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SEARCH GUIDANCE CAN BE ADJUSTED BY EXPERIENCE WITH SEARCH DISCRIMINABILITY

A Thesis Presented

by

JUN HA CHANG

Submitted to the Graduate School of
the University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

SEPTEMBER 2017

Department of Psychological and Brain Sciences

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A Thesis Presented

by

JUN HA CHANG

Approved as to style and content by:

Kyle R. Cave, Chair

Lisa Sanders, Member

Matt Davidson, Member

Caren Rotello, Department Head
Department of Psychological and Brain Sciences

ABSTRACT

SEARCH GUIDANCE CAN BE ADJUSTED BY EXPERIENCE WITH SEARCH DISCRIMINABILITY

SEPTEMBER 2017

JUN HA CHANG, M.A & B.A., CHUNG-ANG UNIVERSITY

M.S., UNIVERSITY OF MASSACHUSETTS

Directed by: Kyle R. Cave

Several recent studies show that previous experience can influence observers' search strategy in a way that improves search performance. The purpose of the present study is to investigate how the experience of difficult color discriminability affects search strategies. Two participant groups either experienced difficult color discriminability in a half of the trials (i.e., hard-discrimination group) or experienced easy search in all trials (i.e., easy-discrimination group) in a dual-target search task. Participants were required to respond to the presence of a target (colored T) among distractors (colored pseudo-L). Eye movements were recorded to understand which feature information is used to guide attention, and behavioral performance was measured to compare search efficiency between the two groups. The hard-discrimination group fixated more distractors with target-dissimilar colors than the easy-discrimination group, suggesting the hard-discrimination group used shape information to guide search more than the easy-discrimination group. However, error rates and response times were not significantly different between groups. The results demonstrate that the experience of difficult color discriminability discourages observers from guiding attention by color, and encourages them to use shape information.

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CHAPTER 1

SEARCH GUIDANCE CAN BE ADJUSTED BY EXPERIENCE WITH SEARCH DISCRIMINABILITY

1.1 Introduction

Visual search is a common activity in our life. You may search for your friend among strangers or a pencil on a desk. Because visual search happens very frequently, we want to save our time and energy while searching. Information we know about a target can help make a search efficient. If you know that your friend likes to wear a particular pink coat, then you can easily search for him/her among others by searching for the coat instead of selecting people randomly. However, this particular search strategy based on previous knowledge of a target can sometimes be subject to interference from observer's experience. For example, let us suppose that this pink coat becomes a fashion trend in a certain group of people. You may examine several people who wear pink coats and realize that none of them is the friend you are searching for. This experience with the pink coat probably influences the way to search for your friend. You could ignore pink coats and try to focus on the friend's height or face. Or you could still think of the pink coat but focus on the precise design of the coat or exact color of the coat. Regardless of your choice, one obvious thing is that this previous experience can make us rethink a current search strategy and influence a future search strategy for a subsequent search. The primary goal of the current study is to investigate how the previous experience of difficult search alters search strategy.

1.1.1 Visual Attention in Visual Search

We are surrounded by unlimited information. However, our visual system is limited. We can only perceive visual inputs within a limited part of the environment (the visual field) through the eyes. Even within the visual field, we can gain high spatial resolution of visual information only from the fovea (Strasburger, Rentschler, & Jüttner, 2011). This fundamental limitation leads the visual system to process the information selectively. We need to keep moving our eyes toward potentially important stimuli or spatial areas.

How can we determine what the potentially important stimuli are and where they are located? Our visual system can solve this problem by attention. Many attention models presume that two processes mainly determine the deployment of attention in visual field (Wolfe, Horowitz, & Cave, 1989; Wolfe, 1994; Wolfe 2007; Desimone & Duncan, 1995; but see Awh, Belopolsky, & Theeuwes, 2012).

First, attention can be driven by an external factor such as the salience of a stimulus, which is called bottom-up attention or stimulus-driven attention. If a single item has a distinguishable attribute compared to surrounding stimuli, this unique item will "pop-out." This salient item captures attention. A red square can be easily detected among blue squares. Second, attention also can be driven by an internal factor such as observer's current goal, which is called top-down attention or goal-driven attention. Observers can allocate attention to target attribute(s) or categories, which can help in distinguishing the target amongst distractors. When a target is a red circle, a red square stimulus is more likely to be attended than a green square stimulus (Kim & Cave, 1995).

The stimulus-driven and goal-driven attentional controls are not independent of each other; they interact during a visual search. Even in a simple feature search that mainly relies on the bottom-up attentional control, the knowledge about a target can help participants to find a target quickly (Bravo & Nakayama, 1992; Experiment 1 and 2, Wolfe, Butcher, Lee, & Hyle, 2003). Similarly, in a more complex search involving the top-down attentional control, participants are attracted by an abrupt onset of a salient stimulus (Theeuwes, 1994; Theeuwes & Burger, 1998). We see another example of this bottom-up attentional capture when we cannot ignore a flash from a camera while we are looking for a friend.

1.2 Visual Target Template

1.2.1 The Definition of the Visual Target Template

Knowledge about a target can help us to efficiently find a target (Bravo & Nakayama, 1992; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Before seeking a target, we are thinking of the target properties that are relevant for finding it. This top-down knowledge about the target is organized into a target representation, which is used to allocate attentional resources. The results of this top-down allocation of attention can be seen both behaviorally and in the activations of individual neurons (Duncan & Humphreys, 1989) This active mental representation is used to guide attention toward items that match the representation itself and to avoid attention to unwanted distractors. This representation is sometimes described as an attentional template (Duncan & Humphreys, 1989, Eimer, 2014), or a target template (Vickery, King, & Jiang, 2005; Hout & Goldinger, 2012).

The effects of the target template have been measured for the last two decades (Desimone & Duncan, 1995; Carlisle, Arita, Pardo, & Woodman, 2011; Woodman & Arita, 2011; Hout & Goldlinger, 2012). The basic logic underlying these studies is that if a target representation is directing attention, the activation of brain areas related to the target would be observed while observers are thinking of the target representation prior to search. Studies of single cell recording with macaque monkeys (Duncan & Humphreys, 1989; Chelazzi, Duncan, Miller, & Desimone, 1998) have shown high firing rates of cells representing target features before the monkeys saw a search array. Studies measuring event-related potentials (ERP) with human subjects also found similar results (Woodman & Arita, 2011; Carlisle, Arita, Pardo, & Woodman, 2011). For example, Woodman and Arita (2011) used ERPs to test for the existence of a target template by using contralateral-delay activity (CDA), which is a marker of maintenance of a visual working memory representation. If participants were holding a target representation given by a target preview, the CDA would be observed during the period between the offset of the target preview and onset of a search array. They observed the CDA during the expected period. Moreover, search accuracy was positively correlated with the amplitude of the CDA. The results demonstrate the target template is active before a search to guide attention.

1.2.2 The Relationship between a Target Template and Visual Working Memory

These results showing the neural activity associated with the target template or attentional template indicate that observers have a representation about a target in advance of a top-down directed visual search. These results give rise to reasonable questions about the relationship between visual search and visual working memory as a place where the target representation is stored. Unsurprisingly, a body of studies show the close relationship between working memory and visual search (Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Soto, Heinke, Humphreys, & Blanco, 2005; Soto & Humphreys, 2006; Soto, Humphreys, & Heinke, 2006; Olivers, Meijer, & Theeuwes, 2006; Beck, Peterson, & Vomela, 2006; Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Olivers, 2009; van Moorselaar, Theeuwes, & Olivers, 2014, but see Woodman & Luck, 2007). For instance, a search distractor matching a representation held in visual working memory can attract more attention in the concurrent search task compared to random search distractors that were not held in visual working memory (Soto, Heinke, Humphreys, & Blanco, 2005; Mannan, Kennard, Potter, Pan, & Soto, 2010). More directly, researchers found similar patterns of ERPs while participants were holding a search target representation and while they were holding visual working memory representations (Arita & Woodman, 2011; Carlisle et al., 2011). These results suggest that information about the search target is represented in visual working memory and becomes a target template to guide attention before a search.

1.2.3 The Effect of Previous Experience in Visual Search

Previous experience might shape attentional behavior just as it does many other aspects of behavior. An action resulting in a positive outcome is likely to be repeated, and an action resulting in a negative outcome (or punishment) is more likely suppressed. Although the idea that explicit behavior can change by the motivation to earn better outcomes based on previous experience is old, it is a relatively new claim that early visual process also follow this rule. Observers more easily and quickly deploy attention toward an item followed by positive consequences such as monetary reward or course credit (Anderson, Laurent, & Yantis, 2011; Anderson & Yantis, 2013; Sawaki, Luck, & Raymond, 2015). For instance, Anderson and Yantis (2013) offered a certain amount of monetary reward for attending to a target item for several blocks. In the subsequent test blocks, participants performed a search task with a different target, but the reward was not provided anymore. As a result, participants were easily distracted by the presence of the previously rewarded item, although the item was neither salient nor shared search target attribute. Moreover, the attentional attraction by the previously rewarded item was stronger when the amount of reward was high rather than low.

One may think that the guidance of attention toward the previously rewarded item is caused by simple associations learned between reward and stimulus. However, one recent study argues against the idea. Lynn & Shin (2015) replicated the finding that participants guided attention toward the previously rewarded item in a subsequent search task. However, when a bigger reward was offered in the subsequent search task (e.g., $100) than in the previous training task (e.g., $50), the interference from the previously rewarded item was diminished. Indeed, the search performance was more influenced by the amount of current reward than the previous reward they had earned. It demonstrates the deployment of attention is more sensitive to the amount of positive outcome rather than associative learning between reward and an item.

Previous search experience might influence not only the deployment of attention for given stimuli, but also the target template that observers hold. The accumulated experience from the repetition of a particular search circumstance could lead observers to develop a target template with more and more effective features (Wolfe, 1994; Navalpakkam & Itti, 2006; Bravo & Farid, 2016). For example, after participants were trained to search for a target among one of three distinct distractor contexts, they can use the corresponding target template for predicted contexts and showed faster response times compared to unpredicted contexts (Bravo & Farid, 2016). These studies demonstrate that the target template can be flexibly developed for efficient search.

1.3 Research Questions

The studies reviewed above show that a target template is created according to the observer's goal, and it can be shaped for efficient search based on the observer's previous experience. Observers can make their own search strategy to a particular search situation and will continue to using it if they experience that using that particular strategy has a benefit in search. However, what if their current strategy does not work sometimes and they experience some difficulty? How does the experience of difficult search influence a search strategy?

One of the strongest factors influencing search difficulty is the similarity of a target to distractors. If a search target share attributes with distractors or has similar attribute with distractors, then more time is generally required to find the target than when the target is presented with dissimilar distractors (Duncan & Humphrey, 1989; Reijnen, Wallach, Stöcklin, Kassuba, & Opwis, 2007). Another factor is heterogeneity between distractors. Compare finding one red ball when it is among three yellow balls and when it is among three differently colored balls. It is more difficult to find a target among heterogeneous distractors than among homogeneous distractors (Duncan & Humphrey, 1989; Farmer & Taylor, 1980; Reijnen, Wallach, Stocklin, Kassuba, & Opwis, 2007). To summarize, search is the most difficult and inefficient when the search target is similar to distractors and distractors are different from each other.

However, these studies have focused on attentional processes for physically different stimuli rather than on strategies to overcome the difficulties that arise. For example, Duncan and Humphreys (1989) measured both response time and accuracy for different types of search displays: heterogeneity and homogeneity display conditions. Because these conditions had physically different displays, they are likely to have different processes. For the homogeneity display condition, even though participants were holding a target template to guide attention, the homogeneity display could boost the salience of a target. On the other hand, because of relatively low salience of the target in a heterogeneous background, there would be no extra support from bottom-up processes. Therefore, search performance in these conditions probably reflected the different combination of the bottom-up and top-down processes, and the different search strategies that might emerge. Thus, there is not a pure measure of how difficult discriminability influences search strategy.

1.4 Present Study

The aim of the present study is to address whether the previous experience of difficulty influences a search strategy, and if so, what strategy is chosen. Participants searched for targets by color in arrays of items with many different colors. One experiences a difficult search if a target is barely distinguishable from distractors. One experiences an easy search if a target is easily distinguishable from distractors. Thus, the search difficulty was determined by the distance between target and distractors in a color space. Also, the difficult search contained a higher proportion of distractors with target-similar colors than the easy search, although the difficult and easy searches had the same number of search items in the search array. Thus, observers who performed the difficult search could experience more difficulty in finding a target because of the high similarity of target and distractors and high proportion of target-similar distractors in a search display.

The experience of difficult color discriminability might make it difficult to guide search by color. Participants could assess their current search strategy and rethink their future search strategy. For instance, if we have the experience of easily identifying a friend by her/his unique pink coat, we are likely to search for the friend by the pink coat next time. However, what if the pink color becomes a trend so that many people wear the similar pink coats? Would we continue to search for the friend by the pink coat or by some other feature?

One possible outcome is that subjects would continue using a target color as a target template to guide attention. However, the high color similarity between a target and distractors could motivate participants to improve a precision of color target template. When a target is hard to distinguish from distractors, a very precise target template can be advantageous. It could help identify the target quickly and reject target-similar distractors.

Several studies provide evidence supporting the idea that the precision of mental representation can be flexible depending on the goal. The flexible representation model is based on the claim that the precision of working memory representations is flexible rather than fixed by condition (Bays & Husain, 2008; Bays, Catalao, & Husain, 2009; but see Luck & Vogel, 1997). Perhaps more attentional resources can be allocated to increase the precision of memory representation. The higher level of attentional resources might reduce noise in the representation, such that precision of the representation can be more specific (Lu & Dosher, 1998; Odegaard, Wozny, & Shams, 2015). In one study, Zokaei, Ning, Manohar, Feredoes, & Husain (2014) showed that the precision of memory representations can be varied depending on the attentional resources allocated. In a separate study, Ye, Hu, Ristaniemi, Gendron, & Liu, (2016) provided two types of prior cue: Valid and random cues. A valid cue indicated the feature dimension of the likely target in the upcoming display, inducing participants to internally allocate attentional resources to enhance the cued feature dimension. A random cue did not offer any information about the target likely feature dimension. The feature dimension of the memory item was more precisely recalled when a valid cue was given than the random cue.

Based on evidence from recent neurophysiological research that a memory representation is stored in visual working memory and then used as a search target template (Woodman & Arita, 2011; Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Meeter, & Olivers, 2014), it is plausible that the precision of the target template can be adjusted just as working memory representations were adjusted. As evidence supporting this idea, Navalpakkam and Itti (2006) found evidence for a fine-grained target template within a single feature dimension. In the study, participants had to search for a T among L's, but with three different levels of luminance intensity depending on the condition. The participants were asked to search for a T with low luminance intensity in the LOW condition, a T with medium luminance intensity in the MID condition, and a T with high luminance intensity in the HIGH condition, among a search array consisting of various Ls with low, medium, and high luminance intensity levels. As a result, the participants more frequently fixated Ls with the same luminance intensity as the target T than those with different luminance intensities. Similar patterns were observed for size and saturation feature dimensions, indicating that the target template can be precise within a feature dimension depending on the observer's purpose.

Another possible outcome from manipulating search difficulty is that participants may avoid using a color target template to guide a search, and start to use some other target property that could possibly improve performance, or at least make search feel less difficult. Previous studies using procedures similar to the present study support this possibility. When participants were required to hold a search target with either another search target (Stroud, Menneer, Cave, & Donnelly, 2012) or an extra working memory item (Menneer, et al., submitted), the guidance of target color information was reduced compared when they held a single search target. Although the type of search difficulty in these studies is different from the current study (holding extra information vs. discriminability), it raises the possibility that search difficulty could change the use of guidance in search.

The dual-target visual search task was used with color-shape conjunctive stimuli in this experiment to be consistent with the previous studies (Stroud, et al., 2012; Menneer et al., submitted). Targets were specified by color given that color can generally be used easily and effectively to guide search. The color of targets kept changing in a trial to trial to ensure the representation is stored in the visual working memory. Each target also had a unique shape, and subjects needed to use this shape information to confirm that a selected item was a target. Shape was less appealing for guiding attention, however, because the target shape (T) was very similar to the shape of the distractors (pseudo-Ls), and search by shape was further complicated by random rotation of each stimulus item. Only color discriminability was manipulated in this experiment, and not shape discriminability. A group of participants (i.e., the hard discrimination group) experienced difficult color discriminability (i.e., 16-color trials) in some trials and relatively easy color discriminability (i.e., 8-color trials) in the remaining trials. Another group of participants (i.e., easy discrimination group) experienced only easy color discriminability. To ensure performance differences between the two groups were not caused by a physical difference between stimuli, only the data for the 8-color trials were compared across groups, so that the stimuli were identical for this comparison. Eye movements were recorded to capture subtle guidance of search.

If the experience of difficult color discriminability leads participants to enhance the color precision of target template, then participants should show more precise guidance of eye movements by color compared to participants do not experience difficult trials. However, if search difficulty encourages shift away from color-guided search in favor of shape-guided search, then hard-discrimination participants should show less precise guidance of color compared to easy-discrimination participants. Finally, according to Stroud et al.'s experiments (2012), distractors that were more similar to the target should be fixated more frequently.

CHAPTER 2

EXPERIMENT

2.1 Method

2.1.1 Participants

64 students from the University of Massachusetts Amherst participated in the experiment for course credits. All participants reported normal vision or corrected-to-normal acuity. The Ishihara test (Ishihara, 1972) was used; it showed no evidence of anomalies in color perception in any of the participants.

2.1.2 Stimuli

Stimulus objects were the same as those that Stroud et al. (2012) used, with the exception that the size of stimuli was a little different. Two different shapes were used. A “T” was a target, and pseudo “L”s were distractors. Each letter was a conjunction of two bars, each 1.04º × 0.37º of a visual angle. For the “T”, one end of the first bar was placed on the middle of the second bar. For the pseudo “L”, the end of the first bar was slightly closer to the left than the right side of the second bar. The center of the first bar was 0.3º away from the left end and 0.7º away from the right end. Each search item was randomly rotated to an orientation of 0º, 90º, 180º, or 270º.

Figure 1 shows the colors of stimulus objects. This was the same set of 16 colors used in the previous study (Stroud et al., 2012). The colors were chosen to have similarly noticeable differences between neighboring color pairs, so that no color appeared to pop out when appearing among the other colors (Menneer, Barrett, Phillips, 2007; Menneer, Donnelly, Godwin, & Cave, 2010). The colors were arranged to form a color ring and labeled by numbers from 1 to 16 (Figure 1). To easily quantify the similarity between colors, we used a concept of "color-step." The number of color-steps represents the distance between two colors on the color ring. For instance, one color-step means that one color is one step away from the other color; in other words, there are next to each other (Figure 1).

There were two different trial types. 16-color trials were created for a difficult search with low discriminability between the target and some of the distractors' colors. The trials in this condition used all 16 colors for targets as well as distractors. Also, the distractor colors that were similar to either of the target colors were presented more frequently than the less similar colors (see Table 1). The 16 colors made up a particular distractor color pool with different frequencies for each target color pair. For example, when the target colors were 7 and 11, the most target-similar colors (i.e., colors 6, 8, 10, and 12) each occupied 12.5% of the distractor color pool, so together those four colors made up 50% of the distractor color pool. The next similar colors (i.e., colors 4, 5, 13, and 14) each occupied 5% of the color pool. The most target-dissimilar colors, which were at least four color steps away from the nearest target color (i.e., colors 1, 2, 3, 15, or 16) each only occupied 2.5% of the color pool. Finally, the distractor colors that were the same as target color (i.e., colors 7 and 11) and the color located between two target colors (color 9) occupied 7.5% and 2.5% respectively.

8-color trials were created for a relatively easy search with high discriminability between the target and distractors. The 8-color trials used eight colors that were equally spaced with two color-steps between the nearest neighbors. These eight colors were represented in equal numbers in the distractor color pool for each pair of target colors. Because the 8-color trials only used half of the 16 colors, there were two subsets, each with half of the 16 colors: 8-odd-numbered-color trials and 8-even-numbered-color trials.

In each trial, there was a sequence of two displays: a pre-cue display and a search display (see Figure 2). In the pre-cue display, two pre-cues were presented to inform the participant of the two possible target colors, either of which might appear on the following search display on that trial. These two targets varied from trial to trial. The target colors were always four color-steps away from each other on the color ring. The two pre-cues were located to the left and right of the central fixation point. The distance between the fixation point and the center of each pre-cue was 1.96° of visual angle. To avoid any bias favoring either the left or right cue, the probability that the left pre-cue became a target was the same as the probability that the right pre-cue became a target.

In each search array display, there were ten search items on a white background. These ten items were arranged in a circle. Each search item was 7.80º of visual angle away from the central fixation point. The distance between centers of adjacent search items was 2.41º of visual angle.

2.1.3 Procedure

Figure 2 demonstrates the procedure. Initially, each participant was tested with the Ishihara vision task to check for color blindness (Ishihara, 1972). After that, there was a set of five practice trials. They were encouraged to ask questions after they completed the practice trials, before the main experiment trials.

At the beginning of each trial, a black dot appeared in the center of the display. The participants were required to fixate their eyes on the dot. When the fixation was close enough to the fixation dot, the experimenter pressed a space bar to start the trial. Two colored “T”s were presented for 1000ms as pre-cues to define potential targets. This pre-cue display was followed by a blank interval for 1000ms. Then, the search array including ten search items was shown until response. Half of the trials were target-present trials and another half were target-absent trials. In the target-present trials, one of the ten items was a target ("T"), which had the color of one of pre-cues in the pre-cue display, and the other nine were "L"s each with a randomly selected color from the distractor color pool. In the target-absent trials, all items were "L"s with random colors from distractor color pool. The target-present and target-absent trials were intermixed in random order.

The participants were required to report whether a target was present or not by pressing one of two buttons on a game controller. High and low tones were given for sound feedback to wrong and correct responses respectively. To inhibit encoding the pre-cue verbally, the experimenter asked the participants to repeat the word "the" through the whole experiment (Baddeley & Hitch, 1974).

There were two distinct participant groups: a hard discrimination group and an easy discrimination group. Both the hard discrimination and easy discrimination conditions consisted of 256 trials. In the hard discrimination group, half of the trials (128 trials) were the 16-colors trials, and other two quarters of the trials were the 8-odd-numbered-color trials (64 trials) and the 8-even-numbered-color trials (64 trials) respectively. The trials were randomly mixed. Half of the participants who were assigned to the easy discrimination group received only 8-even-numbered-colors trials, and the remaining subjects in the easy discrimination group received only 8-odd-numbered-color trials.

After completing the experiment, the experimenter asked the participants whether they realized that some trials were more difficult to detect the target presence than other trials.

2.1.4 Apparatus

The stimuli were presented on a 17-inch Vision Master Pro 514 iiyama CRT monitor (25.7° × 32.5°) positioned 57cm from the participants. It was connected to a computer that interacts with an SR Research Limited Eye-Link II eye tracking system, operating at a sampling rate of 250Hz. Only the right eye was tracked. Both pupil position and corneal reflection were used to determine eye position.

2.2 Results

The purpose of the analysis is to test how previous experience with difficult color discriminability can influence the use of a color target template to guide eye movements. The movement of the right eye was tracked to obtain fixation positions, which were used to calculate the probability of fixation for each of the distractor colors. The fixations to the target were not included in the analysis; only fixations to distractors were included, so that the differences in fixation rate can be attributed entirely to color and not to shape. Thus, the term color-step when used below refers to the distance between the distractor's color and the more similar target color.

To calculate the probability of fixation for a particular color of distractors, I summed up the number of times that distractors with that particular color-step color were fixated at least once in a trial. For example, if two distractors with a 2 color-step color appeared in a trial and were both fixated once, it was counted as two fixated objects. This count for that particular color was divided by the total number of distractors with that particular color-step color that were presented during the entire experiment.

2.2.1 Comparison of 16-color Trials and 8-color Trials

Although 16-color trials were designed for a difficult search, it is necessary to confirm whether this manipulation affected search performance. Response times were compared between the 16-color trials and 8-color trials in the hard-discrimination group, which was the only group to experience both trial types. Table 2 summarizes the error rates and response times. The manipulation of search difficulty was successful. Incorrect trials were excluded in the response time analysis. The response times were slower for the 16-color trials than the 8-color trials, with 48 and 130ms differences for target present and absent trials respectively, indicating that it was difficult to find a target in the 16-color trials compared to the 8-color trials.

Analysis of variance (ANOVA) confirmed this conclusion. There were significant main effects of the trial type (16-color trials vs. 8-color trials), $F(1, 31) = 17.89$, $p < .001$, and of target presence (target present vs. target absent), $F(1, 31) = 124.98$, $p < .001$. The interaction was marginally significant, $F(1, 31) = 4.16$, $p = .05$.

The error data are shown in Table 2. There was no evidence that the error rates were significantly different between the trial types, $F(1, 31) = 2.43$, $p = .13$. The longer response times and similar error rates between the two types of trials demonstrate that in search in the 16-color trials it was more difficult to quickly guide attention toward a target, but once an item was fixated, the difficult discriminability did not prevent participants from identifying the selected item as target or distractor.

In addition, when the experimenters asked after completing the task whether the participants realized that some search trials were more difficult than others, the participants reported that they did not notice any particularly easy or difficult search trials.

2.2.2 Probability of Fixation

The primary purpose of the fixation rate analysis is to test whether previous experience with task difficulty alters how feature information is used to guide eye movements. As mentioned above, the manipulated factor is the difficulty in using a color feature to guide search, which will vary depending on the color similarity between targets and distractors.

I hypothesized that experience with difficult color discriminability would change the search strategy, by either improving the precision of color guidance, or by decreasing the use of color guidance. The effects of color discriminability cannot be accurately tested by comparing the easy and hard discrimination groups directly due to the physically different stimuli in the 16-color trials that only the hard-discrimination group experienced. To avoid this confounding, I used only the 8-color trials from the hard discrimination and easy discrimination groups, excluding the 16-color trials in the hard discrimination group. Planned comparisons were conducted with a Bonferroni correction (FWE = .05) when multiple t-tests were used. Either a Huynh-Feldt correction or Greenhouse-Geisser correction was used where the sphericity assumption was violated.

Figure 3 summarizes the probability of fixation results. Although the data from 16-color trials in the hard-discrimination group were excluded in the analysis, Figure 3 includes them (labeled "Hard (16-color)"). The different colors were organized into five groups, including the non-target color between two target colors, the target colors, and the remaining non-target colors that were either 2 color-steps, 4 color-step, or 6 color-steps away from the nearer target color on the color ring.

To test color guidance, separate analyses were conducted for target-absent and target-present trials. Each was a 2 × 4 mixed-factor ANOVA was performed with a within-subject factor of color-steps (target color, 2 color-step, 4 color-step, and 6 color-step) and a between-subject factor of discrimination group (easy discrimination vs. hard discrimination). The between color was excluded because fixations to it may be driven by a combination of both targets (Stroud et al, 2012). Incorrect trials were excluded.

In the target-absent trials, there was a main effect of color-steps, $F(3, 186) = 231.38$, $p < .001$, suggesting that the participants fixated a distractor more if its color was similar to a target color. This effect replicates the earlier finding that the participants indeed used target colors to guide a search (Stroud, et al., 2012). The main effect of the discrimination group was also significant, $F(1, 62) = 5.23$, $p < .05$, indicating that experience of difficulty affected search guidance. There were more fixations to the distractors in the hard-discrimination group than the easy-discrimination group. More importantly, the discrimination group interacted with color-step, $F(3, 186) = 4.42$, $p < .01$. The difference between hard-discrimination and easy-discrimination participants was greater for distractors that were more dissimilar to the target color. Similar results were observed in the target-present trials except that the fixation probabilities were lower overall because search was terminated earlier, once a target was found. There was a main effect of color-step, $F(3, 186) = 254.98$, $p < .001$, but neither the main effect of discrimination group, $F(3, 62) = 3.78$, $p = .15$, nor the interaction, $F(3, 186) = 4.42$, $p = .15$, was significant.

2.2.3 Estimations of Parameters In a Fixation Model

The interaction of group and color-step appears to be favoring the second hypothesis. The participants in the hard-discrimination group used color less to guide a search, and thus they more frequently fixated the distractors despite their dissimilarity to the target colors. To better understand this interaction in the fixation data, the model developed to characterize search with fixation rate data was used (Menneer, Cave, Stroud, Kaplan, & Donnelly, 2015). The model consists of three parameters: unguided fixation rate (*u*), selectivity (*s*), and target representation (*t*). The unguided fixation rate parameter (*u*) can be understood as a baseline fixation rate to all items regardless of the distance between target and distractor colors. It represents fixations that are not guided by the target template. Thus, if participants often do not use color to guide a fixation and randomly fixate to items, then the value of the unguided fixation rate parameter would be large. The selectivity (*s*) is similar to the slope of the function, representing how quickly the fixation rate drops as the color becomes less similar to the nearer target color. The parameter of the target representation (*t*) is a measure of how broad a range of colors in color space is treated as a target. A high value of the target representation parameter indicates that colors very similar to a target color will receive the same high fixation rates as the target color. When this parameter has a very low value, then even the target color does not have a high fixation rate. Each parameter was estimated for individual participants and independent t-tests were performed to compare parameter values across the two discrimination groups in target-absent and target-present trials separately.

$$f = u + (1 - u)\left(\frac{1}{e^{sc-t}}\right)$$

In the target-absent trials, the values of the unguided fixation rate parameter were significantly higher in the hard-discrimination group than in the easy-discrimination group, $t(58.17) = 2.11$, $p < .05$, suggesting that color guidance was less involved during the search in the hard discrimination group. The hard group participants fixated more to target-dissimilar colors than the easy group participants did, which would not occur if the hard discrimination group participants guided search as effectively as the easy discrimination group did. For the two remaining parameters, there were no significant differences between the two groups, both $t < 1.76$, $p > .08$. Also, in the target-present trials, there were no significant differences, all $t < 1.50$, $p > .14$.

2.2.4 First Fixated Color Across Bins

The primary purpose of the study is to investigate the effect of experience on search strategies. The experience with difficulty in guiding search by a particular color feature could encourage participants to alter their search strategies. If the experience changes search strategies, fixation patterns would change as their experience accumulates. In this part of the analysis, only first fixations to an object in each trial were used. If the participants change their strategy to actively use color guidance, the colors of first fixated objects would become more similar to the target colors as the experiment continues. If participants change their strategy to use less color guidance and deploy attention more randomly, the colors of the first fixated object would become less similar to the target colors as the experiment continues.

All 256 trials including incorrect response trials were split into 16 bins. Then the 16-color trials were excluded in the hard-discrimination group. Figure 4 shows the average color-steps of fixated objects in each bin for both groups. It appears that color guidance diverges between the two groups in the middle of the experiment. The hard discrimination group seems to rely less on color guidance, while the easy discrimination group's fixated colors appear to become more similar to the target color. To check this, a 2×16 mixed-factor ANOVA was performed with a within factor of bins (1 to 16 bins) and a between factor of discrimination groups. There were no significant results of main effects or the interaction, all $F < 2.15$, $p > .13$. However, this could be confounded by eye movements to random directions that naturally occurred just after the onset of a search array instead of reflecting the guidance by a target template. Thus, I repeated the analysis, including the first two fixations in a trial instead of just the first fixation to better capture where participants likely fixated at the beginning of each trial. Figure 5 demonstrates the average of color-steps across bins. There was again no main effect of either bins or group, and no interaction, all $F < 0.70$, $p > .47$.

2.2.5 Error Rates and Response Times

Table 3 shows the mean error rates and response times. The last analysis is to compare error rate and response time data between the two groups. The 16-color trials in the hard-discrimination group were not included in the data analysis. Error rates and response times were each submitted to a 2 × 2 mixed ANOVA with factors of target presence and discrimination group. Participants responded more accurately in the target present trials than in the target absent trials, $F(1, 62) = 293.55$, $p < .001$, but there was no main effect of the discrimination group, $F(1, 62) = 0.0001$, $p = .99$, and no interaction, $F(1, 62) = 0.07$, $p = .80$. The response time data are similar to the error rate data: the participants responded faster in the target present trials than in the target absent trials, $F(1, 62) = 132.30$, $p < .001$, but there was no main effect of the discrimination group, $F(1, 62) = 1.30$, $p = .26$, and no interaction, $F(1, 62) = 0.82$, $p = .37$. These results do not show the key differences that arose in the eye movements analysis. There were no significant differences between hard-discrimination and easy-discrimination groups on the error rates and response times.

CHAPTER 3

GENERAL DISCUSSION

The current study is designed to investigate two research questions: whether experience with different levels of target/distractor discriminability leads to a change of search guidance, and if so, how search guidance is adjusted. I compared two different groups of participants: one experienced difficult color discriminability (hard-discrimination group) in half of the trials, and the other experienced easy color discriminability in all trials (easy-discrimination group). The present study used the same dual-target search paradigm as Stroud et al., 2012, and both discrimination groups replicated their finding that participants fixated the most to distractors with a target color, with fixation rates gradually decreasing as distractors' colors are more dissimilar to the target color. It suggests that the participants used a color target template to guide search regardless of their experience with difficult or easy color discriminability.

This observation is in line with several attention theories that claim that participants can enhance the activation of target-relevant feature representations based on their top-down knowledge of the target stimulus. For example, according to biased competition theory (Desimone & Duncan, 1995) observers allocate attentional resources to target-relevant information to activate it, helping to select efficiently the most target relevant stimulus among competing candidates. Similarly, the guided-search theory (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994; Wolfe & Horowitz, 2004) assumes that top-down activation is accomplished by prioritizing locations that match features known to belong to the target. When a target is not saliently different from its surroundings, the top-down activation would be important for finding the target among distractors. Therefore, although participants experience difficult color discriminability between a target and distractors, they still guide search at least to some extent with the target color, which was an informative feature to distinguish a target among distractors. Intuitively, using a color to guide a search is the best strategy that they could access. It is easy to imagine that searching among ten random search items will take more time than searching among a smaller number of search items that is limited by color.

However, the comparison of fixation probabilities between the two discrimination groups with different experience suggests that the different levels of discriminability plays a role in determining how much color guidance is involved. Participants experienced with difficult color discriminability used less color guidance, and it appeared that they relied more on searching by shape or even searching randomly, without guidance. Moreover, this new search strategy of shape guidance or random search did not give any significant benefit for their performance. The response times were not significantly different between two discrimination groups; rather there was a tendency for the hard-discrimination group to have slower response times than the easy-discrimination group in the 8-color trials.

The finding of reduced color guidance is consistent with previous findings from studies using a very similar research design. Stroud et al. (2012) found that when participants were required to hold two targets simultaneously, they were less likely to rely on color guidance compared to when participants were required to hold a single target. Similarly, Menneer et al. (submitted) observed reduced color guidance in fixation data when participants were asked to hold an additional working memory item during a concurrent search compared to search without the extra working memory task.

Why did hard-discrimination participants use less color guidance? One possibility is that this new strategy of less color guidance produces some benefit in finding a target in the 16-color trials that were excluded from the analysis. Evidence for this benefit might appear as a negative correlation between the response times in 16-color trials and the level of color guidance. To estimate the level of color guidance, the unguided fixation rate parameter of the 8-color trials was calculated for each subject. The correlation between this value and the response time for the 16-color trials was calculated across subjects. As Figure 6 shows, as unguided fixation rate increases, the response times in the 16-color trials increases ($R^2 = .61$, $p < .001$), suggesting that participants who relied less on color guidance performed *worse* than participants who relied more on color guidance. It clearly shows that relying less on color guidance does not give any performance benefit for the 16-color trials.

The idea that subjects would lower their color guidance and thereby slow their responses is quite surprising given many observations in attention research that search guidance is developed in a way to improve performance throughout the accumulated experience. For example, participants can learn spatial configuration through repeated experience and use it to guide search to a target effectively, so that search performance becomes more effective as the experiment continues (Chun & Jiang, 1998; Chun, 2000). Also, when participants were trained to search for a target that was repeatedly surrounded by a particular type of distractors, they developed a search target template corresponding to the distractor type to easily find the target (Bravo & Farid, 2012; 2016). As more general example, visual experts (e.g., radiologists) who have had a plenty of experience in a specific search task perform more quickly and accurately than novices who do not have experience (Parasuraman, 1986; Nodine et al., 1999; Nakashima, Kobayashi, Maeda, Yoshikawa, & Yokosawa, 2013).

However, the present findings suggest that a certain type of experience can induce a shift to less efficient search guidance, resulting in worse performance. If the efficiency of search guidance depends only on the amount of accumulated experience, then the hard discrimination group will show color guidance as active as the easy discrimination group because both groups experienced the same number of trials. Color guidance could be even more active in the hard discrimination group to overcome difficult search trials and improve search performance. However, the results were the opposite of this; the hard discrimination group showed less color guidance than the easy discrimination group.

One possible explanation for the shift away from color guidance is that it could be easier to use the same feature, for example shape information, for both searching and confirming a target than to use two different features sequentially. Participants might feel that the task is more difficult when they use color to search for a target and then switch to using shape to verify fixated search item as a target.

Another possible explanation is that participants prefer certain information to uncertain information. In this task, color guidance is efficient, but the presence of a target color does not guarantee that a fixated item is a target. Even when participants fixate an item that has the exact target color, it is always possible that this item is a distractor, and not a target. Participants might feel that they wasted time because of these attractive distractors. The failing to find a target by color might discourage participants from using color guidance and encourage them to use shape, which is more obviously associated with the target, and it might make participants feel that the shape guidance strategy actually helps their search in this task, although it does not.

Although the experience of difficult color discriminability seems to influence the search guidance, I was not able to find evidence of this change in guidance in the analysis of the first fixated colors from each trial (all $p > .13$) or the first two fixated colors. (all $p > .47$). One possible explanation is that the number of trials was limited, especially in the hard discrimination group because of exclusion of the 16-color trials. The randomization of the 8-color and 16-color trials made it impossible to have equal numbers of 8-color trials in each bin, so that some bins could have very few 8-color trials. Another possible explanation is based on the limited number of color-step colors used. In the 8-color trials used in this analysis, there were only four different levels of color difference between the fixated color and the more similar target color: 0, 2, 4, and 6 color-steps. Among them, 2-color-step colors were more frequently presented than 4- and 6-color-step colors because there was one more 2-color-step color between the two targets. This biased distribution of distractor colors could make it more difficult to measure the variability in first fixated colors. Finally, the amount of change of activation of the color guidance in the course of the experiment may be too subtle. Even though the hard discrimination group participants relied less on color guidance, they did not completely ignore color information in guiding attention; perhaps the difference in fixation patterns across groups caused by different levels of color guidance were smaller than noise between two subject groups. As a result, it could be difficult to find statistically significant differences across bins, especially with a between-subject design that will generally produce bigger individual differences. Also, our laboratory has examined different analyses with fixation rates in many search experiments (mainly contributed by Ryan Papargiris) showing that guidance is less accurate early in the trial. Thus, a few early fixations are probably not enough to reflect the effect of guidance fully.

CHAPTER 4

CONCLUSION

These results show that the experience of difficult color discriminability can influence search guidance. To be specific, if participants experienced difficult color search in some trials, their search was guided less by the color of the target template; instead, participants showed more of a tendency to search for a target randomly, even though this random search did not improve search performance.

4.1 Implications

The present results are relevant to understanding the effect of experience on search strategy, and they may have implications for the development of training programs for visual search tasks. Although we might assume that training or experience have a positive impact on general performance, the findings of the present study suggest that some types of training might lead to worse performance. It might lead to performance costs in real-world situations such as training diagnostic radiologists or pathologists. For example, typically, residents who are in training and lack enough experience with images in their field showed inaccurate, slow diagnostic response because they fixated more to uninformative areas that were unlikely to contain diagnostic information (Krupinski et al., 2006). If a training program offers more complicated images to trainees based on a general belief that training with difficult images could improve performance quickly and accurately, it could lead the trainees to adopt a less efficient search strategy; for instance, they might search randomly in uninformative areas or avoid examining informative areas because it feels easier to do the task this way. If they continue to use the less efficient search strategy, it will be more likely to cause inaccurate and slow diagnostic decisions. Even though they realize that their search strategy is not appropriate or less efficient and try to reorient the strategy, it might require more time to reach a high level of expertise than others who start with an efficient search strategy. A carefully designed program may be necessary to lead trainees to develop an efficient search strategy and to avoid an undesirable strategy.

4.2 Future directions

Although the general conclusion from the present study is that people who experience difficulty using certain information to guide search tried to avoid using that information, there were some participants who still seemed to use color information to guide search. The present study did not include further analysis to investigate what personal characteristics makes them continue using this uncertain but useful information compared to others. Further studies should examine these individual differences that affect which search strategy is chosen.

Also, the question arises as to how discrimination difficulty can change search guidance when there is only a single feature designating targets. In the present study, participants were able to use two types of information (e.g., color and shape) to identify targets, so that participants can still make a correct response by verifying the shape of a search item without using color to guide search at all. To answer this question, we are performing other experiments in which participants only use color information to find a target. To be specific, they need to search for a T that exactly matches one of two target colors, while ignoring distractor T's with other colors. We are recruiting and running participants. This future study would answer how search guidance changes when feature information is limited.

Tables

Table 1: Sample distractor color pool for target color 7 and 11

	Color of distractor															
Trial type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16-color	2.5	2.5	2.5	5	5	12.5	7.5	12.5	2.5	12.5	7.5	12.5	5	5	2.5	2.5
8-color (odd-numbered)	12.5	0	12.5	0	12.5	0	12.5	0	12.5	0	12.5	0	12.5	0	12.5	0

Note. All 16 colors were assigned numbers from 1 to 16. The unit is percentages (%) of colors in the distractor color pool when targets are color 7 and 11. Because the target colors are odd-numbered colors, only 8-odd-numbered-color trials are presented here.

Table 2: Median response time and mean error rate for 8-color trials and 16-color trials in the hard discrimination group.

	8-color trials		16-color trials	
Target presence	RT (ms)	Error rates	RT (ms)	Error rates
Target absent	2153	0.014	2283	0.017
Target present	1456	0.203	1504	0.223

Table 3: Means of median response times for individual participants and mean error rates for easy and hard discrimination groups.

	Easy Discrimination		Hard Discrimination	
Target presence	RT (ms)	Error rates	RT (ms)	Error rates
Target absent	1969	0.017	2153	0.014
Target present	1375	0.200	1455	0.203

Figures

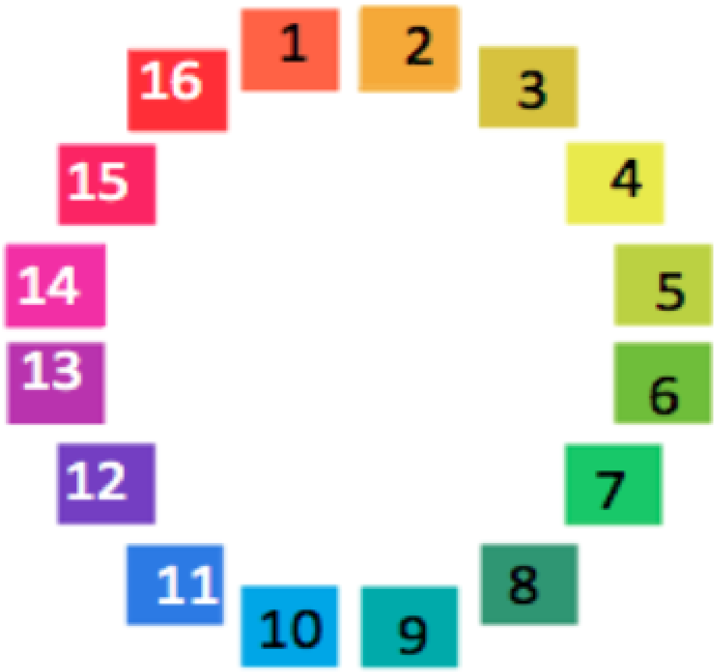

Figure 1: A color ring with the 16 colors used in the experiment. Each color is assigned a unique number from 1 to 16 instead of using names to easily identify the color.

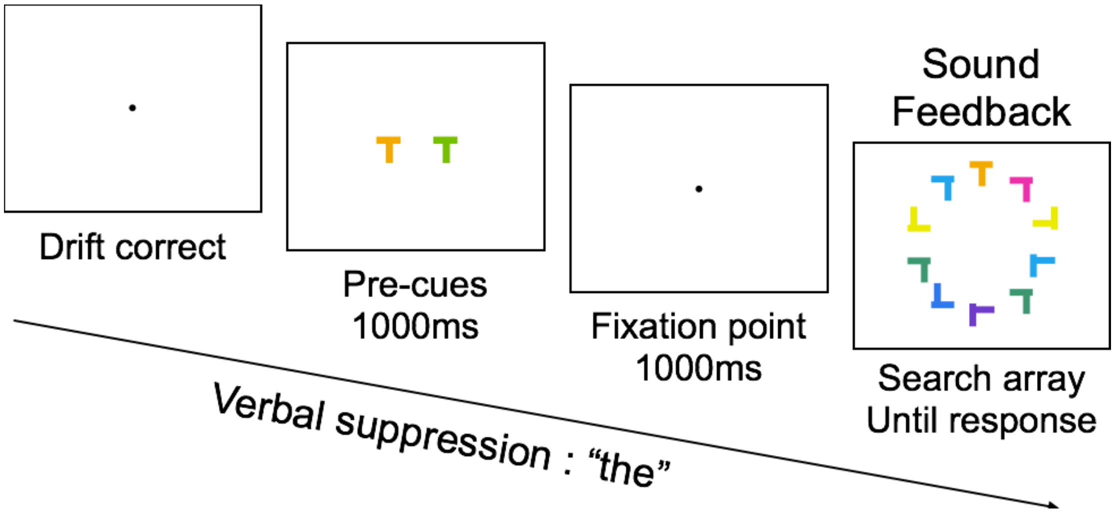

Figure 2: Sample stimuli and procedure. After eye drift was corrected, the two pre-cues were presented to define potential targets for 1000ms. 1000ms after the offset of the pre-cues display, a search array consisting of ten search items was presented until the participant responded.

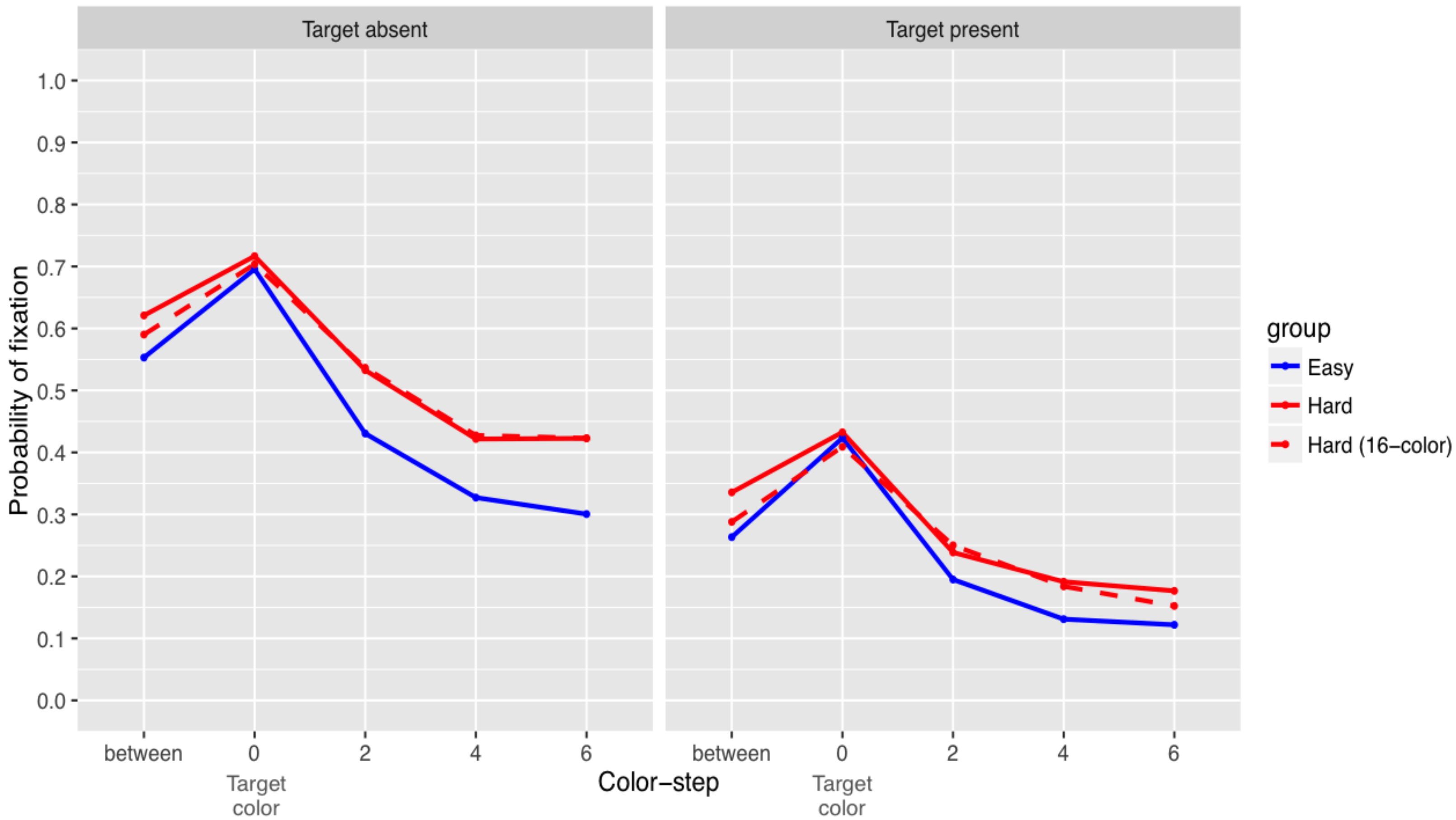

Figure 3: Probability of fixation for target-absent (left) and target-present trials (right). The x-axis represents the color-steps between the nearer target color and distractor's color. The right most position (6) indicates the most target-dissimilar color. The left most indicates the color between two target colors that was excluded from the analysis. The second value on the x-axis (0) indicates the distractors with the exact target colors.

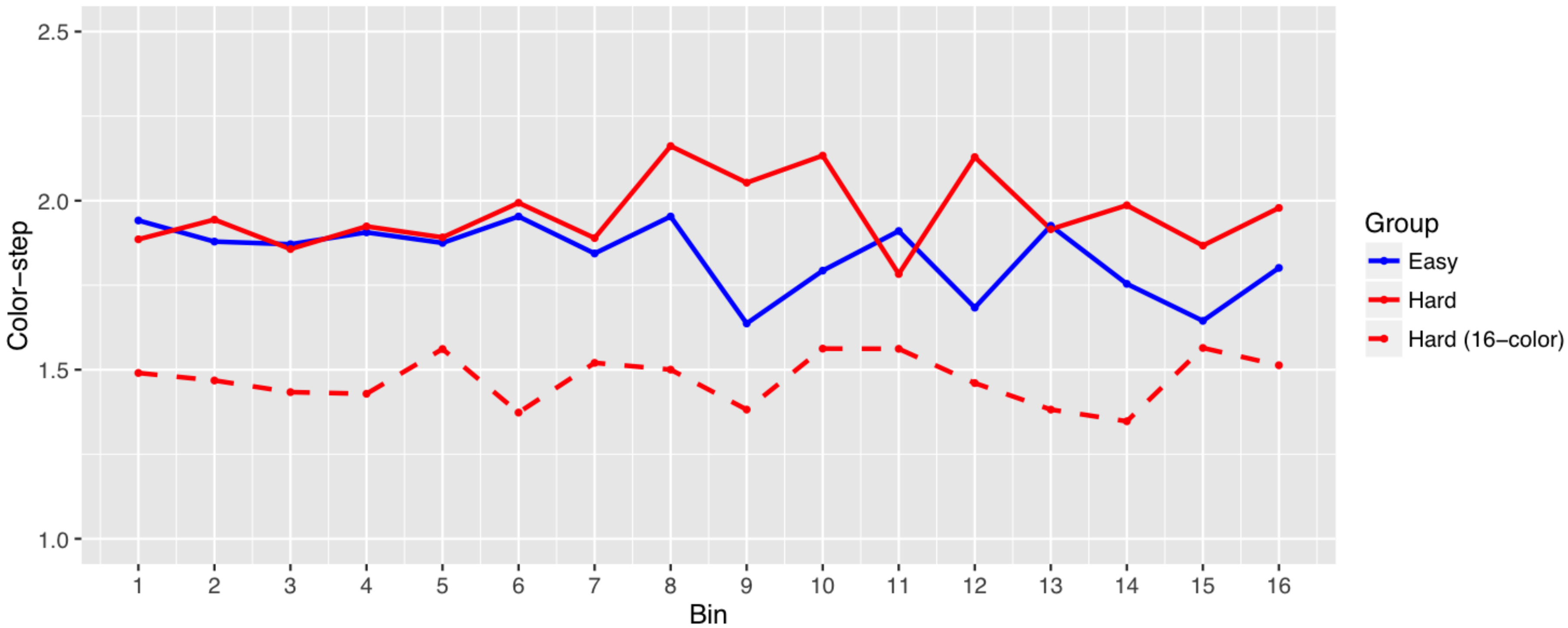

Figure 4: Average color-step of first fixated object across 16 bins. A blue solid line indicates the average color-step of first fixations in easy discrimination group. A red solid line indicates the average color-step of first fixation in hard discrimination group. A red dash line indicates the average color-step of first fixation for the 16-color trials in the hard discrimination group, which are excluded from analysis.

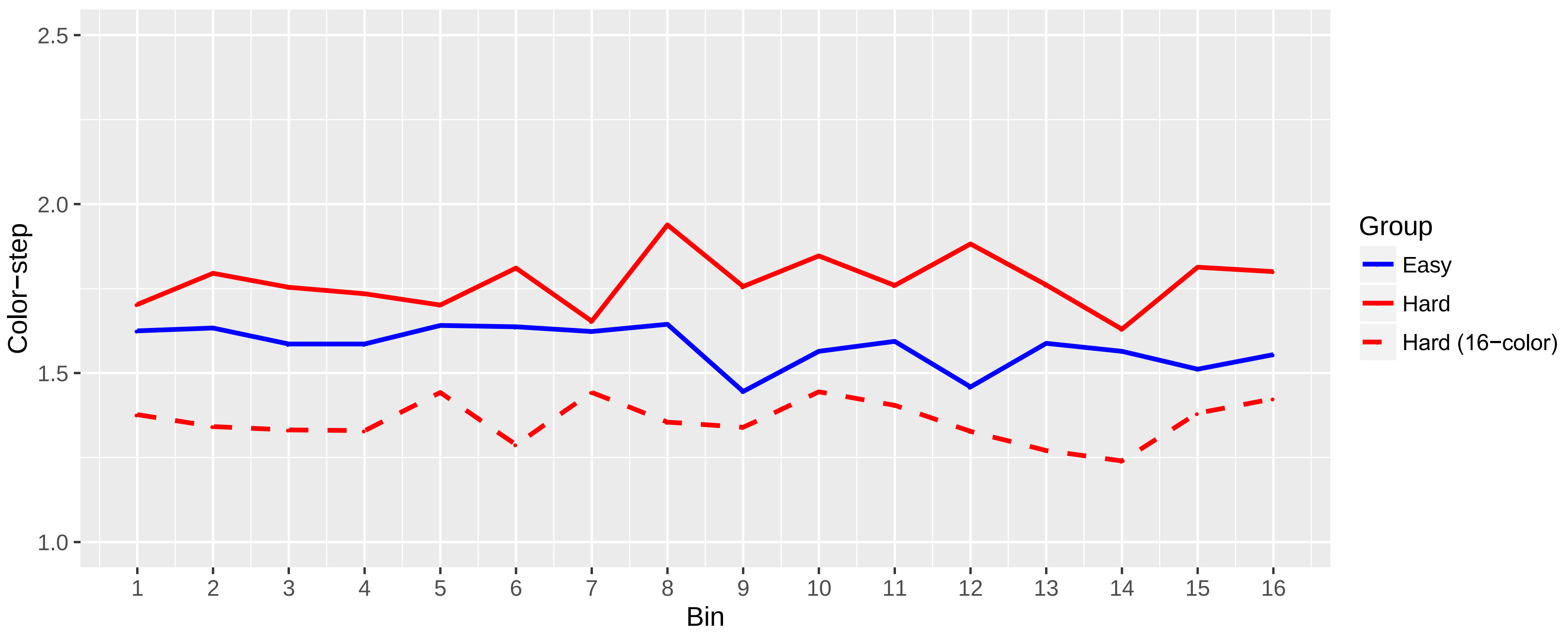

Figure 5: Average color-step of first two fixated objects across 16 bins.

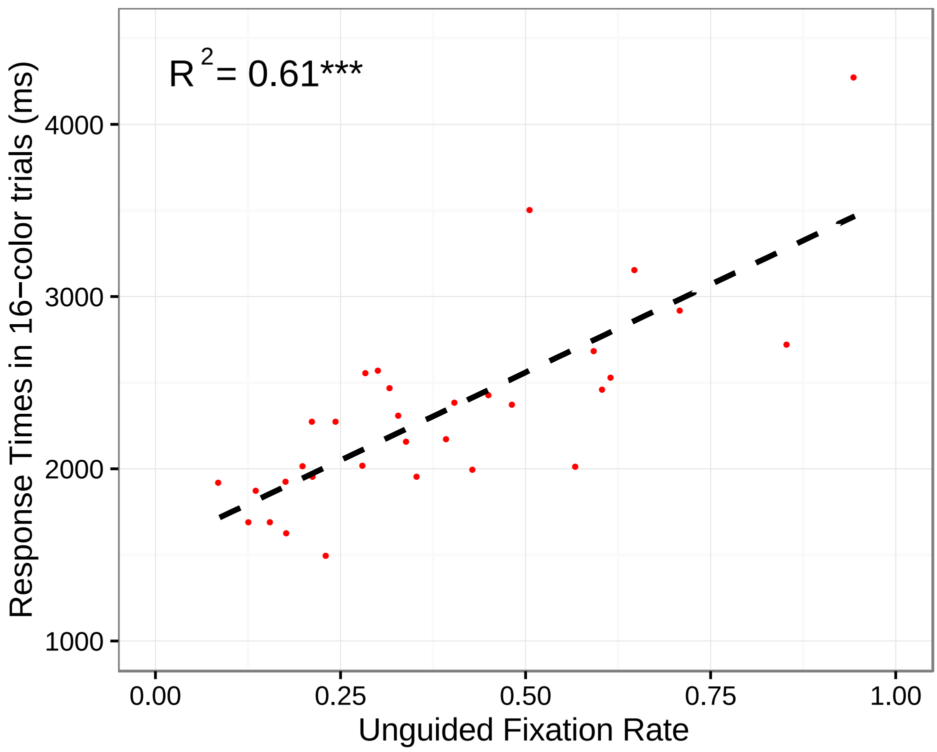

Figure 6: Response times in the 16-color trials as a function of unguided fixation rate. *** $p < .001$

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