April 2021

Experience with difficult target discrimination makes search less efficient: an analysis using eye movements

Junha Chang
University of Massachusetts Amherst

EXPERIENCE WITH DIFFICULT TARGET DISCRIMINATION MAKES SEARCH LESS EFFICIENT: AN ANALYSIS USING EYE MOVEMENTS

A Dissertation Presented

by

JUNHA CHANG

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

DOCTOR OF PHILOSOPHY

February 2021

Department of Psychological and Brain Sciences

EXPERIENCE WITH DIFFICULT TARGET DISCRIMINATION MAKES SEARCH LESS EFFICIENT: AN ANALYSIS USING EYE MOVEMENTS

A Dissertation Presented

by

JUNHA CHANG

Approved as to style and content by:

____
Kyle R. Cave, Chair

____
Jenna Marquard, Member

____
Lisa Sanders, Member

____
Matthew Davidson, Member

____
Caren Rotello, Department Head
Psychology and Brain Science

DEDICATION

To my family who always supports my dream.

My husband, Seok-Yeong Yu, who is the best partner for this long journey.

My first cat, Rummi, just being cute, and helping me to move on.

ACKNOWLEDGEMENTS

I vividly remembered the first week of my graduate life. Because I was not good at speaking and understanding in English, I could not understand well what other people said. It was difficult to follow classes and to lead the lab that I had worked as a TA. I was overwhelmed. On the last day of that week, I cried alone in a restroom on the fourth floor of Tobin Hall. At that moment, I promised to myself. “I will survive and get a PhD. Then, all of these hardships will be just a funny episode to write in my dissertation”. And here I am.

I cannot imagine being here without my advisor, Kyle Cave. There is not a perfect word for how much I appreciated his patience, guidance, and supports. I learned a lot of things from him not only academic lessons but also life lessons. I just hope that I did not spend too much of my fortune to meet him as an advisor.

My deepest appreciation also goes to Dr. Lisa Sanders, Dr. Matt Davidson, and Dr. Jenna Marquard who are the members of my dissertation committee for their service and commitment for my dissertation. Their unsparing supports with valuable resources and expertise has been invaluable to my successful complement and extend my research.

Lastly, I would like to thank all my friends, Merika, Tina, and Andrea, and their emotional supports and friendship.

By writing this, I found myself feeling that I am lucky since I have had so many people who care and support me. You all make my staying at UMass Amherst unforgettable. I am deeply indebted to you all.

ABSTRACT

EXPERIENCE WITH DIFFICULT TARGET DISCRIMINATION MAKES SEARCH LESS EFFICIENT: AN ANALYSIS USING EYE MOVEMENTS

FEBRUARY 2021

JUNHA CHANG

B.A., CHUNG-ANG UNIVERSITY

M.A., CHUNG-ANG UNIVERSITY

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by Professor Kyle R. Cave

Recent studies demonstrate that experience influences observers' strategic attentional guidance in visual searches. The current study explored how experience with difficult target color discrimination influences search strategy. Two participant groups were compared through seven dual-target search experiments: A hard search experience group and an easy search experience group. The easy search experience group performed only the easy color discrimination trials in which the two targets were easily distinguishable from distractors in the color dimension. The hard search experience group performed the same easy discrimination trials in half of the trials. The other half were difficult color discrimination trials in which the two targets were barely distinguishable from some of distractors in the color dimension. Behavioral and eye movement data from only the easy color discrimination trials were analyzed between the two groups. Experiments 1 to 4 were designed to examine the effect of experience with difficult color discrimination on the search strategy in a color-shape conjunction search task. Results showed the hard

search experience group fixated more to colors that were not similar to either of the target colors, suggesting that the experience with difficult color discrimination discouraged the adoption of an efficient search strategy (i.e., color guidance). In Experiments 5 and 6, targets were defined only by color. The hard experience group made more fixations to the intervening colors, suggesting that their search was more likely to be guided by a range template representing the two target colors along with the colors between them in color space. In Experiment 7, additional feedback was provided for incorrect responses to encourage participants to re-evaluate their responses and to take the efficient search strategy. Compared with Experiment 1, there was an overall decrease in recognition error responses and a hint that the feedback might bring the level of color guidance in the hard group closer to the level in the easy groups in Experiment 7. The findings of the current study help in understanding how efficient or inefficient search strategy is built by experience with difficult target color discrimination, and to begin the exploration of procedures that could improve performance in difficult search tasks.

TABLE OF CONTENTS

LIST OF TABLES

Tables Pages

LIST OF FIGURES

Figures Pages

CHAPTER 1

INTRODUCTION

The environment is often full of objects, and our cognitive system has a capacity limit on processing these many stimuli. This cognitive limit leads attention to be allocated selectively to the most important stimulus amongst other stimuli. The selection of attention is driven by two main cognitive controls: bottom-up control and top-down control. Attention can be driven by the salience of stimulus relative to its neighbors. For example, poisonous red mushrooms pop up in a green garden (i.e., stimulus-driven or bottom-up attention). This salient stimulus easily captures attention. Observers' current goal also drives the selection of attention to a stimulus (i.e., goal-driven or top-down attention). For example, if observers try to find a pen on a messy desk, they would deploy attention preferentially to pen-like objects rather than books or a cup. These two controls interact with each other to determine what and where the attention is allocated in the visual environment.

There is also evidence for a third factor shaping attentional control. Deployment of attention can be affected not only by salience of a visual object or observers' internal goals but also by the observers' previous experience (Awh, Belopolsky, & Theeuwes, 2012; Failing & Theeuwes, 2017; Maljkovic & Nakayama, 1994, 1996). The early work investigating the substantial effect of previous experience suggested a priming effect in visual perception (Maljkovic & Nakayama, 1994, 1996). Once observers were exposed to a visual feature, attention was easily deployed to that feature on subsequent trials (Maljkovic & Nakayama, 1994). The priming effect was also observed in a spatial dimension (Maljkovic & Nakayama, 1996). Observers facilitated the deployment of

attention to a location where a target had been presented, but inhibited attention to the location where a distractor had been presented.

Recent studies of the effect of past experience have extended beyond the simple exposure of stimuli (i.e., priming) to other types of visual experience. The context that observers previously encountered is one of the critical experiences determining the way to allocate attention afterward. After seeing a target surrounded by a particular configuration of distractors several times, observers more readily deployed attention to where the target was positioned when they encountered the same configuration (Chun & Jiang, 1998; Chun, 2000); this is often described as a contextual cueing effect. The previous association between a reward and a visual feature also influences the deployment of attention. Observers were more likely to orient attention toward a visual feature that was previously associated with a monetary reward even though this feature was not salient, related to the current target, or currently associated with a monetary reward (Anderson, Laurent, & Yantis, 2011).

More and more studies have converged on a claim that there is some contribution of past experience to the deployment of attention (Awh et al., 2012; Failing & Theeuwes, 2017; Schwark, Dolgov, Sandry, & Volkman, 2013; Theeuwes, 2019; Wolfe, Cain, & Aizenman, 2019). In general, it seems that attention is facilitated and inhibited in a constant manner across multiple searches. This consistency can be advantageous when the current search is the same as or very similar to the previous search experience. In the example of the contextual cueing effect, search performance is fast and accurate when a target is present in its expected location in the previously exposed context (Chun & Jiang, 1998). However, if the current search does not match what previously observers had

experienced, the deployment of attention based on experiences does not always produce better search performance, and may even produce a performance cost (Anderson, 2013; Anderson et al., 2011; Makovski & Jiang, 2010). For example, if the target was not presented in the location that the previous context predicted, slower search performance was observed compared to when it was presented at its expected location (Makovski & Jiang, 2010). Also, attending to a distractor that observers previously had attended for reward can delay the search performance in the current search task (Anderson et al., 2011).

Although the evidence reviewed above demonstrates a consistent pattern of attention allocation to the same stimulus feature or location that observers had attended previously, and this effect of experience results in advantages and disadvantages on search performance, it is still an open question whether the same pattern of attention allocation is observed for under different circumstances. A few studies have suggested that observers can strategically orient attention based on experience to maximize their outcome rather than simply following what they had done previously. Lynn and Shin (2015) trained groups of participants to associate monetary reward (e.g., $50) with a particular visual stimulus. In the testing session, when this reward-associated feature was newly associated with a distractor in an array, the response was delayed compared to when this stimulus was associated with a target, even though there was no monetary reward any more, replicating the previous studies about the reward history on attention deployment. Importantly, however, when the new target was associated with a bigger monetary reward (e.g., $100), the interference of the previously reward-associated stimulus disappeared, indicating strategic control of attention for the potential outcomes.

The aim of the present study is to test for effects of experience on strategic search guidance that are very different from the previous demonstrations that used contextual cuing or associated visual features with reward. I focus on experience with difficult target discrimination in a visual search task. Difficult target discrimination delays responses and lowers response accuracy on the current search trial (Duncan & Humphreys, 1989). However, it is unclear how this experience influences strategic attentional guidance in later trials.

Before diving more deeply into this specific research question, I will review several relevant issues. The literature review below consists of four main topics. First, I will discuss the search template, which is a mental representation of a target that is used to guide search. I will present evidence about the substantial effect of experience on the creation and modification of search templates. The second topic will be the dual-target search paradigm that will be used for the current project. Also, I will focus on the behavioral and attentional costs in the dual-target search task. Then, the third topic will briefly review why eye movement measures can be a useful methodology in the current study. Finally, the sources of inefficient search behaviors will be reviewed and possible ways to improve search performance will be explored.

The Effect of Experience on A Search Template

Visual search tasks have been commonly used to investigate the deployment of visual attention because of their simplicity (searching for a target amongst distractors) and efficiency. The visual search requires a minimum premise that an observer knows the identity of the target or at least the requirements to define the target. If this premise is violated, search arrays are simply full of meaningless stimuli. Once an observer knows

something about the target and encounters the search arrays, these meaningless stimuli turn into collections of targets and distractors.

Although there are some exceptions (e.g., singleton search, Bravo & Nakayama, 1992), most search tasks provide specific information about target features before the presentation of search arrays. Chelazzi, Duncan, Miller, and Desimone (1998) used single cell recording to examine how target information is used to orient attention to a target among distractors. In their study, macaque monkeys were presented with a target-preview that either elicited the strong response (i.e., a "good" stimulus) or very weak response (i.e., a "poor" stimulus) of a cell in inferior temporal cortex. Then, the monkeys were required to search for a target among one or more distractors in a subsequent display. At the moment of the search array presentation, the firing rate of the cell somewhat increased regardless of whether the target was a "good" or a "bad" stimulus. Interestingly, shortly after, the firing rates of the cell increased when the target was the "good" stimulus and decreased when the target was the "poor" stimulus. Chelazzi and his colleagues concluded that when the observers encountered visual objects, those objects competed against one another to be selected, leading to the activation of cells associated with both target-relevant and target-irrelevant features. Then, top-down control increased the activation of cells associated with the target-relevant feature and decreased the activation of cells associated with the target-irrelevant feature, eventually biasing attention toward the target-relevant feature and away from the target-irrelevant features.

The prior information defining the target is often referred to as an attentional template (Duncan & Humphreys, 1989, Eimer, 2014), a target template (Vickery, King, & Jiang, 2005; Hout & Goldinger, 2012) or a search template (Houtkamp & Roelfsema,

2009; Reeder & Peelen, 2013). In the present study, I will use the term "search template" to describe the information used to guide search because the target representation is often used not only for the guidance of attention but also for target verification (Castelhano, Pollatsek, & Cave, 2008; Hout & Goldinger, 2015) and because search can be guided not only by information about a target but also information about distractors under some conditions (Arita, Carlisle, & Woodman, 2012).

The creation and use of search templates can improve search performance by rapidly orienting attention toward a target feature and rejecting target-irrelevant distractors (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). This advantage can grow as experience with the same or very similar search context is accumulated (Menneer, Cave, & Donnelly, 2009; Nodine et al., 1999; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In the beginning, inexperienced observers may choose a random feature as a search template that might be not efficiently guide search. Even if they choose the proper feature, it is still possible to make an inaccurate decision because they are less careful, or because their decision threshold is too high or low (Nodine & Kundel, 1987). After the accumulation of experience with trial and error to find the proper target feature, they can achieve an optimal search template that efficiently guides search and easily distinguishes the target from distractors for that specific search context.

For example, Bravo and Farid (2016) demonstrated that participants were able to build search templates for different search contexts and to take advantage of choosing the optimal search template when they could predict an upcoming search context. Their participants were trained to search for a target among one of three different distractor contexts and were informed which context would be presented by an informative number

cue associated with the specific distractor context. On a testing session, the participants sometimes saw an uninformative cue, which did not carry any information about the distractor context, instead of the informative number cue. The participants found the target significantly faster when they were able to predict the distractor context than when they were not.

Also, Navalpakkam and Itti (2006) showed that the search template can be tuned precisely within a feature dimension if it is necessary. In a task, participants searched for a target (i.e., 180° rotated "L") that was within one of three intervals in the intensity dimension (e.g., LOW, MID, and HIGH) among upright "L" distractors that could be within any of the three intensity intervals. Eye movement results showed that the participants fixated more to the distractors within the target intensity interval than those within the target-irrelevant intervals. For example, when the target intensity interval was LOW, the participants fixated more to the LOW distractors than MID or HIGH distractors and *vice versa*. This selectivity of attention to the specific target feature interval was observed in different feature dimensions such as size or saturation in the same study. They could not find the evidence that this selectivity of attention toward the specific feature interval changed as a function of time, suggesting that the precise search template can be set up quite rapidly. More importantly, the results indicate that observers were able to adjust the target template to precisely match the target feature and thus efficiently find a target in a complicated search in which the distractors differed only slightly from the target within the relevant feature dimension.

Put together, it appears that a search template can be flexible rather than being rigidly determined by a given piece of information about the target (Becker, 2010; Bravo

& Farid, 2012, 2016; Müller, Heller, & Ziegler, 1995; Navalpakkam & Itti, 2006, 2007). This flexibility can provide some advantages on search performance when the exact or a very similar circumstance is encountered later (Nodine & Kundel, 1987; Nodine et al., 1999). Through experience, the searchers might learn the most distinctive target feature to efficiently suppress attention toward distractors that are commonly presented in the specific search context and learn to bias attention toward a target. If there are distractors that are similar to the target, the feature information selected as a search template can be optimally tuned to easily distinguish the target from these similar distractors, eventually leading to efficient search performance.

The evidence above demonstrates that the search template can change to maximize the efficiency of search performance, but this finding assumes that the same search context is repeated. It is still unclear whether these advantages of the optimal search template for one search context can be also effective for a slightly different context. It is possible that the optimal search template built based upon the experience of one context can be also suitable for a similar search context, and it might even work better than a search template that is built without the experience. For instance, assume that observers searched for a red apple among tomatoes, and then started to search for the red apple among oranges. It could be much easier for them to find the red apple compared to other observers who had not search for the red apple among tomatoes. The experience of difficult search may encourage the observers to tune their representation of the red color of the apple more precisely to distinguish it from the similar color of the tomatoes, and this search template can help search efficiently in an easier search (i.e., oranges).

However, some studies have shown that observers do not always take the most effective search strategy despite an ability to do it (Stroud, Menneer, Kaplan, Cave, & Donnelly, 2018; Menneer et al., 2019). The observers simply did not want to build a precise red color representation after searching for the red apple, and then simply search for a red apple just like they did not experience before. Alternatively, they could show the worse search performance after the experience of apple searching because of fatigue from intense searches. Therefore, it is possible that the experience with one search circumstance encourages observers to adopt the inefficient search strategy and maintain that strategy in similar search contexts.

In the current study, the search difficulty was used to create a particular search context. Heterogeneity between a target and distractors influences search difficulty (Duncan & Humphreys, 1989). If the target is different from the surrounding distractors, the search is easier. On the other hand, if the target is similar to the surrounding distractors, the search is harder. For example, it is easier to search for a red apple among green pears, but it is more difficult to search for the red apple among red tomatoes. Based on this finding, the similarity between the target and distractor in color space was manipulated in order to increase or decrease the search difficulty.

Two participant groups were compared to investigate the effect of experience with difficult target discrimination on search strategy: Easy search experience group and hard search experience group. The hard search experience group sometimes experienced some trials of difficult color discrimination trials, in which a target was barely distinguishable from distractors in color space, and some trials of easy discrimination trials, in which the target was easy distinguishable from distractors in color space. The

easy search experience group experienced the easy discrimination trials only. By comparing the pattern of search performance in the easy discrimination trials between the groups, it will be possible to understand how the experience of difficult discrimination influences the similar but slightly easier search and whether it is advantageous or disadvantageous for adopting an efficient guidance of search.

To sensitively measure the impact of differences in search strategy, it is necessary to have an appropriate search task. If a task is too easy to perform, search performance will not be sensitive enough to reflect the expected impact of different strategies. Thus, the current project adopted the dual-target search paradigm in which participants should search for either of two targets. This dual-target search has been shown to be difficult relative to a typical single-target search so that the dual-target search produces performance costs. Depending on whether the adopted search strategy is efficient or not, the dual-target cost also increases or decreases. The following section is a discussion of the dual-target search paradigm and its cost.

Dual-Target Search and Dual-Target Cost

Many studies examining the allocation of attention have relied on a paradigm of visual search with a single target. An observer views a single target in advance and then, after a search array appears, reports the presence of a target or the properties of the target. Because this single-target search task is so straightforward, it is commonly used in research about the allocation of visual attention. The single-target search paradigm has been used to reveal that allocation of visual attention toward a salient stimulus relative to its neighbors (Pomplun, 2006; Sobel, Pickard, & Acklin, 2009; Theeuwes, 1991, 1992;

Treisman & Gelade, 1980; Yantis, 1993) as well as task-relevant features (Bacon & Egeth, 1994, 1997; Desimone & Duncan, 1995; Wolfe, 1994).

Many attention theories have been built based on the paradigm of single target search. For example, Guided Search Theory (Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989) explains that the allocation of attention can be determined by the summed activation of stimulus salience and task-relevant feature maps. Attention is primarily assigned to spatial locations according to each location's summed activation, starting with the highest. This theory explains the mechanism of attentional selection when an observer looks for a single target. According to the Guided Search Theory, the problem of attentional selection can be easily solved; the observer would primarily guide attention toward a stimulus that is the most salient and the most task-relevant.

However, searchers in real-world often encounter multiple target search situations. A college student tries to find a group of friends' faces on Facebook (Wolfe, 2012), or a car driver looks for a traffic road signal and potential hazards like pedestrians, bike riders, or parked cars (Divekar et al., 2013; Yamani, Samuel, Knodler, & Fisher, 2016). A baggage X-ray security scanner needs to find potential threatening objects such as bombs or guns (Menneer et al., 2012), or a radiologist works to detect a tumor or tumors to diagnose (Krupinski, 2010; Nodine & Kundel, 1987; Nodine et al., 1999).

Even though real-world search tasks with multiple targets are common, multiple-target search has received more interest as an experimental paradigm quite recently. The multiple-target search task itself is very similar to the typical single-target search task, but observers must remember more than one target and then respond positively if any of those targets appears in the search array (Barrett & Zobay, 2014; Menneer, Donnelly,

Godwin, & Cave, 2010; Stroud, Menneer, Cave, & Donnelly, 2012; Stroud, Menneer, Kaplan, Cave, & Donnelly, 2018). In these searches, any single target should elicit a “yes” response, and there may never be more than one target in a search array. In another type of multiple-target search, multiple targets may appear within a single array, and observers must detect all of them (Drew, Boettcher, & Wolfe, 2015; Wiegand & Wolfe, 2018; Wolfe et al., 2019). The current review of multiple-target search will be restricted to dual-target searches in which the task is to find either of the targets appearing without any other targets in a search array.

Because observers must handle more than one target, several questions come up in multiple-target search. Would search performance be similar between single-target search and multiple-target search? How would the observers manage two targets to guide attention for search? Answering these questions can be helpful to extend the existing attention theories and broaden our understanding of the mechanism of allocation of attention.

Based on previous dual-target search experiments, the answer for the first question seems clear. The search performance is substantially different between dual-target search and single-target search (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Menneer et al., 2010; Stroud, Menneer, Cave, & Donnelly, 2012). Stroud and his colleagues (2012) tested the exact question in a color-shape conjunction search task and measured eye movements to understand attentional guidance during search. Participants were presented with either a single target (i.e., a colored “T”) or two potential targets before each trial and then asked to report the presence of the target or either of the two targets among similar distractors (i.e., colored pseudo-“L”s). For the dual-target search

condition, the two targets were very similar, moderately similar or relatively dissimilar each other in color space. The fixations to distractors of different colors were measured to examine how search was guided by the colors of the targets. The number of fixations to the distractor colors that were dissimilar to the target colors was higher for the dual-target search condition than the single-target search condition. Also, within the dual-target search condition, the fixation rates to the target-dissimilar distractors increased as the color similarity between the two targets decreased. This less efficient search guidance led to longer RT and lower accuracy in the dual-target search condition than the single-target search condition. Stroud et al. concluded that there was indeed a cost in searching for two discrete targets, and it affected search guidance. This study provided strong evidence of the dual-target cost in the guidance of attention, and in the behavioral responses in the search task.

Although some forms of the dual-target cost appear consistently throughout many replications, the source of this dual target cost is still controversial. On one hand, if our attention system can handle only a single target representation at a given moment (McElree, 2001; Oberauer, 2002; Olivers, Peters, Houtkamp, & Roelfsema, 2011; van Moorselaar, Theeuwes, & Olivers, 2014), observers should search with one target representation for a time, and then switch to another target representation. The dual-target cost may reflect this switching cost (Beck & Vickery, 2019; Ort, Fahrenfort, & Olivers, 2017). On the other hand, there is evidence against this argument, suggesting instead that our attention system can hold multiple target representations and use them to guide attention with equal weight (Beck, Hollingworth, & Luck, 2012; Gilchrist & Cowan, 2011; Grubert, Carlisle, & Eimer, 2016; Grubert & Eimer, 2015; Hollingworth & Beck,

2016), so there must be other factors that produce the dual-target cost, such as the poor quality of target representations or increased noise in decision making (Barrett & Zobay, 2014). When there was not specific instruction and observers were free to determine their own search strategy for two targets, search has been done with some sort of combination of sequential and simultaneous attentional guidance by the two targets (Cave, Menneer, Nomani, Stroud, & Donnelly, 2017). This search pattern can be controlled by an explicit instruction. In a study by Beck et al. (2012), observers searched for two targets simultaneously when explicitly instructed to do so, and they searched for one target and then switched to the other target when instructed to do search sequentially. The review above demonstrates that the way to guide search can be flexible rather than rigid.

Some studies (Stroud et al., 2012, 2018) showed that the multiple-target cost could increase or decrease according to how informative or specific the target information was, suggesting that observers' search strategy can influence the level of the dual-target cost. Related to the current research question, it may be possible that different experiences of search induce observers to adopt different search strategies, leading to the differences in the dual-target cost levels. If previous experience causes search to be guided more efficiently, the dual-target cost will decrease. On the other hand, if the experience with difficult search encourages observers to choose a less efficient search strategy, the dual-target cost will increase. In the experiments presented below, eye movements were measured to understand how experience changes search strategies. The following section will discuss the measure of eye movements for the current specific project.

Eye Movements in Visual Search

Behavioral measurements such as response time (RT) and accuracy are the most common and straightforward measurement to estimate the overall search performance. If the RT is fast and accuracy is high, the search is processed pretty efficiently and accurately. Early work of visual search has focused on RT to infer the search efficiency and overall performance. Observers often search for a target among a certain number of distractors (set size) on each trial. Then, the RT often described as a function of set size. A search slope as a function of set size in RT is often used to infer the search efficiency. If the search slope is shallower for one condition than another condition, it indicates that the processing time per item was shorter for the former condition than the latter condition, suggesting more efficient search for the former condition. The y-intercept is also used to infer non-search processes such as decision making time or preparation (Han & Kim, 2004; Horowitz & Wolfe, 1998; Woodman, Vogel, & Luck, 2001). Without the slope change, the change of intercept indicates non-search process changes. Considering both the slope and intercepts provides one level of information about how efficiently search is completed.

Despite the advantage of RT data analyses, reliance upon only the RT for visual search study has a few limitations. First, the RT slope as a function of set size indicates how rapidly each search item is processed on average while ignoring differences in properties between stimuli. To draw conclusions about the effects of different stimulus properties, the experimental stimuli presented in the search array should have equal or at least similar properties. Therefore, many previous visual search studies measuring only accuracy and RT restricted the stimuli to simple geometrical objects, as in search for a

red vertical bar among red horizonal bars or green vertical bars. However, it is possible that a search array consists of diverse stimuli, and a particular stimulus grabs attention or observers preferentially allocate attention to the stimulus unexpectedly. By using only RT, it is difficult to demonstrate the effect of this particular stimulus on search guidance unless this unique stimulus was intentionally designed in advance by researchers.

The more critical limitation is that RT itself comprises several cognitive processes such as task preparation, the guidance of attention, comparison between internal and external representations, and decision making (Castelhano et al., 2008; Goldstein & Beck, 2018). Thus, if a researcher is interested in a particular cognitive process, RT might not be the ideal tool. For example, even if RTs are numerically the same between two conditions, it does not mean that observers completed the task in the same way. It is possible that it takes more time to guide attention to a target but less time to identify the target in one condition, whereas it takes less time to guide attention to the target and more item to identify the target in another condition, eventually leading to the very similar RTs between the two conditions. One might consider adding a different set size condition to have the search slope and intercept in RT to tease apart these two different processes. However, it adds one more independent factor in experiment design and possibly makes statistical analyses and interpretation complicated, if there are already independent variables besides the set size.

Compared with RT data analysis, eye movement data have several advantages for understanding the search process, including the allocation of attention during search. It must be mentioned that it is possible to shift attention without accompanying eye movements and complete a search (covert attention) (Buschman & Miller, 2009; Murthy,

Thompson, & Schall, 2001; Posner, 1980). However, the current study focused on overt attention that is measurable as gaze fixations (eye landing) or saccades (eye jumps) because it is easier to infer what stimulus or location observers actually allocate attention to at a given time (Irwin & Zelinsky, 2002; Zelinsky & Sheinberg, 1997). For example, if an observer fixates an orange rather than a pear, we can interpret that this observer allocated attention to the orange over the pear. Also, the overt eye movement behavior is highly associated with eventual manual responses (Zelinsky & Sheinberg, 1997). As there are more fixations or saccades, the response time to detect the target generally increases.

These advantages motivate the measurement of both manual behaviors and eye movements in these experiments. Specifically, I calculated the probability of fixation to stimuli of different colors during search, which functions as an index of how strongly the observers activate a search template to guide attention to those colors. For instance, if the probability of fixation to a red color is higher than an orange color, it means that there are more frequent fixations across trials to the red color than the orange color once it is presented, suggesting a higher activation of red to guide search.

The probability of fixations reveals how two targets are represented and how they actively guide search. The current project divided the probability of fixation data into two categories according to the relationship between distractor colors and target colors. I distinguished between intervening colors and outer colors. Because there are two discrete targets in the experiments, there are a few colors that are between the two target colors in color space. For example, if the target colors are red and yellow, these intervening colors can be orange or reddish yellow. If the probability of fixation to the intervening colors is

higher in one condition than another condition, it may indicate that the two target colors are represented as more of a continuum form of search template for the former than the latter condition. In other words, the targets could be represented by a single range of colors that includes both target colors along with the intervening colors. If the probability of fixation to these intervening colors is low, it can indicate that two target colors are represented quite independently. There are other colors that are relatively dissimilar to the target colors compared to the intervening colors, called the outer colors. The probability of fixation to the outer colors reflects how strongly the search template guides attention overall.

The Improvement of Visual Search Performance

An ideal search behavior is to find a target rapidly with few errant behaviors. However, visual search often includes some errant and inefficient behaviors. Observers often fail to fixate a target, and even though they fixate the target it does not guarantee that they make a correct decision. These errant search behaviors can be improved by practice (Baluch & Itti, 2010; Menneer, Cave, & Donnelly, 2009; Nodine et al., 1999). As a search session continues, the accuracy of oculomotor behaviors becomes better, with more frequent fixations to distractors that possess target features (Baluch & Itti, 2010), leading to more accurate or faster search performance (Menneer et al., 2009). Visual search experts such as professional radiologists are good examples of the positive outcome for efficient search from intense practice.

Multiple studies have demonstrated quantitative and qualitative differences between search novices and search experts (Drew et al., 2013, 2017; Krupinski et al., 2006). The experts usually show much better search performance than novices. To be

specific, experienced radiologists fixated more to critical areas and made correct decisions more often than interns or residents in a medical image reading task (Drew & Williams, 2017; Nodine et al., 1999) Professional airport screeners made fewer errors and required less time to first fixate to a target object compared to novices (Liu, Gale, & Song, 2007). The experts are generally more likely to guide attention toward the critical area that contains a target(s) and to make a correct, rapid decision than the novices.

Despite of the superiority of the experts on search performance, they still make errors in decisions. One of the common types of error is misses of the target, or false negatives. In some diagnostic radiology tasks, estimated false negatives rate reached almost 30% (Krupinski, 2010; Wallis, Walsh, & Lee, 1991). What is the source of these errors? One type of error is search error (Krupinski, 2010; Nodine & Kundel, 1987). When observers encounter a complicated search scene, they need to scan the whole search array to sample the image with foveal vision to receive high-resolution visual information. While performing the search task, observers often do not cover whole areas, and some areas containing a target(s) can be neglected (Drew et al., 2013; Rich et al., 2008), resulting in a false negative. A search error is easily recognized when the observer does not fixate to the target, and then reports target absence.

Another possible error type is recognition error (Krupinski, 2010; Nodine & Kundel, 1987). Recognition errors differ from search errors because the observers fixate the target, but nonetheless incorrectly report target absence. Recognition errors are more common when the target is embedded in visually similar distractors. Recognition errors are inferred when the observer fixates the target and then reports target absence.

Error rates can be higher when there are multiple potential targets, which is a common situation in diagnostic radiology, and the need to search for multiple targets substantially impairs search efficiency (e.g., long time to find a target). Inefficient search prolongs the search task and results in mental fatigue. The fatigue encourages searchers to consciously or unconsciously adopt shortcuts to make a decision, resulting in poor and inefficient judgements (Lee, Nagy, Weaver, & Newman-Toker, 2013). Therefore, efforts to improve search performance should focus on preventing false negatives and increasing search efficiency.

In the last experiment of the current project, feedback was provided in order to improve search performance. When participants make an incorrect response, they needed to see the exact search array once again. For target present trials, the feedback array contained either a check mark near a target or a black circle around the target to indicate the target presence and actual location of the target. There are two motivations for the retrospective feedback. First, it alerts the participants to re-evaluate their scanning and to encourage them to look at the areas that they might have missed, which might reduce the number of search errors. Second, because the feedback adds an extra three seconds to the trial, the participants should guide search efficiently to avoid the delay. Thus, the feedback may encourage them to develop an efficient search strategy.

Aims of the Present Study

The aim of the present study is to understand the effects of experience on an observer's search strategy in visual search, and explore one way to improve search efficiency. Specifically, the present study focused on experience with difficult search that is defined by low discriminability between a target and distractors in color space.

Although there is evidence of significant effects of previous experience with expected value (i.e., reward) (Anderson et al., 2011), repeated spatial configuration (Chun & Jiang, 1998; Peterson & Kramer, 2001), or distractor context (Bravo & Farid, 2012, 2016) on search strategy or performance, to my knowledge, the effect of experience with difficult target discrimination by color on search strategy has not been studied.

In the present study, some participants sometimes encountered a difficult search, in which the target color is similar to some of the nontarget colors; this group was called the hard search experience group. This experience with difficult search might encourage participants to tune a search template precisely in color space to overcome this difficult target discrimination. This search template that is precisely tuned for difficult search might also be advantageous for guiding search in a relatively easier search, in which the target color is always fairly different from the nontarget colors. Therefore, the hard search experience group's search template might lead to a smaller dual-target cost compared to the easy search experience group's search template, which is built based on only easy search. However, it is also possible that the experience with difficult search has the opposite effect on search strategy. Some visual search studies have demonstrated that observers were able to efficiently guide search with color information, but they were reluctant to do that under some conditions (Stroud, et al., 2018; Menneer et al., 2019). The difficult color search can frustrate observers so that they are less likely to use color to guide search efficiently.

The first set of experiments was designed to investigate whether the experience with difficult color search affects strategic attentional guidance in a color-shape conjunction search. The second set of experiments is designed to extend the first set of

findings by limiting available feature dimension to merely the color dimension so that observers needed to perform a simple color feature search. The purpose of first two sets of experiments was to understand the general effect of experience on search strategy. Based on that, I propose the third and last experiment to explore a way to improve search performance. This experiment provided additional feedback for an incorrect response, which might encourage the participants to use a more efficient search strategy.

CHAPTER 2

INTRODUCTION

In many visual search tasks, observers already know what to look for. This pre-knowledge of the target information readily activates a memory representation of the target feature. When the observer encounters a search display consisting of various stimuli with different features, visual attention is easily guided toward those stimuli possessing the target feature (Duncan & Humphreys, 1989; Wolfe, 1994). Different terminology has been used by different researchers to refer to this active target representation (e.g., attentional template, search template, target template, or target representation) but the core idea remains about the same across these terms. The search template is created using the target information that is provided before the presentation of the search display, and observers know that this information predicts some aspect of the upcoming target.

The Guided Search model proposed by Jeremy M. Wolfe (Wolfe, 1994; Wolfe et al., 2010) offers an explanation of how prior target information facilitates search. According to the GS model, the deployment of attention is determined by the activation level in an activation map that represents all possible target locations. This map sums up the activation levels of two separate maps for bottom-up guidance and top-down guidance. Attention is preferentially guided toward the spatial location with the highest activation level in the integrated map. It then moves to the second highest activated location in the integrated map. When the target template represents a specific feature, locations that have that feature receive high activation in the top-down map. Therefore, if observers do not have any information about target features in advance, they must rely on

only the saliency information in the bottom-up map, and attention will be easily guided toward the most salient stimulus regardless of whether it is target or not. Numerous studies have found that the benefits of knowing target information in visual search processes can be reflected in response accuracy, search speed, or the time required to identify a target or stimulus.

Several studies have demonstrated that not only target information itself but also the relationship between a target and surrounding distractors affects the guidance of visual attention. The similarity between target and distractors is one of the factors. High target-distractor similarity can decrease search efficiency (Barras & Kerzel, 2017; Duncan & Humphreys, 1992, 1989; Nagy & Sanchez, 1990; Verghese & Nakayama, 1994), because similar distractors will compete to be selected by attention, thus causing interference (Desimone & Duncan, 1995). This interference can be alleviated by weighting diagnostic parts of the feature representation more heavily, which allows attention to be efficiently directed to a target because the target can be better discriminated from the distractors (Alexander, Nahvi, & Zelinsky, 2019; Geng & Witkowski, 2019; Navalpakkam & Itti, 2006, 2007). For example, Navalpakkam and Itti (2006) had participants search for a target with a particular level within a feature space (e.g., small size, if the size was target dimension) among distractors with different levels (e.g., middle or large size) and measured their eye movement patterns during the search. They found significantly higher fixation frequency for small search items than middle or large search items. The identical results were observed when the size of the target switched to middle and corresponding distractors were small or large. This evidence

indicates that observers can use information from distractors to control attention based on a diagnostic property of the search template.

This flexibility of the search template might be not so surprising based on several findings that the search template to be used shortly is stored in some form of visual working memory (Carlisle, Arita, Pardo, & Woodman, 2011; Woodman & Arita, 2011) and that the precision of visual representations stored in VWM can be varied at will (Machizawa, Goh, & Driver, 2012). A common assumption is that an ideal searcher pursues the best search performance with minimum effort, and that performance will require a precise, specific search template.

Search performance can improve as experience with a particular search task is accumulated. Multiple studies have demonstrated the substantial effect of prior history on the guidance of attention (Awh et al., 2012; Failing & Theeuwes, 2017; Maljkovic & Nakayama, 1994, 1996; Theeuwes, 2019; Wolfe & Horowitz, 2017). After an attentional task has been completed, the attentional selection for that task can linger, biasing attention to favor the same spatial location or visual feature that had been attended (Cave & Pashler, 1995; Hoffman & Nelson, 1981; Hoffman & Subramaniam, 1995; Maljkovic & Nakayama, 1994, 1996). The early work investigating the effect of prior experience suggested a priming effect in visual perception (Maljkovic & Nakayama, 1994, 1996), and more recent studies have revealed that experience can be extended from simple exposure of visual stimulus to other types of visual experience, such as a contextual cueing effect (Chun, 2000; Chun & Jiang, 1998) or value-driven attentional capture (Anderson, Laurent, & Yantis, 2011; Anderson, 2013, 2016), which interacts with search strategies.

Earlier studies demonstrating the effect of previous experience have focused on limited search situations in which observers could explicitly or implicitly learn a certain way to deploy attention for better outcome. For example, observers learned to attend preferentially to a target-likely position throughout repeated search blocks with a particular configuration (Chun & Jiang, 1998), or received a monetary reward for rapid attentional guidance to a specific visual feature (Anderson, 2013, 2016). Learning from the search is so powerful that the pattern of attentional guidance seems to persist in later searches, even if it no longer improves performance. However, it is unclear whether previous search experience affects search strategy in other situations in which there is no repetition of spatial configuration or monetary motivation, and in situations in which observers have more flexibility to freely adapt or build their own search strategy in more dynamic searches. More importantly, it is unknown how the strategy built by search experience in one type of circumstance will persist and affect searches in different circumstances.

The present study used search circumstances that are very different from the previous studies that measured priming effects, the contextual cueing effect, or value-driven attention guidance. I focus on how experience with difficult color discrimination changes strategic use of color information to guide attention. Although previous search experiments provided plenty of clues to how search can be made more difficult by target-distractor discriminability, those results do not indicate whether search experience with difficult color discrimination influences a subsequent search and whether this experience can be advantageous or disadvantageous for an observer's strategic guidance of attention.

The current study used a variant of a color-shape conjunction search task consisting of a cue display providing target information in advance of a search display with distractors that may be accompanied by a target. The target was defined by color and shape features but it was always a different shape from the distractors. In the shape dimension, the target was very similar to all distractors, which made it difficult to guide attention by shape in these search arrays. In the color dimension, search arrays were designed to have a high proportion of distractors with colors that were very similar to the target colors for the difficult discrimination experience; this distractor similarity should also lead to a cost in search performance. However, color information is useful to filter out the rest of the distractors with target-dissimilar colors for efficient search guidance. Thus, the task is designed to encourage observers to use primarily color information to guide search. In this search circumstance, an ideal searcher will only attend to target candidates that have target colors or target similar colors, and then verify the shape of each of these candidates to determine whether it is the target.

To answer the question of whether the experience with difficult color discrimination influences search strategy, I compared performance between two participant groups that differed from one another in their experiences with difficult color discrimination. One participant group always experienced an easy search in which the color of the target (i.e., a colored T) was easily distinguishable from those of some of the distractors (i.e., colored pseudo-Ls). The other participant group also experienced the same easy search as the easy search experience group on a half of the trials and, importantly, experienced difficult search in which the colors of the targets were barely distinguishable from those of some of the distractors in the other half of the trials. The

comparison of the two groups' performance can provide information about how the experience causes the difference in performance, if any. This comparison across groups should be limited to only the easy trials, so that the search stimuli are the same for both groups. If previous experience plays a role in shaping attentional guidance, we should see some difference in search performance in the easy search trials between the two groups.

One possible outcome is that the experience with difficult search will cause the hard search experience group to search more effectively than the easy search experience group. In general, observers can maximize search efficiency if they select the most effective target features to guide search (Baluch & Itti, 2010; Bravo & Farid, 2009; Desimone & Duncan, 1995). I expect that both participant groups would use color to some extent to guide search because color guidance can restrict the number of search items that observers must scrutinize. Thus, a member of the hard search experience group, as an ideal searcher, would choose to use color as a main source of attentional guidance, but they should encounter some difficulty on search trials containing some distractors with target-similar colors. The difficult search might prompt these participants to increase the precision of their representation of the target color so that they could easily reject the distractors with target-similar colors. If the hard search experience group responds in this way, their search template will be more precisely tuned for the difficult color search trials, but it should also lead to better search performance in the easy search trials. This account predicts that the hard search experience group will complete search more efficiently in the easy search condition than the easy search experience group, because the hard group will guide search more effectively by their precise color representation in the search template.

Alternatively, the experience with difficult color discrimination might be disadvantageous for search strategy. The experience could encourage the hard search experience group to rely less on color to guide search. Some studies have shown that observers do not always employ the most effective search strategy available to them (Stroud, et al., 2012; Stroud, Menneer, Kaplan, Cave, & Donnelly, 2018; Menneer et al., 2019). In the single-target condition in these experiments, participants searched for a colored T among colored Ls. Attentional guidance by color was generally effective, with fixation rates for each color of distractor increasing with its similarity to the target colors. In the dual-target condition, participants were required to remember two targets and to search for either of them among distractors. In this condition, there were many more fixations for distractors with target-dissimilar colors, indicating most of them were not guided by color. These results suggested the participants performing the dual-target search relied less on color to guide search than the participants performing the single-target search.

Although it is plausible that this dual-target cost arises from fundamental limitations on attentional guidance, a follow-up study (Cave et al., 2020) demonstrates that these fixations that were not guided by colors could be eliminated or at least reduced by a change in search strategy. In Experiment 1 of their study, both search targets and distractors had the same shape (i.e., Ts) so that the only information available to distinguish them was color. This manipulation forced the participants to use color to confirm the target identity, and this led them to also use color more effectively to guide search. Participants performing in this pure-color dual-target search fixated much less to target-dissimilar colors. In other words, color guidance was much more accurate when

subjects were forced to identify targets by color than in the previous experiments in which they had shape information to distinguish targets from distractors. The result suggests one interesting aspect of search strategy: even though observers have the ability to guide search efficiently by color, it appears that they do not use this color information as much as they could. Based on these findings, we hypothesize that participants who experience difficult color discrimination might respond similarly to the way participants responded to the extra difficulty evolved in dual-target search, by ignoring that color information and trying to use shape information to complete the search task.

EXPERIMENT 1

Introduction

Experiment 1 is designed to examine how search strategy can be altered by experience with difficult target/distractor discriminations when target information varies from trial to trial. The task design ensures that target information is stored in visual working memory (Carlisle et al., 2011).

The ideal search strategy is to guide search toward items with the target color. Because the color is useful to find a target, participants should not give up on color guidance. If experience with difficult search encourages participants to tune the target representation more precisely, the hard search experience group will be more likely to fixate to the distractors with a target color or target-similar colors and will be less likely to fixate to the distractors with target-dissimilar colors compared to the easy search experience group. However, if experience with difficult search discourages participants from using color to guide search, the opposite results will be observed: the hard search experience group will be more likely to fixate the distractors that appear in target-

dissimilar colors and less likely to fixate the distractors that appear in the target color or the target-similar colors compared to the easy search experience group.

Some of the descriptions and results of Experiment 1 were also presented in my master's thesis.

Method

Participants

Sixty-four undergraduate students in the University of Massachusetts Amherst participated for course credits (mean age = 20 yrs, male = 8). The Ishihara test (Ishihara, 1972) to test color blindness was administered to all students in this experiment and the following experiments. All participants reported normal vision or corrected-to-normal vision acuity and there was no evidence of anomalies in color perception in any of the participants. I planned to replace all participants whose search error rate was above 30%, but none of the participants was above this threshold.

Stimuli

Each trial consisted of a target preview display and a search array. The target preview display contained two potential targets that were defined by a conjunction of a color and a "T" shape. The target colors were chosen from a set of sixteen colors that was the same color set used in previous studies (Menneer et al., 2007, 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 the colors, I borrowed the concept of "color-step" (Stroud et al., 2012). The number of color-steps represents the distance between two colors on the color ring. For example, a color-step of two indicates that two colors are two steps away from each other (e.g., red and orange) and a color-step of four indicates that two colors

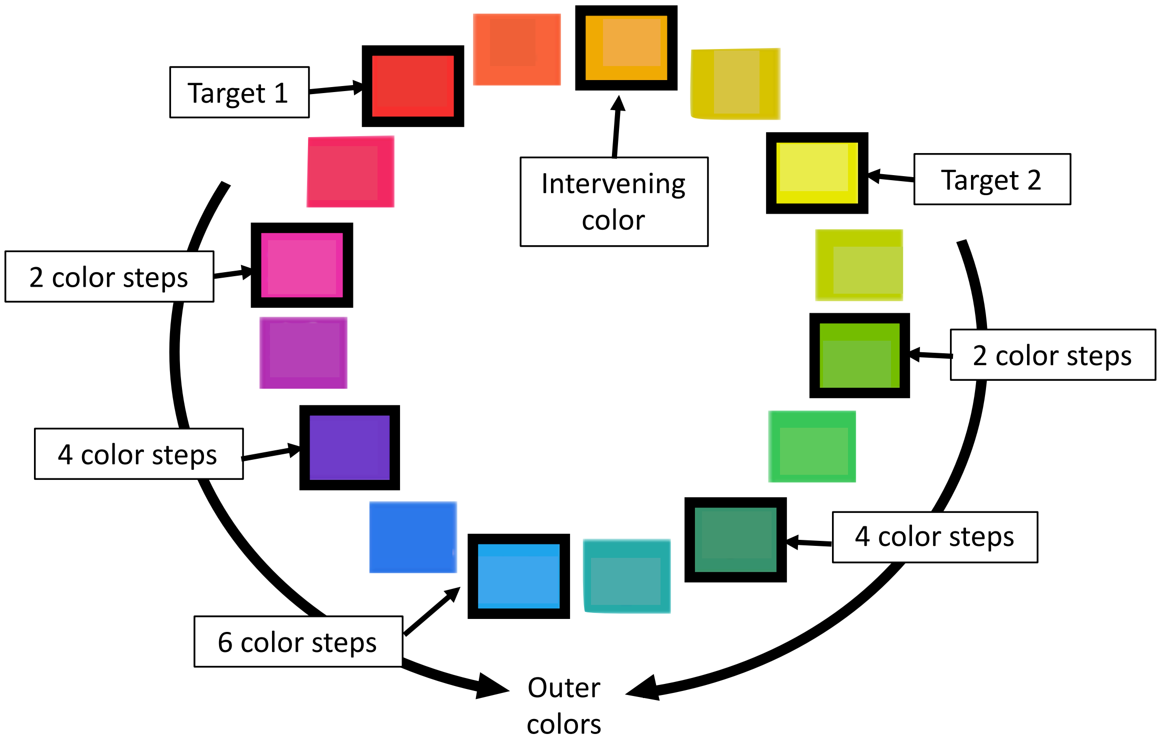

Figure 1. The sixteen colors used in the current experiments are arranged to form a color ring.16-color search trials used all 16 colors and 8-color search trials used eight colors equally spaced on the color ring. In the example above, the colors framed by thick lines were used for one of the 8-color search trials. One of these 8 colors is the intervening color positioned between the two target colors. Colors that are neither the intervening color nor the target colors are labeled "Outer colors", and are positioned outside of locations of the two target colors and the area between them.

are four steps away from each other (e.g., red and yellow) on the color ring. Therefore, as the color-step increases, the dissimilarity between two colors also increases. A pair of target colors was randomly selected from among the sixteen possible pairs on every trial. The two chosen target colors were always separated by four color-steps, so that they were easily distinguishable each other. Each possible pair was presented on an equal number of trials as target cues. The shape of the target was always "T" consisting of two oriented bars with the same size (1.04° × 0.37° of visual angle). Two target cues were placed on

the left and right side with a distance of 1.96° of visual angle from the center of the display.

The search array consisted of ten search items that were either a target and nine distractors or ten distractors, depending on target presence. For each distractor, the shape was always a pseudo-L consisting of two oriented bars (1.04° × 0.37°). The assignment of color to distractors varied between two search difficulty trial types designed to induce different experience in color discrimination. The two types of search difficulty arrays (16-color arrays and 8-color arrays) differed in two respects: The number of distractor colors used and the frequency distribution of the distractor colors. For the 16-color search arrays, distractor colors were assigned from a pool that included all 16 colors in the color ring, and the frequency of the different colors in the pool was adjusted for a particular target-color pair so that target similar colors made up a larger portion of the distractor color pool than target dissimilar colors did. (See Table 1.) For example, when the target colors are 7 and 11, the most target-similar colors are color 6, 8, 10, and 12 (i.e., color 6 and 8 are one step away from target color 7, and 10 and 12 are one step away from target color 11). Each of those four colors occupied 13.2% of the distractor color pool, so together those four colors made up 52.8% of the distractor color pool. The next similar colors were color 4, 5, 13, and 14, which are 2 or 3 color-steps away from the nearer target color; each of these colors occupied 5.3% of the pool. The most target-dissimilar colors, which were at least four color-steps away from the nearer target color, were colors 1, 2, 3, 15, or 16, and each color occupied 2.6% of the pool. Finally, there were the distractors sharing one of the target colors (i.e., color 7 and 11), each of which occupied

5.3%, and distractors with the intervening color two steps away from each of target colors (i.e., color 9), which occupied 2.6% of the pool.

The 8-color search trials used eight colors that were equally spaced on the color ring, with two color-steps between neighbors. Also, the six colors that were not the target colors each occupied 13.2% of the distractor pool, and the two target colors each occupied 10.5% of the distractor color pool. Including the target T's that appeared in the search arrays, all eight colors were equally presented (each color 12.5%) to prevent any bias to particular target colors. Because the 8-color search trials only used half of the sixteen colors, there were two subsets of the 8-color search trials: 8-odd-numbered-color trials and 8-even-numbered-color trials, to avoid perceptual bias to a specific set of eight colors.

Each of the search items, including both targets and distractors, was randomly rotated to one of four orientations (0°, 90°, 180°, or 270°). Each search item was 7.8° of visual angle away from the central fixation point, and item pairs that were adjacent on the circular search array were 2.4° away from each other. A target-present trial contained a target and nine distractors. A target-absent trial contained ten distractors without the target.

To obtain eye movement data for the ten search items, a set of regions of interest (ROI) was assigned offline. The ROIs together formed an annulus over the search items with an outer radius of 9.72° and an inner radius of 5.88° from the center. This annulus was equally divided by ten slices into ten ROI's, with an included angle of 36° for each slice. Each search item location was in the center of one ROI slice. Eye fixations that fell within any part of the ROI were used for eye movement analyses.

Procedure

Each trial began with a drift correction for the eye tracker. Once participants fixated on a black dot at the center of the screen, the experimenter pressed a key on the experimenter computer to begin the trial. After the offset of the drift correction stimulus, a target preview array was presented with two potential targets for 1000ms, followed by a 1000ms blank delay interval. After the delay interval, the search array was presented and remained visible until a response. In each target-present trial, either of the two targets was equally likely to appear as the target in the search array.

The target-present trials and the target-absent trials were intermixed in random order. The participants were required to press one of two buttons on a game controller as accurately and as quickly as possible to report whether the search array contained a target or not. To prevent any verbal encoding of target colors from the preview and to ensure performance truly reflects search guidance by visual representations, the participants were asked to say a word “the” aloud repeatedly through the entire experiment (Baddeley & Hitch, 1974). Depending on the accuracy of the participants’ manual response, one of two different tones was provided as feedback at the end of each trial. There were 256 main experimental trials, preceded by 5 practice trials. There were sixteen target pairs and each target pair was presented on sixteen trials for each participant.

Experimental Design

Each participant was assigned to one of the two experience groups: the hard search experience group or the easy search experience group. In the hard search experience group, half of the trials were the 16-color search trials and other two-quarters of the trials were the 8-odd-numbered-color search trials and the 8-even-numbered-color

search trials, respectively. The trials were randomly intermixed so that the participants did not become aware of the existence of different types of search trials, and they were thus unable to take different search strategies for each type of trials. To ensure that participants in the hard group had not implemented different search strategies for the 8-color and 16-color search trials, at the end of the experiment the experimenter asked the participants whether they realized that some trials were more difficult than other trials, and none of them realized that during the task. In the easy search experience group, half of the participants performed only 8-odd-numbered-color search trials and another half of the participants performed only 8-even-numbered-color search trials, so that these participants did not experience any difficult search trials. In the analyses, only 8-color search trials were used to compare performance between the easy and hard groups so that any performance difference between the two groups could not be attributed to physically different search arrays.

Apparatus

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

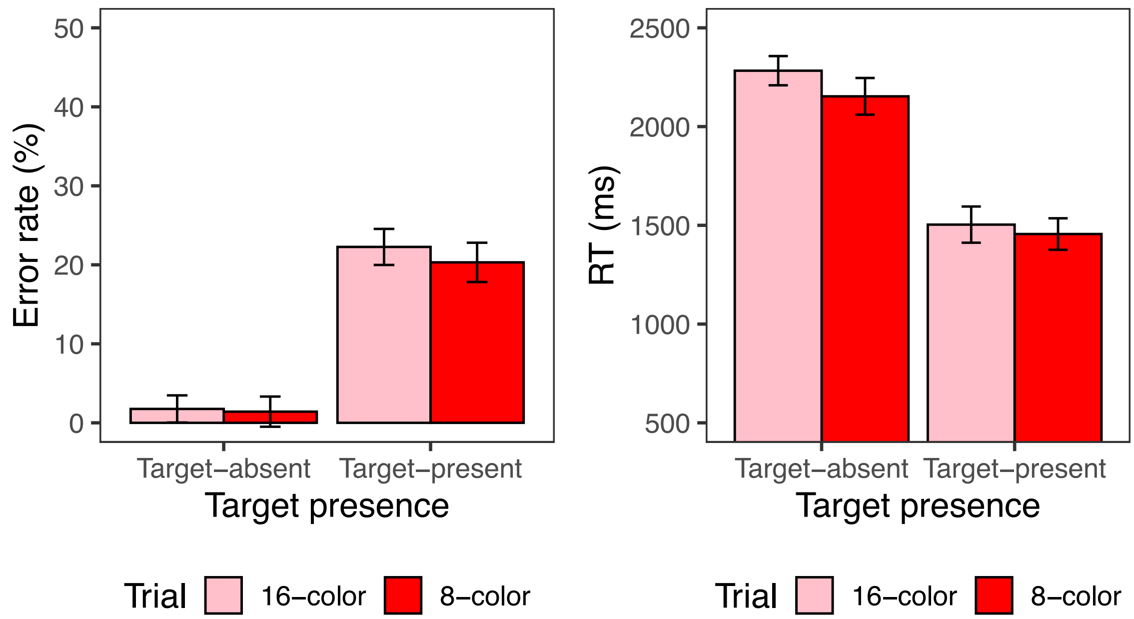

Figure 2. Mean error rates (left panel) and RTs (right panel) in Experiment 1. Pink represents the 16-color search trials and red represents the 8-color search trials. Error bars represent 95% confidence intervals here and in the rest of the figures below.

Results

Error rate and RT

Participants' manual responses were recorded and used to calculate error rate and response time (RT). Trials with incorrect responses were excluded for RT analyses and each individual participant's median RT was calculated with the remaining trials.

To ensure that the 16-color search trials are more difficult than the 8-color search trials, it is necessary to compare search performance between the 16-color trials and 8-color trials within the hard search experience group (Figure 2). Error rates and RT data were submitted to separate repeated-factor ANOVAs with factors of search trial type (i.e., 16-color trials vs. 8-color trials) and target presence (i.e., target-present vs. target-absent). For the error rates, there was no main effect of search trial type, $F(1, 31) = 2.437$, $p = .129$, $\eta_p^2 = 0.006$, but there was a significant main effect of target presence, $F(1, 31)$

= 172.025, $p < .001$, $\eta_p{}^2 = 0.658$. The participants made more error responses for target-present trials than target-absent trials. This factor did not interact with the group factor, $F(1, 31) = 1.455$, $p = .237$, $\eta_p{}^2 = 0.003$.

The RT data show a clearer difference between the two search trial types. The RT was significantly slower in the 16-color search trials than 8-color search trials, $F(1, 31) = 17.891$, $p < .001$, $\eta_p{}^2 = 0.009$, and for the target-absent trials than the target-present trials due to the self-termination once participants found a target, $F(1, 31) = 124.982$, $p < .001$, $\eta_p{}^2 = 0.397$. There was a marginally significant interaction between the two factors, $F(1, 31) = 4.156$, $p = .050$, $\eta_p{}^2 = 0.002$. These results demonstrate that the manipulations to make search difficult were successful, and the participants had difficulty in finding the target in the 16-color search trials in both target-absent and target-present trials, as expected. One might wonder why the error rates were similar between two search trial types, unlike the RT results. It is likely because the participants were allowed to use shape information to confirm the identity of stimulus so that even though the participants fixated to a distractor with the target color, they were able to realize that it did not have the target shape, and then redirected attention to another candidate. In addition, when an experimenter asked whether the participants realized that some search trials were more difficult than others, they reported that they did not notice any particularly easy or difficult search trials, confirming that our manipulation was subtle enough to avoid having separate search strategies for each search type, but it was enough to cause longer RTs for the difficult search (i.e., 16-color trial).

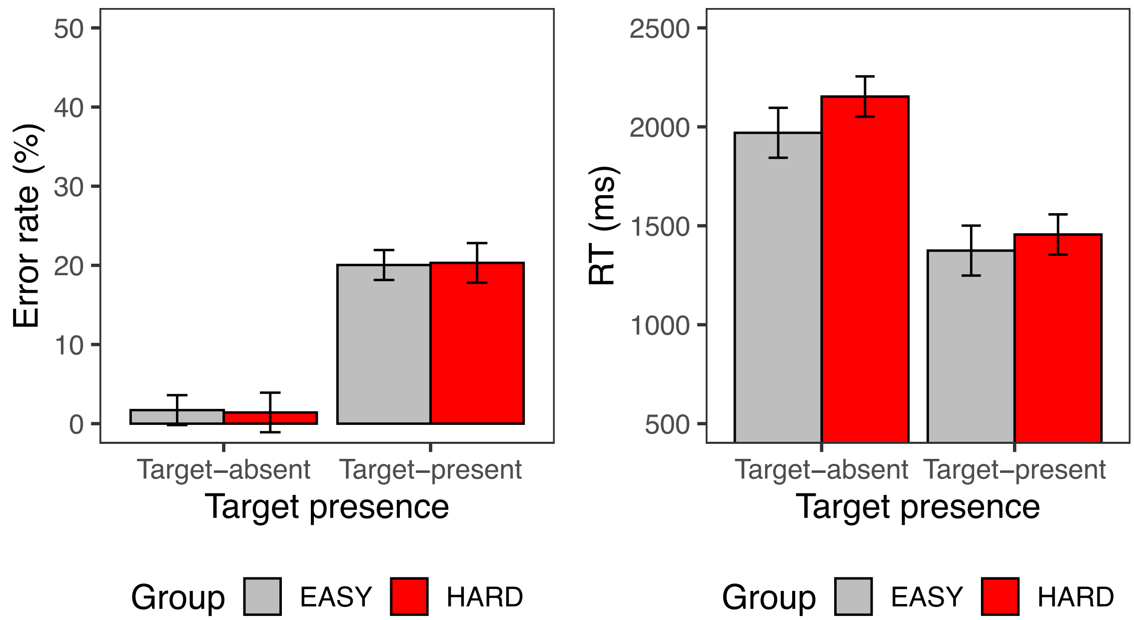

Figure 3. Mean error rates and RTs in Experiment 1. Gray bars represent easy search experience and red bars represent hard search experience. Only the 8-color search trials were used for the hard search experience group; the 16-color search trials were excluded.

The primary comparison is between the two participant groups in the 8-color search trials (Figure 3). First, error rate data in the 8-color search trials from both easy and hard search experience groups were subjected to a mixed-factor ANOVA with a within-subject factor of Target-Presence and a between-subject factor of Group. There was no significant difference between the two groups, $F(1, 62) < 0.001$, $p = .991$, $\eta_p{}^2 < 0.001$. The error rate was higher for the target present trials than the target-absent trials, $F(1, 62) = 293.550$, $p < .001$, $\eta_p{}^2 = 0.692$, replicating the common pattern in many search experiments showing that participants make more misses than false alarms. There was no significant interaction between the two factors, $F(1, 62) = 0.067$, $p = .807$, $\eta_p{}^2 < 0.001$. RTs excluding the 16-color trials were submitted to a mixed-factor ANOVA with the same factors. Similarly, there was no main effect of Group, $F(1, 62) = 1.306$, $p = .258$,

$\eta_p{}^2$ = 0.016, although the mean RT looks numerically larger for the hard search experience group (1804 ms) than the easy search experience group (1672 ms). The RT was significantly longer for the target-absent trials than the target-present trials, $F(1, 62) = 132.299$, $p < .001$, $\eta_p{}^2 = 0.289$. There was no significant interaction between the two factors, $F(1, 62) = 0.822$, $p = .368$, $\eta_p{}^2 = 0.002$. The error rate and RT combined together do not show a meaningful difference between the two participant groups.

Probability of Fixation

The goal of the eye movement analysis is to test whether the experience with the difficult color discrimination trials alters how color information is used to guide search. I hypothesized that experience with the 16-color search trials can change search guidance so that there is either more or less reliance on the target colors for attentional guidance. In this analysis and in the eye movement analyses for the following experiments, we primarily focused on the results on the target-absent condition, because this condition provides more fixation data, given that searches are usually terminated once a target is found. Despite the emphasis on the results of the target-absent condition for interpretation, the results of the target-present condition are also reported.

Only correct trials were included for eye tracking data analyses. Because of the fundamental difference between the 8-color search stimuli and 16-color search stimuli in color discriminability between the target and the distractors, only the 8-color search trials, which both groups experienced, were used for further analyses for group comparison.

To quantify the search guidance levels, the probability of fixation was calculated with the fixations to distractors only. Excluding the fixations to the actual target ensures that any differences in the probability of fixation between colors can be attributed purely

to color guidance and not to shape. The analyses focused on the probability of fixation across the color-step distances between the color of the fixated distractor and the color of its more similar target. Therefore, the term color-steps when used below refers to the distance between the distractor's color and the nearer target color on the color ring.

The probability of fixation was calculated by the following steps (Stroud et al., 2012): (1) First, I summed up the number of distractors with a particular color that appeared and were fixated at least once in a trial. Because the distractor colors were randomly selected from the distractor color pool, it was possible to have multiple distractors with the same color in a single trial. For instance, if there were two different distractors with a particular shade of green in the search array and the participant fixated each of the distractors at least once, it was counted as two fixated objects for that color. Whereas, for the same situation, if a participant fixated only one of the two distractors, it was counted as one fixated object for that color, even if this object received multiple fixations. (2) Next, I summed up the number of distractors with that particular color that appeared in the entire experiment, regardless of whether they were fixated or not. (3) The fixation rates for the different colors were obtained by dividing (1) by (2). Each of these values reflects the probability that a particular color was fixated throughout the entire experiment. (4) For two colors with the same color-step value, their fixation rates were averaged to obtain a fixation rate for that color step, which results in the probability of fixation. If the probability of fixation to a particular color-step is high, it means that a participant was more likely to fixate to colors of this color-step value. If the probability of fixation to a particular color-step color is low, it means that the participant was less likely to fixate to colors of this color-step value.

From this calculation, I can obtain the probabilities of fixation for five levels of color-steps. Here, the five levels of color-step were classified by whether the colors were placed outside (i.e., outer colors) or inside (i.e., intervening colors) of the two target colors on the color ring (Figure 1). Thus, there is one intervening color-step between the two target colors, and there are four outer color-steps (color-step of 0, 2, 4, and 6). A previous study (Stroud et al., 2012) suggested that the intervening color might be influenced equally by the two target colors, unlike the outer colors, so that its fixation rate was relatively higher than outer colors' fixation rates. Also, the intervening color is in the part of color space that connects the two target colors, so that the fixation rate to the intervening color can be used to infer whether two target colors were represented as a single color continuum or as two discrete colors. Based on this account, the probabilities of fixation for the intervening color and outer colors were analyzed separately. For the following analyses, comparisons were conducted with a Bonferroni correction (FWE=.05) where multiple t-tests were used. A Welch's t-test was used where the assumption of equal variances for independent samples was violated (Welch, 1947). A Greenhouse-Geisser correction was used where the sphericity assumption was violated.

Figure 4 summarizes the probability of fixation results for each condition in each group. First, I performed the statistical analyses for the outer colors. The fixation rates for the outer colors were subjected to separate mixed-factors ANOVAs for target-absent trials and target-present trials, each with these factors: a within-subject factor of color-step (0, 2, 4, and 6 color-step) and a between-subject factor of search experience group (easy search experience vs. hard search experience). The probability of fixation for the outer colors systematically decreased as the color-step increased in the target-absent

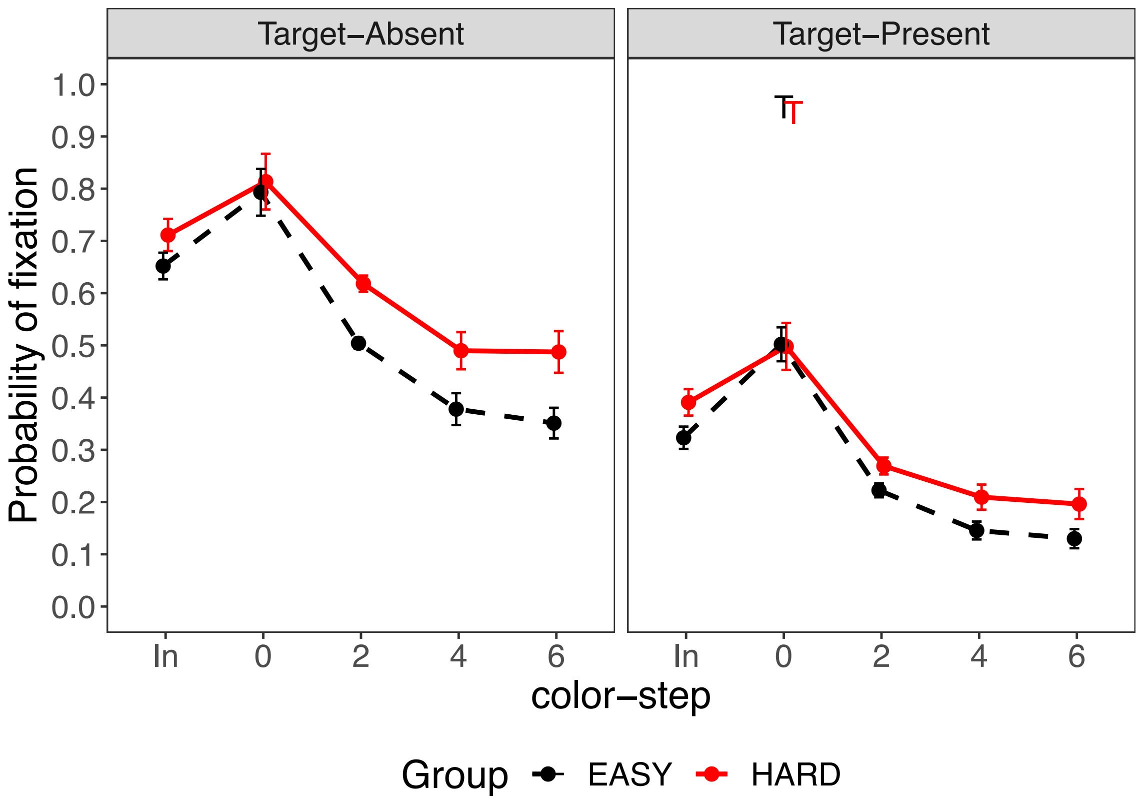

Figure 4. Probability of fixation for the target absent (left) and target present 8-color trials (right) in Experiment 1 (varied target). A black dashed line represents the easy search experience group and a red solid line represents the hard search experience group. The x-axis represents the distance between a distractor's color and the nearer target color in the color ring (i.e., color-step). On the x-axis, "In" represents the intervening distractor color, which is between the two target colors on the color ring. Distractors that shared one of the target colors are plotted over the "0" value on the x-axis. In the target-present panel, a "T" represents the probability of fixation for an actual target presented in a search array.

trials, $F(3, 186) = 208.682$, $p < .001$, $\eta_p{}^2 = 0.448$, indicating that the participants were more likely to fixate the distractors with the target colors or target-similar colors than the distractors with target-dissimilar colors. This pattern replicated the results from previous studies using a similar experimental design (Stroud et al., 2012), and confirmed that the participants used color information to guide search. The main effect of group was also significant, $F(1, 62) = 6.407$, $p < .05$, $\eta_p{}^2 = 0.072$, showing that the probability of

fixation was higher for the hard search experience group than for the easy search experience group. More importantly, the interaction between the two factors was statistically significant, $F(3, 186) = 4.357$, $p < .05$, $\eta_p{}^2 = 0.017$. Four follow-up comparisons with t-tests were performed on each color-step, and *p* values were corrected with FWE (0.05/4 = .0125). In the target-absent trials, the probability of fixation was not statistically different between the two groups at color-step 0, $t(61.6) = 0.970$, $p = .336$, $d = 0.245$, but it was higher for the hard search experience group than the easy search experience group at color-step 2, $t(61.6) = 2.88$, $p = .006$, $d = 0.719$, marginally at color-step 4, $t(61.1) = 2.125$, $p = .038$, $d = 0.531$, and at color-step of 6, $t(59.5) = 2.605$, $p = .011$, $d = 0.651$.

Similar results were observed in the target-present trials, but the patterns were relatively weaker, since the overall probabilities of fixation were lower due to self-termination in the target-present trials. There were a main effect of color-step, $F(3, 186) = 290.230$, $p < .001$, $\eta_p{}^2 = 0.597$, a marginal main effect of experience group, $F(1, 62) = 3.391$, $p = .070$, $\eta_p{}^2 = 0.036$, and a marginal interaction, $F(3, 186) = 3.175$, $p = .062$, $\eta_p{}^2 = 0.016$.

Next, I compared the probabilities of fixation for the intervening color between the two participant groups, with separate comparisons for target-present and target-absent conditions. When the target was absent, the probability of fixation was higher for the hard search experience than the easy search experience group (0.711 and 0.652 respectively), but it was not statistically significant, $t(61.97) = 1.745$, $p = .085$, $d = 0.436$. When the target was present, the hard search experience group fixated more to the intervening color than the easy search experience group (0.390 and 0.323 respectively), $t(61.87) = 2.769$, *p*

$< .01$, $d = 0.664$. Finally, I compared the probabilities of fixation to an actual target between the two groups. These values are shown as T's on the right panel of Figure 4. There was no significant difference between the hard and easy search experience groups, $t(60.03) = 0.413$, $p = .681$, $d = 0.103$.

In sum, the probability of fixation results showed two interesting patterns. First, the probability of fixations for the outer colors decreased as a function of color-steps regardless of search experience. It indicates that the participants used color information to search for targets. The probability of fixation was the highest for the distractors appearing in target colors and reduced as the color-step of the distractor's color increased. The more important finding is that fixation rates for the distractors appearing in target-dissimilar colors were higher for the hard search experience group than the easy search experience group. This evidence demonstrates that experience can alter the strategy of search guidance, and more specifically that difficult search experience can encourage observers to rely less on color information to guide search in the current experiment.

Mean Color-Step Across Blocks

As shown in the probability of fixation results, the experience of difficult color discrimination induced the hard search experience group to make more frequent fixations toward target-irrelevant colors even for the 8-color search trials in which target color was relatively easier to distinguish from distractors. The question remaining is when this difference happened. In the next analysis, I tried to examine this question by comparing the average color-step values across blocks between the two search experience groups. Considering Figure 4, if participants relied more on color guidance, there would be more fixations on the target color or target-similar color; that is; on color-step of 0 or color-step

of 2, and the average color-step of fixated colors would be near 0. If the reliance on color guidance became weaker, the mean color-step of fixated colors would be larger. I expect to see a significant group difference with respect to the mean color-step develop at some point as participants progress through the experiment.

To calculate the average color-step value, only fixations falling on one of the ten regions of interest (ROI) were considered, and multiple fixations to the same ROI were counted as one fixation. This is to rule out the potential problem from multiple fixations that were not caused by strong attention guidance but simply by fixation shifts within an object during a rest before the motor response is completed. Then, the color-steps of fixated items in that ROI were considered on each trial. For instance, if a participant made fixated three different items in a trial, and the color-steps for those items are 0, 2 and 4, then the mean color-step is 2 on that trial. The 256 trials were split into 16 blocks. The 16-color trials from the hard search experience group and incorrect trials from the both groups were excluded. The mean color-step value on a block was calculated by summing up the color-steps of the remaining trials and dividing by the number of the remaining trials.

Figure 5 shows the average color-step for each group for each of the sixteen blocks. It appears that the difference between the groups in average color-step value increases somewhat toward the end of the experiment. To confirm this demonstration, the average color-step values for each block were submitted to a mixed-factor ANOVA with a within-subject factor of block (from 1 to 16) and a between-subject factor of group (hard vs. easy group). There is a significant main effect of group, $F(1, 62) = 5.607$, $p < .05$, $\eta_p^2 = .076$, suggesting that the average color-step value was significantly higher

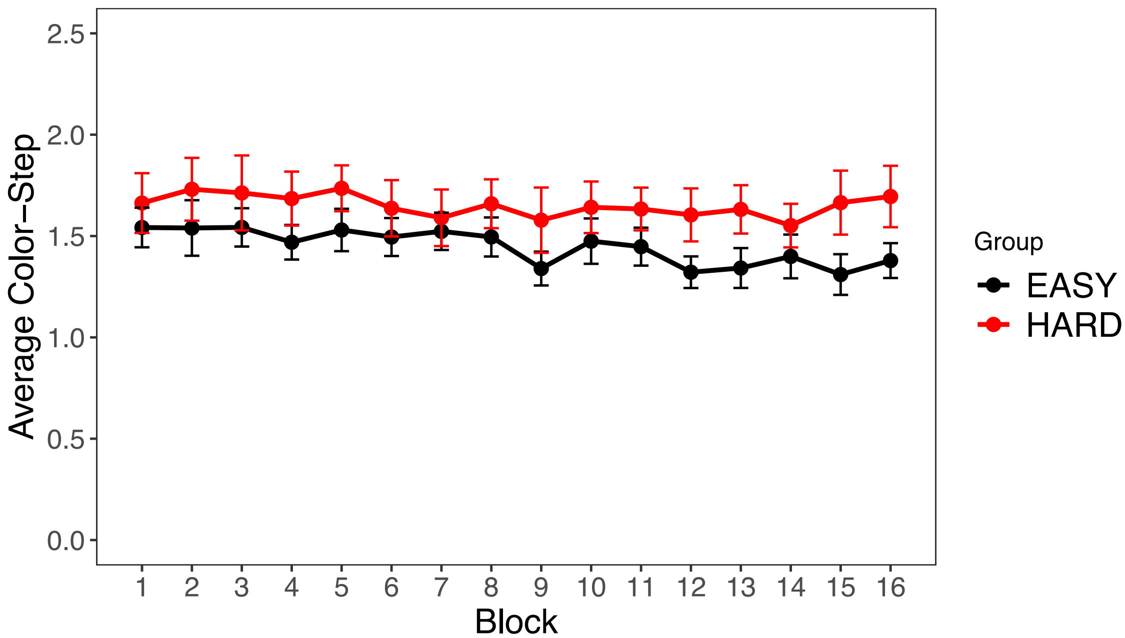

Figure 5. Average Color-Step values as block continues. Only 8-color search trials were included in the analysis and were divided into 16 blocks for each block in Experiment 1.

for the hard search experience group than the easy search experience group, which is expected from the fixation rate results. Because the hard search experience group was less likely to guide search by color, they were thus more likely to fixate colors that differed more from the target and thus had higher color step values. The main effect of block was also significant, $F(1, 62) = 11.832$, $p < .01$, $\eta_p{}^2 = .016$, indicating that the average color-step decreased as the block continued. This decrease in color-step implies a general practice effect (Menneer et al., 2009). However, the interaction between the two factors was not significant, $F(1, 62) = 2.824$, $p = .097$, $\eta_p{}^2 = .004$, even though there is a trend of interaction as mentioned above.

Attentional Guidance and Target Verification Times

Based on the results of fixation rate and mean color-step, I found that the experience with difficult color discrimination affects the level of color guidance. To be

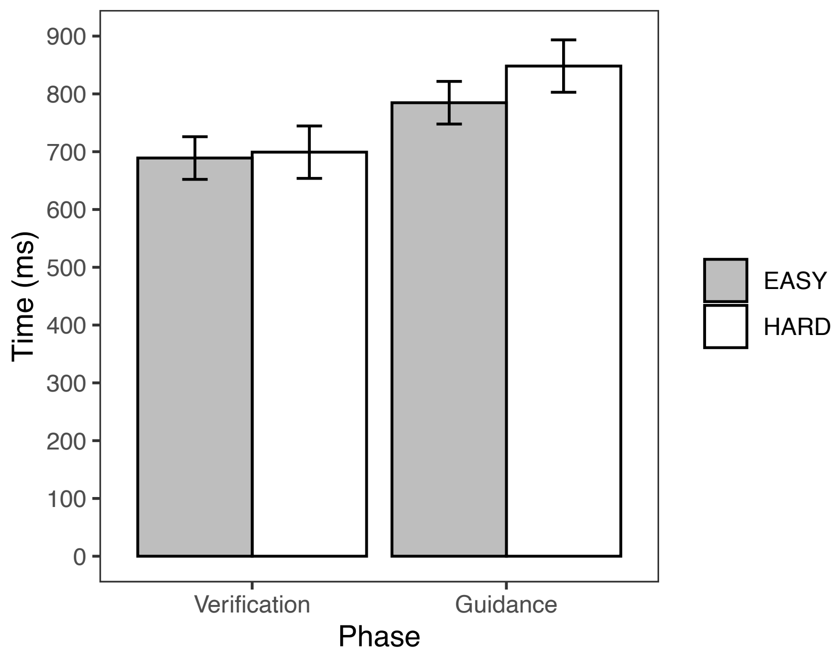

Figure 6. Mean times for Attentional Guidance phase and Target Verification phases for the 8-color trials in Experiment 1.

specific, the experience discouraged participants from adopting active color guidance, leading them to spend more time searching among target-irrelevant distractors. However, it is also possible that this difficult color discrimination experience affects visual processing after the search is done. That is, participants might take more time to verify a target once it is fixated. To test this possibility, response times were divided into two phases; attentional guidance and target verification. The attentional guidance phase is defined by the time interval between the onset of a search array and the onset of the first fixation to the target. The target verification phase is defined by the time interval between the onset of the first fixation to the target and the manual response. Because this measure is based on the fixations arriving at the target, only target present trials were included for the analyses. Only correct trials were included.

Figure 6 shows the mean time taken to complete each phase. The data were subjected to a mixed-factor ANOVA with a between-subject factor of Group and a within-subject factor of search Phase. There was no significant main effect of group, $F(1, 62) = 0.884$, $p = .350$, $\eta_p^2 = 0.011$. The main effect of phase was significant, $F(1, 62) = 36.423$, $p < .01$, $\eta_p^2 = 0.110$, demonstrating that it took more time to arrive at the target for the first time than to verify a target once it was fixated. However, there was no interaction between the two factors, $F(1, 62) = 1.726$, $p = .193$, $\eta_p^2 = .005$.

Discussion

Experiment 1 was designed to examine how experience with difficult target/distractor discrimination by color influences an observer's search guidance. Two participant groups were compared: an easy search experience group who did not experience any difficult discrimination, and a hard search experience group who experienced difficult discrimination on half their trials. The eye movement results showed a gradual decrease in the probability of fixation as color-step increased, showing that the participants used target color information to guide search toward items similar to the targets, whether or not they had previously experienced difficult discriminations (i.e., 16-color trials). This eye movement pattern replicated previous observations from a similar experimental design in which participants were not required to conduct a concurrent verbal suppression task (Stroud et al., 2012). Also, this result is in line with several attention theories claiming that pre-knowledge about a target biases attention toward target features (Desimone & Duncan, 1995) and guides attention toward a

stimulus that shares the target features or target-similar features (Wolfe, 1994; Wolfe et al., 2004).

More importantly, the comparison of fixation rate between the two groups revealed that this guidance by color information can be altered by experiencing difficult color discrimination. The hard search experience group fixated more to target-dissimilar distractors than the easy search experience group did, indicating that the participants who experienced difficult color discrimination relied less on the color guidance compared to the participants without that experience. Consistent with the fixation rate, the mean color-step value of the fixated items also supported this idea. It should be emphasized again that these different fixation patterns between the two groups were obtained with the exact same type of search array (i.e., 8-color search trials), which ensures that the group differences reflect differences in search strategies based on the participants' own subjective experience. The tendency toward longer RT for the hard search experience group suggests that their reluctance to use color information does not give significant benefits for performance; rather it comes at a potential cost.

These results conflict with one of the hypotheses described earlier: that difficult color discriminations would induce participants to tune a precise search template to precisely guide attention toward a stimulus that contains the exact target color or only very similar colors. One possible relevant factor is that participants might need a succession of trials with the same targets to adjust their target representation. Many studies observing the adjustment or development of target representation have presented participants with a constant target over hundreds of trials so that the participants do not need to update their target representation every trial and instead keep tuning their search

template (Bravo & Farid, 2016; Navalpakkam & Itti, 2006). In Experiment 1, the target varied from trial to trial. Therefore, the hard search experience group simply adopted a strategy of relying less on the varying target colors instead of relying more on them, perhaps because they implicitly realized that it is difficult to guide search by color on some trials. To test the effect of target color variation across trials, the target colors will be held constant in the following experiment.

EXPERIMENT 2

Introduction

Experiment 1 provided clear evidence for the negative effect of experience with difficult color discrimination on search guidance when targets changed from trial-to-trial. In the task, observers had a one-second interval to generate and tune the search templates before they saw a search array. This time might be too short for both creating and adjusting the search templates. If targets are consistent across many trials so that observers do not need to generate new search templates on every trial for the changing targets, they might be able to tune their search templates precisely.

If consistent targets allow the hard search experience group to create more precise color representations within the search templates, it will produce a pattern opposite to that of Experiment 1: There will be fewer fixations to the target-dissimilar distractors and more fixations to the target or target-similar distractors, along with faster RT and smaller mean color-step, in the hard search experience group than the easy search experience group. If the target consistency does not influence the search strategy and if the existence

of difficult color experience is the only relevant factor, then the results will be similar to those of Experiment 1.

Method

Participants

Sixty-four undergraduate students from the University of Massachusetts Amherst who did not take part in Experiment 1 participated (mean age = 19.7, male = 13). All had normal or corrected-to-normal vision and no one reported color blindness. Four participants were replaced because their accuracy was below the criterion (70%).

Stimuli and Procedure

The stimuli and procedure were identical to those of Experiment 1 except for two changes. First, the target colors were consistent across all the trials for an individual participant. Each participant was assigned one of sixteen target color pairs and instructed to remember them for the entire experiment. The second change was related to this new change. The participants in the hard search experience group whose target colors were odd numbered colors (e.g., 1 and 5) did not perform 8-even-numbered color search trials. The other participants, whose target colors were even numbered colors (e.g., 2 and 6), did not perform 8-odd-numbered color search trials. Therefore, one-half of the participants in the hard search experience group performed 16-color search trials in half of the trials and 8-odd-numbered search trials in the remaining half. The other half of the participants in the hard group performed a mixture of 16-color trials and 8-even-numbered color search trials. For the hard search experience participants, both trial types were randomly mixed, as in Experiment 1. Each participant in the easy search experience group performed only

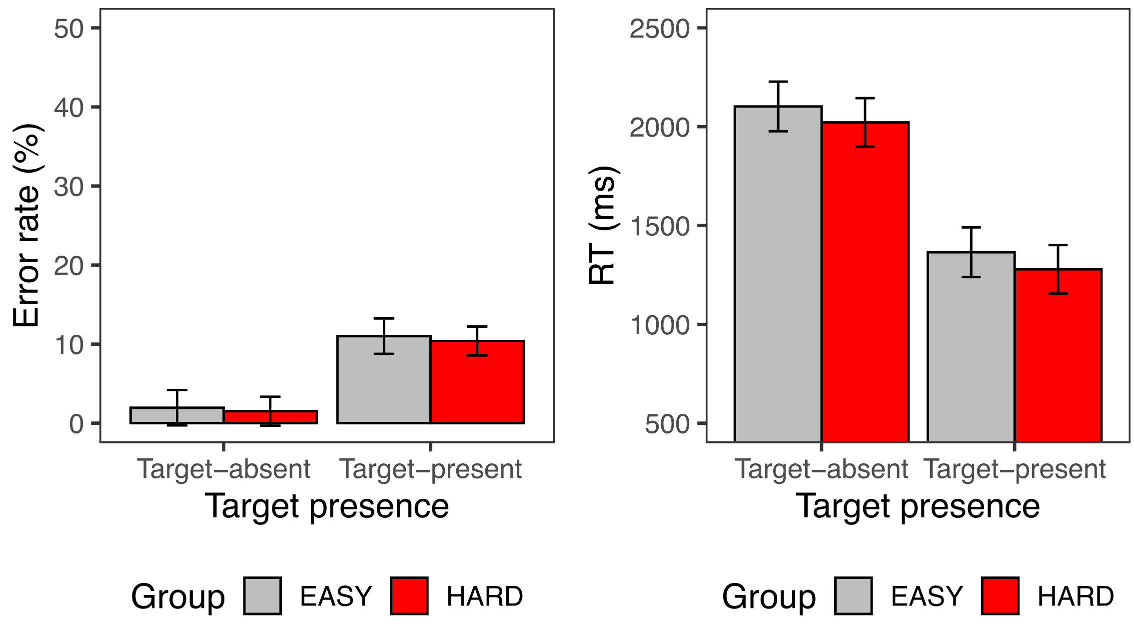

Figure 7. Mean error rate (left) and RT (right) for the 8-color trials for the easy search experience group (gray) and hard search experience group (red) in Experiment 2 (consistent targets).

either the 8-odd-numbered color or 8-even-numbered color search trials, as in Experiment 1.

Results

Error Rate and RT

Figure 7 shows mean error rate and RT results for each participant group on target-absent and target-present trials. Both the error rate and RT results of Experiment 2 were similar to those of Experiment 1. For the error rates, there was no significant main effect of group, $F(1, 62) = 0.182$, $p = .671$, $\eta_p^2 = 0.002$, and the error rate was significantly lower in target-absent trials than target-present trials, $F(1, 62) = 80.137$, $p < .001$, $\eta_p^2 = 0.340$. There was no significant interaction, $F(1, 62) = 0.008$, $p = .932$, $\eta_p^2 < 0.001$. Analogous to the error rate results, in RT, there was no main effect of group,

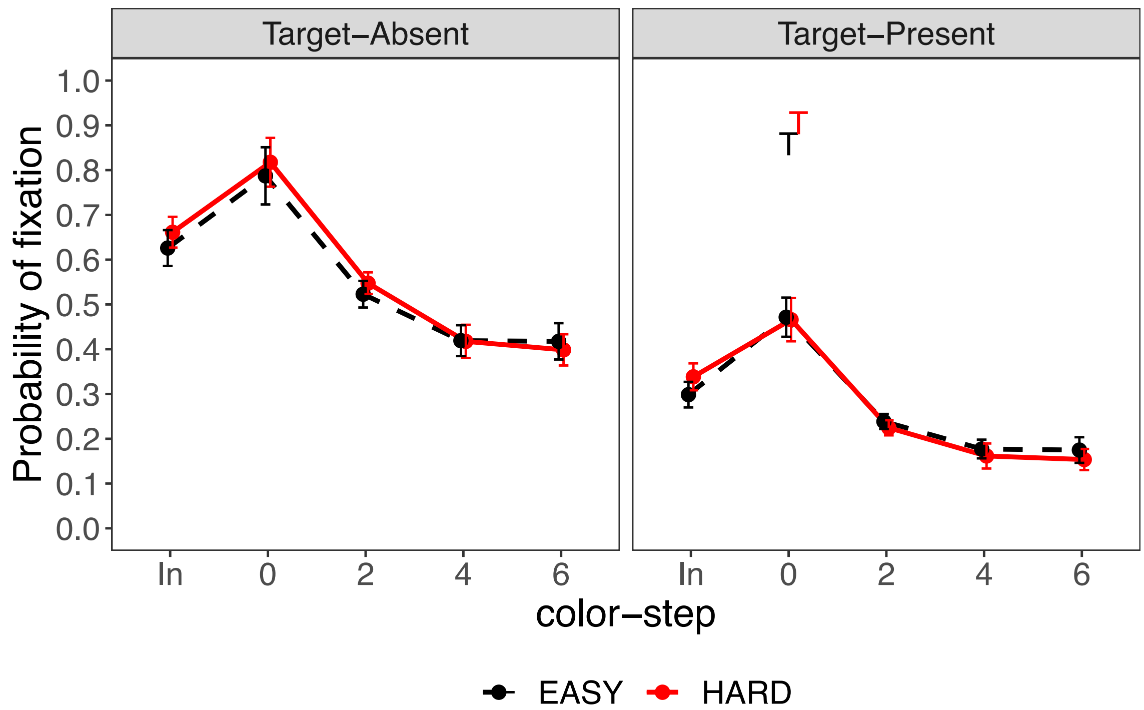

Figure 8. Probability of fixation for the target absent (left) and target present 8-color trials (right) in Experiment 2 (consistent target). A black dashed line represents the easy search experience group and a red solid line represents the hard search experience group.

$F(1, 62) = 0.467$, $p = .497$, $\eta_p^2 = 0.006$, and there was a significant main effect of target presence, $F(1, 62) = 147.829$, $p < .001$, $\eta_p^2 = 0.322$, demonstrating significantly longer RT for the target-absent trials than target-present trials. The two factors did not interact, $F(1, 62) = 0.002$, $p = .962$, $\eta_p^2 < 0.001$.

Probability of Fixation

Figure 8 shows the fixation probabilities for Experiment 2 and two lines, each representing search experience group, are overlapping each other, which implies the disappearance of the group difference with respect to color guidance. To confirm it, the same statistical analyses as used in Experiment 1 were conducted. For the outer colors, there was no main effect of participant group in the target-absent trials, $F(1, 62) = 0.036$,

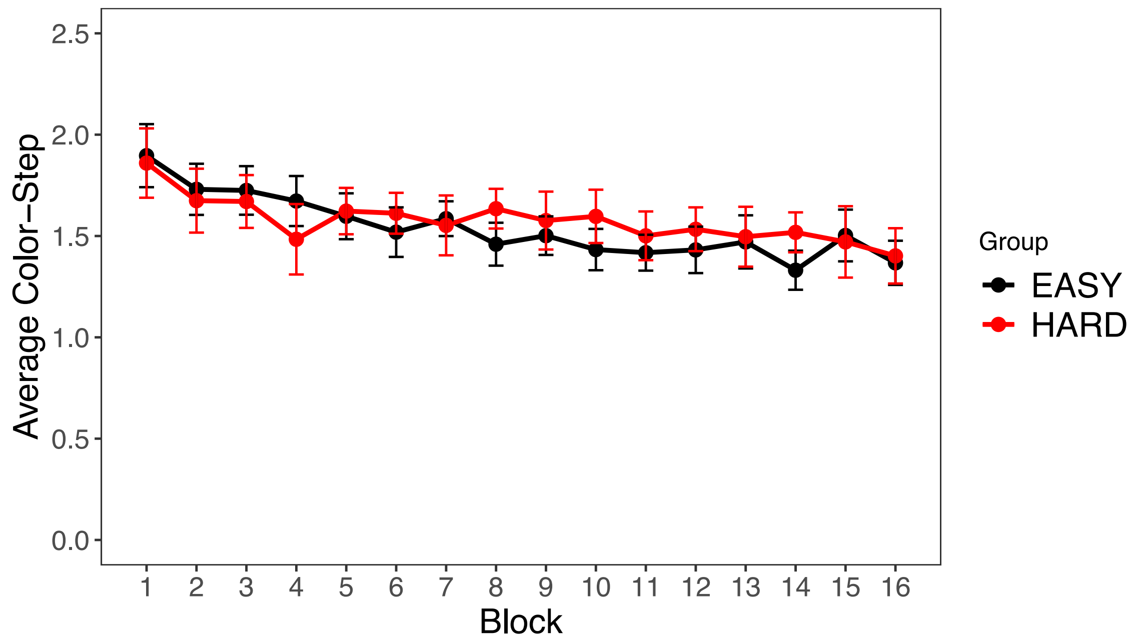

Figure 9. Average Color-Step values across sixteen blocks in Experiment 2. Only 8-color search trials were included in the analysis.

p = .848, $\eta_p{}^2 < 0.001$, and there was a gradual decrease in the probability of fixation as a function of color-steps, $F(3, 186) = 158.702$, $p < .001$, $\eta_p{}^2 = 0.380$. This factor did not interact with the factor of participant group, $F(3, 186) = 0.627$, $p = .472$, $\eta_p{}^2 = 0.002$. Similarly, in the target-present trials, there was no main effect of participant group, $F(1, 62) = 0.335$, $p = .565$, $\eta_p{}^2 = 0.003$. The main effect of color-step was significant, $F(3, 186) = 183.805$, $p < .001$, $\eta_p{}^2 = 0.518$, and it did not interact with the factor of group, $F(3, 186) = 0.096$, $p = .821$, $\eta_p{}^2 < 0.001$.

In addition, I performed separate independent t-tests for the intervening color, but there was no significant group difference in either target-absent and target-present trials, $t(60.68) = 0.712$, $p = .479$, $d = 0.178$, and $t(62.00) = 1.200$, $p = .234$, $d = 0.300$. Similarly, the probability of fixation to the actual target was not significantly different between the two participant groups, $t(57.27) = 1.625$, $p = .110$, $d = 0.406$.

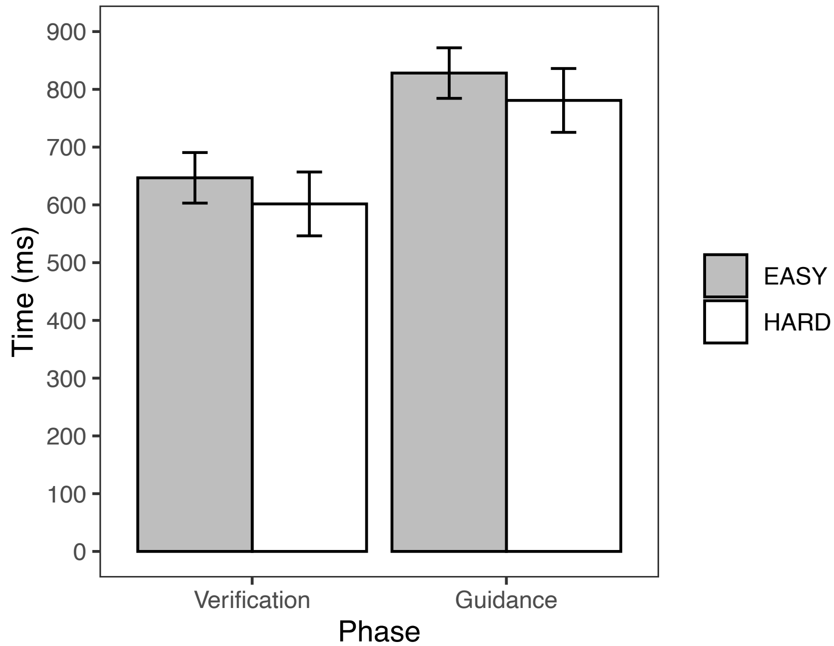

Figure 10. Mean time for Attentional Guidance and Target Verification phases for the 8-color trials in Experiment 2.

Mean Color-Step Across Trials

Figure 9 demonstrates the change in average color-step across the sixteen blocks. As expected based on the fixation rate result, the average color-steps of two groups seem indistinguishable from one other across all blocks. Statistical analyses revealed that there was no significant main effect of group, $F(1, 62) = 0.148$, $p = .700$, $\eta_p^2 = .002$, but a significant main effect of block, $F(1, 62) = 34.844$, $p < .001$, $\eta_p^2 = .070$, suggesting a gradual decrease in the mean color-step as participants progressed through the blocks. The interaction was also not significant, $F(1, 62) = 1.710$, $p = .195$, $\eta_p^2 = .003$.

Attentional Guidance and Target Verification Times

Trials with correct responses that included at least one fixation on the target were included for analyses to understand the two phases in performing this task. In Figure 10, the experience with difficult color discrimination does not seem to influence either the

attentional guidance or the target verification phase. The target verification time is numerically shorter for the hard search experience group than the easy search experience group. Statistical analyses showed that there was no significant main effect of group, $F(1, 62) = 1.470$, $p = .229$, $\eta_p{}^2 = .016$, but there was a significant main effect of phases, $F(1, 62) = 54.392$, $p < .001$, $\eta_p{}^2 = .203$, and these two factors did not interact, $F(1, 62) = 0.001$, $p = .964$, $\eta_p{}^2 < .001$.

Discussion

Experiment 2 examined whether the experience with difficult color discrimination occurred when the target information remained the same for a given participant throughout the entire experiment. Contrary to Experiment 1, I could not find any evidence that supports the experience effect in the behavioral measures, the fixation rates, the mean color-steps or the two phases analyses.

Comparing Experiments 1 and 2

In Experiment 1, the hard search experience group showed more fixations to the target-dissimilar distractor colors than the easy search experience group, indicating that experience with difficult discrimination led to less color guidance. Experiment 2 was conducted to test whether the same experience effect was observed while the targets were consistent in the identical procedure, but there was no significant experience effect.

To confirm whether this lack of evidence for the experience effect in Experiment 2 was caused by target consistency, the fixation rates for the outer colors from Experiments 1 and 2 were submitted to a mixed-factor ANOVAs with an additional

factor of target consistency (varying targets for Experiment 1 and consistent targets for Experiment 2) separately for target-absent and target-present trials. In the target-absent trials, the three-way interaction was marginally significant, $F(3, 372) = 3.387$, $p = .056$, $\eta_p{}^2 = 0.007$. This three-way interaction was not significant in the target-present trials because of the lower number of fixations, $F(3, 372) = 1.933$, $p = .160$, $\eta_p{}^2 = 0.005$. None of the other results reached the significant level, $ps > .1$, except for the main effects of color-step in both target-absent and-present trials, $ps < .001$. The marginal three-way interaction on target-absent condition implies that when targets changed from trial-to-trial, the hard search experience group relied less on color to guide search compared to the easy search experience group. However, when targets were consistent, this strategy difference between the two groups disappeared.

The absence of a group difference in Experiment 2 demonstrates that target consistency plays an important role on strategic attentional guidance. Target consistency has been demonstrated as a critical factor in search performance in previous studies. For any given target, the target information is represented and held in visual working memory (VWM) to guide search in a search display. When the targets are consistent in at least three successive search trials, long-term memory (LTM) takes part in holding the search template and making it available to guide attention (Carlisle et al., 2011; Woodman, Carlisle, & Reinhart, 2013). Once the search template receives some support from LTM, it can save some of the time necessary to establish the search template, and can easily verify the target in search arrays, leading to an improvement of RT and/or accuracy (Goldstein & Beck, 2018; Wolfe, Butcher, Lee, & Hyle, 2003).

In Experiment 1, even though color guidance could have improved search performance, the benefit may have been less for the hard search experience group. This group sometimes experienced very difficult search, in which some distractors' colors were very similar to target colors (i.e., 16-color trials). This high color similarity between the target and the distractors would hamper not only efficient search guidance, but also target verification. In this difficult search condition, the fact that many of the distractors were similar to a target would reduce the benefits of using the color information to guide attention and verify a target, compared to the easy search condition.

Varying targets can limit the benefit of color guidance by interacting with the experience with difficult search. When targets were varied on each trial, both search experience groups were probably prevented from creating a LTM search template. It is likely to take more time to establish a search template on each trial, and also to make it difficult to verify the target once it is attended. The experience with difficult color discrimination and the disadvantages from varying targets together appear powerful enough to discourage the hard group from using color guidance consistently across their trials. Whereas, despite the varying targets, the easy search experience group obtains performance benefits by using color guidance effectively during search due to the low target-distractor color similarity, leading them to choose relatively strong color guidance as a search strategy.

In Experiment 2, when the targets were consistent, the observers could easily take advantage of the LTM search template, which probably allowed relatively faster establishment of the search template and target verification than when the targets were varied. Even though the high similarity between the target and distractors in the difficult

search condition discouraged color guidance, that effect might have been overcome by the benefits of consistent targets, so that the hard search experience group continued to rely on color guidance as much as the easy search experience group did.

Even though the results from Experiment 2 give us a hint that the place where target information is stored interacts with visual search experience to determine the level of strategic attentional guidance, questions still remain about Experiment 1. In Experiment 1, two manipulations were applied to difficult target discrimination trials: color frequency distribution and the number of colors. Which manipulation is responsible for altering the search strategy of the hard search experience group? These manipulations will be tested separately in Experiments 3 and Experiment 4.

EXPERIMENT 3

Introduction

In Experiment 1, I manipulated two different properties of the search arrays to make search difficult: (1) the frequency distribution of colors and (2) the number of colors used. Experiments 3 and 4 each tested one manipulation while controlling the other. In Experiment 3, the number of colors was fixed at sixteen for all trials, but different frequency distributions were applied across trials to make color discrimination easier or more difficult. For the easy discrimination trials, all sixteen colors were equally represented within the distractor color pool, whereas for the difficult discrimination trials, target-similar colors occupied more positions within the distractor color pool than the target-dissimilar colors, just as in Experiment 1's difficult discrimination trials. In

Experiment 4, the frequency distribution of colors was fixed across trials to be flat, but eight and sixteen colors were used in different trials to produce easy and difficult discrimination respectively.

If the color frequency distribution affects subjective experience of difficult color discrimination rather than the number of colors, the same results as in Experiment 1 would be observed in Experiment 3, but not in Experiment 4. Whereas, if the number of colors, rather than the color frequency distribution, affects the experience of difficult color discrimination, the same results as Experiment 1 would be observed in Experiment 4, but not in Experiment 3. If both of the manipulations are responsible for the effects in Experiment 1, then both Experiments 3 and 4 will produce effects similar to Experiment 1, although the effects might be weaker in Experiments 3 and 4.

Method

Participants

Sixty-four undergraduate students who did not participate in the previous experiments were recruited (mean age = 20.0, male = 12) and nine of those participants whose accuracies were lower than the criterion (70%) were replaced. Half of the participants were assigned to the easy search experience group and the other half were assigned to the hard search experience group.

Stimuli and Procedure

There were no 8-color search trials for easy search experience. Instead, there were two types of 16-color trials; a uniform frequency distribution for easy color discrimination and a non-uniform frequency distribution for difficult color

discrimination. In the uniform frequency distribution trials, all sixteen colors were equally represented in the distractor color pool. Each color, including the two target colors, occupied 6.25% of the distractor color pool. For the non-uniform frequency distribution trials, the same 16-color trials that were used in Experiment 1 were used again. Thus, the only difference between the uniform 16-color trials and the non-uniform 16-color trials was whether the distribution of sixteen distractor colors was uniform or not. The easy search experience group performed a search task with only uniform 16-color search trials. the hard search experience group performed the search task with uniform 16-color search for half the trials and non-uniform 16-color search for the other half. These two types of 16-color search trials were randomly intermixed. Other stimuli and procedures were identical to those of Experiment 1.

Results

Error Rate and RT

The aim of Experiment 3 is to confirm whether the experience with difficult search trials created solely by non-uniform frequency distribution alters search strategy for the hard search experience group. Analogously to the previous experiments, the uniform 16-color search trials that both experience groups performed were used to compare the two groups, so that any differences found in the comparisons could not be attributed to differences in the stimulus.

The first interest is to ensure that the manipulation of frequency distribution actually makes search difficult. Repeated-measure ANOVAs with factors of target presence and search trial type were performed on the error rate and RT measures within

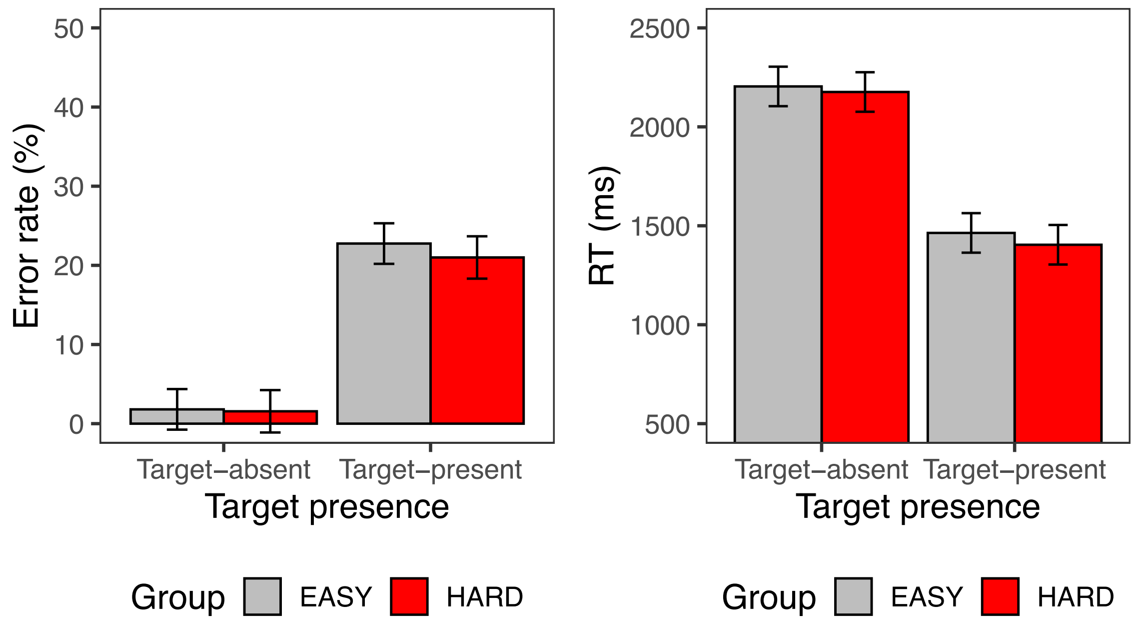

Figure 11. Mean error rate (left) and RT (right) for the easy search experience group (gray) and the hard search experience group (red) in Experiment 3. Only uniform 16-color search trials from both groups were included in the statistical analyses and presented here.

the hard search experience group. The error rate was higher when a target was present than absent, $F(1, 31) = 135.332$, $p < .001$, $\eta_p^2 = .629$, but there was no significant main effect of trial type, $F(1, 31) = 0.175$, $p = .678$, $\eta_p^2 < 0.001$, and no interaction, $F(1, 31) = 0.001$, $p = .967$, $\eta_p^2 < .001$. For the RTs, the participants responded significantly faster when the target was present than absent, $F(1, 31) = 144.023$, $p < .001$, $\eta_p^2 = 0.496$. More importantly, as expected, the RTs were also faster for the uniform 16-color search trials than the non-uniform 16-color search trials, $F(1, 31) = 34.151$, $p < .001$, $\eta_p^2 = 0.017$, suggesting that it was more difficult to conduct the non-uniform 16-color than the uniform 16-color trials as expected. There was no interaction, $F(1, 31) = 0.583$, $p = .450$, $\eta_p^2 < 0.001$.

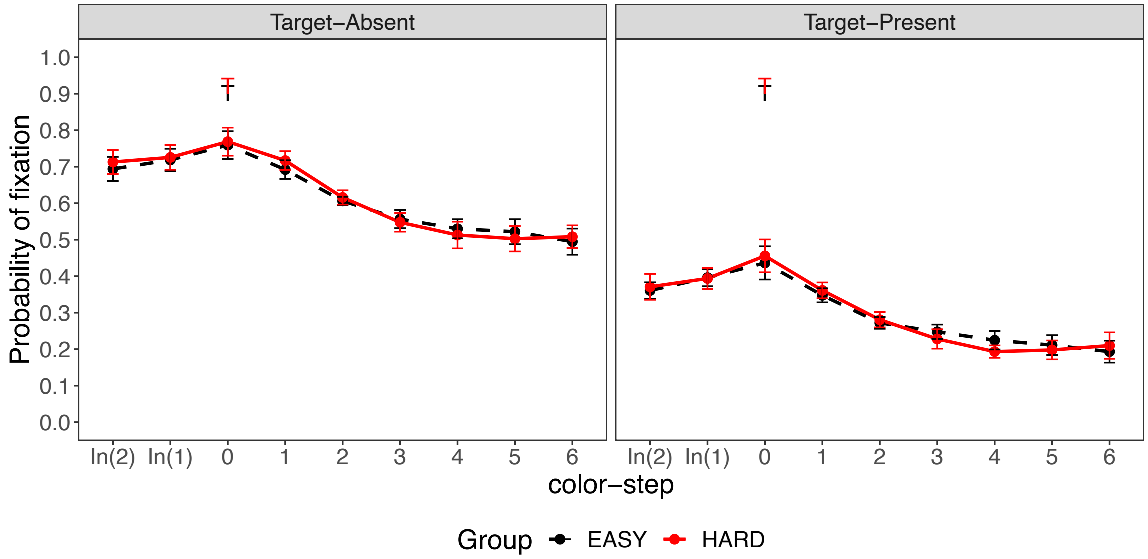

Figure 12. Probability of fixation for the target absent (left) and target present trials (right) in Experiment 3. Because we compared the fixation rate for all sixteen colors between the groups, there are more color-steps in Experiment 3 than previous experiment.

The behavioral pattern similar to that observed in Experiment 1 suggests that the manipulation of the color distribution indeed affected target discrimination, leading to a difference in search performance between the search types. The next question is whether the experience with the non-uniform 16-color search trials was difficult enough to cause the hard search experience group to adopt a search strategy of less color guidance. To address this question, the behavioral data from only the uniform 16-color search trials from both groups were submitted to a mixed-factor ANOVA with factors of group and target presence. As shown in Figure 11, there were main effects of target presence in both error rate, $F(1, 62) = 247.029$, $p < .001$, $\eta_p{}^2 = 0.651$, and RT, $F(1, 62) = 238.404$, $p < .001$, $\eta_p{}^2 = 0.379$, indicating that the participants made more errors and faster responses when the target was present than absent. Neither the main effect of group nor the interaction was significant, *ps* > .4.

Probability of Fixation

For the probability of fixation, separate mixed-factor ANOVAs were performed with factors of Group and outer Color-step (i.e., color-step 0, 1, 2, 3, 4, 5, and 6) for target-absent and target-present trials. The fixation rates decreased systematically as color-step increased in both target-absent and target-present trials, $F(6, 372) = 101.877$, $p < .001$, $\eta_p^2 = 0.193$, and $F(6, 372) = 89.566$, $p < .001$, $\eta_p^2 = 0.319$, respectively. There was neither a main effect of group nor an interaction, *ps* > .4. Unsurprisingly, the same patterns were found when the fixation rate for the intervening colors were submitted to separate mixed-factor ANOVAs with the identical factors of color-step (-1 and -2) and group for the target-present and target-absent trials. The fixation rate was significantly higher when the color-step was closer to the target color, $F(1, 93) = 5.763$, $p < .05$, $\eta_p^2 = .006$ and $F(1, 93) = 4.375$, $p < .05$, $\eta_p^2 = .012$, in the target present and absent trials respectively, but the main effects of group and interactions were not significant, *ps* > .5. Even though RT was slower for the non-uniform 16-color than the uniform 16-color

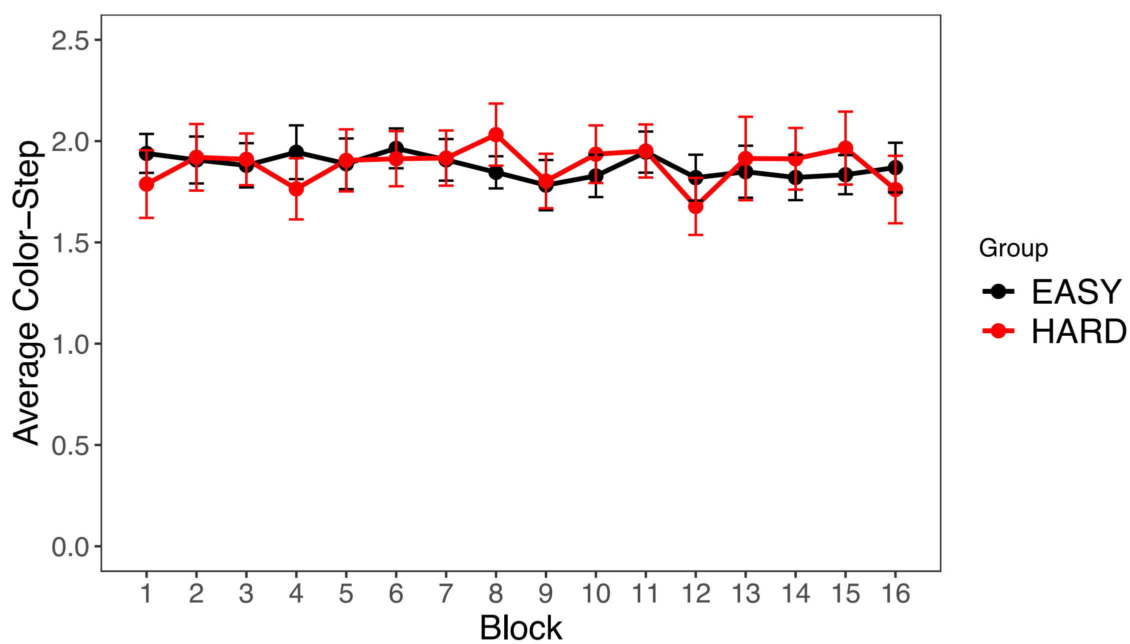

Figure 13. Average Color-Step values as block continues in Experiment 3. Only uniform 16-color search trials were included in the analysis.

search trials, there was no enough evidence that the two search experience groups used different search strategies for the uniform 16-color search trials. This result may indicate that the manipulation of frequency distribution by itself is not enough to make the hard search experience group feel the difficulty of the color guidance and change their search strategy.

Mean Color-Step Across Trials

The mean color-step was calculated for each of the 16 blocks. There were three missing cells in the data for two participants because the error trials and 16-color trials were excluded: the 3rd and 8th blocks for one easy search experience participant and the first block for one hard search experience participant. In order to fill these cells, the mean of the two neighboring cells was used for the participant in the easy search experience group and the value of color-step in the second block was used for the participant in the

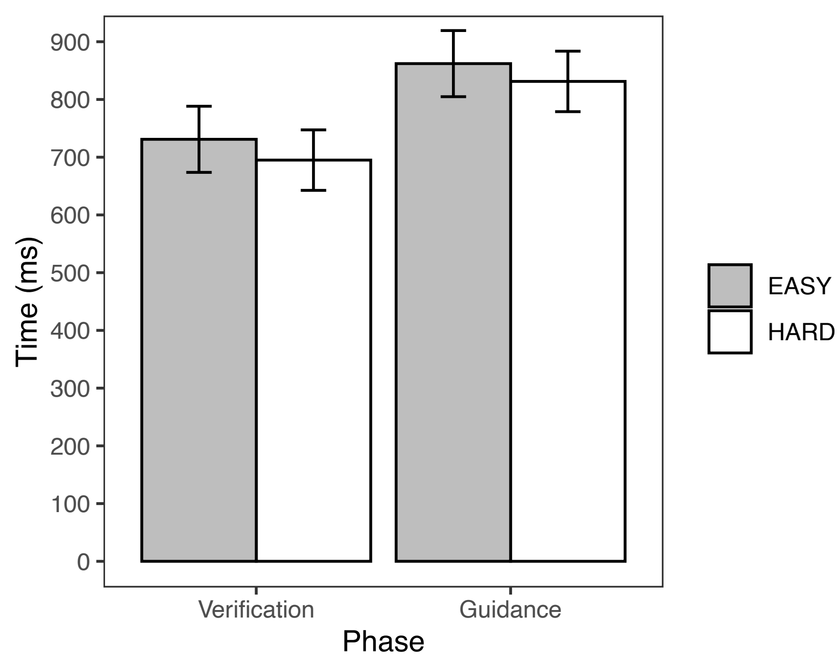

Figure 14. Mean time for Target Verification and Attentional Guidance phases in Experiment 3.

hard search experience group. As is depicted in Figure 13, there was no meaningful difference between the groups. None of the statistical results reached significance, *ps* > .2

Attentional Guidance and Target Verification Times

As in the previous experiments, the RTs in the correct target-present trials were divided into two phases: attentional guidance and target verification (Figures 14). A mixed-factor ANOVA with factors of Phase and Group was conducted. The main effect of Phase was significant, $F(1, 62) = 24.684$, $p < .001$, $\eta_p{}^2 = .092$, but the main effect of Group and the interaction between the Phase and Group did not reach significance, *ps* > .5.

Discussion

Experiment 3 aimed to test whether the manipulation of the frequency distribution of the distractor colors contributed to the weak color guidance observed in Experiment 1. Here I found a gradual decrease in fixation rate as the distractors' colors with rising dissimilarity to the target color, which is consistent with previous studies of visual search using the identical paradigm (Cave, Menneer, Nomani, Stroud, & Donnelly, 2018; Menneer et al., 2012; Stroud et al., 2012). However, I could not find evidence that experience with nonuniform color distribution by itself was enough to impair color guidance for the hard search experience group.

EXPERIMENT 4

Introduction

Experiment 4 maintains a consistently uniform distribution of distractor colors while manipulating the number of possible distractor colors between the easy and the hard discrimination trials. Considering the results of Experiment 3, two possible results are expected. If the decrease in search guidance caused by the subjective experience with difficult target discrimination is triggered purely by the manipulation of the number of colors, then the results of Experiment 4 should be the identical to those of Experiment 1. That is, the color guidance for the hard search experience group will be weaker than for the easy search experience group. On the other hand, if the decrease in color guidance was the result of an interaction between the two manipulations in Experiment 1, then the results of Experiment 4 should be the similar to those of Experiment 3; that is, no group difference in search guidance and consequent behavioral performance.

Methods

Participants

Thirty-two undergraduate students were recruited and assigned in the hard search experience group (mean age = 19.4, male = 8), and three of those participants were replaced for low accuracy.

Stimuli and Procedure

Analogously to Experiment 3, there were two types of color discrimination trials, but in this case, the difference between trial types was defined with respect to the number of colors being used. For difficult color discrimination trials, all sixteen colors were used, and these were distributed equally in the distractor color pool just as in the uniform 16-color- search trial in Experiment 3. For the easy color discrimination trials, eight colors were used, and these colors were distributed equally in the distractor color pool, just as in the 8-color search trials of Experiment 1 (i.e., uniform 8-color search trial). The easy search experience group included only these uniform 8-color search trials. The stimuli and procedures for this group were identical to those in the easy search experience group of Experiment 1, and thus the data from that group were used. The hard search experience group performed the search task with the uniform 8-color search trials for one half of their trials, and the uniform 16-color search trials for the other half. Except for these changes, all stimuli and procedure were identical to Experiment 1.

Results

The results below include data from the easy search experience group in Experiment 1 and newly collected data from the hard search experience group in

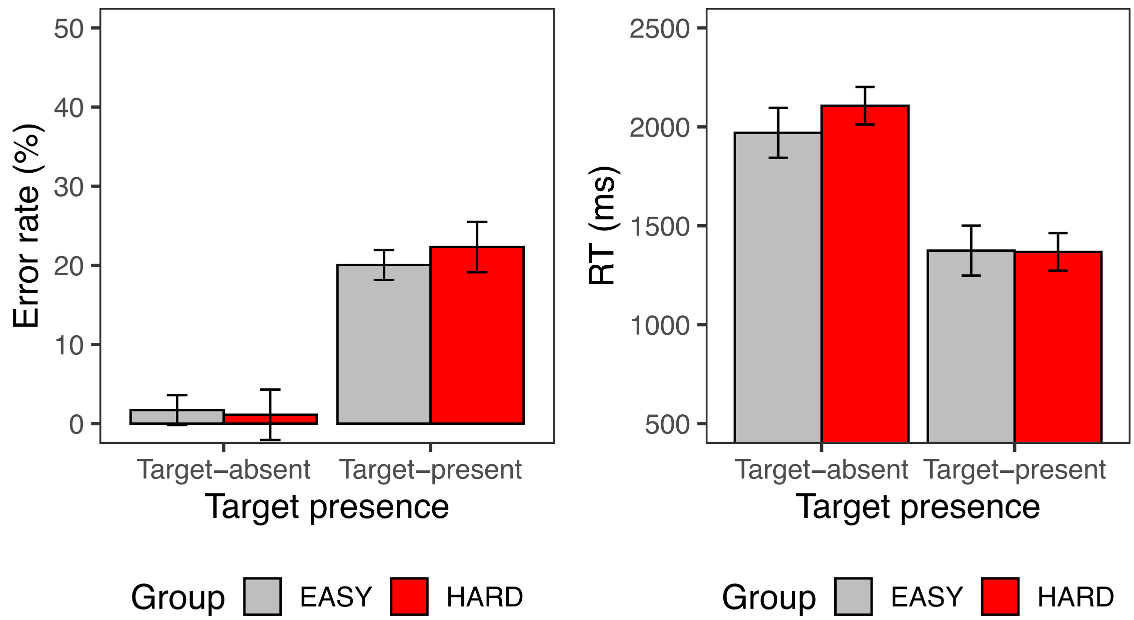

Figure 15. Mean error rate (left) and RT (right) for the easy search experience group (gray) and the hard search experience group (red) in Experiment 4. Only uniform 8-color search trials from both groups were included in the statistical analyses and presented here.

Experiment 4. Just as in previous analyses, the difficult color discrimination trials (that is, the uniform 16-color search trials) were excluded from the hard search experience group to avoid the confounding issue of the physical difference in the search arrays between the two type of discrimination trials.

Error Rate and RT

The behavioral data from the 8-color-uniform search trials for the two groups were subjected to mixed-factor ANOVAs with a within-subject factor of Target Presence and a between-subject factor of Group. In both error rate and RT (Figure 15), the main effects of Target Presence were significant, $F(1, 62) = 237.236$, $p < .001$, $\eta_p{}^2 = 0.646$ and $F(1, 62) = 237.236$, $p < .001$, $\eta_p{}^2 = 0.646$, showing a higher error rate and slower RT for

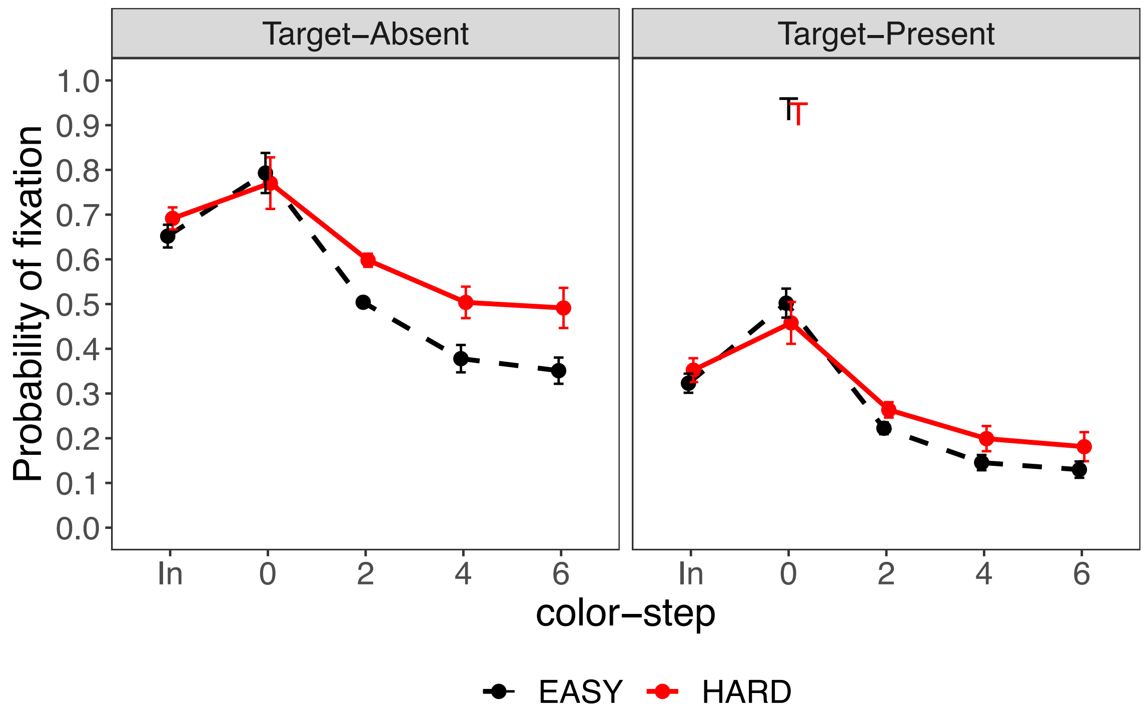

Figure 16. Probability of fixation for the target absent (left) and target present trials (right) in Experiment 4.

the target-absent than target-present trials. However, none of other main effects or the interactions reached a significant level, *ps* > 1.

Probability of Fixation

The fixation rates from Experiment 4's hard search experience group and Experiment 1's easy search experience group are shown in Figure 16, separately for target-absent and target-present trials. The graph clearly shows that the fixation rates of the hard search experience group higher than those of the easy search experience group for the higher color-step values. Along with the significant main effect of Color-Step, $F(3, 186) = 164.420$, $p < .002$, $\eta_p{}^2 = .400$, the main effect of Group, $F(1, 62) = 4.799$, $p < .05$, $\eta_p{}^2 = .054$, reflects the effect of experience with the uniform 16-color search trials on target-absent fixation rate. The hard search experience group fixated more frequently

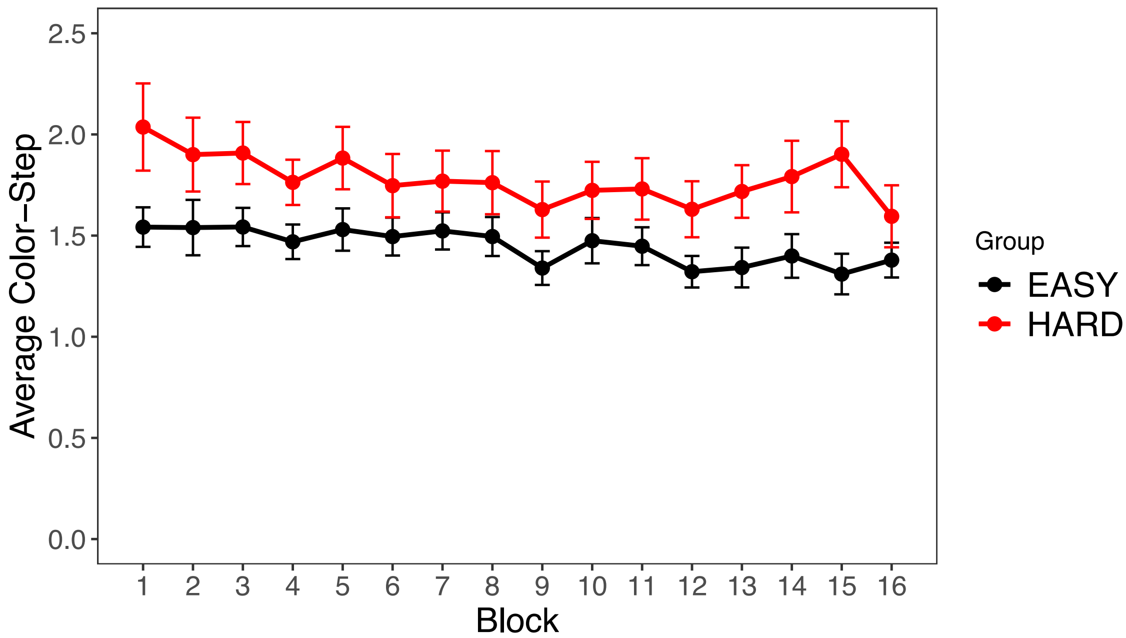

Figure 17. Mean Color-Step across blocks in Experiment 4.

to distractors than the easy search experience group did. Finally, the interaction of Group and Color-Step of outer colors was significant, $F(3, 186) = 8.187$, $p < .001$, $\eta_p^2 = .032$, indicating that the difference of fixation rates between the groups increased as the distractors' colors differed more from the targets' colors. As Figure 16 shows, both groups' fixation rates were very similar for the target colors (color-step of 0), but the hard search experience group fixated more to distractors than the easy search experience group at the color-step of 2, and this gap was bigger at the color-steps of 4 and 6. Similar but weaker results were found in the target-present trials. There was no significant main effect of Group, $F(1, 62) = 1.485$, $p = .227$, $\eta_p^2 = .014$. The main effect of Color-Step, $F(3, 186) = 237.059$, $p < .001$, $\eta_p^2 = .601$, and the interaction of Group and Color-Step were significant, $F(3, 186) = 5.758$, $p < .001$, $\eta_p^2 = .035$.

In addition, there were no significant differences between the groups for the intervening colors in both target-absent trials, $t(61.965) = -1.162$, $d = -0.290$, or the

target-present trials, $t(61.993) = -1.177$, $p = .243$, $d = -0.294$, and there were also no significant differences for the actual target that was presented as T in the figure, $t(48.333) = 0.587$, $p = .559$, $d = 0.146$.

Mean Color-Step Across Trials

As clearly demonstrated in Figure 17, the average color-step value was significantly higher for the hard search experience group than the easy search experience group, $F(1, 62) = 13.745$, $p < .001$, $\eta_p{}^2 = .167$, illustrating the less efficient search guidance for the participants who experienced the difficult target discrimination trials that were created solely by increasing the number of distractor colors. The main effect of Block was also significant, $F(1, 62) = 23.973$, $p < .001$, $\eta_p{}^2 = .033$, indicating a decrease in mean color-step values as the experiment progressed, suggesting a general practice effect. The interaction between the Group and Block was not significant, $F(1, 62) = 0.003$, $p = .952$, $\eta_p{}^2 < .001$.

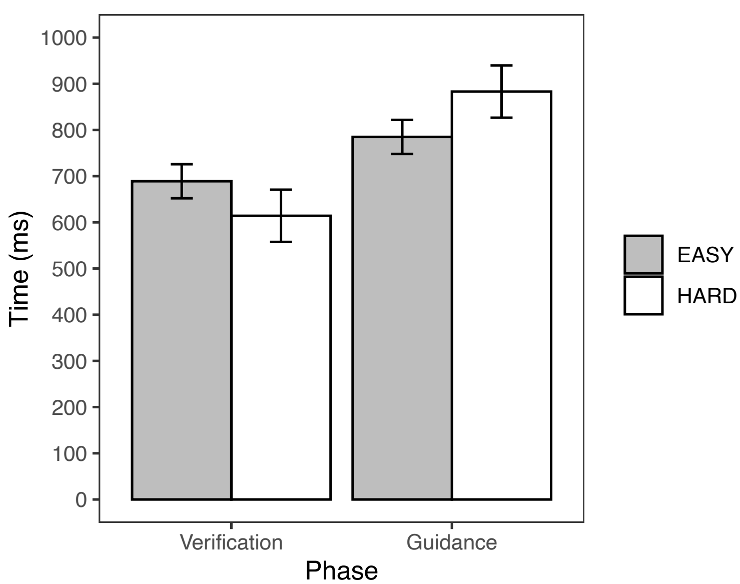

Figure 18. Mean time for Target Verification and Attentional Guidance phases in Experiment 4.

Attentional Guidance and Target Verification Times

The time required to complete each phase of the task was analyzed with a mixed factor ANOVA of the correct target-present trials with factors of Group and Phases. There was no main effect of Group, $F(1, 62) = 0.094$, $p = .759$, $\eta_p{}^2 = .001$, but a significant main effect of Phase, $F(1, 62) = 60.761$, $p < .001$, $\eta_p{}^2 = .212$, and the interaction between the Group and Phases factors was significant, $F(1, 62) = 13.655$, $p < .001$, $\eta_p{}^2 = .057$. As is illustrated in Figure 18, the attentional guidance took significantly longer for the hard search experience group than the easy group, $t(61.329) = -2.462$, $p < .05$, $d = -.564$, but there was no significant difference in target verification time between the easy and hard search experience groups, $t(61.066) = 1.528$, $p = .131$, $d = .371$.

Discussion

The main finding of Experiment 4 is that hard search experience group showed weaker reliance on color guidance than the easy search experience group. I found more frequent fixations to target-dissimilar colors and higher mean color-step values for the participants who experienced the difficult color discriminations. These results indicate that Experiment 4 successfully replicated the observation of Experiment 1, even though the current experiment only manipulated the number of colors rather than both the number of colors and frequency distribution of the colors.

The increase in the total number of colors seems to increase the search difficulty in two ways. First, as the total number of potential distractor colors is increased, the

similarity between distractors is decreased. Duncan and Humphreys (1989) found the search efficiency decreased as the distractor-distractor heterogeneity increased. Second, as more colors were included from the color ring, some of the distractors had colors very similar to the target colors (i.e., color step of 1), increasing the target-distractor similarity. Inefficient search among distractors with target-similar features has been observed in many previous studies of visual search (Duncan & Humphreys, 1989a; Nagy & Sanchez, 1990; Reijnen, Wallach, Stöcklin, Kassuba, & Opwis, 2007; Treisman & Gelade, 1980; Verghese & Nakayama, 1994; Wolfe, 1994). The high distractor-distractor heterogeneity and low target-distractor discriminability made the search difficult, and eventually the experience with these trials encouraged the participants to perform the search with less active color guidance, even when facing trials with relatively easily color discriminations.

In addition, I observed in the two phases analyses that the hard search experience group took a significantly longer time to guide the eyes to a target. There was a similar trend in Experiment 1, but it was not significant. This pattern might account for the higher fixation rate in the hard search experience group compared to the easy group. For participants in the hard group, their fixations wandered around the target-dissimilar distractors in a more undirected way, so that the eyes took more time to arrive at the target for the first time.

GENERAL DISCUSSION

In earlier studies, the participants' previous experience with a task has been shown to have a positive effect on search performance, often in the form of a practice

effect. As experience accumulates, observers acquire information about a target or surrounding distractors and create an optimal search template that helps to differentiate the two and rapidly orient attention to a likely target stimulus. The current study aims to examine the question of whether any type of experience can be beneficial, or whether certain experiences can impair performance. To answer this question, the present study focused on the experience of difficult color discrimination and tested whether this experience alters an observer's search strategy and if so, what search strategy is adopted. One hypothesis was that observers who experience difficult color discriminations would take color information as a primary source of search guidance, and rely more on color information to overcome the difficult color discrimination. Alternatively, this experience might encourage the participants to rely less on color information due to the difficulties in making the color discriminations that are required to select probable targets. The results of the experiments here seem to support the latter hypothesis under the appropriate level of difficult search experience.

Across the four experiments, I found a consistent eye movement pattern showing that participants used target color information to guide search regardless of whether they experienced the difficult target discrimination or not. The participants were more likely to fixate to the target-similar colors and less likely to fixate to the target-dissimilar colors, replicating the previous experiments used the similar T/L search paradigm (Cave, Menneer, Nomani, Stroud, & Donnelly, 2018; Menneer et al., 2019, 2012; Stroud et al., 2012, 2018). This guidance of attention toward target colored stimuli is in the same line with visual attention theories that claim the cognitive ability to guide attention toward a stimulus that shares target features (Desimone & Duncan, 1995; Wolfe, 1994; Wolfe et

al., 2003). The high fixation rates to the target-similar colors indicate that preference for colors similar to the target.

Indeed, there is a strategic reason for active color guidance other than the nature of the color feature dimension in the current experimental setting. Prioritizing target color can filter out a significant number of distractors in a search display. Suppose that participants created a liberal search template including all colors that were within two color-steps of a target on the color ring. For example, if the target colors are 7 and 11, the search template would include the colors from 5 to 13 in Table 1. In 8-color search trials, they could filter out 39.6% of distractors, because their colors were at least 4 color-steps away from the target colors, and thus participants could easily orient attention toward the rest of the candidates, which were more likely to be the target. Filtering can become more efficient as the search template becomes more selective in the color dimension. On the other hand, the target shape (i.e., T) in these experiments could be presented in one of four different orientations (upright, left-oriented, right-oriented, and inverted) and the distractors shared vertical and horizontal line features with target. This high target-distractor similarity in shape would not induce the participants to guide search preferentially by shape information. Instead, we would expect participants to utilize the shape information to scrutinize a search item once it was fixated.

Based on this logic, the current finding in Experiment 1 is somewhat surprising. The level of color guidance differed depending on experience with difficult color discrimination. Participants for whom the distractor colors were sometimes easily confusable with the target colors showed more fixations that were not guided by color than other observers who always searched for the target among distinctive distractors. It

should be noticed that the frequent unguided fixations of the hard search experience group were observed in the search arrays with only distinctive distractors, which were physically identical to what the easy search experience group saw. These results support the idea that the different experience of color discrimination leads to different search strategies between the groups, and furthermore that it discouraged participants from adopting an efficient search strategy; that is, active color guidance. The experience of difficult color discrimination may encourage the participants to think that the color is not so useful in finding a target, leading them to allocate fewer attentional resources to the color dimension within the search template. This belief might be more enhanced in Experiment 1, in which the target colors varied from trial to trial, which is known as another important factor of difficult search (Goldstein & Beck, 2018; Wolfe et al., 2003). Thus, despite the sacrifice of efficiency, in reality, the combination of accumulated experience of difficult color discrimination and varying target colors probably urges the hard search experience group to assign less attentional weight to color in guiding search.

The results of Experiment 2 confirmed and expanded the conclusions of Experiment 1 by showing that that there was no group difference in terms of search guidance when the target information can be moved to Long-Term Memory due to the consistent targets. As a search with the identical target(s) is repeated, the target representation moves from Visual Working Memory (VWM) to Long-Term Memory (LTM) (Carlisle et al., 2011; Woodman et al., 2013). Once the target representation is stored in LTM, the search can be more efficient than when it stays in VWM (Goldstein & Beck, 2018). These advantages of LTM representation could compensate for the unpleasant experience of difficult color discrimination, and thus encourage the hard

search experience group to continue to guide search by color as much as the easy search experience group.

These results showing that observers sometimes adopted an inefficient search strategy seem inconsistent with many other studies arguing that observers adopt an efficient strategy for better search performance. The particular feature dimension that can be used most effectively to distinguish between a target and distractors is strategically weighed more heavily in attentional resource allocation (Alexander et al., 2019; Bravo & Farid, 2012, 2016; Lee & Geng, 2019). Even within a single feature dimension, the precision of a target representation can be optimally adjusted to easily eliminate the confusable distractors that have feature values very similar to the target but slightly different (Bravo & Farid, 2016; Navalpakkam & Itti, 2007; Won, Haberman, Bliss-Moreau, & Geng, 2020). One might argue that less reliance upon color is indeed an efficient search strategy in Experiment 1 because the color is not an effective feature at least in half of the trials (i.e., 16-color search trials). However, this argument faces two problems. First, observers lose the advantages of color guidance in the other half of the trials (i.e., 8-color search trials) in which distractors have colors easily distinguishable from the targets. Second, even in the difficult search trials (i.e., 16-color search trials), color can still reduce the number of distractors that must be fixated. 58.1% of search items have target colors or target-similar colors (1 color-step). Instead of looking at all ten search items to verify whether its shape is a T or L, color can restrict attention to around six items that have a target or target similar color. Thus, less reliance on color is not an efficient search strategy for either type of search trial.

The current finding is more compatible with the recent idea that observers often do not adopt the most effective search strategy, and instead choose a sub-optimal strategy that can conserve cognitive resources (Irons & Leber, 2018; Menneer et al., 2019; Stroud et al., 2018). Some of Stroud and his colleagues (2018)'s experiments used the same general T/L dual target search paradigm that is used in the experiments presented here, but their participants were informed that the target color can be any of eight different colors. Their results showed a weak and rather ineffective level of color guidance. Cave and his colleagues (2020) extended this finding by comparing fixation patterns between different search tasks; one is the same T/L search used here, and the other is a pure-color search in which a target was defined only by color, so that the shape information was not relevant in identifying a target. Their pure-color participants had to rely upon color to identify a target for the efficient search guidance, and this apparently also prompted them to use color information to guide fixations as well. As a result, the unguided fixations that selected target-dissimilar colors and the spatially sequenced fixations in a row within the search array (which they called "step-paths") were significantly less frequent in pure-color search than in color-T/L search. This pure-color search performance demonstrates that participants are able to guide search by color as a very efficient search strategy, a less efficient approach relying on shape information to identify targets was often used during T/L search, and it resulted in many unguided fixations. The experience with difficult color discrimination has an effect similar to the alternative shape information in their study. The hard search experience group in Experiments 1 and 4 could have allocated more cognitive resources to color guidance. However, instead of doing so, the hard

search experience group made less use of active color guidance even though it led to an extra cost in eye movements.

In addition, Experiments 3 and 4 extended our findings and provided more specific information about the factors affecting search guidance. Only the number of possible distractor colors affected the efficiency of the search strategy; the distribution of colors by itself had no measurable effect. These comparisons indicate that it is not just any difficult discrimination that will encourage participants to lower their level of search guidance; a specific level of difficulty in color discrimination is necessary.

If the lower reliance of color guidance is the consequence of strategic choice, then when does it start? The results of average color-step show that the color guidance does not change much as a function of time (blocks). This suggests that this strategic selection for color guidance is set up quite early, perhaps, within initial 16 trials. This rapid setting is also observed in another study (Navalpakkam & Itti, 2006) although their study focused on the precise search template over time. However, the current study was not specifically designed to track changes in guidance over time. Each block of trials for each participant comprised different numbers of the two trial types. Because the 16-color search trials (or nonuniform 16-color trials in Experiment 3) and 8-color search trials were randomly intermixed across all the trials for a given subject, the number of 16-color search trials within each block was highly likely different in each block. Some hard search experience blocks could have more of this trial type than others, making it difficult to directly compare performance across participant groups.

My findings can broaden our theoretical understanding of visual attention. Many visual attention theories have focused on stimulus-driven and goal-driven attention.

Several recent theories suggest history-driven attention (or selection history) as the third factor (Awh et al., 2012) that can influence attentional selection. Even though there is a general understanding that previous experience can affect attention, only certain effects of this sort have been demonstrated, such as the automatic attentional orientation that is formed by association between a stimulus and a reward (see review by Failing & Theeuwes, 2017) or by the exposure of a recent visual stimulus (Maljkovic & Nakayama, 1994, 1996). However, the current findings demonstrate a very different way in which previous experience affects search performance. They suggest that experience with difficult color discrimination discourages color guidance in visual search, leading to search that is less efficient than it could be. Also, this shift of search strategy does not occur for every increase in difficulty; it only occurs when participants experience a specific level of difficulty.

CHAPTER 3

INTRODUCTION

Visual selective attention allows us to prioritize a task-relevant stimulus and to suppress task-irrelevant stimuli that potentially cause interferences in a search that is filled with numerous stimuli from simple features to more complex objects. The deployment of visual attention on a visual field is determined by several mechanisms. The bottom-up attention control operates to a stimulus that is more salient than its neighbors and the top-down attention control operates to a stimulus that matches the current goal. Selection history can also facilitate to orient attention to the stimulus that had been attended regardless of its salience or the relevance to the current goal (Awh et al., 2012; Theeuwes, 2018). Relative to these three mechanisms, a search strategy has been overlooked as a critical factor to guide attention in a certain way. The strategy has been used as inclusive term. It has been considered as the part of top-down attention control (Bacon & Egeth, 1994; Kiss, Grubert, & Eimer, 2013; Sobel & Cave, 2002) or a confounding factor to explain individual variations in performance (Schunn & Reder, 2001; Sternberg & Grigorenko, 1997) rather than an independent research topic *per se*. Although many attention theories have explained well in describing how these mechanisms interplay and determine the orientation of attention to a particular stimulus over others, it is still open question of how that mechanisms can be affected by individual's strategy.

Recently, there have been attempts to understand how the deployment of attention is affected by a specific strategy and what motivates that strategy to be built (Irons & Leber, 2020; Proulx, 2011). Some of the attempts have demonstrated that target relevant feature can be strategically prioritized in a complicated search task, leading the efficient search performance (Kiss, Grubert, Petersen, & Eimer, 2012), but other studies have found that the chosen strategy was not always ideal to cause the most efficient attentional control (Irons & Leber, 2018, 2020). For instance, Irons and Leber (2018) showed that observers preferred to adapt the suboptimal search strategy which was not the ideal in terms of search performance, but it reduced subjective cognitive efforts compared to the optimal search strategy. Not only the subjective cognitive efforts but previous search experience also encouraged to select the inefficient search strategy (Cave et al., 2020; Stroud et al., 2018).

Experiments of Chapter 2 has focused on the effect of specific experience of color discrimination on search guidance and found evidence that a certain experience can discourage the participants from adopting an efficient search strategy. In this task, the participants were required to search for either of two targets (i.e., colored Ts) amongst distractors (i.e., colored pseudo-Ls) and respond whether the target was present or not. When search targets were varied on each trial (Experiment 1), the participants who experienced difficult color discrimination were less likely to rely on target color information to guide search compared to other participants who did not have this experience, even though active color guidance could significantly reduce the number of distractors that are inspected. The consequence of this inefficient search strategy was reflected by the frequent unguided fixations to the target-irrelevant distractors. On the

other hand, when the search targets were consistent, the participants with the difficult color discrimination relied on the color information to guide search just as much as the participants without the difficult search experience did. Taken together, these results indicate that the participants were more reluctant to use color information to guide search when it was necessary to revise the target information on every trial. However, with consistent targets, participants could avoid the extra cognitive burden required to revise the target information and could expect to receive the advantages of a Long-Term Memory on search processes. Without this extra cognitive burden, participants are more likely to continue using color to guide search. With consistent target colors, the participants' active use of the target colors to guide search is unaffected by their experience with difficult color search.

However, in the experiments of Chapter 2, the target was defined by both color and shape features. In order to encourage participants to guide by target color information, the shapes of target and distractors were very similar (i.e., "T" vs. pseudo-"L") and each display item was randomly rotated. However, it was impossible to completely ignore the shape to complete the task. The participants had to confirm the shape of a search item because there were some distractors with the same color as the target (i.e., a pseudo "L" with a target color). Although the actual results demonstrate that both groups used color to guide search, at least to some extent, it was possible for participants to complete the search by ignoring the target colors but by focusing on the target shape to identify the target. The use of shape information in Experiments in Chapter 2 gives participants a way to confirm the target's identity once it has been fixated. This possibility of identifying the target purely by shape may allow the hard

search experience group to rely less upon the target color information and more upon the target shape information.

This alternative explanation raises a question: Would observers use a similar search strategy if they are forced to use only color information and not shape information to identify targets? To test this question, the two experiments used an experimental design that was very similar to the previous experiments, except that targets and distractors were defined only by color rather than a conjunction of color and shape features. The shapes of both targets and the distractors were the same (i.e., "T") but their colors were different. Therefore, only color information is available to identify a target.

Cave and his colleagues (2020) investigated the effect of relevant target features on search performance in a similar experimental setting. They found relatively higher error rates when participants were forced to use color only (i.e., the pure-color search condition) compared to when they were allowed to use both color and shape information (i.e., color-T search) in a dual-target search task (Experiment 1 in Cave, et al., 2020). More importantly, participants were much less likely to fixate distractors that were dissimilar to the targets in the pure-color search condition than the color-T search condition. These results indicate that the observers were able to use only color to guide search and identify targets, and also that guidance purely by color is substantially efficient for dual-target search.

The purpose of the present study is to examine whether and how the experience with difficult target color discrimination affects search strategy when only color is available for search processes and there is no alternative shape information that could be used. To test this, I compared the behavioral and eye movement data between two

participant groups with or without the experience of difficult target discrimination (i.e., a hard search experience group and an easy search experience group). Moreover, the previous experiments of Chapter 2 demonstrated that target consistency is a critical factor influencing search strategy, and so the effect of target consistency will be also tested across Experiment 5 (consistent targets) and Experiment 6 (varied targets) in this chapter.

It is possible that this experiment design will force the hard search experience group to adopt an even more efficient search strategy. They might create a very precise search template in color space to overcome the high color similarity between the targets and the distractors. If so, the hard search experience group will fixate target-dissimilar distractor colors less than the easy search experience group. Another possibility is that the combination of this new experiment design and difficult target discrimination could make search processes too difficult. As in Experiment 1, the hard search experience group might adopt an even more inefficient search strategy by relying much less on color guidance.

EXPERIMENT 5

Method

Participants

Sixty-four undergraduate students participated in the experiment for course credits (mean age = 19.9, male = 19). Every participant was tested for color blindness with the Ishihara test (Ishihara, 1972). None of the participants reported color-blindness and all participants reported normal vision or corrected-to-normal visual acuity. Nine participants who did not reach the criteria (70% of accuracy) were replaced.

Stimuli

The stimuli were identical to those in Experiment 2, except that all of the items in the search display were T's; there were no pseudo-L's. A colored "T" was used for both targets and distractors. The "T" shape was created by combining two identical bars with a size of 1.04° × 0.37°. Each stimulus color was selected from a set of perceptually distinguishable sixteen colors that were used in previous studies (Menneer et al., 2007, 2010). The sixteen colors were assigned numbers from 1 to 16 (see Table 2). By numbering them, it is easy to indicate which color was referred to. More importantly, I could use these numbers to index the similarity between the colors. As is depicted in Figure 1, the sixteen colors were arranged to form a color ring and each was numbered according to its position in order around the ring. For example, the color numbered 1 is next to the color numbered 2, and the color numbered 2 is next to the color numbered 3 and so on. By calculating the distance between the two numbers of specific colors on the ring, we can estimate the similarity between the two colors. This concept of "*color-step*" has been used as a measure of color dissimilarity in previous studies (Stroud et al., 2012, Cave et al., 2020, Menneer et al., 2018). For instance, the color 1 is 2 color-steps away from the color 3 but 4 color-steps away from the color 5, which indicates that the color 3 is more similar to the color 1 than the color 5.

Each experimental trial consisted of a target preview display and a search display. The target preview display presented two possible targets that were placed on the left and right side, each with a distance of 1.96° from the center of the display. The search array presented ten search items. Either nine distractors and one of the targets or ten distractors were presented for target-present and target-absent trials, respectively. The colors of the

two targets were always 4 color-steps away from one another on the color ring, so that they were easily distinguishable each other.

There were two types of search array trials: 16-color search trials for difficult color discrimination and 8-color search trials for easy color discrimination. For the difficult color discrimination, or 16-color search trials, all sixteen colors on the color ring were used for targets and distractors. Two of the colors that were four color-steps away each other were chosen for the target for a given participant and fourteen colors remained and were assigned to the distractor color pool. Each distractor color made up a specific proportion of the pool depending on its color similarity to the nearer target color. Colors close to the target color made up a large proportion of the pool while colors that were very different from the target made up a low proportion. Table 2 shows the sample distractor color pool when the target colors were 7 and 11. Because color was the only feature that defined the target, there were no distractors with the target colors; that is, a color-step of 0. The distractor colors with color-step of 1 (i.e., color 6, 8, 10, and 12) occupied a total of 58% of the pool (each 14.5%). The colors 5 and 13, which were not in between the two target colors and were similar to the target (color-step of 2), each occupied 15.8% (each 7.9%) and the colors 4 and 14 (color-step of 3) each occupied 10.6% (each 5.3%). The colors that were more than 3 color-steps occupied 13% of the pool (each 2.6%). Finally, the color that was placed in between the two target colors occupied 2.6%.

For easy color discrimination, or the 8-color search trials, eight colors that were equally spaced on the color ring were used. Two of the colors that were four color-steps away from each other were selected for the targets, and the six colors that remained were

assigned to the distractor color pool with roughly equal proportion. Because it was impossible to assign exactly equal frequency for all six colors, two colors of the six were randomly selected for a set of 32 trials, and each of these colors occupied 16.8% of the pool. The remaining four colors occupied 16.4% for each. I do not believe that this frequency difference (0.4%) causes a significant impact on biasing to particular colors because of random selection and the small frequency difference.

The ten search items in each stimulus array were each presented at one of four orientations (0°, 90°, 180°, 270°), and together they formed a circular array. Each item was 7.8° away from the center fixation, and 2.4° away from its neighbors. Even though all eye movements were recording during the task, only eye movements that fell within a set of regions of interest (ROI) were included for analysis. The ROIs formed an annulus over the search items with an outer radius of 9.72° and an inner radius of 5.88° from the center. The annulus was equally divided by ten slices into ten ROIs corresponding to each search item.

Procedure

A trial started with a drift correction for the eye tracker. Once participants fixated on the center dot, the experimenter pressed a key on their experimenter computer to manually begin the trial. After the offset of the drift correction, the target preview display was presented for 1000ms with two potential targets. After a 1000ms blank delay interval, the search array was presented and remained visible until the participants made a response. Either of the two targets was equally likely to appear as the target in the target-present search arrays. The target-present and target-absent trials were randomly intermixed. The participants were asked to press one of two buttons on a game pad as

accurately and as quickly as possible to report whether a target was presented or not. One of two different sound tones were provided depending on response accuracy at the end of each trial. Each participant was assigned one of sixteen possible target color pairs and these were consistent for that participant in the entire experiment, so all target colors were balanced across the set of 16 colors.

The participants were assigned to either of two search experience groups: the hard search experience group or the easy search experience group. Sixteen of the participants in the hard group performed 16-color search trials for one half of the trials and 8-color search trials with odd numbered colors for the other half. The other sixteen participants in the hard group performed 16-color search trials for one half of the trials and 8-color search trials with even numbered colors for the other half of the trials. The two trial types were randomly intermixed, and participants were not informed that there were different types of trials. The participants in the easy group performed either 8-color search trials odd numbered colors or 8-color search trials with even numbered colors.

Half of the participants in each group performed the additional verbal suppression task to prevent verbal encoding of the target colors (Baddeley & Hitch, 1974) for all trials in the experiment and the other half of the participants did not. However, it turned out there was no significant main effect of the verbal task and no interactions with the other factors in the probability of fixation, $ps > .1$, so that the two participant groups with and without the verbal suppression task were collapsed together for further analyses.

<u>Results</u>

The 8-color search trials that both experience groups conducted were used and compared to prevent any confounding from the disparity in discrimination. By doing so, the only difference between the two groups was whether they performed the 16-color search trials or not.

Error Rate and RT

As is illustrated in Figure 19, there was no obvious difference in behavioral responses from the experience with the difficult color discrimination. The error rates were submitted to a mixed-factor ANOVA with a between-subject factor of group (i.e., easy search experience group vs. hard search experience group) and a within-subject factor of target presence (i.e., target-present vs. target-absent). The error rate was significantly higher for the target-present trials than target-absent trials, $F(1, 62) = 76.139$, $p < .001$, ${\eta_p}^2 = 0.313$. There was no main effect of group, $F(1, 62) = 0.874$, $p = .353$, ${\eta_p}^2 = 0.008$, and no interaction, $F(1, 62) = 2.760$, $p = .101$, ${\eta_p}^2 = 0.016$. For the analysis of RT, only correct trials were included. The RT was significantly longer for the target-absent trials than target-present trials because of self-termination, $F(1, 62) = 63.622$, $p < .001$, ${\eta_p}^2 = 0.082$, and RT was numerically longer for the hard search experience group than the easy search experiment group (i.e., 1142ms and 995ms, respectively), but it did not reach significance, $F(1, 62) = 3.304$, $p = .074$, ${\eta_p}^2 = 0.046$. Also, there was no interaction between two factors, $F(1, 62) = 1.007$, $p =.320$, ${\eta_p}^2 = 0.001$. To sum up, there was no significant effect of difficult color discrimination

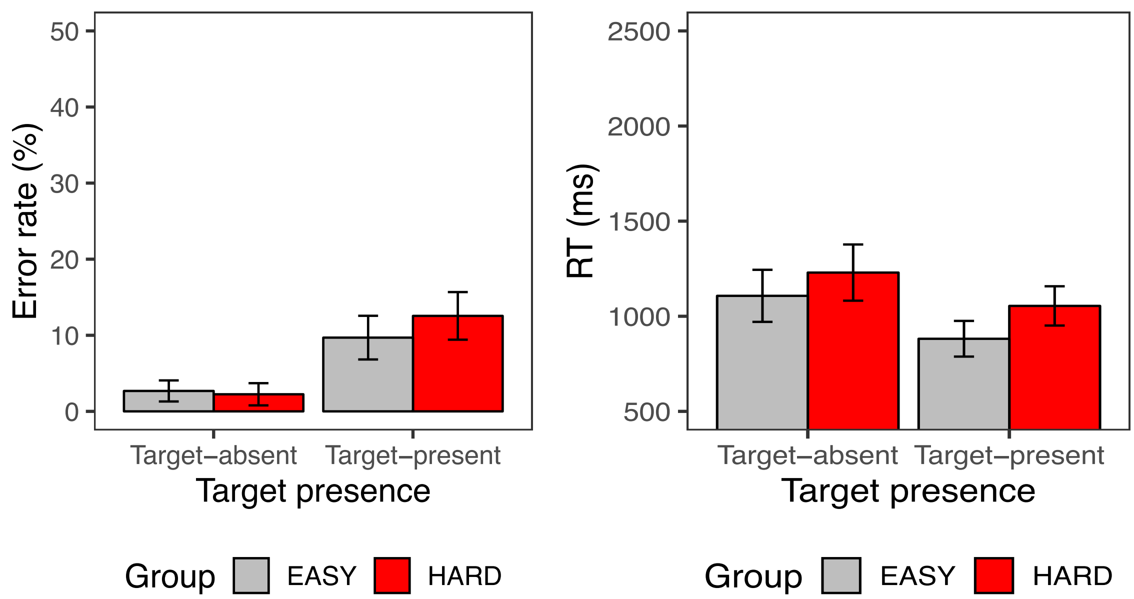

Figure 19. Mean error rate (left) and RT (right) for the easy search experience group (gray) and hard search experience group (red) in Experiment 5. Only 8-color search trials from both groups were included in the statistical analyses and in the graphs presented here.

experience on error rates and RTs, except for a marginally longer RT for the hard search experience group compared to the easy search experience group.

Probability of Fixation

Figure 20 shows overall probability of fixation on every color-step for both groups. Because there were no distractors with the target colors, there are no data points for 0 color-step in the figure. One noticeable difference between the groups can be found on the intervening color that is indicated by “In” on the figure: the fixation rate was higher for the hard search experience group than the easy group. This value reflects the fixation rate for the intervening color, which was the color between the two target colors on the color ring. A high frequency of fixations to the intervening color implies that that color is highly activated and involved as a part of search template when it comes to guide

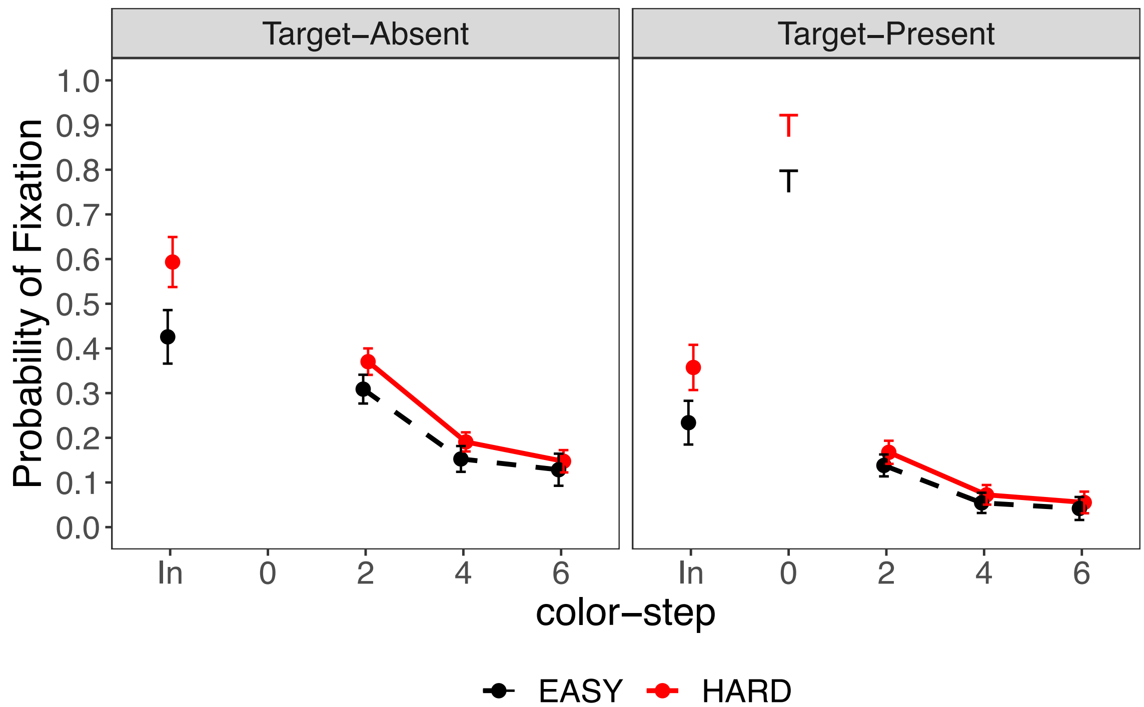

Figure 20. Probability of fixation in Experiment 5 (consistent targets). A black dashed line represents the easy search experience group, and a red solid line represents the hard search experience group. The digits on the x-axis indicate the color-step between the color of the fixated distractor and the nearer target color on the color ring. There is no data point on ”0” because there were no distractors with the target colors. On the x-axis, “In” stands for an intervening color placed between the two target colors on the color ring. In the Target-Present plot (right), a “T” represents the probability of fixation for the actual target.

search. An independent t-test confirmed this observation. The hard search experience group fixated more to the intervening color than the easy search experience group in the target-absent trials, $t(60.04) = 2.726$, $p < .01$, $d = 0.681$, and also in the target-present trials, $t(62) = 2.702$, $p < .01$, $d = 0.676$.

Despite of significant group difference in the intervening color, the fixation rates for the outer colors (i.e., color-step of 2, 4, and 6) do not seem different between the two experience groups. The probability of fixation data for these outer colors were submitted to mixed-factor ANOVAs with a between-subject factor of group (easy search experience

group vs. hard search experience group) and a within-subject factor of color-step (color-step of 2, 4, and 6) for target-absent and target-present trials separately. In the target-absent trials, the fixation rates gradually decreased as the color-step increased, indicating that the participants were less likely to fixate the distractors that were less similar to the target colors, $F(2, 124) = 179.946$, $p < .001$, ${\eta_p}^2 = 0.332$. This pattern of gradual decrease as a function of color-step was observed in the previous experiments and other studies (Stroud, et al., 2012; 2018) and indicates that the participants used color to guide search. As predicted above, there was no significant group difference, $F(1, 62) = 1.871$, $p = .176$, ${\eta_p}^2 = 0.024$, and no interaction between the group and the color-step factors, $F(2, 124) = 1.751$, $p = .178$, ${\eta_p}^2 = 0.005$. Similarly, in the target-present trials, there was no main effect of group, $F(1, 62) = 2.013$, $p = .161$, ${\eta_p}^2 = 0.020$, but the main effect of color-step was significant, $F(2, 124) = 75.759$, $p < .001$, ${\eta_p}^2 = 0.302$. There was no interaction between the two factors, $F(2, 124) = 0.397$, $p = .673$, ${\eta_p}^2 = 0.673$. In addition, the fixation rate for the targets was significantly higher for the hard search experience group than the easy search experience group, $t(47.42) = 2.42$, $p < .05$, $d = 0.604$.

The probability of fixation data revealed two interesting findings. First, experience with difficult search produced no difference in attentional guidance for the outer colors (i.e., color-step 2, 4, and 6), some of which were similar to one of target colors while others were relatively dissimilar to both target colors. However, difficult search experience did lead to a significant difference in attentional guidance to the intervening color, which was relatively similar to and equally close to both target colors. This difference was not found in the previous experiments in Chapter 2 or other studies with very similar experimental stimuli and procedures (Stroud et al., 2012; 2018). This

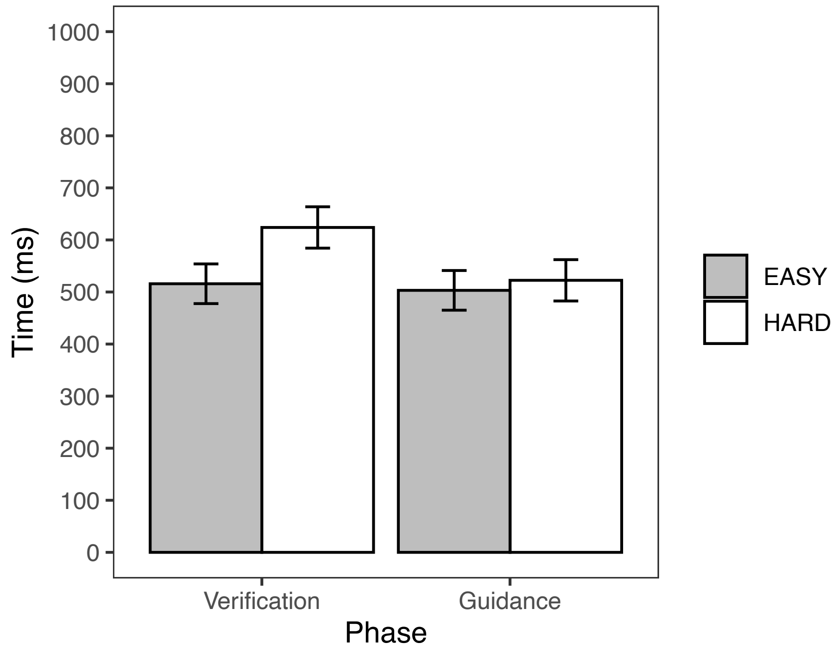

Figure 21. Mean time for attentional guidance and target verification in Experiment 5. Attentional guidance is the interval between the search array onset and the first fixation on a target (right) and target verification is the interval between the first fixation on a target and manual response (left).

pattern may suggest that in this search task the hard group applied a unique search strategy. The more frequent fixations to the intervening color suggest that the hard search experience group was more likely to create a continuum search template connecting two target colors at the edge of the search template and including the colors between them in color space, rather than creating a separate search template for each of the target colors.

Attentional Guidance and Target Verification

The difference between the two groups in the probability of fixation for the intervening color motivates further analysis to explore details of the search process. Previous studies with eye movement data suggested that a single search trial can be divided into multiple phases (Castelhano et al., 2008; Goldstein & Beck, 2018) and the

different search circumstances can influence the different phases independently. For example, Castelhano and her colleagues (2008) divided the search trial into two phases (i.e., attentional guidance and target verification) according to the time that the target was first fixated, in order to test the effect of typicality of a target on each phase. They found that if the target was a typical object in a category, it sped up the target verification phase, but not attentional guidance phase.

This analysis can provide evidence on which search phases are influenced by search experience when targets are defined solely by color. In the current analysis, search trials were divided into two phases by the first fixation to the actual target as in Castelhano et al. (2008). The attentional guidance phase is defined by the time interval between the onset of search array presentation and the first fixation to the actual target. The target verification phase is defined by the time interval between the first fixation to the actual target and the manual response.

Since the analyses require trials with the fixation on the target, only target-present trials with at least one fixation on the target were used for the analyses. The trials with incorrect responses were excluded. As is depicted in Figure 21, there is a hint of interaction between the experience group and phases. A mixed-factor ANOVA with a between-subject factor of group (easy vs. hard) and a within-subject factor of phase (guidance vs. verification) was conducted to confirm this observation. The main effect of group was not significant, $F(1, 62) = 2.762$, $p = .101$, $\eta_p{}^2 = .034$, and the main effect of phase was significant, $F(1, 62) = 8.952$, $p < .01$, $\eta_p{}^2 = .027$, suggesting that target verification time took longer than the attentional guidance time. More importantly, the significant interaction between the two factors, $F(1, 62) = 5.416$, $p < .05$, $\eta_p{}^2 = .017$,

revealed that the target verification time was significantly longer for the hard search experience group than the easy group, $t(60.704) = 2.047$, $p < .05$, $d = .511$, but there was no significant difference between the two groups in the attentional guidance time, $t(60.962) = 0.650$, $p = .517$, $d = .162$.

Discussion

The results of Experiment 5 showed that the experience with difficult target discrimination affected the form of search template and it caused performance cost. The hard search experience group fixated more to the intervening color than the easy search experience group did, indicating a higher level of activation for the intervening color. The relatively higher activation of the intervening color suggests a possibility of creating a continuum form of search template that covers a region within color space by including two target colors at the edge and the intervening color in the middle. This continuum search template may readily guide attention toward not only stimuli with the target colors but also to those with colors between them in color space.

Contrary to the fixation rate to the intervening color, the hard search experience group did not show the higher fixation rate for the other outer colors, including the outer colors that were 2 color-steps away from a target, even though these colors were just as similar to a target color as the intervening color. If the experience with difficult color discrimination raises overall activation of the target colors, the hard search experience group should show a higher fixation rate for the 2 color-step outer colors than the easy search experience group, just as the hard group showed more fixations for the intervening

color. The similar fixation rates across groups for the overall outer colors, including the 2 color-step outer color, rules out the possibility of an overall increase of activation around the target colors and instead suggests an increased activation of the intervening color, which together with the two target colors could form a unified color-range template to guide search.

The performance cost found in the target verification phase supports the idea of the range search template. Once participants fixated to a target, they needed to compare the search template and the external target stimulus. The intervening color contained in the range search template might have interfered with accurate comparison processing. This interference required extra time to separate the color of the fixated target from the intervening color and match it to one of the target colors within the range template. This comparison may have been easier and more straightforward in the experiments described in Chapter 2, in which participants were more likely to form two individual search templates, each representing one of the target colors.

To our surprise, I found no significant difference in the attentional guidance phase between the two groups. One might expect to observe a similar performance cost in guidance. The distractors with the intervening color would be likely to capture attention for the hard search experience group holding the range search template. One possible explanation is that even though the range search template readily assigned attention to the stimuli with the intervening color, attention was quickly withdrawn from it. A study conducted by Kiss, Grubert, and Eimer (2012) using electrophysiological evidence seems to support this possibility. In their Experiment 1, they measured and compared the amplitude of the N2pc, which is a marker of the selection of spatial attention, across three

conditions in which a singleton distractor shared either one, both or neither features of a color-size conjunction target. The large N2pc amplitude for singletons that shared at least one feature with the target was observed, indicating that feature of the distractor captured attention. Contrary to the electrophysiological evidence, their behavioral evidence demonstrated that interference occurred only when there was the singleton distractor that contained both target-defining features. They concluded that attention is initially guided toward stimuli containing any target feature, then rapidly withdrawn from nontarget objects that share some but not all features with the current target. In the current experiment, color was a sole target-defining feature dimension rather than a conjunction of features from two different dimensions, but it can be understood similarly. The hard search experience group may have guided attention to the colors that matched the color spectrum within the range template. However, once participants fixated to the intervening color, they were able to rapidly determine that this distractor did not adequately match either target color, and then withdrew attention. Whereas, once they fixated to the actual target, they started to compare the range target representation and actual fixated target, and it took more time because of the ambiguity of the search template.

In sum, the probability of fixation and target verification time together demonstrate that experience with difficult color discrimination encouraged the participants to create a range search template that included the two target colors at the two ends of the range, with the intervening color in the middle. This contrasts with Experiment 1, in which participants sometimes avoided color guidance, but when they did use color guidance, they were more likely to create two individual templates for the two target colors.

However, it is unclear whether the search strategy of the hard search experience group, which seems to favor of a single range representation encompassing the two target colors, would be observed when the targets vary from trial-to-trial. It might be possible to adjust two separate target representations into a single continuum search template only when target information is consistent so that it can be stored in Long-Term Memory. It is also possible that, in the more resource demanding search, the hard group would be less likely to build a continuum search template. In Experiment 6, I will push the hard search experience group harder by varying the targets from trial to trial and requiring them to store the target representation without the support of LTM.

EXPERIMENT 6

Introduction

In Experiment 5, the hard search experience group was more likely to create a range form of search template than the easy search experience group, which led to frequent fixations to the intervening color and longer target verification time. In Experiment 6, target colors change every trial, so that participants do not have the advantage of storing search templates in LTM. I believe that the change of target colors on every trial creates a critical cognitive burden and influences search strategy.

It is more demanding to store and update new target information on every trial in Experiment 6, compared to the previous experiment in which the participants can recycle the same target information over and over. The high cognitive burden from varying targets could induce the hard search experience group to create a single range search

template rather than two discrete search templates for the two target colors just as Experiment 5. Alternatively, the hard search experience group might abandon the strategy of a range search template and instead utilize two separate target templates, just as the easy search experience group did. Such a result might indicate that creation of a range template requires some assistance from LTM. If so, we would see similar results between the hard and easy search experience groups.

Method

Participants

Sixty-four participants who did not participate in any of the previous experiments participated for course credits (mean age = 19.7, male = 16). Only participants who had normal vision or corrected-to-normal vision were eligible to participate. The new manipulation of varying targets significantly increased the task difficulty. It was necessary to set up a new criterion for rejection because poor performance was likely due to the task difficulty rather than a low commitment to the task. Therefore, In Experiment 6, the search accuracy was considered only in the 8-color search trials, and participants whose accuracy was not above 70% were excluded and replaced for analyses. Under this new criterion, ten participants in the easy search experience group and fourteen participants in the hard search experience group were replaced.

Stimuli and Procedure

The experimental procedure was identical to that in Experiment 5, except for two changes. First, the target colors varied from trial to trial. Second, for the participants in

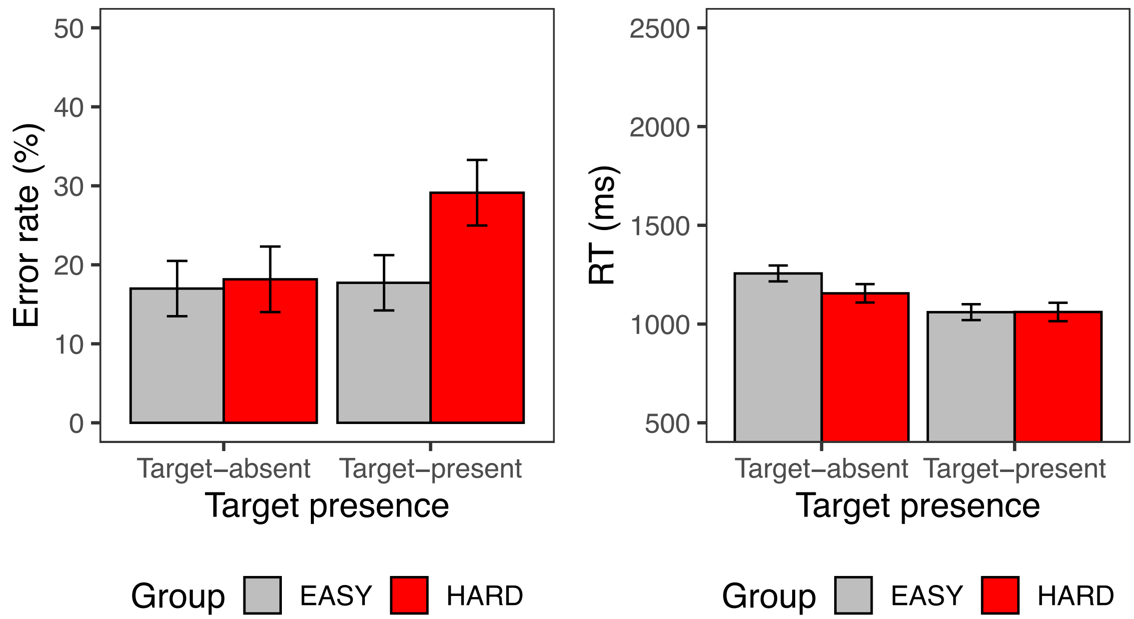

Figure 22. Mean error rate (left) and RT (right) for the easy search experience group (gray) and hard search experience group (red) in Experiment 6. Only 8-color search trials from both groups were included in the statistical analyses and presented here.

the hard search experience group, a quarter of their trials were 8-color search trials with even numbered colors, and a quarter were 8-color search trials with odd numbered colors. The other half of the trials, as in Experiment 5, were 16-color trials. Error rates, RTs, probability of fixation, and two phases were analyzed as in the analysis of Experiment 5.

Results

Error Rate and RT

Figure 22 shows the average error rates and RTs. The error rate was higher for target-present trials than target-absent trials, $F(1, 62) = 9.648$, $p < .01$, $\eta_p{}^2 = .089$ and for the hard search experience group than the easy, $F(1, 62) = 19.365$, $p < .001$, $\eta_p{}^2 = .102$.

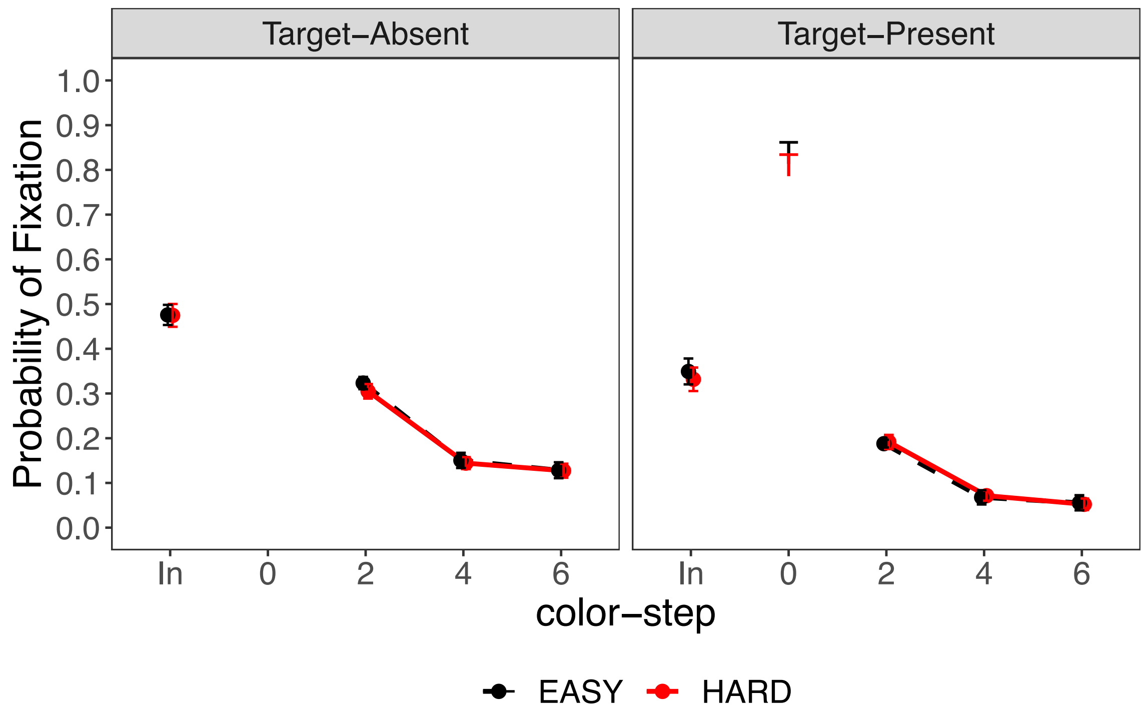

Figure 23. Probability of fixation in Experiment 6 (varied targets).

This group difference was particularly larger when the target was present (11%) than when it was absent (1%), $F(1, 62) = 7.382$, $p < .01$, $\eta_p{}^2 = .070$. For RTs, there was no main effect of group, $F(1, 62) = 0.628$, $p = .430$, $\eta_p{}^2 = .009$. The main effect of Target Presence was significant, $F(1, 62) = 46.266$, $p < .001$, $\eta_p{}^2 = .071$, and the interaction of Target Presence and Group was also significant, $F(1, 62) = 5.666$, $p < .01$, $\eta_p{}^2 = .009$. The RT tended to be longer for the easy than hard search experience group in the target-absent trials and the RT difference between the two groups was much smaller in the target-present trials, but these comparisons did not reach significance in further tests, *ps* > .2. To better understand this interaction between the Group and Target Presence, I compared RTs between the target-present and target-absent trials for each group. Both search groups showed a decrease in RT from the target-absent to target-present trials, but the decrease was larger in the easy search experience group (196ms), $t(31) = 7.031$, *p*

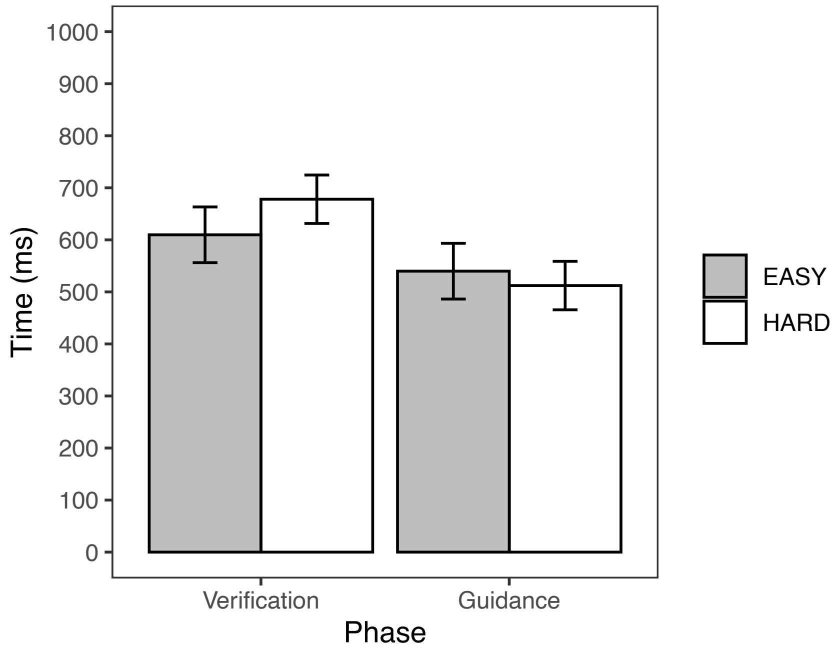

Figure 24. Mean time for the attentional guidance and target verification phases in Experiment 6. Attentional guidance is the interval between the search array onset and the first fixation on a target (right) and target verification is the interval between the first fixation on a target and manual response (left).

< .001, d = .565, than in the hard search experience group (94ms), $t(31) = 2.918$, $p < .001$, d = .424.

One intriguing finding in the behavioral results is the significantly high level of missed targets for the hard search experience group compared to the easy search experience group. Such a difference was not observed in Experiment 5, in which the targets were consistent. The higher misses for the hard search experience group suggests that target consistency was a critical factor for accurately detecting a target.

Probability of Fixation

As is depicted in Figure 23, there was no group difference in the fixation rates for Experiment 6 for any of the color-steps, including the intervening color, which showed a

higher fixation rate for the hard search experience group in Experiment 5. Further analyses confirmed this observation. In both target-absent and target-present trials, the fixation rates for the intervening color were not significantly different between the two groups, $t(58.86) = 0.038$, $p = .969$, $d = .009$, and $t(55.11) = 0.654$, $p = .515$, $d = .155$, respectively. Similarly, there was no significant difference in the probability of fixation to the actual target presented in the search array, $t(61.04) = 1.199$, $p = .235$, $d = .299$. For the three outer colors, there was no main effect of Group with or without the target presented, *ps* > .3, and no interaction between the Group and Color-Step, *ps* > .2. As expected, in both target-absent and present trials, the probability of fixation systematically decreased as the color-steps of the outer colors increased regardless of the group, $F(2, 124) = 367.654$, $p < .001$, $\eta_p^2 = .545$, and $F(2, 124) = 340.274$, $p < .001$, $\eta_p^2 = .628$, respectively, indicating color guidance.

Attentional Guidance and Target Verification

As in Experiment 5, response times in each search trial were divided into an attentional guidance and a target verification phase based on the time of the first fixation to the actual target in the target-present trials (see Figure 24). The main effect of Group was not significant, $F(1, 62) = 0.336$, $p = .563$, $\eta_p^2 = .003$ and the main effect of Phase was significant, $F(1, 62) = 22.995$, $p < .001$, $\eta_p^2 = .108$, showing that it took more time to verify a target after it was first fixated than to guide eye fixations to the target. The interaction between the two factors was marginal, but not significant, $F(1, 62) = 3.803$, $p = .055$, $\eta_p^2 = .019$.

Discussion

Experiment 6 aimed to investigate whether the hard search experience group utilizes a continuum search template when targets vary from trial-to-trial just as Experiment 5, in which targets were consistent for the entire experiment. The results of Experiment 6 demonstrated a different pattern than that in Experiment 5. I found no experience effect on the behavioral and eye movement results, except for the more missed targets in the hard search experience group than the easy search experience group. One possibility is that the experience earned from the 16-color search trials might have biased their response criterion to report target absence. In the 16-color search trials, the distractors with 1 color-step occupied 58% of the distractor pool. Because the color is only target-defining feature of the targets, it would be challenging to discriminate a target amongst so many target-similar distractors. These confusable distractors might induce the participants to make the wrong decision about the presence of target, even in the 8-color search trials in which the target was relatively easier to distinguish from the distractors.

GENERAL DISCUSSION

The present experiments investigated whether the experience with difficult color discrimination affects how participants strategically form a search template when a target is defined by color. In an easy search experience group, the participants had to search for either of two potential targets embedded in distractors that appeared in distinguishable colors. A hard search experience group had to search for either of the targets in search arrays including a high proportion of the confusable distractors with target-similar colors in half of the trials. I measured the probability of fixation to different colors and the time required for two sequential search phases within a trial. The probability of fixation was

adopted to examine the extent to which target similar distractors attracted the attention (Menneer, et al., 2007; Stroud, et al., 2012). The target verification time, which was the later phase of the search process, reflected the time to identify the fixated target by comparing it with the search template (Castelhano et al., 2008). By using behavioral and eye movement measures, I wanted to investigate whether the experience of difficult discrimination encouraged observers to create an effective search template and if so, which search stage was influenced by the search template.

Experience with Difficult Color Discrimination Induced a Range Search Template

The results of the experiments showed evidence that an inefficient search template, or more specifically, a range search template, was more likely to be used by the participants who experienced the difficult color discrimination in half of their search trials. The fixation rate to the intervening color was higher for the hard than the easy search experience group. This suggests that attention was readily deployed to the intervening color because this color was involved in the active search template and formed part of a range search template. Also, the target verification phase required more time for the hard than the easy search experience group, suggesting extra difficulty in the comparison process due to the range search template.

This higher probability of fixation to the intervening color was comparable to what Stroud et al. (2018) found in their experiment paradigm. They specified the target colors by a range of different colors with the two target colors at the outer ends of the range and expected that participants would generate a range search template. In their results, the participants with this range target preview fixated more to not only the intervening colors and target colors but also to outer colors that were not contained in the

range target preview, compared to the participants who were presented with two discrete target preview colors. Stroud et al. concluded that the increased fixation rates to both outer and intervening colors indicated that the range target preview decreased the use of color guidance. If the results of Experiment 5 in the current study were caused by an overall decrease in color guidance, then increased fixation rates should be observed in both the intervening color as well as outer colors. However, the current experiment found higher fixation rates only in the intervening color, and not in the outer colors, even for the outer color that were 2 color-steps away from a target color, indicating that color guidance decreased only to the intervening color, but not for the outer colors. This fixation rate pattern was consistent with the original expectation of Stroud et al (2018) about a range search template to guide attention. It seems that the experience with difficult target discrimination encouraged participants to generate a range search template when only color information and not shape information is available to identify the target. The fact that the difficult search experience encouraged the use of a range target was surprising in this experiment, especially because Stroud et al tried and failed to encourage the use of a range target by previewing the target colors by displaying a unified range of colors that included the colors between the targets.

Even though I am proposing the range template account as the main claim to explain the current finding, there is another possible way to interpret the results. It is possible to have the third representation for the intervening color as part of a search template. By activating the representation of the intervening color, the hard search experience group could expect to have similar performance to the easy search experience. As the activation in the middle can spread out to the two target colors, the activation of

target colors will attract additional attention in a search array[1]. The current experiment paradigm was not able to test this possibility. A future study is necessary to assess this possibility.

Target Consistency plays a critical role in forming a range Template

In Experiment 6, I tried to examine whether the inefficient search strategy (i.e., a range search template) was still used when target information was varied from trial to trial. Error rate was generally high for the varying target condition, replicating the earlier studies showing that varying the target makes search harder and more demanding and results in a cost in the search process (Goldstein & Beck, 2018; Wolfe et al., 2004).

The present results are consistent with previous experiments finding a benefit of a consistent target on some stages of search processing (Carlisle et al., 2011; Goldstein & Beck, 2018; Grubert et al., 2016a; Hout & Goldinger, 2010). Goldstein and Beck (2018) used a visual search task in which a target was a particular color and participants were required to discriminate the target from distractors. They observed shorter times to establish a search template and shorter times to verify the target once it was fixated for consistent target than varied target conditions, but the time necessary for the attentional guidance stage was unaffected. Similar to their findings, I found the marginal interaction of Experiment (Experiment 5 vs. 6) and Phases (Attentional guidance vs. Target verification), $F(1, 124) = 3.815$, $p = .053$, $\eta_p^2 = .018$: there was an overall increase in target verification time when targets were varied from trial-to-trial compared to when the targets were consistent (ΔM = 74.0ms), but no significant difference in the attentional

---

[1] This explanation was suggested by David Huber during a cognitive seminar at the University of Massachusetts Amherst. I appreciate his valuable idea for this alternative explanation.

guidance stage (ΔM = 13.2ms). Although both studies only found evidence about the cost of varying targets in the target verification stage, this cost seems to influence a different aspect of behavioral performance in the present study than in Goldstein and Beck's (2018): the present study showed the cost from the varying targets in error rates, but Goldstein and Beck's study (2018) showed the costs in RTs. This discrepancy may be attributable to the number of targets to be held in working memory. While Goldstein and Beck asked participants to remember a single target, the current study asked them to remember two targets and search for either of them. This additional task difficulty of searching for two targets (Grubert, Carlisle, & Eimer, 2016b; Stroud et al., 2012) (Stroud et al., 2012; Grubert et al., 2016) may make observers sacrifice performance accuracy rather than prolonging their responses.

More importantly, whether target information was consistent or varied seemed to alter the strategic way in which search templates were formed. The frequent inefficient fixations to the intervening color were observed only in the easy experience group, and not in the hard search experience group, as indicated by the significant interaction between Experiment and Group for the intervening color, $F(1, 124) = 6.097$, $p < .05$, $\eta_p^2 = .046$, and both groups showed very similar fixation patterns across all of the color-steps for the outer colors. The divergent fixation pattern for consistent and varied targets was well in line with the target verification time: Longer verification time for the hard than the easy search experience group was only observed in the consistent but not in the varied target condition. Also, electrophysiological evidence has demonstrated that novel target information is stored and remained in visual working memory, but that identical target information repeated over several trials eventually moves to Long-Term Memory (Arita

et al., 2012; Woodman, Carlisle, & Reinhart, 2013). Storing target information in LTM can be advantageous to search processes, as demonstrated above. In Experiment 5, in which target information was consistent and stored in LTM, the hard search experience group could save cognitive resources because they did not need to update and consolidate the new target representation. The surplus cognitive resources allowed them to consider a different search strategy, such as creating a single range search template in LTM instead of two precise search templates for the two targets. Even though the range search template itself was not optimal in terms of the efficiency of search performance, the hard search experience group might have preferred the single range template over the two separate templates because it could reduce the cognitive demands associated with maintaining the two templates. Also, the participants might have a subjective feeling that the search was less effortful to conduct with the single range template than the two discrete representations, especially in the difficult discrimination trials (Irons & Leber, 2020). However, if the target information varied from trial-to-trial, the hard search experience group was denied the advantages of the LTM template and would not have spare cognitive resources to recreate a range template. Thus, the hard search experience group would not adopt the range search template, and would instead maintain two target representations serving as two search templates, just as the easy search experience group did. The results of Experiments 5 and 6 suggest that a range search template needs the support of LTM and the motivation of lightening the cognitive burden from the difficult color discrimination.

Relationship to Chapter 2's results

The findings in Chapter 3 replicate the results of Chapter 2 in that experience with difficult color discrimination alters the search strategy of representing target color information. As in Chapter 2, participants who performed some difficult color discriminations did not adopt the optimal strategy that was primarily reliant on color to guide a search, and instead made frequent fixations to distractors that were unlikely to be a target. Even though the finding of the present study is consistent with the results of Chapter 2 with respect to the selection of a suboptimal search strategy after difficult color discrimination experience, the detailed aspect of the strategies shows important differences. In Chapter 2, the hard search experience group relied less on color guidance itself, resulting in the frequent unguided fixations to the outer colors that were dissimilar to the target color. In Chapter 3, the hard search experience group built a range form of search template to guide search, resulting in the frequent fixations to the intervening color that was equally similar to the two target colors.

Note that the experimental design used Chapter 3 differed from Chapter 2 in an important aspect. In Chapter 2, the targets were colored T objects and the distractors were colored pseudo-L objects, so that the target could be identified by shape even if the color information was ignored, although the fixation rates indicate that color guidance was still used on some trials. The target-defining shape feature can allow the hard search experience group to rely less on color guidance. In Chapter 3, this alternative strategy was not available as the targets and distractors had the same shape, so that shape was not a feature to identify the target. The results of the present study, therefore, show that observers who experienced difficult color discrimination still preferred to adopt a strategy

that was not optimal, and created a range color template with the support of LTM when there was no alternative feature (i.e., shape) to rely on.

CONCLUSION

Experiments 5 and 6 have demonstrated that observers adjusted the target representations serving as a search template based on the experience of search difficulty. The results show that participants who conducted difficult color discrimination fixated more to the distractors appearing in the color that was equally similar to the two target colors and took a longer time to verify a target once it was fixated than other participants who did not have the experience of difficult color discrimination. These results suggest a range form of search template connecting the two target colors and including the intervening color in the middle for the hard search experience group. They did so even though the range search template did not seem to benefit search for the target; rather it led to costs in terms of search guidance and comparison. Moreover, this strategy difference between the groups was observed only when the task was less demanding due to consistency of the targets across trials. The present findings argue against two common assumptions of human behavior: that we pursue the strategy that is the most efficient, and that experience with a task is usually beneficial. These findings add to the growing body of studies demonstrating preference for a suboptimal search strategy that is expected to alleviate cognitive burdens or efforts (Irons & Leber, 2020) over the optimal strategy that produces the best performance. Furthermore, it extends the current findings on what

specific strategy will be used in a dual-color search task, and how that strategy is shaped by experience.

CHAPTER 4

EXPERIMENT 7

Introduction

We often make mistakes when trying to search for a target, regardless of how complex or simple the visual scene is. A target is often neglected, or a non-target is considered as the target. The consequences of these mistakes are broad. The result of missing gravy sauce on a table is eating dry turkey, but missing a tumor in a mammogram can lead a serious medical malpractice.

A series of experiments mentioned above have demonstrated that participants did not always adopt an efficient search strategy to guide attention in a visual scene. An earlier experience with demanding search can strengthen the preference for the less efficient strategy. This strategy probably worsens search performance when observers are under time pressure, as they are when scanning luggage on a moving conveyor belt in an airport or scanning x-ray images for emergent medical situations. Also, the repeated searches can make them exhausted and seduce them into adopting an inefficient strategy that decreases search performance. How, then, can we encourage searchers to choose the strategy that increases the quality of search performance?

It is necessary to understand what kind of errors or inefficient behaviors occur in order to increase the quality of search performance and encourage searchers to choose the optimal search strategy. If we can understand the factors underlying the mechanism of bad performance, it will be possible to improve search performance by removing those factors.

Identifying the sources of errors in visual search has been a goal not only in laboratory studies of visual attention, but also in studies of how medical images are interpreted to detect tumors and other critical anomalies. In tests of medical image interpretation in which experts must detect a target or multiple targets, the errors that searchers made are often classified into three different categories (Krupinski, 2010; Nodine & Kundel, 1987): sampling errors, recognition errors, and decision-making errors. In a complex search scene, searchers often make a decision before inspecting whole area of an image, which can lead them to skip areas containing a target. This sampling error can be indicated by response errors reporting target absence without looking at the target. Recognition errors can be identified by the observation that the searchers made a miss response shortly after fixating the target. Even though searchers fixate the target or near the target, it does not guarantee that they will make a correct decision, especially if the target is camouflaged or embedded. Several studies have demonstrated that an embedded target requires multiple fixations on the target area lasting up to three seconds to successfully identify the target and make a correct decision (Kundel, Nodine, & Carmody, 1978; King, Stanley, & Burrows, 1984). A decision-making error is more commonly observed in medical image reading situations. Often searchers detect the part of a camouflaged target, but they decide that it is not a target and it is a variant of a normal nodule. Decision-making errors can be identified by the observation of frequent fixations over a long duration (> 3s) in an area containing the target combined with a miss response. These errors occurred in not only medical image reading but also in simpler laboratory-setting searches or other real-world searches, and are often a critical factor in performance.

In terms of the improvement of search performance, the efficient guidance of attention should be accompanied by accurate decision-making. In the long-term, efficient search guidance could shorten the time necessary for the search tasks so that searchers will be less fatigued (Brady, 2017; Lee, et al., 2013). To promote efficient search, Experiment 7 provided feedback. Throughout the previous experiments, auditory feedback was given at the end of each trial to indicate whether the response was correct or not. This tone might encourage the participants to focus on the task itself, but it does not encourage the participants to re-evaluate their response or allow them to confirm where the target was in the search array. In Experiment 7, new extra feedback was given for trials with incorrect responses. When the participants make a wrong response, they will see the exact search array for several seconds. If the participants make an error, they are required to spend an additional three seconds viewing the feedback display. As they make more errors, the task itself takes more time. To avoid this delay, the participants may work to search more thoroughly compared to when this feedback is not provided.

When the search display was re-presented after an error, a spatial marker that took the form of a green check mark in one condition and a black circle in another condition was added to indicate the location of the target if the target was present. The presence of the spatial marker in a search array was expected to encourage the participants to re-evaluate their eye movements on a search. If the incorrect response was due to ignoring the area containing the target, the spatial marker would help them to realize that the carelessness of their searches and encourage them to inspect the whole search array in the following trials. Whereas, if the incorrect response was due to a careless decision while

fixating on the area containing the target, the feedback marker would encourage them to spend a certain amount of time examining the area that including the target.

The expected benefits of the additional feedback motivated additional analyses beyond the basic behavioral and eye movement analyses to determine the sources of errors. In medical image reading studies, the incorrect misses after fixating the target were classified as either Recognition errors or Decision-Making errors depending on the duration of fixations to the target area; specifically, if they had multiple fixations (> 3s) or a single fixation with a duration over 1/3 second. In the current study, I focused on only the Search Errors and Recognition Errors. The Decision-Making Errors were included in the category of Recognition Error. As mentioned above, the primary reason for the Decision-Making Errors is that the target was camouflaged or deeply embedded in the search array. However, the current target was easily detectable by its shape (i.e., “T”) from the shape of distractors (i.e., “L”), and all search items were spatially separated from each other on the white background so that there is no way to confuse a fixated target for a variant of the distractor after a long duration fixation. The Search Error was defined by the probability of missing the target given the participants did not fixate to the target, and the Recognition Error was defined by the probability of missing the target given the participants fixated to the target. By comparing these two types of errors between Experiments 1 and 7, we can understand how the feedback changes search behavior and search strategy.

Method

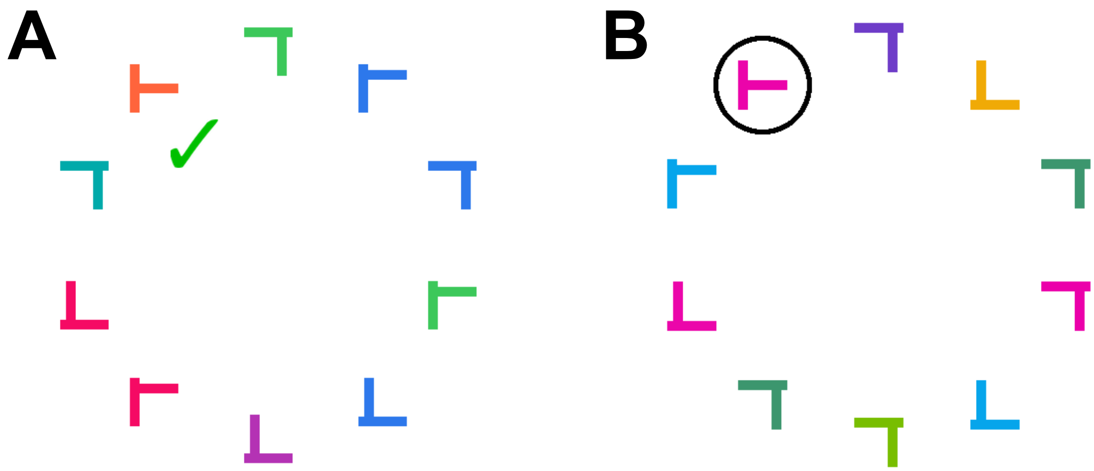

Figure 25. Sample search arrays with a spatial feedback mark in Experiment 7. When participants made an incorrect response, a search array was presented again. If the corresponding trial was target-present trial, an extra visual feedback marker either (A) a green check mark or (B) a black circle surrounding the target indicating the location of the target was presented together. If the trials were target-absent trials, the search array was presented without the spatial marker.

Participants

I had originally planned to recruit sixty-four participants for this experiment, as in the previous experiments. However, forty-four participants were recruited for Experiment 7 because participants testing was limited by COVID-19. Thirteen participants were assigned to the easy search experience group and another thirteen participants were assigned to the hard search experience group for the green check mark condition. Nine participants were assigned to the easy and another nine participants were assigned in the hard search experience group for the circle condition. Average age was 20.0 years and five of the participants were male. The Ishihara test was administrated by an experimenter, and all participants reported corrected-to-normal vision without color anomality. Course credits were provided for the participation. One participant replaced for the low accuracy.

Stimuli and Procedure

The identical stimuli and procedure of Experiment 1 were used except for the addition of the feedback display when the response was incorrect. In the green check mark condition, after the participants reported the presence of the target for a target-absent trial, the search array appeared again for 3 seconds. If they reported the absence of the target for the target-present trial, the search array containing a green check mark (1.86° × 1.86°) was presented for 3 seconds. This check mark was distanced 4.85° of visual angle from the center of a search array (See Figure 25A). In the circle mark condition (Figure 25B), a black circle (radius: 1.37°) was presented and surrounded the target, replacing the green check mark. This black circle surrounding the target was presented for 1 second, followed by 1s of search array without the circle and then presented again for 1 second, so that the circle appeared to blink.

Results

The data from the green check mark and black circle conditions were aggregated together for further analyses.

Results of Experiment 7

Before comparing the results against Experiment 1, the results of Experiment 7 are presented here, but the graphs in this section contain results from both Experiments 1 and 7 with labels of "Without Feedback" and "With Feedback" for easy visual comparison. First, I compared RTs between 8-color and 16-color search trials within the hard search experience group to demonstrate the different levels of search difficulty between the trial types. As expected from Experiment 1, the error rates were not

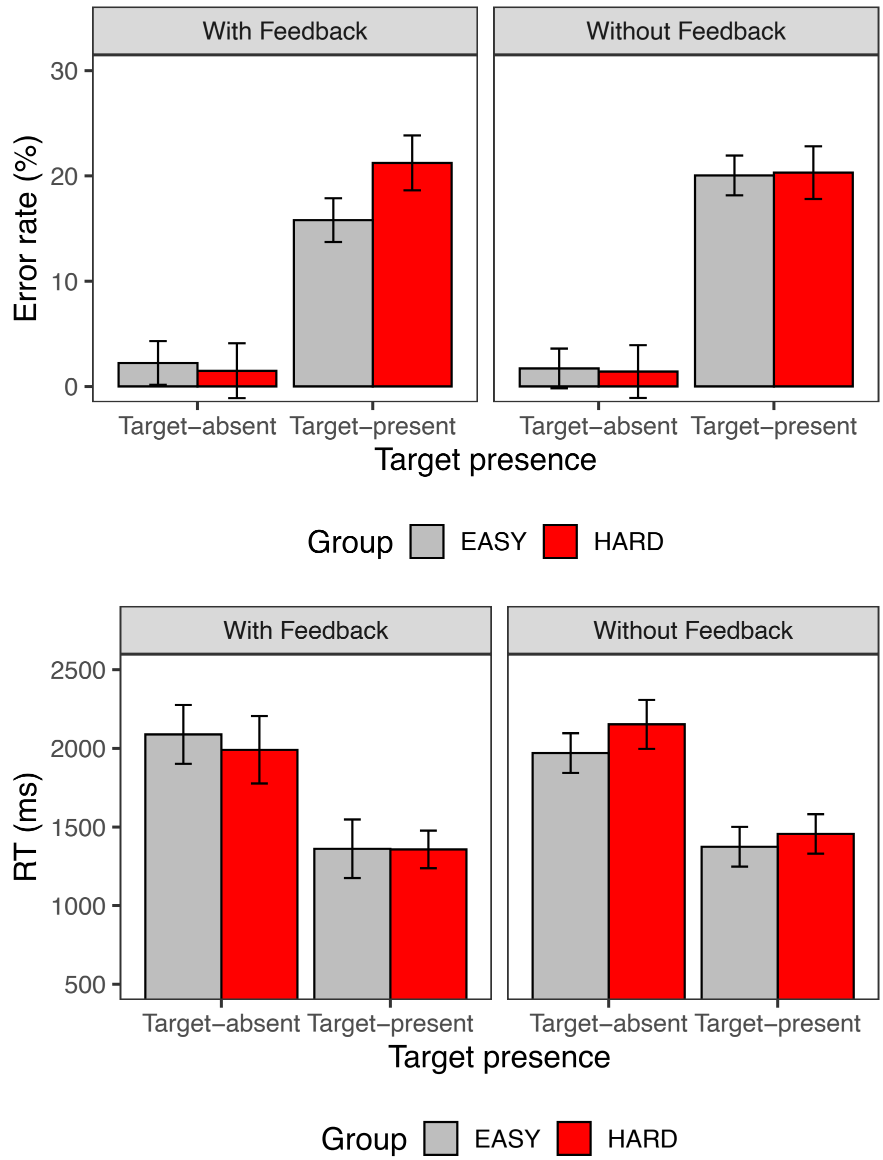

Figure 26. Error rates (Top) and RTs (Bottom) in Experiment 7 (Left; *With Feedback*) and Experiment 1 (Right; *Without Feedback*). The stimuli and procedure in Experiment 7 were identical to those of Experiment 1, except for an additional feedback display after wrong responses.

significantly different between the 8-color and 16-color search trials, $F(1, 21) = 1.243$, $p = .277$, $\eta_p^{\ 2} = .004$, but the RT was significantly slower for the 16-color search trials than the 8-color search trials, $F(1, 21) = 12.768$, $p < .01$, $\eta_p^{\ 2} = .010$, and this RT difference

was larger when the target was absent than present, $F(1, 21) = 15.943$, $p < .001$, $\eta_p{}^2 = .005$, confirming the successful replication of Experiment 1.

The left graphs in Figure 26 (labeled "With Feedback") show the mean error rates and RTs for each search experience group. Both the error rates and RTs from Experiment 7 were submitted mixed-factor ANOVAs with factors of Target Presence and Group separately. For error rates, the main effect of Target Presence was significant, $F(1, 42) = 216.041$, $p < .001$, $\eta_p{}^2 = .602$, showing higher error rates for the target-present trials than the target-absent trials. The main effect of Group was not significant, $F(1, 42) = 1.787$, $p = .188$, $\eta_p{}^2 = .029$, but the interaction between the Group and Target Presence was significant, $F(1, 42) = 7.434$, $p < .01$, $\eta_p{}^2 = .049$, demonstrating that the hard search experience group made more false alarms than the easy search experience group and this group difference was not observed when a target was not presented. For RTs, the main effect of Target Presence was significant, $F(1, 42) = 91.961$, $p < .001$, $\eta_p{}^2 = .256$, showing slower RT for target absent trials than target-present trials. There was no significant main effect of Group, $F(1, 42) = 0.096$, $p = .758$, $\eta_p{}^2 = .001$, and the interaction of Group and Target Presence was not significant, $F(1, 42) = 0.437$, $p = .511$, $\eta_p{}^2 = .001$.

Next, I analyzed the probability of fixation in order to understand how search guidance varies across conditions. The left graphs in Figure 27 (labeled "With Feedback") show the probability of fixation for each experience group as a function of color-step. The group difference for the target-dissimilar colors that was observed in Experiment 1 was no longer as apparent. Detailed analyses confirmed this observation. The probability of fixation for the outer colors was submitted to mixed-factor ANOVAs

with a within-subject factor of Color-Step (i.e., color-step 0, 2, 4, and 6) and a between-subject factor of Group (i.e., easy search experience vs. hard search experience group). The analyses were conducted separately for target-absent and target-present trials. In both target-absent and target-present trials, the fixation rate decreased as the color-step increased, $F(3, 189) = 142.589$, $p < .001$, $\eta_p^2 = .307$, and $F(3, 189) = 133.061$, $p < .001$, $\eta_p^2 = .451$, respectively. None of the other factors reached significance, *ps* > .6. Similarly, I could not find any significant differences between the two groups for intervening color or the target, *ps* > .6.

Comparison with Experiment 1

The primary aim of Experiment 7 is to examine whether providing additional visual feedback improves search performance, especially the participants who adopted the inefficient search strategy when they occasionally experienced difficult color discrimination trials. The comparison of behavioral performance was conducted by mixed-factor ANOVAs with an additional factor of Experiment (Experiments 1 and Experiment 7). The error rate was significantly higher for target-present than target-absent, $F(1, 104) = 478.016$, $p < .001$, $\eta_p^2 = .644$, and this factor interacted with group, $F(1, 104) = 4.365$, $p < .05$, $\eta_p^2 = .016$, showing that the hard search experience group made more errors than the easy search group in target-present trials, and this group difference was indistinguishable in target-absent trials. For RTs, the main effect of target presence was significant, $F(1, 104) = 218.643$, $p < .001$, $\eta_p^2 = .269$. None of other main effects or two-way or three-way interactions reached significance for the behavioral data, *ps* > .2.

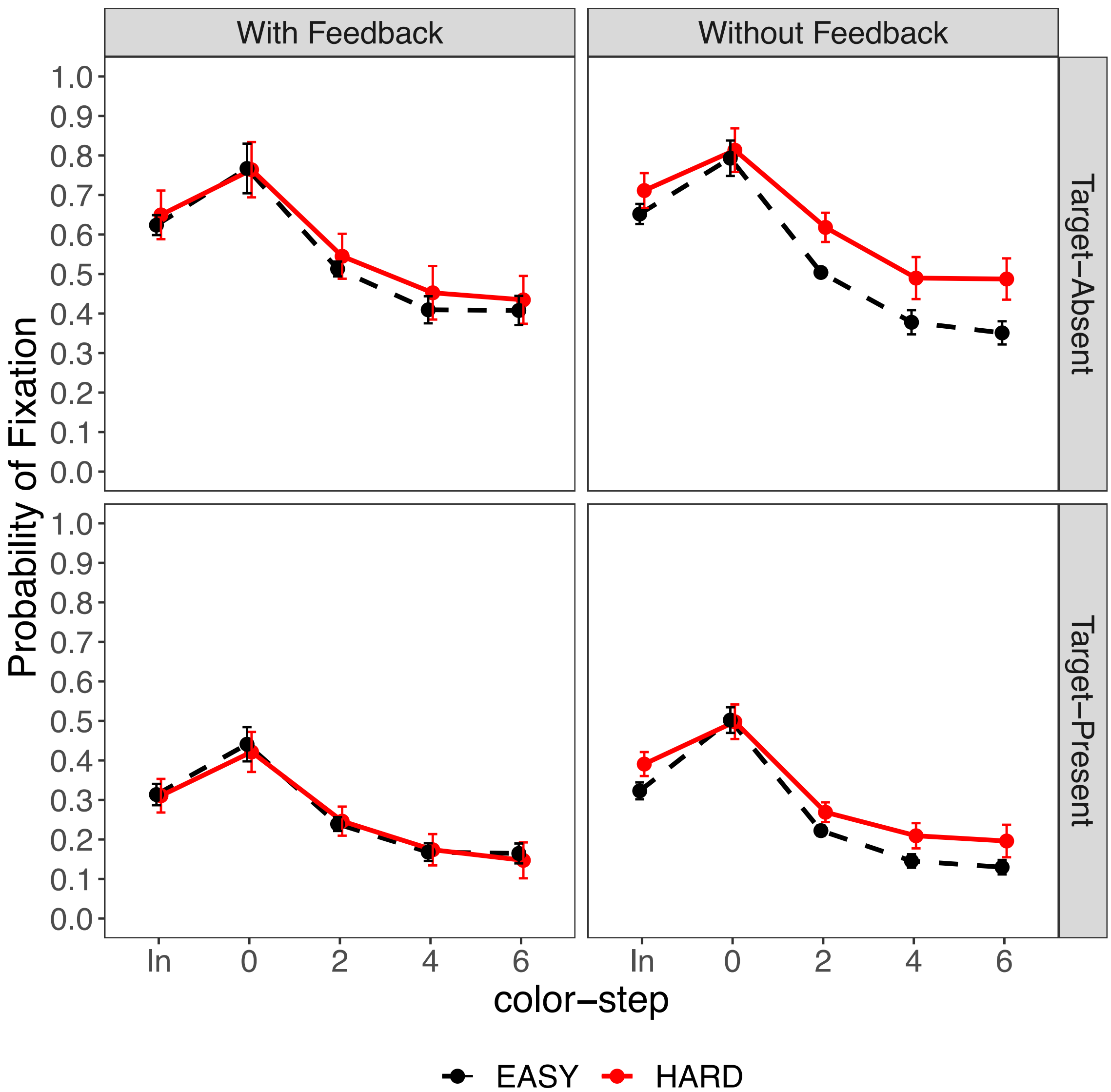

Figure 27. The probability of fixation as a function of color-step in Experiment 7 (Left; "With Feedback") and Experiment 1(Right; "Without Feedback"). Top panels indicate target-absent trials and bottom panels indicate the target-present trials. The stimuli and procedure in Experiment 7 were identical to those of Experiment 1, but an additional feedback display was provided after the participants made a wrong response.

Even though there was no observable difference that was caused by the additional feedback on explicit search performance, it is still possible that re-watching a search display after making an incorrect response can affect the pattern of eye movements. According to the right graphs (Experiment 1) in Figure 27, without the additional

feedback, the hard search experience group fixated more frequently to target-dissimilar colors than the easy search experience group did. Whereas, with the additional feedback, the hard search experience group fixated to these colors as frequently as the easy search experience group. To confirm this observation, the fixation rates of the two experiments were analyzed with mixed-factor ANOVAs with an additional factor of Experiment. Only the probability of fixation data for the outer colors, which showed the most obvious group difference in Experiment 1, was used for the following statistical analysis. Consistent with Experiment 1, the fixation rates gradually decreased with increasing color-step, $F(3, 312) = 307.404$, $p < .001$, $\eta_p{}^2 = .394$, and $F(3, 312) = 402.436$, $p < .001$, $\eta_p{}^2 = .540$, for target-absent and target-present trials respectively. In the target-absent trials, the interaction between the Group and Color-Step was marginal, $F(3, 312) = 3.212$,

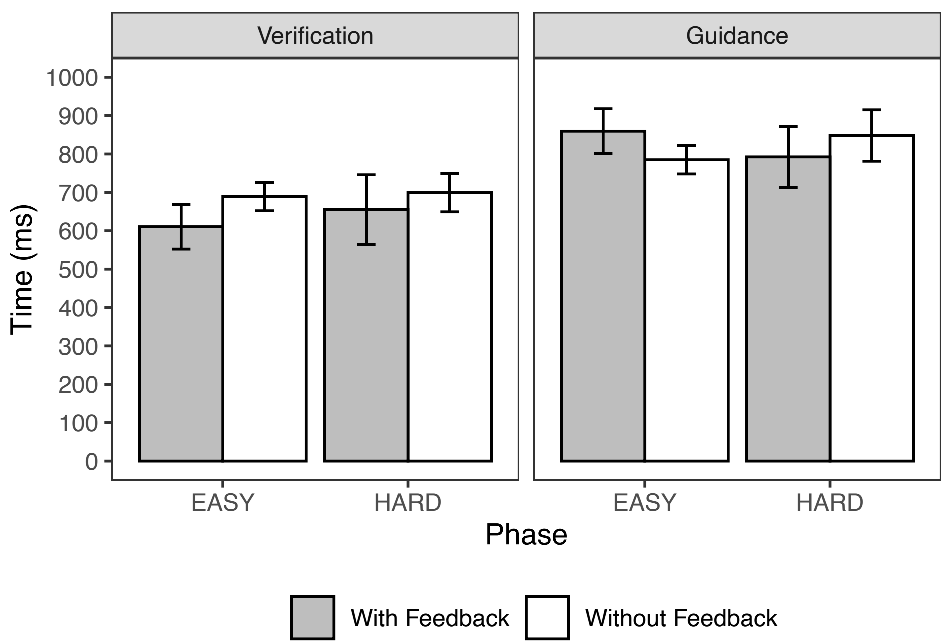

Figure 28. Mean time for Target Verification and Attentional Guidance in Experiments 1 and 7. Left panel represents the target verification phase and right panel represents the attentional guidance phase. Gray bars indicate the mean time in Experiment 7 (With Feedback) and white bars indicates the mean time in Experiment 1 (Without Feedback).

p = .066, $\eta_p{}^2$ = .006, suggesting that the hard search experience group fixated more to colors that were dissimilar to the target colors than the easy search experience group. This interaction was not observed in the target-present trials, $F(3, 312) = 2.177$, p = .132, $\eta_p{}^2$ = .006. Also, I found a significant interaction between the Color-Step and Experiment only in the target-present trials, $F(3, 312) = 5.050$, $p < .05$, $\eta_p{}^2$ = .014. None of the other factors was significant, and more importantly the three-way interactions were not significant, *ps* > .2. As with the behavioral results, I could not find firm evidence of an effect of feedback on the probability of fixations even though Figure 27 shows a hint of a three-way interaction.

Finally, I compared the attentional guidance and target verification times between Experiments 1 and 7 (Figures 28). A mixed-factor ANOVA similar to that used in Experiment 1, but with an additional between-subject factor of Experiment (Experiments 1 and 7) was applied to the times. As the three-way interaction of Experiment, Group and Phase was significant, $F(1, 104) = 5.666$, $p < .05$, $\eta_p{}^2$ = .011, each Target Verification and Attentional Guidance were analyzed with a two-way ANOVA with factors of Experiment and Group. For the Target Verification phase, there was a marginal but not significant main effect of Experiment, $F(1, 104) = 3.063$, p = .083, $\eta_p{}^2$ = .028, indicating the possibility of a positive effect on the time to identify a target. The mean target verification time was 694.07ms without feedback, but it was 632.81ms with feedback. There was no main effect of Group, $F(1, 104) = 0.610$, p = .436, $\eta_p{}^2$ = .005 and the interaction was not significant, $F(1, 104) = .239$, p = .625, $\eta_p{}^2$ = .002. For the Attentional Guidance phases, none of the main effects or interactions reached a significance, all *ps* > .1.

Source of Error Response

The motivation of Experiment 7 is to prevent misses observed in Experiment 1 and other similar search experiments as shown above. The frequent misses imply that participants did not inspect the search display carefully, and made an impetuous response even before fixating the area containing the target. This careless behavior would be reinforced by the unpleasant experience of difficult target color discrimination.

According to studies of medical image interpretation, failing to look at the area containing a target in these complex images is not the sole explanation for the high rate of error responses. Kundel, Nodine, & Carmody (1978) classified three different types of source of error when missing a target that was present: Search Error, Recognition Error, and Decision-Making Error. In a search error, a target is never fixated. In a recognition error, a target is briefly fixated but the observer did not recognize the target and makes another fixation to a different area. A decision-making error is defined as a miss after the observer made a stable fixation of long duration or multiple fixations on the target; decision-making errors are attributed to low signal-to-noise ratio. In the current experiment, I excluded the possibility of the decision error because the target was easily identified by its shape, unlike the target in medical images that were often covered or blurry. Only the search errors and recognition errors were measured to reveal any changes in search pattern caused by the feedback. The search error rate was calculated as follows: First, I summed up the number of the target-present trials in which the participants did not fixate the target and reported a "target-absent" response. Then the number of the specific trials was divided by the total number of target-present trials in

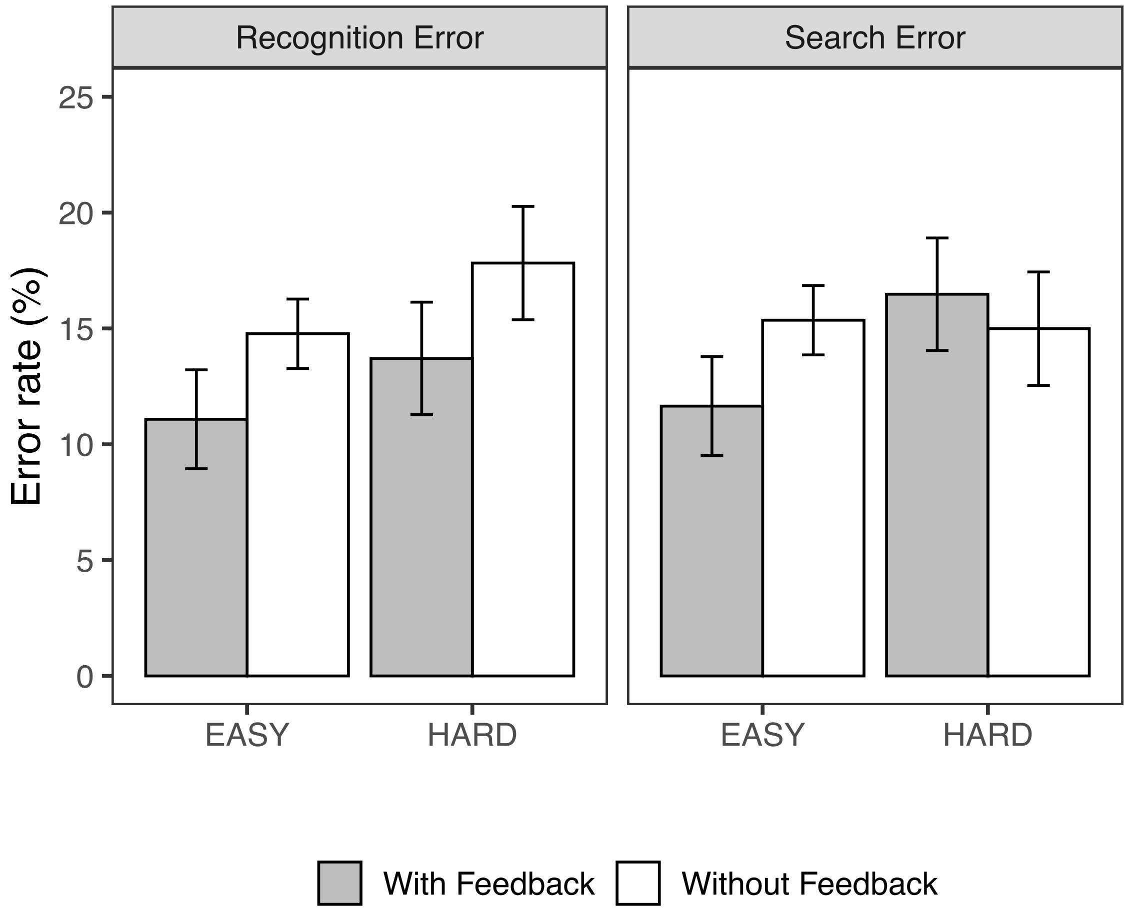

Figure 29. Mean error rates for two types of source error in Experiments 1 (white; Without Feedback) and 7 (gray; With Feedback). The recognition error indicates the response error of reporting “target absence” for target-present trials while fixating to the target in a trial. The search error indicates the response error of reporting “target absence” for target-present trials while never fixating to the target in a trial.

entire experiment. For the recognition error rate, I summed up the number of target-present trials in which the participants fixated to the target and reported a “target-absent” response, and that number of trials was divided by the total number of target-present trials.

Figure 29 shows the mean recognition errors and search errors for each participant group with and without feedback. It seems that overall error rates were lower with

feedback than without feedback. Moreover, this trend is more clearly observed in the recognition errors than the search errors. To test the observation, a statistical analysis was conducted. The error rates were submitted to a mixed-factor 2 x 2 x 2 ANOVA with Error Type (search error vs. recognition error), Experiment (Exp 1 vs. Exp 7), and Group. The mean error rate was numerically lower with feedback than without feedback, but the difference did not reach significance, $F(1, 104) = 3.608$, $p = .060$, ${\eta_p}^2 = .025$. The main effect of Group was marginal, but not significant, $F(1, 104) = 3.692$, $p = .057$, ${\eta_p}^2 = .026$. The interaction between Experiment and Error Type was marginal, but not significant as well, $F(1, 104) = 3.430$, $p = .066$, ${\eta_p}^2 = .008$. Finally, the three-way interaction was also marginal, $F(1, 104) = 3.474$, $p = .065$, ${\eta_p}^2 = .008$. None of the other results were significant or marginal, *ps* > .3.

To better understand the effect of feedback on each type of error, I performed separate ANOVAs with two factors of Experiment and Group for the search errors and recognition errors. For the recognition errors, the main effect of Experiment was significant, $F(1, 104) = 6.368$, $p < .05$, ${\eta_p}^2 = .057$, showing a lower error rate with feedback than without feedback. The main effect of Group was marginal but not significant, $F(1, 104) = 3.371$, $p = .0691$, ${\eta_p}^2 = .031$; error rate was numerically higher for the hard search experience group (M = 16.14%) than the easy search experience group (M = 13.26%). The interaction between the factors was not significant, $F(1, 104) = 0.018$, $p = .891$, ${\eta_p}^2 < .001$. For the search errors, neither the main effects nor the interaction were significant, *ps* > .1. These results, combined with the two phases results, indicate that the participants who received the feedback after wrong decision verified a

target more rapidly and accurately than participants who did not, demonstrating the improvement of search performance by the feedback.

DISCUSSION

A series of experiments have demonstrated that participants did not always adopt the best search strategy and rather preferred an alternative strategy that often entails performance costs. This may be a reasonable choice if the consequent cost is bearable and it can conserve some form of cognitive efforts. In these searches, the consequence of less reliance on color guidance is frequent unguided fixations and increased time to verify a target. In Experiment 7, a feedback display based on response accuracy was provided to improve search performance. When the participant made a wrong decision, they were forced to spend a fairly long amount of time (3s) viewing a repetition of the search display. The participants presumably wanted to complete their task as quickly and accurately as possible, so that re-viewing the search display worked as punishment, motivating the participants to avoid incorrect responses and increase performance quality. Also, the presence of a spatial marker indicating a target location should encourage the participants to inspect the search array carefully if they skipped the areas containing the target, and might lead them to evaluate their current strategy and make more careful decisions.

In the comparison between Experiment 1 (without the feedback) and Experiment 7 (with the feedback), I could not find strong evidence of any effect of feedback on the guidance of search in the probability of fixations, or in the timing of the attentional

guidance phase. Despite the clear demonstration of a potential three-way interaction of Experiment, Group, and Color-Step in the analysis of fixation rates (Figure 27), it did not reach a significance. One possible explanation is the lack of statistical power due to the smaller number of participants (N=44) than what I planned (N=64). Another possible explanation is that re-viewing the search array with a spatial cue indicating the location of the target might not be effective in encouraging efficient guidance of search. This possibility is consistent with a few recent studies investigating the role of feedback on fixations (Drew & Williams, 2017; Grubb & Li, 2018; Peltier & Becker, 2017). Drew and Williams (2017) allowed the participant to freely move their eyes across a natural scene and asked them to report a target. The important manipulation was to provide information regarding which areas had or had not been fixated. However, this online eye-tracking feedback did not yield any reliable improvements in the efficiency of search guidance. I expected that the spatial target location cue provided retrospectively might induce the participants to visit the target location once again and encourage them to fixate every possible location that might contain a target carefully in the following trial. The current feedback based on response accuracy does not seem to be enough to encourage them to guide eye movements more efficiently.

However, the feedback improved the decision-making process once participants fixated to the target. In contrast to the overall behavioral and probability of fixation results, the source of error responses showed a significant decrease in recognition errors in both hard and easy search experience groups when the feedback was provided, compared to when it was not. This pattern indicates that participants were more careful to make a correct decision when they are aware of feedback coming if they made an

incorrect response. Because there was no difference between Experiments 1 and 7 in RT, it does not imply a speed-accuracy trade-off effect.

Although the findings of the current experiment were limited due to the low power and limited significant results, the trend of the positive effect of feedback on eye movements has an important implication for both the guidance of search and consequent decision-making. The simple feedback that is given here can decrease the errors that searchers often make even after fixating a target, and participants who experienced difficult color discrimination and selected inefficient color guidance can switch to a more efficient strategy that relies more heavily on color guidance.

CHAPTER 5

GENERAL DISCUSSION

The current study was designed to (1) investigate the effect of search experience on strategic guidance of attention and (2) examine the effect of feedback about response accuracy on strategic guidance of search and decision-making. In this last chapter, I will summarize the results of the seven experiments and discuss the limitations of the present study and possibilities for future research.

The purpose of the first four experiments is to understand the effect of experience on strategic guidance of search. Specifically, experience varied across participant groups because the color discriminability between targets and distractors was manipulated to make the search more difficult. Two different participant groups with different search experience were required to search for a colored T among pseudo- Ls. An easy search experience group performed only easy color discrimination trials (i.e., 8-color trials) in which a target was easily distinguishable from distractors in the color dimension. Separately, a hard search experience group performed the same easy color discrimination in half of their trials, as well as a difficult color discrimination (i.e., 16-color trials) in the other half of their trials. To rule out the possible explanation that any group difference was caused by the performance in the difficult color discrimination trials, the data from the difficult color discrimination trials were excluded in the analyses. In Experiment 1 with varied targets, I found a higher probability of fixation to the target-dissimilar colors for the hard search experience group than the easy search experience group, indicating less reliance on color

guidance. Also, a trend toward longer RT in the hard search experience group than the easy search experience group supported the claim that the experience of difficult color discrimination discouraged the participants from adopting an efficient search strategy. However, in Experiment 2, in which the target information was consistent across the trials, this group difference in the probability of fixation was not observed. This result suggests that Long-Term Memory plays an important role in the selection of a search strategy. Experiments 3 and 4 separately tested two different manipulations that were applied to make color discriminability more difficult in Experiment 1: the color frequency distribution and the number of colors. I could replicate the results of Experiment 1 only in Experiment 4 in which the number of colors was manipulated but not the color frequency distribution.

The results of Experiment 1 raised a question of whether the same strategy was observed even if the shape information was not available to identify a target. In Experiments 5 and 6, I limited the color information to only available feature information to identify the target by changing the shapes of distractors to “T”, which was the same as the target. When the target information was consistent (Experiment 5), the hard search experience group fixated more on the intervening colors than the easy search experience group did, suggesting the range representation to guide search. However, this difference was not significant when the target information was varied from trial-to-trial (Experiment 6). The results of Experiments 5 and 6 were consistent with Experiments 1 and 2 in terms of the negative effect of experience on strategic guidance of attention. However, more importantly, the type of inefficient strategy that the hard search experience group adopted was different depending on the limited target information.

Finally, Experiment 7 was an attempt to improve search performance by providing additional feedback. Unlike the existing auditory feedback that followed immediately after a correct or incorrect response, this additional feedback allowed the participants to see the search array again with a spatial marker indicating the target location if one was present. Despite the low power, I found a hint of improvement of strategic guidance search for the hard search experience group and a significant decrease in recognition errors in both hard and easy search experience groups.

Even though I found clear evidence of the negative effect of the experience of difficult color discrimination, more work is necessary to answer the question of how we use the experience in building search strategies. In the current studies, I limited the experience to difficult color discrimination because it is one of the most effective factors for influencing search efficiency (Duncan & Humphreys, 1989). However, other types of manipulations can affect search efficiency. For example, the set size of the search array has been known to delay the response times in a conjunction search (Treisman & Gelade, 1980). Increasing the set size of the search array might lead to results that are similar to or different from the current study. Also, performance might be shaped by adding different and stronger motivations such as a monetary reward. The current study relied simply on participants' motivation of completing the task, and this approach resulted in participants taking an inefficient strategy. The monetary reward has been demonstrated in other paradigms as a strong motivation for improving performance. Thus, if a monetary reward is provided for better performance, such as fewer fixations to the target-dissimilar distractors or accurate response, we might see the opposite pattern to what I have found in the current study.

TABLES

Table 1. Sample frequency distribution of the distractor color pool when target colors are 7 and 11 in Experiments 1 and 2. Sixteen colors are labeled by numbers. The number within the parentheses indicates the color-step between the nearer target color and the corresponding color. Negative numbers indicate that these colors intervene between the two target colors on the color ring. Because the targets are odd numbers, the 8-even-numbered-color trials do not exist for this target pair. The histogram below the table illustrates the frequency of colors for the 16-color trial.

	Color of distractors															
Trial type	1 (6)	2 (5)	3 (4)	4 (3)	5 (2)	6 (1)	7 (0)	8 (-1)	9 (-2)	10 (-1)	11 (0)	12 (1)	13 (2)	14 (3)	15 (4)	16 (5)
16-color	2.6	2.6	2.6	5.3	5.3	13.2	5.3	13.2	2.6	13.2	5.3	13.2	5.3	5.3	2.6	2.6
8-color (odd-number)	13.2	0	13.2	0	13.2	0	10.5	0	13.2	0	10.5	0	13.2	0	13.2	0

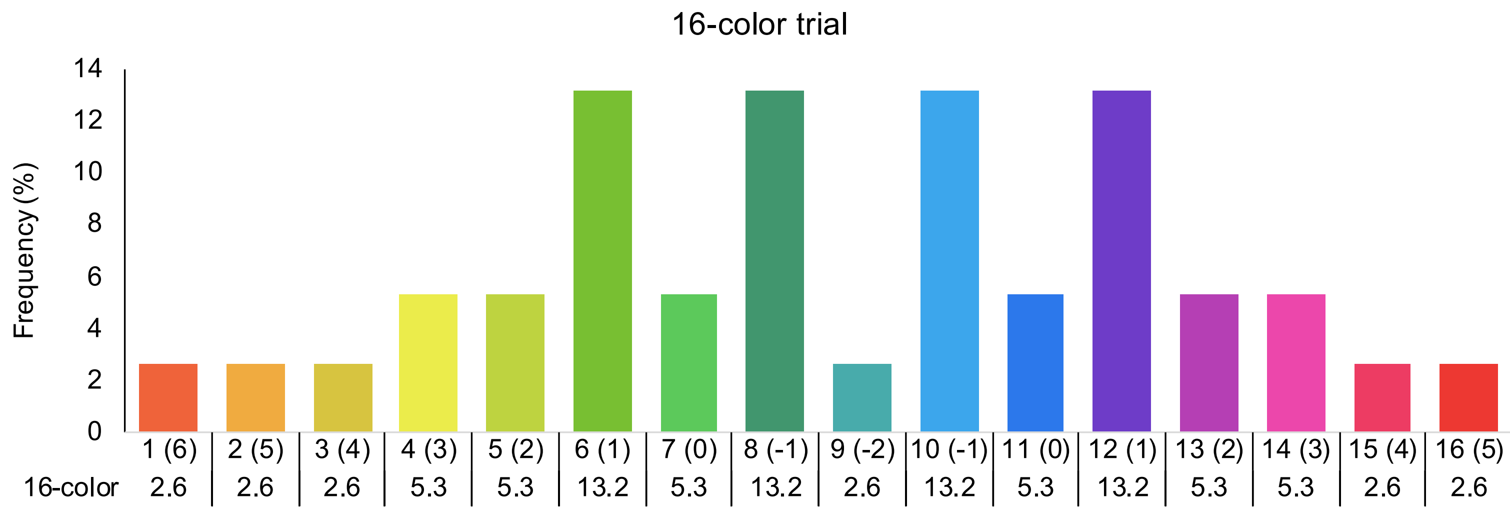

Table 2. Sample frequency distribution of the distractor color pool when target colors are 7 and 11 in Experiments 5 and 6. In 8-color trials, it is impossible to assign exactly the same frequency across all six colors because there were no distractors with target colors, so two randomly chosen colors occupied 16.4% of the positions, while the other colors each occupied 16.8%. In this table, those two random colors are color 1 and color 9.

	Color of distractors															
Trial type	1 (6)	2 (5)	3 (4)	4 (3)	5 (2)	6 (1)	7 (0)	8 (-1)	9 (-2)	10 (-1)	11 (0)	12 (1)	13 (2)	14 (3)	15 (4)	16 (5)
16-color	2.6	2.6	2.6	5.3	7.9	14.5	0	14.5	2.6	14.5	0	14.5	7.9	5.3	2.6	2.6
8-color (odd-number)	16.4	0	16.8	0	16.8	0	0	0	16.8	0	0	0	16.4	0	16.4	0

BIBILOGRAPHY

Aizenman, A., Drew, T., Ehinger, K. A., Georgian-Smith, D., & Wolfe, J. M. (2017). Comparing search patterns in digital breast tomosynthesis and full-field digital mammography: an eye tracking study. *Journal of Medical Imaging*, *4*(04), 1. https://doi.org/10.1117/1.JMI.4.4.045501

Alexander, R. G., Nahvi, R. J., & Zelinsky, G. J. (2019). Specifying the Precision of Guiding Features for Visual Search. *Journal of Experimental Psychology : Human Perception and Performance*.

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011). Value-driven attentional capture. *Proc Natl Acad Sci U S A*, *108*(25), 10367–10371. https://doi.org/10.1073/pnas.1104047108

Anderson, B. A. (2013). A value-driven mechanism of attentional selection. *Journal of Vision*, *13*(2013), 1–16. https://doi.org/10.1167/13.3.7.doi

Anderson, B. A. (2016). The attention habit: How reward learning shapes attentional selection. *Annals of the New York Academy of Sciences*, *1369*(1), 24–39. https://doi.org/10.1111/nyas.12957

Arita, J. T., Carlisle, N. B., & Woodman, G. F. (2012). Templates for rejection: Configuring attention to ignore task-irrelevant features. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 580–584. https://doi.org/10.1037/a0027885

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bacon, W. F., & Egeth, H. E. (1994a). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/BF03205306

Bacon, W. F., & Egeth, H. E. (1994b). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/BF03205306

Bacon, W. F., & Egeth, H. E. (1997). Goal-directed guidance of attention: evidence from conjunctive visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *23*(4), 948–961. https://doi.org/10.1037/0096-1523.23.4.948

Baddeley, A., & Hitch, G. (1974). Working Memory. *The Psychology of Learning and Motivation: Advances in Research and Theory*. https://doi.org/10.1126/science.1736359

Baluch, F., & Itti, L. (2010). Training top-down attention improves performance on a triple-conjunction search task. *PLoS ONE*, *5*(2). https://doi.org/10.1371/journal.pone.0009127

Barras, C., & Kerzel, D. (2017). Target-nontarget similarity decreases search efficiency and increases stimulus-driven control in visual search. *Attention, Perception, & Psychophysics*, (2010). https://doi.org/10.3758/s13414-017-1367-9

Barrett, D. J. K., & Zobay, O. (2014). Attentional control via parallel target-templates in dual-target search. *PLoS ONE*, *9*(1). https://doi.org/10.1371/journal.pone.0086848

Beck, V. M., Hollingworth, a., & Luck, S. J. (2012). Simultaneous Control of Attention by Multiple Working Memory Representations. *Psychological Science*, *23*(8), 887–898. https://doi.org/10.1177/0956797612439068

Beck, V. M., & Vickery, T. J. (2019). Multiple states in visual working memory: Evidence from oculomotor capture by memory-matching distractors. *Psychonomic*

Bulletin & Review. https://doi.org/https://doi.org/10.3758/s13423-019-01608-7 Multiple

Becker, S. I. (2010). The Role of Target-Distractor Relationships in Guiding Attention and the Eyes in Visual Search. *Journal of Experimental Psychology: General*, *139*(2), 247–265. https://doi.org/10.1037/a0018808

Brady, A. P. (2017). Error and discrepancy in radiology: inevitable or avoidable? *Insights into Imaging*, *8*(1), 171–182. https://doi.org/10.1007/s13244-016-0534-1

Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics*, *51*(5), 465–472. https://doi.org/10.3758/BF03211642

Bravo, M. J., & Farid, H. (2012). Task demands determine the specificity of the search template. *Attention, Perception, and Psychophysics*, *74*(1), 124–131. https://doi.org/10.3758/s13414-011-0224-5

Bravo, M. J., & Farid, H. (2016). Observers change their target template based on expected context. *Attention, Perception, & Psychophysics*, (January), 829–837. https://doi.org/10.3758/s13414-015-1051-x

Bravo, M. J., & Farid, H. (2009). The specificity of the search template. *Journal of Vision*, *9*(1), 1–9. https://doi.org/10.1167/9.1.34

Buschman, T. J., & Miller, E. K. (2009). Serial, Covert Shifts of Attention during Visual Search Are Reflected by the Frontal Eye Fields and Correlated with Population Oscillations. *Neuron*, *63*(3), 386–396. https://doi.org/10.1016/j.neuron.2009.06.020

Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional Templates in Visual Working Memory. *Journal of Neuroscience*, *31*(25), 9315–9322.

https://doi.org/10.1523/JNEUROSCI.1097-11.2011

Castelhano, M. S., Pollatsek, A., & Cave, K. R. (2008). Typicality aids search for an unspecified target, but only in identification and not in attentional guidance. *Psychonomic Bulletin & Review*, *15*(4), 795–801. https://doi.org/10.3758/PBR.15.4.795

Cave, K. R., Menneer, T., Kaplan, E., Stroud, M. J., Chang, J., Newsome, C., & Donnelly, N. (2020). We Can, but Often Don't , Guide Search Effectively when there are Two Targets or a Working Memory Load.

Cave, K. R., Menneer, T., Nomani, M. S., Stroud, M. J., & Donnelly, N. (2018a). Dual target search is neither purely simultaneous nor purely successive. *Quarterly Journal of Experimental Psychology*, *71*(1 Special Issue), 169–178. https://doi.org/10.1080/17470218.2017.1307425

Cave, K. R., Menneer, T., Nomani, M. S., Stroud, M. J., & Donnelly, N. (2018b). Dual target search is neither purely simultaneous nor purely successive. *Quarterly Journal of Experimental Psychology*, *71*(1 Special Issue), 169–178. https://doi.org/10.1080/17470218.2017.1307425

Cave, K. R., & Pashler, H. (1995). Visual selection mediated by location: Selecting successive visual objects. *Perception & Psychophysics*, *57*(4), 421–432. https://doi.org/10.3758/BF03213068

Cave, K. R., Tamaryn Menneer, Mohammad S. Nomani, Stroud, M. J., & Donnelly, N. (2017). Dual target search is neither purely simultaneous nor purely successive. *Quarterly Journal of Experimental Psychology*, 8–10.

Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of Neurons in

Inferior Temporal Cortex During Memory- Guided Visual Search. *Journal of Neurophysiology*, *80*, 2918–2940.

Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences*. https://doi.org/10.1016/S1364-6613(00)01476-5

Chun, M. M., & Jiang, Y. (1998). Contextual Cueing: Implicit Learning and Memory of Visual Context Guides Spatial Attention. *Cogn. Psychol.*, *36*(1), 28–71. https://doi.org/10.1006/cogp.1998.0681

Desimone, R., & Duncan, J. (1995). Neural Mechanisms of Selective Visual Attention. *Annual Review of Neuroscience*, *18*, 193–222. https://doi.org/10.1016/j.cub.2014.02.049

Divekar, G., Pradhan, A. K., Masserang, K. M., Reagan, I., Pollatsek, A., & Fisher, D. L. (2013). A simulator evaluation of the effects of attention maintenance training on glance distributions of younger novice drivers inside and outside the vehicle. *Transportation Research Part F: Traffic Psychology and Behaviour*, *20*, 154–169. https://doi.org/10.1016/j.trf.2013.07.004

Drew, T., Vo, M. L.-H., Olwal, A., Jacobson, F., Seltzer, S. E., & Wolfe, J. M. (2013). Scanners and drillers: Characterizing expert visual search through volumetric images. *Journal of Vision*, *13*(10), 3–3. https://doi.org/10.1167/13.10.3

Drew, T., Boettcher, S. E. P., & Wolfe, J. M. (2015). Searching while loaded: Visual working memory does not interfere with hybrid search efficiency but hybrid search uses working memory capacity. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-015-0874-8

Drew, T., & Williams, L. H. (2017). Simple eye-movement feedback during visual search

is not helpful. *Cognitive Research: Principles and Implications*, *2*(1), 44. https://doi.org/10.1186/s41235-017-0082-3

Duncan, J., & Humphreys, G. (1992). Beyond the search surface: visual search and attentional engagement. *Journal of Experimental Psychology. Human Perception and Performance*, *18*(2), 578–588; discussion 589-593. https://doi.org/10.1037/0096-1523.18.2.578

Duncan, J., & Humphreys, G. W. (1989a). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458. https://doi.org/10.1037/0033-295X.96.3.433

Duncan, J., & Humphreys, G. W. (1989b). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458. https://doi.org/10.1037/0033-295X.96.3.433

Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences*, 1–10. https://doi.org/10.1016/j.tics.2014.05.005

Failing, M., & Theeuwes, J. (2017). Selection history: How reward modulates selectivity of visual attention. *Psychonomic Bulletin & Review*, *25*(2), 514–538. https://doi.org/10.3758/s13423-017-1380-y

Geng, J. J., & Witkowski, P. (2019). Template-to-distractor distinctiveness regulates visual search efficiency. *Current Opinion in Psychology*, *29*(November), 119–125. https://doi.org/10.1016/j.copsyc.2019.01.003

Gilchrist, A. L., & Cowan, N. (2011). Can the focus of attention accommodate multiple, separate items? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(6), 1484–1502. https://doi.org/10.1037/a0024352

Goldstein, R. R., & Beck, M. R. (2018). Visual search with varying versus consistent attentional templates: Effects on target template establishment, comparison, and

guidance. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(7), 1086–1102. https://doi.org/10.1037/xhp0000520

Grubb, M. A., & Li, Y. (2018). Assessing the role of accuracy-based feedback in value-driven attentional capture. *Attention, Perception, and Psychophysics*, *80*(4), 822–828. https://doi.org/10.3758/s13414-018-1494-y

Grubert, A., Carlisle, N. B., & Eimer, M. (2016a). The control of single-color and multiple-color visual search by attentional templates in working memory and in long-term memory. *Journal of Cognitive Neuroscience*, *28*(12), 1947–1963. https://doi.org/10.1162/jocn

Grubert, A., Carlisle, N. B., & Eimer, M. (2016b). The control of single-color and multiple-color visual search by attentional templates in working memory and in long-term memory. *Journal of Cognitive Neuroscience*, *28*(12), 1947–1963. https://doi.org/10.1162/jocn

Grubert, A., & Eimer, M. (2015). Rapid Parallel Attentional Target Selection in Single-Color and Multiple-Color Visual Search. *Journal of Experimental Psychology : Human Perception and Performance*, *41*(1), 86–101.

Han, S. H., & Kim, M. S. (2004). Visual search does not remain efficient when executive working memory is working. *Psychological Science*, *15*(9), 623–628. https://doi.org/10.1111/j.0956-7976.2004.00730.x

Hoffman, J. E., & Nelson, B. (1981). Spatial selectivity in visual search. *Perception & Psychophysics*, *30*(3), 283–290. https://doi.org/10.3758/BF03214284

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787–795.

https://doi.org/10.3758/BF03206794

Hollingworth, A., & Beck, V. M. (2016). Memory-Based Attention Capture when Multiple Items are Maintained in Visual Working Memory. *Journal of Experimental Psychology. Human Perception and Performance*, *42*(7), 319–335. https://doi.org/10.1037/xhp0000230

Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature*, *394*(6693), 575–577. https://doi.org/10.1038/29068

Hout, M. C., & Goldinger, S. D. (2010). Learning in repeated visual search. *Attention, Perception & Psychophysics*, *72*(5), 1267–1282. https://doi.org/10.3758/APP

Hout, M. C., & Goldinger, S. D. (2015). Target templates: How the precision of mental representations affects attentional guidance and decision-making in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *77*, 128–149. https://doi.org/10.1037/a0023894

Houtkamp, R., & Roelfsema, P. R. (2009). Matching of visual input to only one item at any one time. *Psychological Research*, *73*(3), 317–326. https://doi.org/10.1007/s00426-008-0157-3

Irons, J. L., & Leber, A. B. (2018). Characterizing individual variation in the strategic use of attentional control. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(10), 1637–1654. https://doi.org/10.1037/xhp0000560

Irons, J. L., & Leber, A. B. (2020). Developing an Individual Profile of Attentional Control Strategy. *Current Directions in Psychological Science*, *29*(4), 364–371. https://doi.org/10.1177/0963721420924018

Irwin, D. E., & Zelinsky, G. J. (2002). Eye movements and scene perception: Memory for

things observed. *Perception and Psychophysics*, *64*(6), 882–895. https://doi.org/10.3758/BF03196793

Ishihara, S. (1972). The Series of Plates Designed as a Tests for Colour-Blindness. *Nature*. Retrieved from http://adsabs.harvard.edu/abs/1910Natur..82Q.429E

Kiss, M., Grubert, A., & Eimer, M. (2013). Top-down task sets for combined features: Behavioral and electrophysiological evidence for two stages in attentional object selection. *Attention, Perception & Psychophysics*, *75*, 216–228. https://doi.org/10.3758/s13414-012-0391-z

Kiss, M., Grubert, A., Petersen, A., & Eimer, M. (2012). Attentional Capture by Salient Distractors during Visual Search Is Determined by Temporal Task Demands. *Journal of Cognitive Neuroscience*, *24*(3), 749–759. https://doi.org/10.1162/jocn_a_00127

Krupinski, E. A. (2010). Current perspectives in medical image perception. *Attention, Perception & Psychophysics*, *72*(5), 1205–1217. https://doi.org/10.3758/APP

Krupinski, E. A., Tillack, A. A., Richter, L., Henderson, J. T., Bhattacharyya, A. K., Scott, K. M., … Weinstein, R. S. (2006). Eye-movement study and human performance using telepathology virtual slides. Implications for medical education and differences with experience. *Human Pathology*, *37*(12), 1543–1556. https://doi.org/10.1016/j.humpath.2006.08.024

Kundel, H. L., Nodine, C. F., & Carmody, D. (1978). Visual scanning, pattern recognition and decision-making in pulmonary nodule detection. *Investigative Radiology*, *13*(3), 175—181. https://doi.org/10.1097/00004424-197805000-00001

Lee, C. S., Nagy, P. G., Weaver, S. J., & Newman-Toker, D. E. (2013). Cognitive and

system factors contributing to diagnostic errors in radiology. *American Journal of Roentgenology*, *201*(3), 611–617. https://doi.org/10.2214/AJR.12.10375

Lee, J., & Geng, J. J. (2019). Flexible weighting of target features based on distractor context. *Attention, Perception, & Psychophysics*, 1–13. https://doi.org/https://doi.org/10.3758/s13414-019-01910-5 40

Liu, X., Gale, A., & Song, T. (2007). Detection of Terrorist Threats in Air Passenger Luggage: Expertise Development. *IN: 41st Annual IEEE International Carnahan Conference on Security Technology, Ottawa, Ontario*, *8–11*(October), 301–306.

Lynn, J., & Shin, M. (2015). Strategic top-down control versus attentional bias by previous reward history. *Attention, Perception, & Psychophysics*, (77), 2207–2216. https://doi.org/10.3758/s13414-015-0939-9

Machizawa, M. G., Goh, C. C. W., & Driver, J. (2012). Human Visual Short-Term Memory Precision Can Be Varied at Will When the Number of Retained Items Is Low. *Psychological Science*, *23*(6), 554–559. https://doi.org/10.1177/0956797611431988

Makovski, T., & Jiang, Y. V. (2010). Contextual cost: When a visual-search target is not where it should be. *Quarterly Journal of Experimental Psychology*, *63*(2), 216–225. https://doi.org/10.1080/17470210903281590

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, *22*(6), 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception and Psychophysics*, *58*(7), 977–991. https://doi.org/10.3758/BF03206826

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *27*(3), 817–835. https://doi.org/10.1037/0278-7393.27.3.817

Menneer, T., Barrett, D. J. K., Phillips, L., Donnelly, N., & Cave, K. R. (2007). Costs in Searching for Two Targets: Dividing SearchAcross Target Types Could Improve Airport SecurityScreening. *Applied Cognitive Psychology*, *21*(December 2006), 1057–1075. https://doi.org/10.1002/acp

Menneer, T., Cave, K. R., & Donnelly, N. (2009). The Cost of Search for Multiple Targets: Effects of Practice and Target Similarity. *Journal of Experimental Psychology: Applied*, *15*(2), 125–139. https://doi.org/10.1037/a0015331

Menneer, T., Cave, K. R., Kaplan, E., Stroud, M. J., Chang, J., & Donnelly, N. (2019). The relationship between working memory and the dual-target cost in visual search guidance. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(7), 911–935. https://doi.org/10.1037/xhp0000643

Menneer, T., Donnelly, N., Godwin, H. J., & Cave, K. R. (2010). High or low target prevalence increases the dual-target cost in visual search. *Journal of Experimental Psychology. Applied*, *16*(2), 133–144. https://doi.org/10.1037/a0019569

Menneer, T., Stroud, M. J., Cave, K. R., Li, X., Godwin, H. J., Liversedge, S. P., & Donnelly, N. (2012). Search for two categories of target produces fewer fixations to target-color items. *Journal of Experimental Psychology. Applied*, *18*(4), 404–418. https://doi.org/10.1037/a0031032

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*(1), 1–17.

https://doi.org/10.3758/BF03211845

Murthy, A., Thompson, K. G., & Schall, J. D. (2001). Dynamic dissociation of visual selection from saccade programming in frontal eye field. *Journal of Neurophysiology*, *86*(5), 2634–2637. https://doi.org/10.1152/jn.2001.86.5.2634

Nagy, A. L., & Sanchez, R. R. (1990). Critical color differences determined with a visual search task. *Journal of the Optical Society of America A*, *7*(7), 1209. https://doi.org/10.1364/josaa.7.001209

Navalpakkam, V., & Itti, L. (2006). Top-down attention selection is fine grained. *Journal of Vision*, *6*, 1180–1193. https://doi.org/10.1167/6.11.4

Navalpakkam, V., & Itti, L. (2007). Search Goal Tunes Visual Features Optimally. *Neuron*, *53*(4), 605–617. https://doi.org/10.1016/j.neuron.2007.01.018

Nodine, C. F., & Kundel, H. L. (1987). Using eye movements to study visual search and to improve tumor detection. *Radiographics*, *7*(6), 1241–1250. https://doi.org/10.1148/radiographics.7.6.3423330

Nodine, C. F., Kundel, H. L., Mello-Thoms, C., Weinstein, S. P., Orel, S. G., Sullivan, D. C., & Conant, E. F. (1999). How experience and training influence mammography expertise. *Academic Radiology*, *6*(10), 575–585. https://doi.org/10.1016/S1076-6332(99)80252-9

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 411–421. https://doi.org/10.1037//0278-7393.28.3.411

Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in*

Cognitive Sciences, *15*(7), 327–334. https://doi.org/10.1016/j.tics.2011.05.004

Ort, E., Fahrenfort, J. J., & Olivers, C. N. L. (2017). Lack of Free Choice Reveals the Cost of Having to Look for More Than One Object. *Psychological Science*, 1–25. https://doi.org/10.1177/0956797617705667

Peltier, C., & Becker, M. W. (2017). Eye movement feedback fails to improve visual search performance. *Cognitive Research: Principles and Implications*, *2*(1), 47. https://doi.org/10.1186/s41235-017-0083-2

Peterson, M. S., & Kramer, a F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception & Psychophysics*, *63*(7), 1239–1249. https://doi.org/10.3758/BF03194537

Pomplun, M. (2006). Saccadic selectivity in complex visual search displays. *Vision Research*, *46*(12), 1886–1900. https://doi.org/10.1016/j.visres.2005.12.003

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Proulx, M. J. (2011). Individual differences and metacognitive knowledge of visual search strategy. *PLoS ONE*, *6*(10). https://doi.org/10.1371/journal.pone.0027043

Reeder, R. R., & Peelen, M. V. (2013). The contents of the search template for category-level search in natural scenes. *Journal of Vision*, *13*(3), 13–13. https://doi.org/10.1167/13.3.13

Reijnen, E., Wallach, D., Stöcklin, M., Kassuba, T., & Opwis, K. (2007). Color similarity in visual search. *Swiss Journal of Psychology*, *66*(4), 191–199. https://doi.org/10.1024/1421-0185.66.4.191

Rich, A. N., Kunar, M. A., Van Wert, M. J., Hidalgo-Sotelo, B., Horowitz, T. S., &

Wolfe, J. M. (2008). Why do we miss rare targets? Exploring the boundaries of the low prevalence effect. *Journal of Vision*, *8*(15), 15–15. https://doi.org/10.1167/8.15.15

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, *84*(1), 1–66. https://doi.org/10.1037/0033-295X.84.1.1

Schunn, C. D., & Reder, L. M. (2001). Another source of individual differences: Strategy adaptivity to changing rates of success. *Journal of Experimental Psychology: General*, *130*(1), 59–76. https://doi.org/10.1037/0096-3445.130.1.59

Schwark, J. D., Dolgov, I., Sandry, J., & Volkman, C. B. (2013). Simultaneous attentional guidance by working-memory and selection history reveals two distinct sources of attention. *Acta Psychologica*, *144*(2), 269–278. https://doi.org/10.1016/j.actpsy.2013.06.017

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological*, *84*(2), 127–190. https://doi.org/10.1037/0033-295X.84.2.127

Sobel, K. V., & Cave, K. R. (2002). Roles of Salience and Strategy in Conjunction Search. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1055–1070. https://doi.org/10.1037/0096-1523.28.5.1055

Sobel, K. V., Pickard, M. D., & Acklin, W. T. (2009). Using feature preview to investigate the roles of top-down and bottom-up processing in conjunction search. *Acta Psychologica*, *132*(1), 22–30. https://doi.org/10.1016/j.actpsy.2009.06.003

Sternberg, R. J., & Grigorenko, E. L. (1997). Are cognitive styles still in style? *American*

Psychologist, *52*(7), 700–712. https://doi.org/10.1037/0003-066X.52.7.700

Stroud, M. J., Menneer, T., Cave, K. R., & Donnelly, N. (2012). Using the dual-target cost to explore the nature of search target representations. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 113–122. https://doi.org/10.1037/a0025887

Stroud, M. J., Menneer, T., Kaplan, E., Cave, K. R., & Donnelly, N. (2018). We can guide search by a set of colors, but are reluctant to do it. *Attention, Perception, and Psychophysics*. https://doi.org/10.3758/s13414-018-1617-5

Theeuwes, J. (1991). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception & Psychophysics*, *49*(1), 83–90. https://doi.org/10.3758/BF03211619

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*(6), 599–606. https://doi.org/10.3758/BF03211656

Theeuwes, J. (2018). Visual Selection: Usually Fast and Automatic; Seldom Slow and Volitional. *Journal of Cognition*, *1*(1), 1–15. https://doi.org/10.5334/joc.13

Theeuwes, J. (2019). Goal-driven, stimulus-driven, and history-driven selection. *Current Opinion in Psychology*, *29*, 97–101. https://doi.org/10.1016/j.copsyc.2018.12.024

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

van Moorselaar, D., Theeuwes, J., & Olivers, C. N. L. (2014). In competition for the attentional template: Can multiple items within visual working memory guide attention? *Journal of Experimental Psychology: Human Perception and*

Performance, *40*(4), 1450–1464. https://doi.org/10.1037/a0036229

Verghese, P., & Nakayama, K. (1994). Stimulus Discriminability in Visual Search. *Vision Res*, *34*(18), 2453–2461.

Vickery, T. J., King, L.-W., & Jiang, Y. (2005). Setting up the target template in visual search. *Journal of Vision*, *5*(1), 81–92.

Wallis, M. G., Walsh, M. T., & Lee, J. R. (1991). A review of false negative mammography in a symptomatic population. *Clinical Radiology*, *44*(1), 13–15. https://doi.org/10.1016/S0009-9260(05)80218-1

Welch, B. L. (1947). The generalization ofstudent's' problem when several different population variances are involved. *Biometrika*, *34*(1/2), 28–35.

Wiegand, I., & Wolfe, J. (2018). Hybrid visual and memory search is preserved in older age. *Journal of Vision*, *18*(10), 531. https://doi.org/10.1167/18.10.531

Wolfe, J. M. (1994). Guided Search 2 . 0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238.

Wolfe, J. M. (2007). Guided Search 4 . 0 Current Progress With a Model of Visual Search. *Integrated Models of Cognitive Systems*, 99–120. https://doi.org/10.1167/1.3.349

Wolfe, J. M. (2012). Saved by a Log. *Psychological Science*, *23*(7), 698–703. https://doi.org/10.1177/0956797612443968

Wolfe, J. M., Butcher, S. J., Lee, C., & Hyle, M. (2003). Changing Your Mind: On the Contributions of Top-Down and Bottom-Up Guidance in Visual Search for Feature Singletons. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 483–502. https://doi.org/10.1037/0096-1523.29.2.483

Wolfe, J. M., Cain, M. S., & Aizenman, A. M. (2019). Guidance and selection history in hybrid foraging visual search. *Attention, Perception, and Psychophysics*, *81*(3), 637–653. https://doi.org/10.3758/s13414-018-01649-5

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided Search: An Alternative to the Feature Integration Model for Visual Search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 419–433. https://doi.org/10.1037/0096-1523.15.3.419

Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. *Nature Human Behaviour*, *1*(3), 1–8. https://doi.org/10.1038/s41562-017-0058

Wolfe, J. M., Horowitz, T. S., Kenner, N., Hyle, M., & Vasan, N. (2004). How fast can you change your mind? The speed of top-down guidance in visual search. *Vision Research*, *44*(12), 1411–1426. https://doi.org/10.1016/j.visres.2003.11.024

Wolfe, J. M., Horowitz, T. S., Palmer, E. M., Michod, K. O., Van Wert, M. J., & Wolfe, J. (2010). Getting in to Guided Search. *Tutorials in Visual Cognition*, (January), 93–119.

Won, B. Y., Haberman, J., Bliss-Moreau, E., & Geng, J. J. (2020). Flexible target templates improve visual search accuracy for faces depicting emotion. *Attention, Perception, and Psychophysics*. https://doi.org/10.3758/s13414-019-01965-4

Woodman, G. F., & Arita, J. T. (2011). Direct Electrophysiological Measurement of Attentional Templates in Visual Working Memory. *Psychological Science*, *22*(2), 212–215. https://doi.org/10.1177/0956797610395395

Woodman, G. F., Carlisle, N. B., & Reinhart, R. M. G. (2013). Where do we store the memory representations that guide attention? *Journal of Vision*, *13*(3), 1–1.

https://doi.org/10.1167/13.3.1

Woodman, G F, Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*(3), 219–224. https://doi.org/10.1111/1467-9280.00339

Woodman, Geoffrey F, Carlisle, N. B., & Reinhart, R. M. G. (2013). Where do we store the memory representations that guide attention? *Journal of Vision*, *13*(3), 1–17. https://doi.org/10.1167/13.3.1

Yamani, Y., Samuel, S., Knodler, M. A., & Fisher, D. L. (2016). Evaluation of the effectiveness of a multi-skill program for training younger drivers on higher cognitive skills. *Applied Ergonomics*, *52*, 135–141. https://doi.org/10.1016/j.apergo.2015.07.005

Yantis, S. (1993). Stimulus-Driven Attentional Capture and Attentional Control Settings. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(3), 676–681. https://doi.org/10.1037/0096-1523.19.3.676

Zelinsky, G. J., & Sheinberg, D. L. (1997). Eye Movements during Parallel-Serial Visual Search. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(1), 244–262. https://doi.org/10.1037/0096-1523.23.1.244