trial.

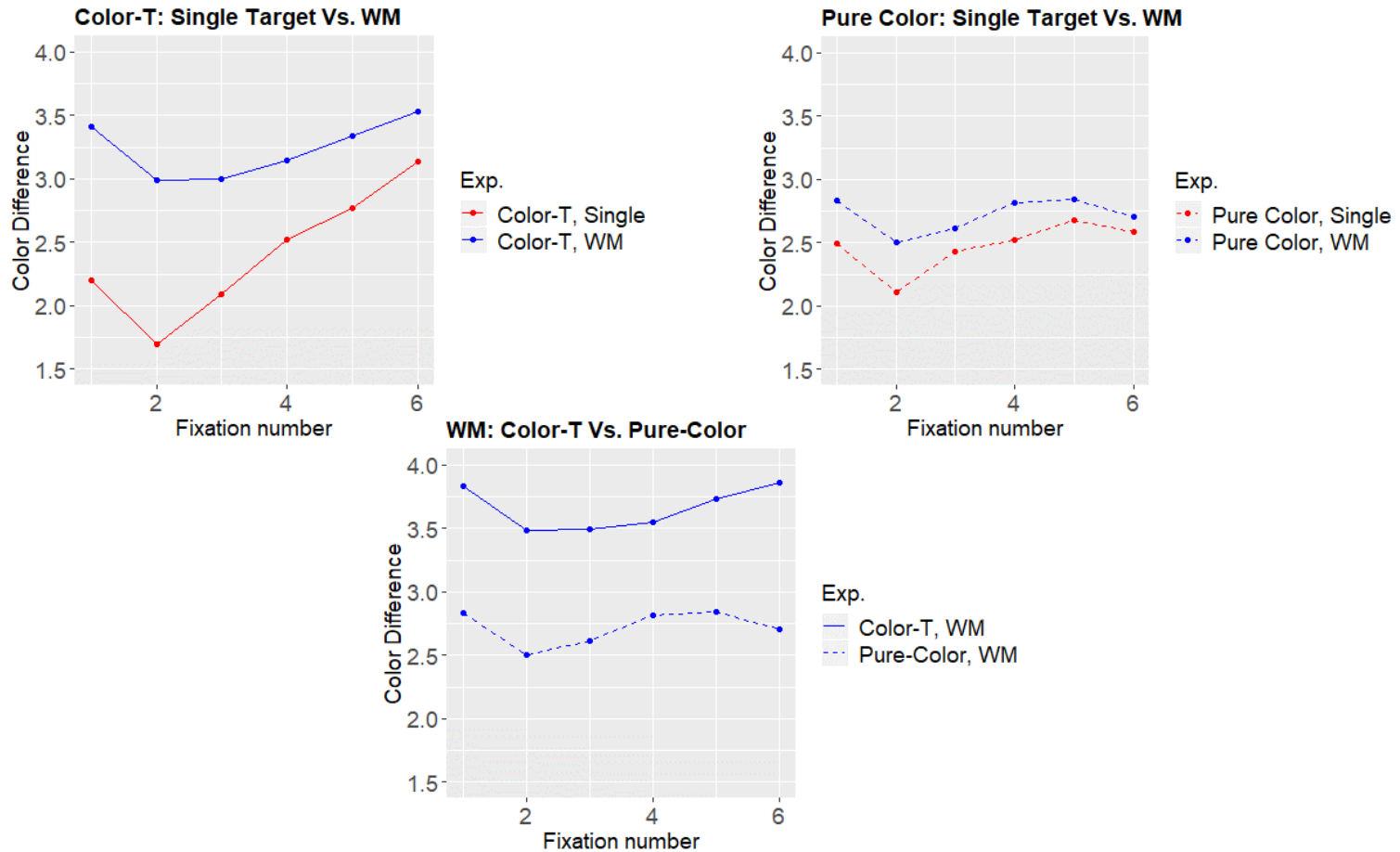


Figure 13: (Left) Average color difference values for fixations 1-6 for single target color-T search (blue) and color-T search with a WM task (red). (Right) Average color difference values for fixations 1-6 for single target pure-color search (red) and pure color search with a WM task (blue). (Below) A comparison of the average color difference values for fixations 1-6 of the color-T (red) and pure-color (blue) WM experiments. The y-axis represents the average color difference while the x-axis indicates the fixation number.

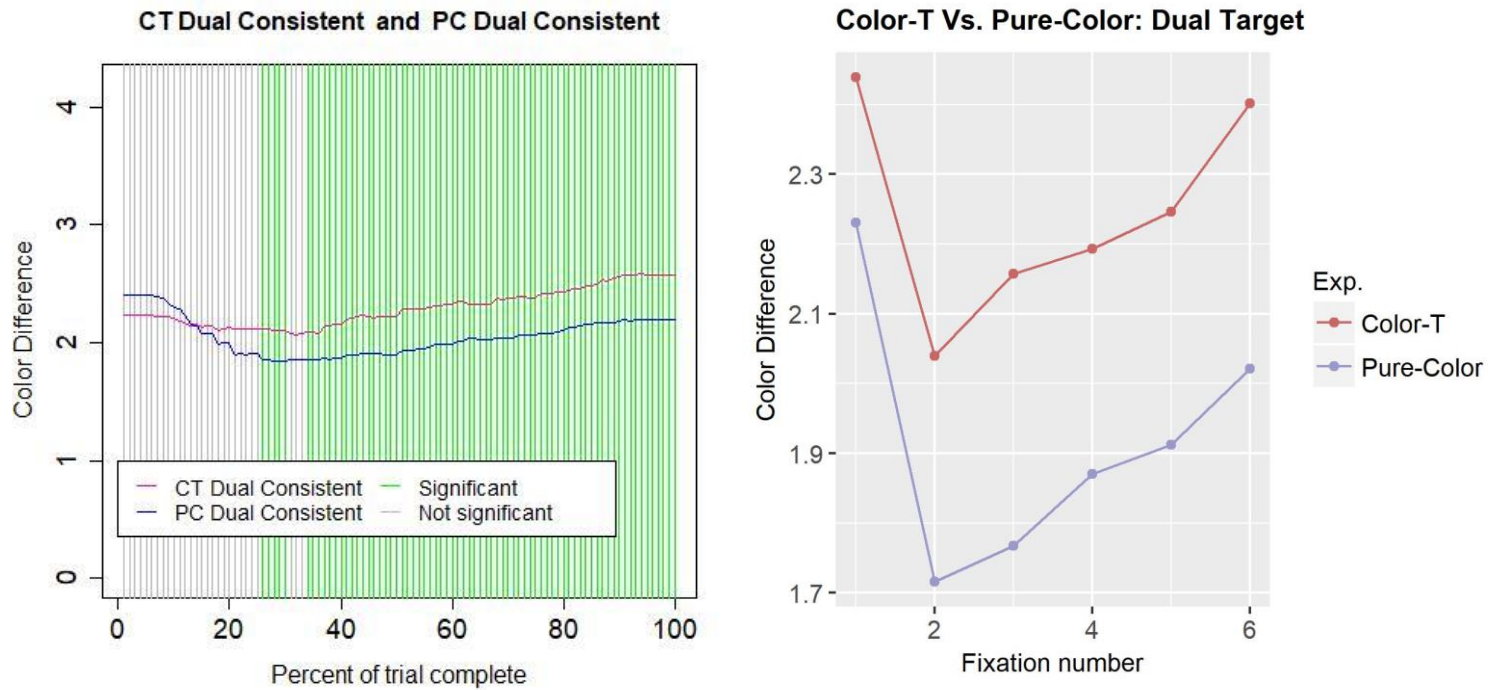


Figure 14: (Left) A comparison of dual target pure color (blue) and color-T (red) search. A significant difference ($p < .05$) between the two lines is indicated by the green bars. The y-axis indicates the average color difference (in color steps) from the target color. The x-axis represents the duration of the trial. (Right) Average color difference values for fixations 1-6 for pure color (blue) and color-T (red) dual target search. The y-axis represents the average color difference while the x-axis indicates the fixation number.

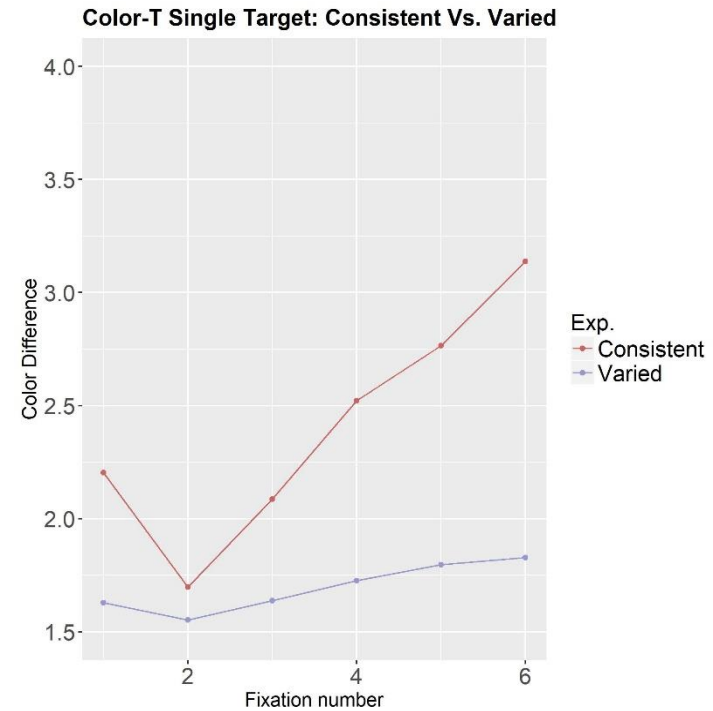
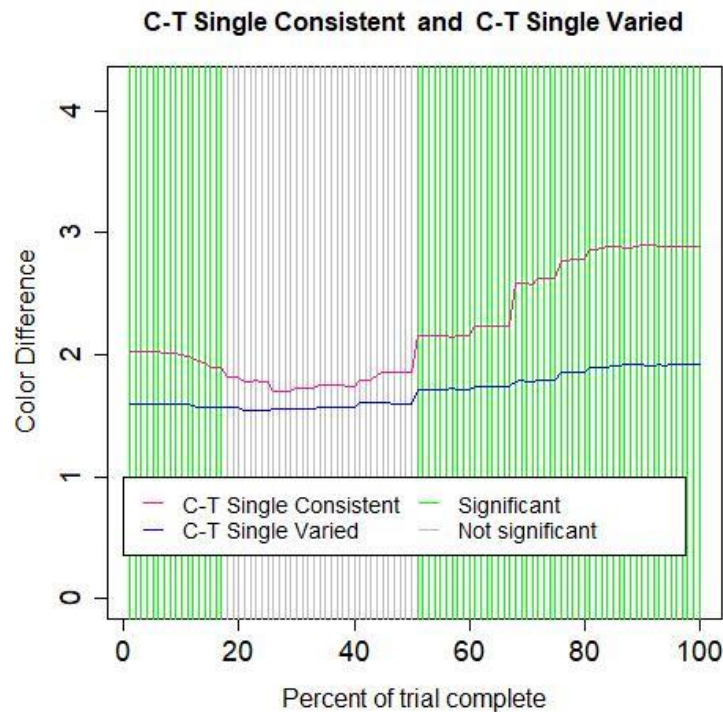


Figure 15: (Left) A comparison of the consistent (red) and varied (blue) target condition in a single target color-T search. A significant difference ($p < .05$) between the two lines is indicated by the green bars. The y-axis indicates the average color difference (in color steps) from the target color. The x-axis represents the duration of the trial. (Right) Average color difference values for fixations 1-6 for consistent (red) and varied (blue) single target color-T search. The y-axis represents the average color difference while the x-axis indicates the fixation number.

Color-T Single Target: Consistent Vs. Varied

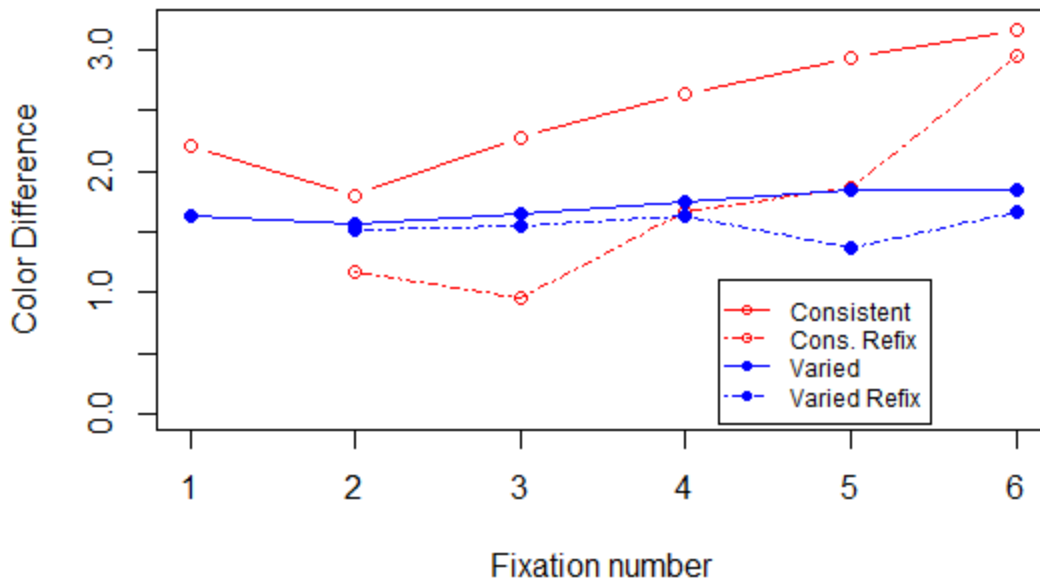


Figure 16: Average color difference values for the first six fixations in consistent (red) and varied (blue) target color-T search. The x-axis indicates the fixation number and the y-axis represents the average color-difference. For each condition, the dotted line corresponds to the average color difference when the indicated fixation number is a refixation, while the solid line represents all novel fixations.

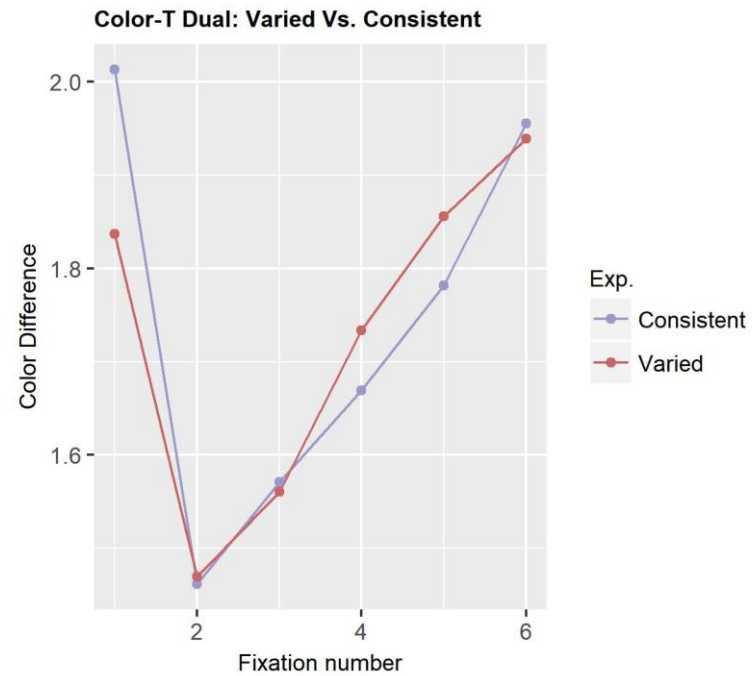
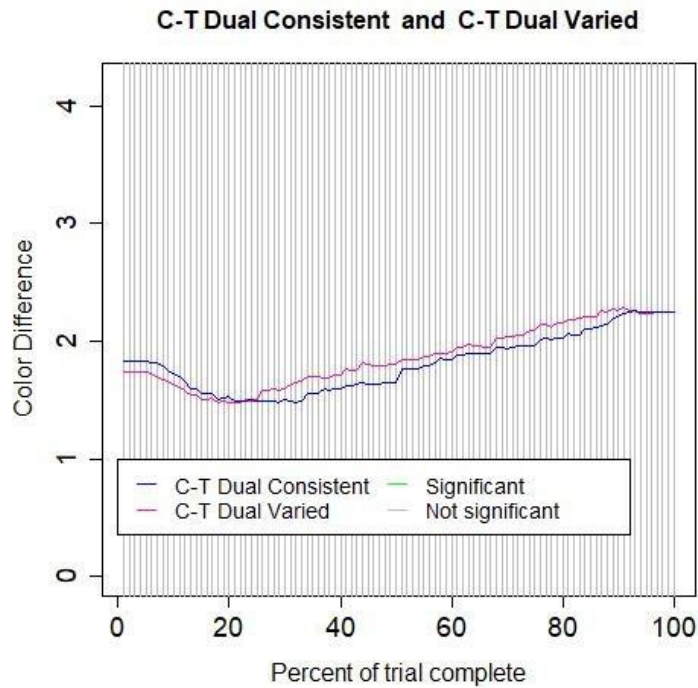


Figure 17: (Left) A comparison of the consistent (blue) and varied (red) target condition in a dual target color-T search. A significant difference ($p < .05$) between the two lines is indicated by the green bars. The y-axis indicates the average color difference (in color steps) from the target color. The x-axis represents the duration of the trial. (Right) Average color difference values for fixations 1-6 for consistent (blue) and varied (red) dual target color search. The y-axis represents the average color difference while the x-axis indicates the fixation number.

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