Why is it Difficult to Search for Two Colors at Once? How Eye Movements Can Reveal the Nature of Representations During Multi-target Visual Search

WHY IS IT DIFFICULT TO SEARCH FOR TWO COLORS AT ONCE? HOW EYE MOVEMENTS CAN REVEAL THE NATURE OF REPRESENTATIONS DURING MULTI-TARGET VISUAL SEARCH

A Dissertation Presented

By

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ABSTRACT

WHY IS IT DIFFICULT TO SEARCH FOR TWO COLORS AT ONCE? HOW EYE MOVEMENTS CAN REVEAL THE NATURE OF REPRESENTATIONS DURING MULTI-TARGET VISUAL SEARCH

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Visual search consists of locating a known target amongst a field of distractors. Often times, observers must search for more than one object at once. Eye movements were monitored in a series of visual search experiments examining search efficiency and how color is represented in order to guide search for multiple targets. The results demonstrated that observers were very color selective when searching for a single color. However, when searching for two colors at once, the degree of similarity between the two target colors had varying effects on fixation patterns. Search for two very similar colors was almost as efficient as search for a single color. As this similarity between the targets deceased, search efficiency suffered, resulting in more fixations on objects dissimilar to both targets. In terms of representation, the results suggest that the guiding template or templates prevailed throughout search, and were relatively unaffected by the objects encountered. Fixation patterns revealed that two similarly colored objects may be represented as a single, unitary range containing the target colors as well as the colors in between in color space. As the degree of similarity between the targets decreased, the two targets were more likely to be represented as discrete separate templates.

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CHAPTER 1

INTRODUCTION

Envision assembling a jigsaw puzzle of the planet Earth. Puzzles typically consist of several pieces that are different shapes and different colors. At the beginning stages of assembling the puzzle, you have the end goal in mind with many oddly shaped and different colored pieces. You decide that the best strategy is to first concentrate your efforts on completing the water and search for pieces that are primarily blue. As you complete more of the water, you determine the approximate shape of the pieces you need as well. When you search through the pile of pieces, you most likely will come across some pieces that are blue, but not the correct shape, others that are not blue, but match the correct shape, and still others that are neither blue nor an appropriate shape. In order to be successful in this type of search, one must be able to attend to objects that share a combination of features that comprise the intended target, while simultaneously ignoring objects that do not fit the target criteria.

As you complete more of the puzzle, you decide to start putting together more than just the water. In an attempt to complete the puzzle more efficiently, you begin to search for more than one piece at a time. You notice that the remaining pieces can be distinguished from one another by color: different shades of blue for water; greens and browns for land; and white for ice. The task is now considerably more difficult while you attempt to search for multiple colors simultaneously. The scattered pieces in front of you share differing amounts of information associated with both of the target pieces, and thus receive limited amounts of processing resources. You begin to question whether it is

more efficient to search for multiple colors simultaneously, or to conduct separate individual searches for each piece one after another.

The scenario described above is one example of the many possible tasks that are collectively referred to as visual search. One important question involved in these types of tasks is how the human visual system efficiently guides search to fulfill the goal or goals of the observer. The puzzle is an example of an everyday visual search task for multiple objects. However, there are many other instances in which searching for multiple objects is necessary. Drivers are constantly bombarded by a number of different stimuli, and typically more than one object is of interest. For instance, an early morning commuter may be searching for a place to get coffee as well as an open parking space. Or perhaps a place to get fuel and a place for breakfast? In a more critical setting, airport security screeners are given a very limited amount of time to search for objects that differ in shape, size, color and orientation. Costs or breakdowns associated with searching for multiple items at once can be detrimental and at worst catastrophic. In simultaneous search for multiple objects, what conditions are necessary to produce a benefit or result in a cost compared to searching for the individual targets separately? The current project is aimed at exploring the dynamics of search for multiple targets.

The current investigation will primarily examine how search may be guided across the single feature dimension of color (see Wolfe and Horowitz, 2004 for review regarding guiding features). For the purposes of this paper, a dimension is defined as a set of feature values of a particular type. For example, red, green, blue and orange are all features within the dimension of color. When searching for different colored puzzle pieces, is it better to search for similarly colored pieces (*e.g.* the different shades of blue

in the ocean), or pieces that are different colors (*e.g.* the blue of the ocean and the green of the land)? The answer appears to be based on a number of different factors, from the observer's representation of the target (top-down) to the characteristics of the actual objects (bottom-up). It is the interaction between these two levels of information that influences search (Findlay & Walker, 1999; Wolfe, Cave & Franzel, 1989).

Focusing on the top-down, conceptually driven contribution, a main goal of the current project is to investigate how these representations are maintained in order to guide search. Consider how the observer represents these colors in memory to guide search. There are at least three plausible hypotheses to explain how two targets within the same dimension are represented. The first hypothesis predicts that two targets may be represented as separate templates that are held in memory concurrently, and search proceeds in a functionally *parallel* manner (Moore & Osman, 1993). In this case, parallel does not refer to the preattentive scanning of a display, but rather to the simultaneous maintenance of both target representations, with the two guiding search concurrently. This scenario will be referred to as the 'simultaneous' hypothesis. The second possibility is that a separate template is constructed for each target and the observer alternates between each representation. According to this hypothesis, search would only be guided by one object at a time. This would result in a somewhat less efficient search pattern, with attention drawn to objects sharing the target features, but with search occurring in a functionally *serial* manner, in the sense that control switches between target templates with search being guided by one target after another. This will be referred to as the 'alternating' hypothesis. Quinlan and Humphreys (1987) suggested that search for multiple targets may occur via a process that either switches between objects or

dimensions, with certain dimensions affording easier switching than others. The final hypothesis is that a 'target range' is created that includes the two target features and the entire set of features between them in the relevant feature space (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Menneer, Cave & Donnelly, 2009). That is, if one target was the color blue and the other target was the color red, a target range would contain every color within the spectrum of colors falling between blue and red (e.g. purple). This would result in inefficient search, with attention being drawn to objects that are dissimilar from either target objects. However, this would afford the advantage of requiring only one template. This will be referred to as the range hypothesis.

The following review of the relevant literature is separated into three main components: 1) theories and models of visual search, 2) eye movements and saccadic selectivity, and 3) search for multiple targets. A discussion of visual search will provide the context for the current investigation while an analysis of saccadic selectivity will lend to a more in-depth look into the dynamics involved in visual search. Finally, highlighting conditions in which multi-target search can be efficient and inefficient will lead to a deeper understanding of how these multiple targets are represented.

Visual Search

The jigsaw puzzle is an example of a rather complex visual search in which both the targets and the distractors share a number of different properties. To explore the cognitive processes involved in visual search, it is important to utilize objects with features that can be carefully controlled in an experimental setting. A classic puzzle piece-shaped object may contain numerous curves and edges containing multiple features, whereas basic shapes such as squares or letters contain features that are easier to

control and manipulate. With a higher level of control, researchers can isolate properties that guide search. A large body of research has utilized these basic stimuli in order to characterize the mechanisms underlying visual search. One of the main goals of this research is to understand the allocation of attention throughout the search process.

During visual search, attention can be allocated either covertly or overtly. Covert attention refers to the distributing of resources, in the absence of eye movements, to a particular location of interest. Conversely, overt attention is the act of directing the eyes to a specific location or object. Understanding how these two processes interact will reveal a more complete picture of visual search. The first series of experiments and theories summarized below attempt to characterize the spread of covert attention in visual search. These studies utilize two types of search, feature and conjunction search, which have been the topic of a multitude of studies spanning almost three decades (Treisman & Gelade, 1980).

In feature search, the target is defined by a single feature that is not present in any of the distractors. For example, if an observer is searching for a blue T amongst red Ts, the defining feature of color will guide search. Most feature searches result in what is called ‘pop-out’, in which the target is located quickly and automatically based on the defining feature. Search is very efficient and search times are independent of the number of objects in the display. Based on these results, it appears that the visual system is tuned to automatically detect salient, isolated features. However, when a target is defined by a combination of more than one feature, search is much more difficult. Searches like these are referred to as conjunction searches and are characterized by a target containing the combination, or conjunction, of two or more features.

In conjunction searches, the target is defined by the combination of two features and some distractors share one of the target features while other distractors share the other feature, making search more difficult compared to feature search. If an observer is searching for the same blue T, but this time among red Ts and blue Ls, the result is markedly different. Instead of the target being defined by the unique feature of color, it is defined by the combination of feature and shape. Some of the distractors are blue Ls, which share the feature of color with the target while some of the distractors are red Ts that share the feature of shape with the target. Conjunction searches are often much slower than feature searches, with attention being drawn to the features that are common to both the target and distractors. Search is hypothesized to proceed in a serial manner, with individual items (or perhaps small groups of items) receiving attention. Since individual features cannot be located automatically as in feature searches, a more focused analysis of the items is needed to locate the combination of features that defines the target. In this case, search for an individual feature will result in selection of multiple objects (as opposed to pop-out with feature search), which will be inefficient. Based on the results of studies utilizing the paradigm described above, several researchers have attempted to model this complex process of visual search.

There are several advantages in using these types of paradigms to study search. The composition of the stimulus objects and displays can be tightly controlled, as can the amount of time subjects view each array. The spread of attention is inferred based on the amount of time it takes for a subject to respond, and the accuracy of those responses. However, there is no way of determining which specific objects received attention during search. This is one case in which the use of eye movements (discussed in the next

section), may hold an advantage. Nevertheless, many influential theories were based on the paradigms described above.

Several models of visual search can be traced back to Ulric Neisser (1967), who was amongst the first researchers to propose a multistage theory of attention. These models describe the search process as beginning with preattentive mechanisms that act together in parallel across the visual field, extracting the information necessary for focal attention. Then, through attentive mechanisms, visual objects are segmented from one another and subsequently identified. This framework is admittedly an oversimplification by Neisser, leading to many refinements. Hoffman (1979), for example, built upon Neisser's assumptions and proposed a more formal two-stage model of visual search. According to Hoffman, when presented with a display and the task of searching for an item embedded within a field of distractors, each item in the display is scanned in parallel and compared to the critical item or items held in memory. Each item is then hierarchically organized based on its similarity to the target and transferred by means of selective attention to a serial stage wherein each item is compared with the target until a response can be made.

Around the same time Hoffman (1979) set forth his model, Treisman and Gelade (1980) proposed what is arguably one of the most influential theories of visual search: Feature Integration Theory. Based on a similar framework to that of Hoffman (1979) and Neisser (1967), this theory describes visual search that proceeds via a two stage process, beginning with a preattentive stage that operates in parallel, followed by a serial stage that facilitates more difficult searches. Where the theory diverges from previous iterations is the emphasis on separable features. According to the theory, feature

detection occurs early on in the preattentive stage, whereas conjunctions of multiple features require attention and thus serial processing. The important aspect of Feature Integration Theory is that search takes place in two distinct, separate search stages. Feature Integration Theory was a parsimonious theory that accounted for an abundance of results of various feature and conjunction search tasks that were available at the time. However, Feature Integration could not account for later evidence that demonstrated shallower search slopes in certain types of conjunction searches (Nakayama & Silverman, 1986; Wolfe, et al., 1989; Cave & Wolfe, 1990). Treisman and Sato (1990) investigated this further and claimed that these results were most likely due to a mechanism that separates a display into sets of likely distractors, allowing the set containing the target to be scanned via a feature search. This separation may occur based on objects containing features within the display that are clearly not contained in the target.

Given the constraints placed on Feature Integration based on these results, Wolfe, et al. (1989) developed a more comprehensive model that built upon Feature Integration and extended the two stages to include a "carryover" of information from the parallel to the serial stage. Their model for visual search was aptly named *Guided Search*, which uses the features extracted in the parallel phase and interactions of top-down and bottom-up mechanisms to *guide* search in the serial phase. Features such as color and orientation, or perhaps even entire objects (Wolfe, 1996) are utilized by parallel mechanisms to segregate displays to further guide the serial mechanisms. Top-down guidance occurs through a target template representation held in working memory, whereas bottom-up guidance is driven by the stimulus properties that together direct the focus of attention. However, it is worth noting that several researchers have challenged

the claim that conjunction searches are even operating via serial mechanisms and contend that some searches may be carried out by a limited capacity parallel mechanism. (Townsend, 1990; see also Thornton & Gilden, 2007 for a review).

Recall that attention can be allocated either covertly or overtly. As mentioned previously, a considerable amount of research is devoted to examining the spread of covert attention. A common measure of covert attention involves measuring reaction times to an attentional 'probe' or spatial cue briefly presented to a stimulus display. Through such measures, covert attention has been likened to a moving spotlight (see Cave & Bichot, 1999 for a review) or a more flexible 'zoom-lens' (C.W. Eriksen & St. James, 1986; C.W. Eriksen & Yeh, 1985; Laberge, 1983). Other evidence has demonstrated that the spread of covert attention may be task-specific, and could resemble more of a graded distribution with the highest level of processing at the center, while slowly degrading in resolution with increasing distance from the focus of attention (Downing, 1988; Downing and Pinker, 1985; Henderson, 1991; Hughes & Zimba, 1985; Laberge and Brown, 1986; Laberge and Brown, 1989). More recently, ERP methods, which provide a direct measure of brain activity based on the electrical potentials across the scalp, have focused on determining the components associated with the shifts of covert attention (Eimer, van Velzen, Forster & Driver, 2003; Harter, Miller, Price, & Lalonde, 1989; Mangun & Hillyard, 1991; Nobre, Sebestyen, Miniussi, 2000; Talsma, Slagter, Nieuwenhuis, Hage, & Kok, 2005). While these methods have provided converging evidence regarding the dynamics of spatial attention, a detailed discussion is outside the scope of this investigation. More germane to the current project, overt attention is easily monitored by examining the various characteristics of saccades and

fixations. Many researchers suggest a strong link between covert and overt attentional mechanisms; however the nature of this relationship is cause for much debate. The current investigation will utilize traditional measures of response time and accuracy as well as the eye movement records of subjects during a visual search task. What follows is a discussion of visual search studies that have focused on measures of eye movements.

Eye Movements and Visual Search

The complexities of search behavior are not captured solely by measures of the time taken to inspect an array and register a button press (Zelinsky, et al., 1997). These measures can be augmented by eyetracking. Eye movements are characterized by brief periods of steady fixations, separated by rapid movements called saccades (see Rayner, 1998, for a review). The majority of information is acquired during these fixations, although some may argue that processing can continue across saccades (Irwin, Carlson-Radvansky & Andrews, 1995; Irwin, 1998; Irwin & Gordon, 1998). Eye movements have been shown to contain a rich source of information that some argue contain all the necessary information contained in reaction time studies (Williams, Reingold, Moscovitch & Behrmann 1997; Zelinsky, Rao, Hayhoe & Ballard, 1997). Specifically, high correlations were found between the number of saccades made and response times during search (Zelinsky & Sheinberg, 1997). Although covert attention may be independent of eye movements, it can confidently be said that if an object is fixated, that object was the focus of attention at some point during the trial (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Irwin, 1992; Henderson, 1996; Henderson, Pollatsek & Rayner, 1989).

An abundance of research has demonstrated that visual attention and saccadic eye movements are closely related (Deubel & Schneider, 1996; Hoffman & Subramanian, 1995). During search, visual attention precedes a saccade to a stimulus location and the two mechanisms are coupled to the extent that attention guides eye movements toward the intended object. This orienting of attention prior to an eye movement appears obligatory and Henderson, et al. (1989) concluded that the two processes are "functionally, though not structurally linked (p.205)." That is, although attention is necessary to direct an eye movement, it may be that the two rely on separate underlying mechanisms. Given this relationship between attention and eye movements, a fixated object has probably received covert attention at some point prior to the arrival of the saccade. Thus, by monitoring eye movements, one can obtain at least a partial record of the areas of a display in which attention has visited, knowing that attention must have preceded each fixation. The extent to which these two mechanisms are linked has been the focus of further research.

Eye movement methods have been applied to theories of attention. Parker (1978) proposed a multi-stage theory of object processing similar to Feature Integration Theory and Guided Search. He utilized a change-detection paradigm in which subjects were required to identify the presence or absence of an object that was either moved or removed in between two presentations of the display. The model is similar to the perceptual cycle developed by Neisser (1971), which describes a process of object recognition that progresses from covert identification of objects to the guidance of an eye movement. Even when the object of interest was removed in between display presentations, a saccade still continued to that previously occupied location on some

trials, giving evidence that the eye movement was either programmed in advance or could not be inhibited once initiated/programmed. Parker added that although information entering the periphery is degraded compared to the acuity of the fovea, extrafoveal processing may be sufficient. This is a very stimulus-driven model and these results may be partially accounted for through the Guided Search model in that the acquisition of information in the periphery may correspond to the bottom-up activation that guides search. Parker does not go into great lengths regarding top-down guidance, but does mention that expectations are developed upon viewing the target. The question arises as to what extent covert visual attention is involved in the processing of displays requiring multiple saccades.

While the models of visual search make clear predictions regarding serial and parallel search, most do not incorporate contributions from eye movements. Although some of the previous studies discussed included long exposure times, allowing multiple eye movements, measures of eye tracking were not integrated in the designs. Feature Integration Theory (Treisman & Gelade, 1980) and Guided Search (Wolfe et al., 1989) make strong claims regarding the movement of attention in search, but there is ambiguity as to how much of this movement is covert and how much is eye movements. Zelinsky and colleagues took the first steps towards investigating the role of eye movements in search by proposing that eye movement measures were strongly linked to reaction time behavior (Zelinsky, 1996; Zelinsky, Roa, Hayhoe, & Ballard, 1997; Zelinsky & Sheinberg, 1997).

Eye movement methods allow for a wealth of dependent measures that characterize the eyes' behavior. Saccades are typically measured in terms of length and

fixations are measured in terms of the amount of time spent at a specific location. Other common measures include the average number of fixations made per trial as well as the latency before an initial saccade is made. Zelinsky and Sheinberg (1997) determined that the most sensitive measure to index parallel and serial search behavior was the number of fixations rather than the average fixation duration. This does not imply that fixation durations are a useless measure, as they discovered a trend with the initial saccade latencies reflecting a dichotomous serial/parallel distinction. Zelinsky and Sheinberg speculate that when information can be extracted in parallel, latency to make an eye movement is greatly reduced. However, if search requires a more global, covert analysis, then perhaps more focused scanning is needed, leading to longer latencies before leaving the initial central location. As an appropriate control, a condition was included to test whether eye movements were actually necessary to complete their parallel and serial search tasks. The results confirmed that the task in their experiments could be completed with equal success with or without the benefits of eye movements. This control was implemented for two purposes: 1) to confirm that the task they employed reflected parallel and serial search patterns with a more traditional dependent measure (RT) and 2) that eye movements may not have been necessary in their task, but subjects chose to use them as part of a natural search behavior. What is critical is that a strong link between eye movements and traditional RT analyses was observed under the appropriate experimental setting. Although the current project is not designed to compare serial and parallel search, it does rely on the assumption put forth by Zelinsky and et al., (1997) that eye movements will characterize the search process in ways that RT and error analyses alone cannot.

Because measures of eye movements give both a temporal and spatial component of search, it is possible to measure not only the relative contributions of top-down and bottom-up processes, but also at what point in search each mechanism dominates. Utilizing similar methods, Van Zoest and Donk (2006) provided converging evidence that it is erroneous to think that either top down or bottom up dominate in a given time window, but rather stimulus control (bottom up) operates early in saccadic selection and goal driven control (top down) assumes control later in saccadic selection. They demonstrated that saccadic selection was more influenced by stimulus salience for fast eye movements only, whereas target-distractor similarity influenced saccadic selection later in time (and consequently had no effect on fast eye movements). Together both Zelinsky and et al., (1997) and Van Zoest and Donk demonstrate that both bottom up and top down mechanisms are important for saccadic selectivity, but that they may operate in different time windows.

The models of visual search discussed earlier predict that search may proceed via two stages, and that targets can be identified in parallel or with serial inspection. Zelinsky et al., (1997) set out to determine if eye movements could be used to index such search behaviors by utilizing a visual search task that produced typical response time serial search slopes. The results demonstrated the expected pattern of behavior based on RT paradigms, which suggested that each item was attended to in a serial fashion. However, the eye movement behavior revealed something quite different. Typically, the initial saccades exhibited what is known as the “center of gravity” effect (also known as the global effect), in which a fixation is directed to the middle of a group of objects of interest, even though no objects appeared near that location. The second fixation landed

closer to the object of interest, but it was not until the third fixation that the target was directly analyzed. The key factor missing from the observed scanpaths was any evidence of a serial process directing search towards individual objects in the display. What the results did suggest was a spread of attention occurring on a global scale and proceeding to a more local analysis.

In terms of the already established search theories, their results suggested something more along the lines of Guided Search with a gradual progression from a parallel analysis to a more serial analysis (Zelinsky et al., 1997). As the set sizes increased, there appeared to be more of a reliance on this center of gravity strategy. Interestingly, when only one object was present, subjects still directed their initial fixation to the center of the display. Zelinsky et al., interpreted this as reflecting the entire stimulus display space as being relevant to each search task regardless of the number of items present. It is important to note that only set sizes of 1, 3 and 5 were utilized, when typically research of this kind involves much larger set sizes. In a control similar to that utilized by Zelinsky and Sheinberg (1996), subjects were required to complete the task without making any eye movements. The only quantitative difference between the two experiments was an increase in false alarms in the eye movement condition. The results demonstrated that this task could also be completed with equal efficiency with and without eye movements, further strengthening the claim that although eye movements may not be necessary to complete some tasks, eye movements are a part of the natural search behavior.

In another test of the center of gravity effect, Findlay and Brown (1996) developed a rather unique paradigm that required subjects to scan every item in a display

while monitoring for a specific two digit number. A display consisted of multiple circles each inscribed with a two digit number. Subjects had to first fixate a circle in the upper left hand corner, which contained the 'target number' to scan for throughout the trial. Subjects then were required to fixate every circle and to keep track of how many times the target number appeared. The last thing the subject had to do was fixate a circle at the lower right of the display and determine if the number in that circle matched the number of instances of the target number found during that trial. Findlay and Brown determined that selection occurred via 'spatial selection' in this task because the similarity between the objects made selection by features impossible.

When two potential objects occupied relatively similar locations, the center of gravity effect took shape (Findlay & Brown, 2006). In other words, as the circles appeared closer to each other, the saccades landed increasingly closer to the midpoint between the two objects. The object closest to fixation was considered the intended landing point of the saccade, while any other object within a specified range was viewed as a distractor. Inaccurate saccades generally landed somewhere between the target circle and a distractor circle. Although the fixation landed closer to the target, the direction of the saccade on the majority of these instances (75%) was in line with the distractor. Fixations preceding an inaccurate 'global effect' saccade were longer than average fixations, suggesting that more time is spent covertly scanning before a saccade is made. This may also reflect a process by which after a certain amount of time expires, a saccade must be made. Findlay and Brown determined that the optimal saccadic accuracy occurred when a target was relatively in isolation, demonstrating that subjects are fairly good at identifying a potential target extrafoveally and subsequently planning an accurate

saccade. The presence of a nearby distractor contributed heavily to saccadic error. These results converge with those of Zelinsky et al. (1997) suggesting that attention gradually progresses from parallel to serial. Overall, it appears that saccades are fairly accurate and the system is able to scan multiple objects in parallel when deciding to execute a saccade to more than one object of interest.

Two principles have emerged out of this line of research: 1) There are conditions in which making eye movements is not exactly necessary, but the visual system still utilizes saccades as part of the natural search behavior, and 2) If multiple objects of interest are present in a display, sometimes the eyes are directed to the midpoint between these objects. These two notions lead to one obvious question: What is the optimal search strategy? If the eye movement system were to operate in an economical fashion, the center of gravity effect would make sense. It would be a waste of energy and resources to visit two locations of interest if all the necessary information could be gathered by fixating a location in between the two objects. Also, if all of the necessary information can be obtained without moving the eyes, then attention should operate through covert mechanisms only. However, visual search is much more complex than simply holding the eyes stationary, and many factors influence whether enough information could be extracted from the center of two objects, including task difficulty, acuity, top-down processing, bottom-up properties or any interaction of these. This leads back to the question regarding the relationship between covert and overt attentional mechanisms.

Covert and Overt Attention

According to a wealth of research, it appears as though covert and overt attentional mechanisms are complementary processes (Findlay, 1997; Findlay, Brown & Gilchrist, 2000; Findlay & Gilchrist, 2003). Findlay and Walker (1999) proposed a multi-level model attempting to explain the process of saccade generation based on parallel processing and competitive inhibition. Their model is at one extreme and assigns no role to an internal scanning process of covert attention. This is in sharp contrast with Feature Integration Theory and Guided Search, which provide accounts that do not separate the relative contributions of covert attention and eye movements. It is important to understand that while strong arguments can be made for both sides of this debate, it appears to be accepted that covert and overt attention are both operating at different time courses and functioning in a complementary fashion.

Covert attention operates on a much faster time scale than planning and executing an eye movement. In fact, multiple shifts of attention can be made in the 250 – 300 ms it takes to plan and execute an eye movement (Rayner, 1998). A long standing question revolves around the extent of the relationship between covert attention and eye movements. Findlay and Brown (2006) outlined three ways in which covert attentional processes might operate while selecting a target. The first is a location based account consistent with the spotlight metaphor of attention. Attention travels from location to location, and information falling within the beam is facilitated for further processing while information falling outside the beam is inhibited. Consistent with a physical spotlight, movement is tied to a controlled mechanism that is involved in planning and executing the movement of the beam. (Remington & Pierce, 1984; Shulman, Remington,

& McLean, 1979; Tsal, 1983 The second possibility is an object-based account in which selection occurs if bottom-up cues are present and strong enough in a display. Finally, they hypothesize that selection may occur based on separable features as a result of biased competition between the features present in the target. A searcher may develop a target template to guide search, which results in differing levels of neural competition based on the similarity between the target and the distractors. (Desimone & Duncan, 1995).

One of the main goals of the research on visual search is to understand the relationship between covert and overt attentional mechanisms. Although the current project will not directly address this issue, it will utilize eye movements to reveal information about how targets are represented to guide search. Through this, it will be determined how representation guides overt search towards specific objects. It may be possible that the same properties are guiding covert search, but the current design does not allow for this distinction to be made. The experiments presented here rely on the assumptions that these measures of eye movements are appropriate indices of visual search behavior as described previously. One of the main goals is to garner insight as to how the visual system represents two targets in order to guide search. In the proposed experiments, search behavior will be determined by analyzing the identity of the objects that are fixated throughout the experiment, which will provide an objective measure of selectivity based on the dimension of color. The current experiments will utilize a similar design and method to Stroud, Menneer, Cave, Donnelly and Rayner (submitted). Stroud et al. measured the probability that an object color was fixated one or more times during a trial. They determined that this was a more sensitive measure to index selectivity in this

type of search compared to more common measures of average fixation duration, average number of fixations and average saccade length. The current project will utilize the same method of analyzing data in an attempt to characterize selectivity similar to Stroud et al.

The act of programming an eye movement to an object of interest is a complex behavior based on a number of factors. What follows is a discussion of the research surrounding guidance and saccadic selectivity.

Guidance and Saccadic Selectivity

Feature Integration Theory describes how features in more difficult conjunction searches are extracted for further processing, and Guided Search shows how feature maps are activated across both stages of processing. These models make predictions regarding the spread of attention and incorporate very little discussion regarding eye movements. Given that eye movements are integral to the natural search behavior, it is important to identify what leads to the planning and execution of an eye movement. An obvious candidate for the basis of eye movement control is the separable features inherent to the models of visual search. Wolfe and Horowitz (2004) attempted to compose a "master list" of different features that guide attention in visual search. According to their work, objects were constructed of features that were defined as 'guiding' if they fulfilled a number of criteria: 1) they produced efficient search slopes (ideal if close to 0 ms/item), 2) feature presence was detected more readily than feature absence (characteristic in search asymmetries), 3) they produced illusory conjunctions, 4) there was some level of tolerance for distractor heterogeneity, 5) they produced texture segregation based on the unique basic feature. The candidate list of features was placed on a continuum ranging from "undoubted attributes" to "probable non-attributes." Features appearing in the first

category include color, orientation, motion and size that clearly satisfy all the aforementioned criteria. Shape is considered a probable attribute and Wolfe and Horowitz admit that shape is one of the most difficult features to classify. They point to the fact that some characteristics of shape clearly guide attention, but the problem occurs when trying to decide exactly what those properties are. Shape is more of an abstract entity when compared to what defines color and orientation. Wolfe and Horowitz concluded that features that guide search are mostly a product of bottom up attributes, but do not focus much on how these features influence eye movement behavior. Although previous work has demonstrated that many of these features influence eye movements (Findlay & Walker, 1999; Williams, 1967; Williams & Reingold, 2001), one should be cautious when considering their entire list in terms of overt attention.

The current investigation utilizes manipulations of color and shape with the primary focus on color, which is a guiding feature according to Wolfe and Horowitz (2004). Sixteen different colors will be used to afford a high degree of color selectivity. Subjects will be encouraged to search based on color, but a subtle shape manipulation will be implemented to make the search task more difficult and encourage focused attention and eye movements. This manipulation involves a target T with pseudo L distractors created from two rectangles of the same size. The relative relationship between the two target colors will be manipulated to test the observers' ability to maintain two separate target representations despite increasing dissimilarity between the targets. The combination of salient color differences and the subtle shape manipulation will require subjects to make multiple eye movements. The key to determining how

these objects are represented should be reflected by the mechanisms that underlie these eye movements.

When it comes to features that attract eye movements, search can be characterized as being comprised of two stages that operate in sequence: 1) acquisition or selection of a potential target via extra-foveal vision in order to direct an eye movement and 2) identification, which is the classification of an object through direct fixation (Williams, 1967). Although directly fixating an object will lead to identification, this does not imply that a fixation is a necessary prerequisite for identification. Several researchers have demonstrated that objects can be successfully identified extrafoveally (Stroud, Menneer, Cave, Donnelly & Rayner, submitted; Zelinsky, 1996). Through a moving window paradigm, Rayner and Fisher (1987) identified two distinct regions of the visual field during active search: a central decision region and a more eccentric preview region. These regions could encompass approximately nine characters with the decision region covering around 3 – 4 characters. The size is flexible and Rayner and Fisher demonstrated that the regions could be adjusted according to the characteristics of the distractors in the display. The region could be extended to include more letters if the distractors were dissimilar to one another and constricted when the letters were similar. Thus, what is termed 'the span of effective stimulus' in visual search can be influenced by a number of factors from both top-down and bottom up mechanisms (Bertera & Rayner, 2000; Pomplun, Reingold, & Shen, 2001; Scialfa & Joffe, 1998). Taking a closer look at the dynamics involved in visual search, Williams focused on the acquisition process, or the observer's ability to selectively fixate objects given various characteristics of the target.

Results of Williams' (1967) research revealed that search can be guided more effectively depending on the specific features given to the subject prior to search. Williams utilized an atypical search paradigm consisting of 100 items per display. Each object was defined by a unique combination of color, shape and orientation with a unique two-digit number printed within each object. Subjects were required to locate one of the two digit numbers and were given various amounts of information regarding the identity of the stimulus containing the number. When color and shape, color and size, or color, size and shape were given, subjects mainly relied on color to guide search. In fact, the pattern of fixations in the color condition did not differ significantly from the other conditions in which color was given as a specific feature along with other features. These results provided strong evidence that color is a salient feature used to guide visual search. Williams speculates that search and subsequent selection of objects proceeds in one of two ways. The first involves a serial, object by object analysis with each fixated object resulting in a choice decision task. When the object is determined to be a distractor, a subsequent object is identified parafoveally as the goal of the next saccade. Given acuity constraints, objects closer to the current fixation receive the highest degree of processing. This strategy involves more of a local analysis of an array. The second alternative, which resembles previously discussed visual search models (Treisman and Gelade, 1980; Wolfe et al., 1989), requires more of an initial global scan based on the dominant feature of the target. Thus, saccades are influenced by the characteristics of the target as well as the salient bottom-up features of the objects in the display, which coincides again with the notion that visual search proceeds via the interaction of both top-down guidance and bottom-up mechanisms.

Utilizing a more typical search task compared to Williams (1967), Zelinsky (1996) defined guidance as the number of covert attentional shifts necessary to find a target during visual search, with effective guidance indicated by flat search slopes and short inspection times. He contends that Guided Search (Wolfe et al., 1989) is the most appropriate model for selecting peripheral information necessary for further investigation through eye movements. To test this, Zelinsky manipulated the similarity of the distractors to the target in a standard conjunction search, with half of the distractors sharing one feature with the target (similar) and the other half sharing no features with the target (dissimilar). Subjects viewed a preview of the target to locate before each trial, which is in contrast to Williams, who only supplied the searcher with limited information regarding the target features (color, size or shape) prior to search. Zelinsky predicted that if saccadic selectivity was guided by preceding covert attentional scans, then no dissimilar distractors should be fixated (aside from the occasional error). The results were quite surprising in that there were no significant differences in eye movements to similar and dissimilar distractor types. In other words, subjects did not elect to employ the optimal strategy of selecting only objects that are similar to the target for eye movements. Zelinsky interpreted these results as being at odds with Guided Search, although he admits that Guided Search makes no specific predictions about eye movement behavior. He speculates that the only way these data can fit within the framework of Guided Search is if saccades are directed in a very non-precise manner, falling on objects that are not the intended target previously identified covertly. These results suggest that eye movements may serve mostly as an imprecise additional level of

scanning of areas that covert attention has already visited. This leaves open a rather important question of exactly what features are guiding search.

A pattern of data emerged from a number of researchers regarding a hierarchy of features that guide visual search (Williams, 1967; Wolfe & Horowitz, 2004; Zelinsky, 1996). Williams and Reingold (2001) attempted to further disentangle these possible features that may guide search as evidenced by patterns of eye movements. The difficulty of the task was manipulated by altering the similarity between the target and the distractors. In the high discriminable condition, the target and distractors consisted of dissimilar letters (C and T). On the other hand, the low discriminable condition included letters less obvious differences (E and F). Williams and Reingold confirmed results found by Williams (1967) in that subjects fixated objects that shared the target color more often than objects that shared the target orientation or target shape. In the low discriminable condition, saccades directed towards distractors sharing the target color increased significantly from the first saccade to the second but did not increase for distractors that shared the same shape or orientation as the target. This suggests that when search is inefficient, the use of color to guide search may increase as search progresses. Convergent with Williams, it appears that color is a dominant feature that guides visual search. Their results were at odds with Zelinsky and they attribute the discrepancy mostly to methodological and analysis issues. They conclude by stating that guidance plays a large role in directing saccadic eye movements and their data can be accounted for by Guided Search. Since Guided Search does not include hypotheses about eye movement behavior, it is difficult to compare between Guided Search and theories of saccadic selectivity. However, eye movement behavior is influenced by both top-down

and bottom-up information (similar to the visual search models), and this saccadic system appears to be quite flexible.

This flexible nature is exemplified in recent work that demonstrates that saccadic selectivity and guidance are based on a number of different factors (Pomplun, Reingold, & Shen, 2001; Williams, & Reingold, 2001). Consistent with the work described previously, Shen, Reingold, and Pomplun (2000) showed an advantage in terms of guidance by color compared to shape. However, by manipulating the relative ratios of distractors that shared features with the target, they could influence which feature primarily guided search. For example, if a small proportion of distractors shared the same color as the target while a larger proportion were the same shape, search could be biased in favor of color. This is known as the distractor-ratio effect, which states that when distractors are more biased towards a specific feature, search becomes easier (Shen, Reingold, & Pomplun, 2000; 2003). That is, when the proportion of distractors that share features with the target decreases, the more likely the features of the target become more salient. Although Shen et al. provided conditions where shape guided search, it came at extreme distractor-ratios where very few distractors shared the same shape as the target. Guidance based on color was accomplished with less dramatic distractor ratios strengthening the argument that color may primarily guide search (when available).

Shen et al. (2000) claim that the distractor-ratio effect in terms of guidance can be accounted for by Guided Search. Recall that Guided Search purports that attention is allocated serially, via the activation of feature maps through the interaction of top-down and bottom-up information. Shen et al. hypothesize that a similar saccade map is created to guide eye movements every 250 – 300 ms. According to this, covert attention and

saccadic eye movements play a complementary role. Covert attention spreads quickly, but is limited by the resolution in the periphery while overt attention (eye movements) operate on a slower time scale, but can resolve to a higher degree through direct fixation. This bears close resemblance to the sequential attentional model proposed by Henderson (2002), which also posits a complementary relationship between covert and overt attention.

The flexible nature of the saccadic system most likely is attributed to both top-down guidance and bottom-up information. The research reviewed demonstrates that once enough information is gathered to identify the target, search can be guided a number of different ways. However, the majority of the research reviewed involves search for a single, clearly defined target. The current investigation aims to extend these findings to establish how two targets guide search. The addition of a second search target would test some of the assumptions set forth by the previous research. In terms of general search behavior, eye movements should be driven by similar mechanisms described by the research reviewed (Bertera & Rayner, 2000; Williams & Reingold, 2001; Zelinsky, 1996). The current project is designed to address how targets are represented to guide search. If two targets can produce effective guidance, then it may be a reflection of common features between the two targets. If there are no features that are common, then perhaps multiple levels of guidance can be obtained. However, if searching for multiple targets results in a cost, it may be an issue grounded in how the target features are initially represented. The nature of dual target search is explored in the following section.

Search for Multiple Targets

Visual search for a single target amongst distractors may require the searcher to construct an internal representation or mental template of the object of interest (Desimone & Duncan, 1995). This representation guides search via top-down mechanisms through the activation of feature maps (Treisman & Gelade, 1980; Wolfe, et al., 1989). For targets defined as combinations of features from two different dimensions (*e.g.* color and orientation), feature maps are activated separately for each dimension. If more unique information regarding the target is available, as with triple conjunctions (color, orientation and size), stronger activation of the feature maps occurs, resulting in more efficient search. Search for multiple targets creates a different requirement in that the search target is defined by two different feature values within the same feature dimension. For example, if the two search targets are a red square and a blue square, then target set is defined across the dimension of color. If Guided Search predicts that search occurs via the sum of these independent features, then objects dissimilar from either target would be activated. In the case of the red and blue object, the sum of the two features values would result in a purple object. Likewise, if the targets were defined along the dimension of orientation, the target template would be oriented somewhere in-between the two targets. Thus, Guided Search would predict a representation consistent with the range hypothesis described earlier.

While Guided Search predicts an account based on summation, the integrated competition hypothesis posits search based more on competition (Duncan, Humphreys & Ward, 1997). According to this theory, search for multiple objects requires internal representations or templates of each object that competes for processing time. The object that produces the highest degree of neural activation, either through bottom up salience or

top down guidance, ‘wins out’ as the object that guides search, which is more consistent with the alternating hypothesis discussed previously. Rather than a problem of summation, search efficiency should be a result of competition between the two target values. The current project aims to disentangle these hypotheses through the observation of eye movements. If fixations to objects are an accurate reflection of the target template or templates held in working memory, then strong inferences can be made regarding the template utilized to guide search.

Despite the constraints inherent to the two models discussed above, certain conditions exist under which searching for two targets simultaneously can be efficient. Perhaps the oldest evidence for successful dual target search demonstrated that after extensive practice (repeated trials over a number of days), familiar alphanumeric characters could be found with relative ease (Neisser, Novick & Lazar, 1963; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977). Efficient search for multiple targets may be a reflection of the observer constructing a target template that closely matches the specific target properties after repeated exposure. Other evidence of efficient dual target search for two dissimilar targets has shown that when each target was defined by a salient feature from a different dimension (shape, size, color), so that each target was a feature singleton, the strong feature differences could guide search bottom-up (Quinlan & Humphreys, 1987; Treisman, 1988; Treisman and Gelade, 1980). While these unique examples highlight an important aspect of efficient dual target search, they do not reveal much if anything regarding how multiple targets are mentally represented to guide search. In regard to top-down guidance, others have demonstrated efficient multitarget search when targets are defined across single feature dimensions. D’Zmura (1991)

suggested that search for multiple targets may occur in parallel if the targets share similar, but distinct hues. He described how optimal filters may be activated if the targets are defined by hues that are close in feature space and in a way that distractors do not have hues that fall between target colors in color space. As the number of objects that occupy the feature space between targets is limited, search efficiency increases.

Efficient search has been demonstrated for multiple targets that were similar to one another along a single dimension of either color (Stroud, Menneer, Cave, Donnelly & Rayner, submitted) or orientation (Barrett, Menneer, Phillips, Cave & Donnelly, 2003). However, efficiency suffered when separation between targets increased, and the process of selection became much less efficient, which is consistent with D'Zmura's findings. Barrett et al. expand on D'Zmura's explanation that the breakdown is associated with the "chromatic detection mechanism's" inability to produce efficient multi-target search. An effective target template can be used for single targets and two very similar targets. However, dual target costs are a result of separating the features within each dimension. That is, as the feature values between the targets increase, the system has trouble utilizing an effective template. This is not the only instance of a cost associated with searching for multiple targets and in fact it generally is less efficient to conduct a single dual target search compared to individual searches (Wing & Alport, 1972).

The mechanisms surrounding decrements in search performance from searching for multiple objects are not well understood, but many circumstances leading to a dual target cost have been identified. Dual target costs have emerged based on measures of response times and accuracy in a number of different conditions in both basic and applied research settings. Two targets were found with lower accuracy and longer response times

compared to conducting separate, individual searches for color patches, oriented bars and complex abstract shapes (Menneer, Barrett, Phillips, Donnelly & Cave, 2004; 2007) as well as familiar alphanumeric characters (Kaplan & Carvellas, 1965). With regard to applied research, search through x-ray images in a manner consistent with airport security screeners demonstrated similar dual target costs. (Menneer, Auckland, Donnelly, & Cave, 2006; Menneer et al., submitted). As highlighted before, measures of response time and accuracy only paint part of the picture. To further understand what contributes to this cost and more importantly how these two targets are represented, it is important to view eye movement records.

Eye movement patterns have revealed one major contribution to this cost. Stroud et al. (submitted) required observers to locate two targets defined along the dimensions of both shape and color. The results demonstrated a cost in terms of a higher proportion of fixations to distractor objects that were dissimilar to either of the search targets. For example, when given an orange and blue object to search for, fixations were made on a disproportionately high number of purple and green objects that clearly did not resemble either of the targets. One could argue that the mere novelty of the task coupled with inexperienced searchers is a possible contribution to this dual target cost. However, this is not the case and a dual target cost was still present after extensive practice both in terms of accuracy and response time (Menneer, Auckland, Donnelly, & Cave, 2006; Menneer et al, submitted) and eye movement measures (Menneer, Li, Stroud, Butler, Cave, & Donnelly, 2008). Evidence for multi-target costs have been shown in studies with animal subjects as well. As part of a bird's natural foraging behavior, they must constantly search for food while simultaneously avoiding predators, providing an

example where multiple target search is essential to survival. Dukas and Kamil (2000) hypothesized that the bottleneck occurred at the attentional level, with blue jays experiencing a cost at detecting predators in the periphery as a result of attention focused on a centrally located food target. However, this cost has been shown to disappear in small set sizes in pigeons with practice (Vreven & Blough, 1998). Collectively, both the animal and human literature point to an inability to search for multiple targets efficiently.

The current project utilizes the same stimulus colors as Barrett et al. (2003), which were adopted from Menneer et al. (2004; 2005). Sixteen colors were chosen that were equally spaced along a ring in CIExy color space to ensure that the relative salience of each color was equal. Barrett et al. required observers to search for two colors adjacent on the color ring (e.g., red and orange), two colors separated by four color steps on the color ring (e.g., red and green) or two colors separated by eight color steps (opposite to each other on the color ring). The results demonstrated longer RTs and lower accuracy in the 4-step and 8-step condition compared to the adjacent condition. These results clearly demonstrate not only a cost associated with searching for two targets, but also a cost when searching for items with increased intervening distractor colors. However, Barrett et al. were constrained to simple measures of response time and accuracy associated with increasing set sizes, which makes it impossible to extract an index of selectivity. Exactly what led to the disadvantage for the conditions that included a higher degree of separation in color space between the two targets? This is where measures of eye movements may reveal a stronger picture of search for two separate targets.

Not only are eye movements part of natural search behavior, but they will also reveal to what degree observers can select the target objects and ignore distractors. The objects that are fixated in the course of a search should be determined by the target template or templates that are activated in memory during search. Indexing selectivity through the probability that an item will be fixated throughout the experiment should reveal how these targets are represented.

The Current Investigation

The current study investigates how observers represent two targets during a visual search task. Stroud et al. (submitted) established specific conditions under which searching for dual targets can be either efficient or inefficient. To produce efficient search, two targets shared the same color but were comprised of different shapes constructed of the same two constituent parts. Conversely, search efficiency was reduced considerably, as revealed by errant fixations, when the two targets differed both along the dimensions of shape and color. The experiment was designed to emulate real world searches conducted by airport security screeners searching for guns, knives and bombs amongst various distractors. The stimuli were constructed from two rectangles as abstract representations of guns, knives and bombs. Further, the experiment encouraged color selectivity, but also contained a difficult shape manipulation. Thus, the reduction in selectivity may be a reflection of the objects containing features across two different dimensions, but it is difficult to disentangle the effects each dimension has on this reduction. The current study utilizes a similar paradigm but maintains tight control over the features and dimensions used. The purpose of the current investigation is to examine how multiple targets that vary across a single feature dimension are represented to guide

search. To what extent do two targets that differ across a single feature dimension guide search efficiently, and will a systematic breakdown in selectivity occur with increasing separation between the target objects? The current experiments will utilize the probability that an object is fixated (which will be discussed later) as the primary dependent measure, which will provide insight as to how multiple targets are represented to guide search (Stroud, et al.). Search efficiency will be measured by comparing these fixation probabilities to different colored objects as a function of the color of the search target or targets. As secondary measures, standard response times and accuracy measures will be calculated, but are not the focus of the investigation.

CHAPTER 2

EXPERIMENTS 1A AND 1B

Introduction

The overall goal of the current project is to reveal the nature of the target representations that guide search for multiple targets within the dimension of color. Experiment 1A will contribute to this goal by examining dual target search in two conditions that vary the similarity between the two different color targets. Experiment 1B consists of search for a single color, which will serve as a baseline measure in order to show the effects of the addition of a second target. Barrett et al. (2003) demonstrated a cost in reaction time and accuracy when observers were searching for two dissimilar target colors relative to similar target pairs. The current experiments will reveal a more complete picture of search by the addition of eyetracking by including measures of eye movements. If saccades are directed towards objects that match the features included in the mental representation, then the fixated objects should reveal the nature of this representation. Further, eye movements provide additional data on search behavior that go beyond the measures used by Barrett et al.

In each experiment of the current study, subjects searched for a target 'T' amongst distractor 'L's. Experiment 1A was designed to investigate how search changes with the relative similarity between the two target colors. These two dual target conditions will be compared to the single target condition in Experiment 1B to assess the degree to which adding a second target affects search. If the results with two similar color targets mirror the single target search, then it is possible that that both types of search relied on similar guiding mechanism. If the objects with colors in between the two dissimilar target colors

receive the same number of fixations as the targets themselves, then this would provide evidence for the range representation in which the template includes all of the feature values contained within and between the two target colors. For example, if the two targets are red and yellow, then a large proportion of fixations should land on orange colored objects since orange lies in between the two target colors in color space. However, if significantly fewer fixations are made on the intervening colors, then it would give rise to the possibility that the two target templates are represented separately.

Method

Subjects

Thirty-two University of Massachusetts students, 25 females and 7 males with ages ranging from 18 – 22 years (Mean = 19.53, SD = 1.23) took part in Experiment 1A. Sixteen additional students, 12 females and 4 males (Mean age = 21.94, SD = 2.93), participated in Experiment 1B. All subjects reported normal or corrected to normal vision as well as normal color vision. Subjects received course credit as compensation for participating in the experiment.

Stimuli

Stimulus objects consisted of ‘T’s and ‘L’s each constructed from two rectangles 1.04º x 0.37º degrees of visual angle. The ‘T’ was comprised of one rectangle bisecting the other rectangle, resulting in 0.5 degrees of offset on both sides. The pseudo ‘L’s consisted of the two rectangles joined together with an offset of 0.3 degrees on the short side and approximately 0.7 degrees on the long side. The Ls were assembled in this manner to slightly resemble the Ts and thus encourage more fixations per trial. (See Figure 1 for an example of an array containing the two types of objects.)

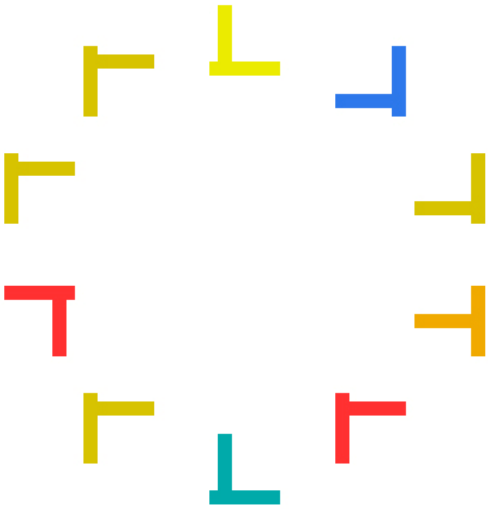

Figure 1: A sample array consisting of a target T and distractor Ls.

The stimuli were colored using sixteen separate colors drawn from a set of colors spaced in a ring in CIExy space. The colors are the same as those utilized by Menneer (2004; 2007) and Stroud et al. (submitted), which are arranged so that no single color will visibly pop-out from the others (see Figure 2). The colors were selected so that the differences across luminance and hue were slightly beyond the 'just noticeable' differences outlined by Wyszecki and Stiles (1982).

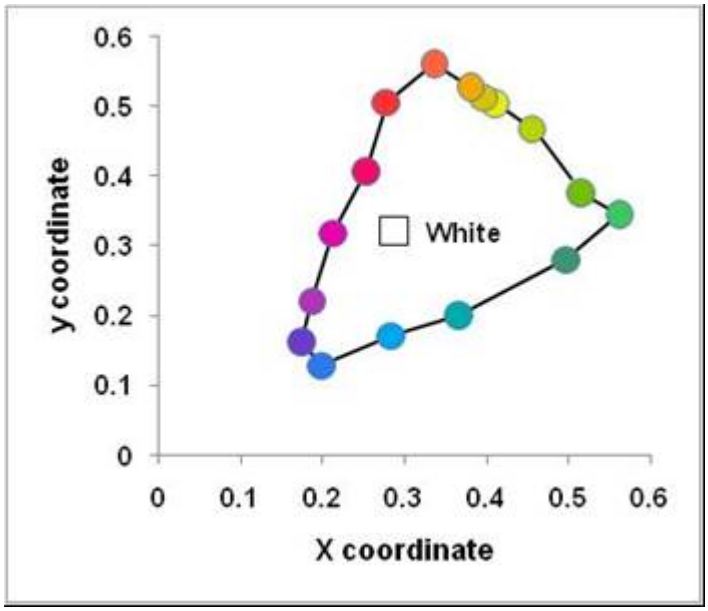

Figure 2: CIE (x,y) coordinates of the color ring used for the targets and distractors.

Each display contained ten randomly selected objects (T or L) placed on a white background. Each object was placed in one of ten locations equally spaced around an imaginary circle with a radius of 9.8º of visual angle. Each object appeared at a random orientation of 0º, 90º, 180º, or 270º. (See Figure 1 for a sample array.) The distractors were randomly assigned to locations across the different trials from a pool of objects without replacement, so that each combination of the 16 colors and four orientations was represented equally often, resulting in 38 instances of each possible combination. Since the arrays were generated randomly, it was possible for multiple objects of the target color to appear on the same trial. Each subject was assigned a specific color pair as target colors to search for, so that every possible two-color combination with one of the two chosen color separations was represented across subjects. For the 1-step separation, target pairs consisted of colors immediately next to one another in color space (separated by 1-step on the ring of 16 colors), while in the 4-step condition, the pairs are separated

by three colors (see Figure 3). The entire experiment consisted of 256 trials, with the target appearing in 50% of the trials. Of those 128 trials, each target of the pair appeared in 64 trials.

Figure 3: Sample target stimuli which precede each trial. The left panel shows target pairs from the adjacent separation, while the right panel shows target pairs from the 4-step separation. Note that the stimuli were not presented in black rectangles.

Design

Three factors were varied in Experiment 1A: Color Step, Target Set and Target Presence. Color Step was defined as the relative position of each object's color within the ring relative to the target color, specifically as the number of steps between the two colors. The factor of Target Set had two levels specified by the number of color steps on the color ring between the two targets. In the 1-step condition, the two targets were adjacent to each other on the color ring with no intervening colors, and in the 4-step condition, the targets were separated by 4 color steps (containing three intervening colors between the two targets). Subjects searched for a target T which was present in half of the trials. The resulting design was a 2 (Target Set: 1-step versus 4-step) x 7 (Color Step: Target color, 1 step from target, 2 steps, etc.) x 2 (Target Presence: Present versus Absent) mixed factorial design with Target Set as the only between-subjects manipulation. The primary dependent measure was the probability that an object color was fixated, and secondary dependent measures included response time and accuracy.

Experiment 1B was identical to Experiment 1A without the factor of separation, since it included only the condition for searching for the single target.

Apparatus

The stimuli were presented on a 17 inch Viewsonic 17PS CRT monitor attached to a Pentium 166 MHZ computer interfaced with an SR Research Limited Eye-Link II eye tracking system with a spatial resolution and a sampling rate of 500 Hz (2 ms temporal resolution). Subjects viewed the stimuli with binocular vision, but only the right eye was tracked. Subjects were seated 57 cm from the monitor with the entire display subtending 25.7º x 32.5º of visual angle. Both pupil position and corneal reflections were tracked to no more than .40º of visual angle error, while subjects kept their head still in a chin rest.

Procedure

Subjects first completed an informed consent requiring some basic demographic information. Before the experiment began, the Ishihara test for color deficiency was administered to insure subjects had normal color vision (Ishihara, 1917). Subjects were then shown a sample display and informed that they should search for the single T on each trial that could be one of two possible colors. Subjects were notified that the two target colors would never both be present in the same trial, thus making it a disjunctive OR search task, and that a target T will be present on 50% of the trials. Subjects responded on a SR Research issued Microsoft game controller with the right button signifying present, and the left button representing absent. The two buttons were the same size and subjects were required to rest their index fingers on each button to avoid any unnecessary searching. The first 16 subjects were assigned to the 1-step Target Set

and the remaining searched for the 4-step Target Set. Each subject searched for one of the 16 possible target pairs, and the two target colors remained the same for that subject for the duration of the experiment. Subjects completed five practice trials during which they were free to ask any questions before beginning the experiment. The entire experiment lasted approximately 30 minutes, and subjects were properly debriefed upon completion.

The order of events for each trial was as follows: 1) a dot appearing at the center of the screen to correct for any slippage of the equipment (drift correct), 2) presentation of the two possible target 'T's for 1000 ms, 3) a central fixation point for 1000 ms, 4) presentation of the search array until a response was given (See Figure 4 for a graphical depiction of the procedure)

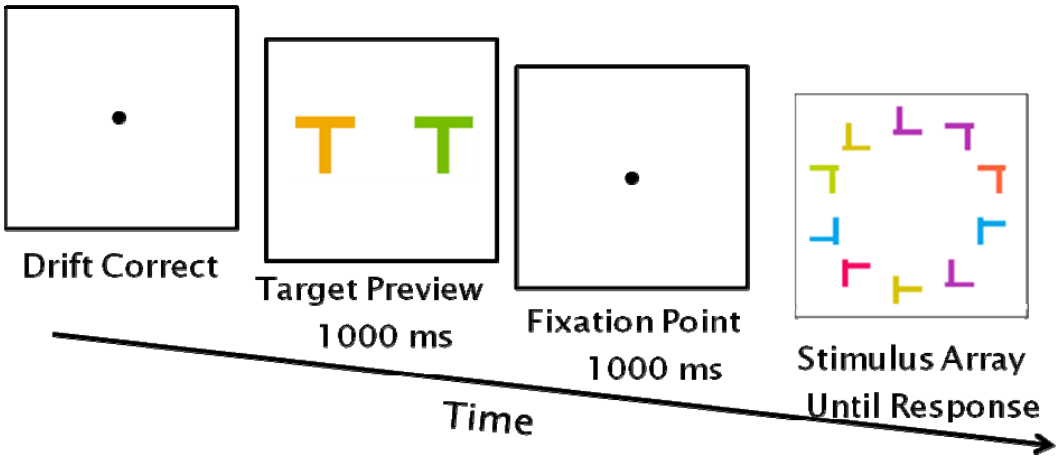

Figure 4: A pictorial display of the procedure used for each experiment.

Results

Primary analyses involved comparing performance between Target Sets for accuracy and response times. Subsequent analyses were aimed at measuring color selectivity by determining the fixation probabilities of for each distractor color. These proportions were calculated as the probability that an object with a given color was fixated one or more times during a trial as a proportion of the total number of instances that the specific color appeared throughout the experiment. Thus, the analysis focused on whether an object with a specific color was fixated or not. Only the distractor Ls were included in the analysis of fixation probabilities so that the results reflected only guidance based on color, and not shape. (The other analyses and figures across all five experiments will also only include distractor fixations.) Where appropriate, planned comparisons with a Bonferroni correction (FWE = .05) were conducted. For each result reported, an alpha level of .05 was considered reliably different.

For Experiment 1A, accuracy and response times were submitted to a 2 (Target Set: 1-step versus 4-step) x 2 (Target Presence: absent versus present) mixed analysis of variance with Target Set as a between-subjects factor.

Accuracy

Subjects in the 1-step Target Set (Mean error rate = 3.2%) significantly outperformed those in the 4-step Target set (6.0%), $F(1,30) = 10.22$, $p = .003$. For both Target Sets, subjects were more accurate when the target was absent compared to when it was present, $F(1,30) = 86.01$, $p < .01$. When the target was present, performance in the 4-step Target Set (10.6%) was worse than the 1-step Target set (5.0%), while there was no difference between the two Target Sets for target absent trials (mean difference =

0.2%), producing a significant Target Set x Target Presence interaction, $F(1,30) = 18.23$, $p < .001$.

Response Times

Response times in the 1-step Target Set (1302 ms) were significantly faster compared to the 4-step Target Set (1747 ms), $F(1,30) = 475.59$, $p < .001$. Subjects also responded faster when the target was present (1230 ms) than when it was absent (1819 ms), $F(1,30) = 77.87$, $p < .01$. This difference between present and absent trials was more pronounced in the 4-step Target Set reflecting a significant Target Set x Target Presence interaction, $F(1,30) = 5.51$, $p = .026$. The pattern of results for the response times mirrored the results for accuracy revealing little to no evidence of a speed-accuracy tradeoff.

Probability of Fixation

Refer to Figure 5 for the results of the fixation probabilities for Experiment 1A. The possible object colors are represented along the X-axis. The target color is identified by the shaded region and color distance from the target increases along the X-axis in the direction of the arrow. The data point on the far right of the figure represents the color on the opposite side of the color ring, which is least similar to the targets. The peaks of the lines within the shaded region demonstrate that subjects were color selective and directed a large proportion of their fixations to distractors of the target color. The diverging lines reveal that selectivity was reduced for subjects searching for target colors separated by four color steps relative to colors adjacent to one another on the color wheel. Analyses were aimed at confirming this pattern shown in the figure. For Experiment 1A, the fixation probabilities for each distractor color were submitted to a 2 (Target Set: 1-step

versus 4-step) x 2 (Target Presence: present versus absent) x 7 (Color Step: target – 6 Steps from the target) mixed analysis of variance. In order to satisfy the main assumptions of the ANOVA, only data points that were common across both Target Sets were included in the analysis. These data points are the ones for each color step that includes both a purple square and green triangle in Figure 5. The results revealed a relatively strong color selectivity: subjects directed a greater proportion of fixations toward the target color and distractor colors one to two steps form the target color, compared to the remaining field of distractor colors, $F(6,180) = 215.9$, $p < .001$. Objects four to six steps from the target color were fixated at a higher frequency in the 4-step Target Set, resulting in a significant Target Set x Color Step interaction, $F(6,180) = 4.025$, $p = .001$ (Figure 5).

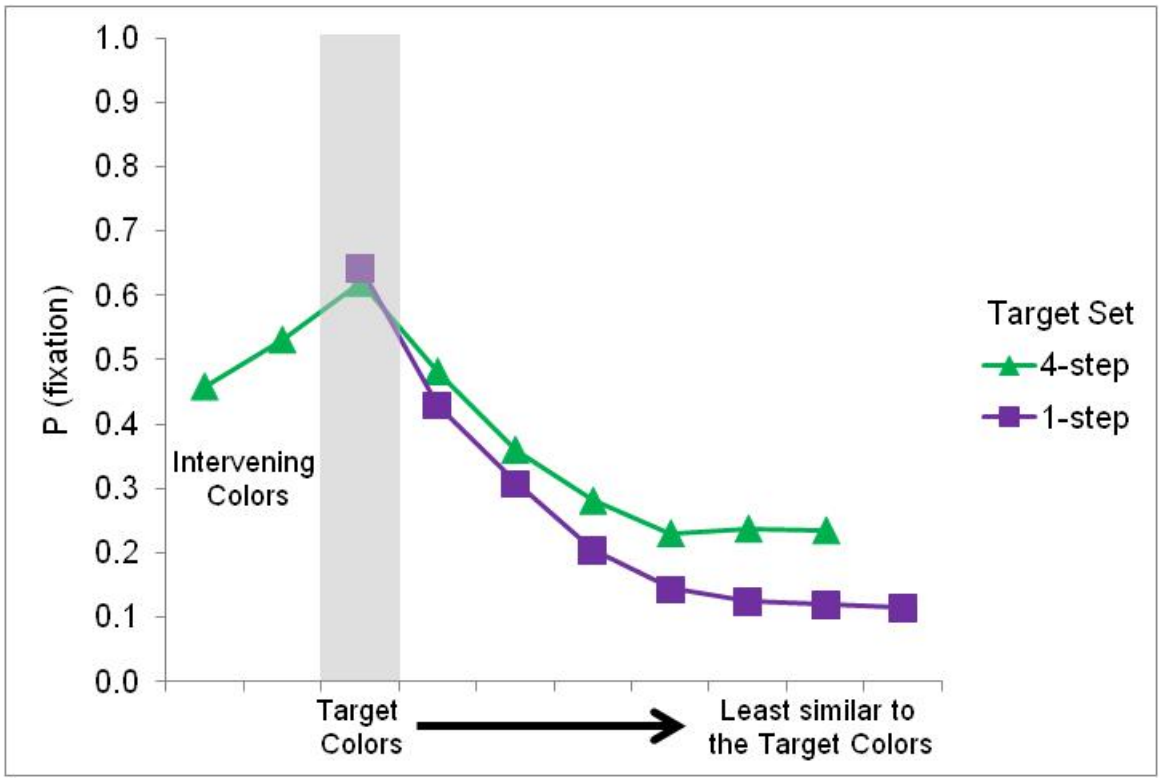

Figure 5: The probability of fixation for the 1-step and 4-step Target Sets. These data are collapsed across all target color pairs and the shaded bar represents the two target colors. The two points to the left of the shaded bar represent the three colors that are between the two targets on the color ring. The x-axis represents the relative distance on the color wheel that each color was from the target. The point the furthest to the right occupied the opposite side of the color ring from the target. Only the data points common to both Target Sets were included in the analysis, but fixations to all objects were included in the figure.

As suggested by the response times and accuracy, subjects fixated objects at a higher frequency when the target was absent (.446) than when it was present (.185), $F(1,30) = 219.34$, $p < .001$. Fewer fixations were made in target present trials compared to when the target was absent, reflecting that the target was located relatively early on in search. Figure 6 shows the fixation probabilities for both target present and absent trials collapsed across both Target Sets. These results suggest that fixations are initially directed towards the target color, and after the target is not located, search is broadened to

include a wider range of possible colors. This notion was supported by a significant Target Presence x Color Step interaction, $F(6,180) = 57.25$, $p < .001$.

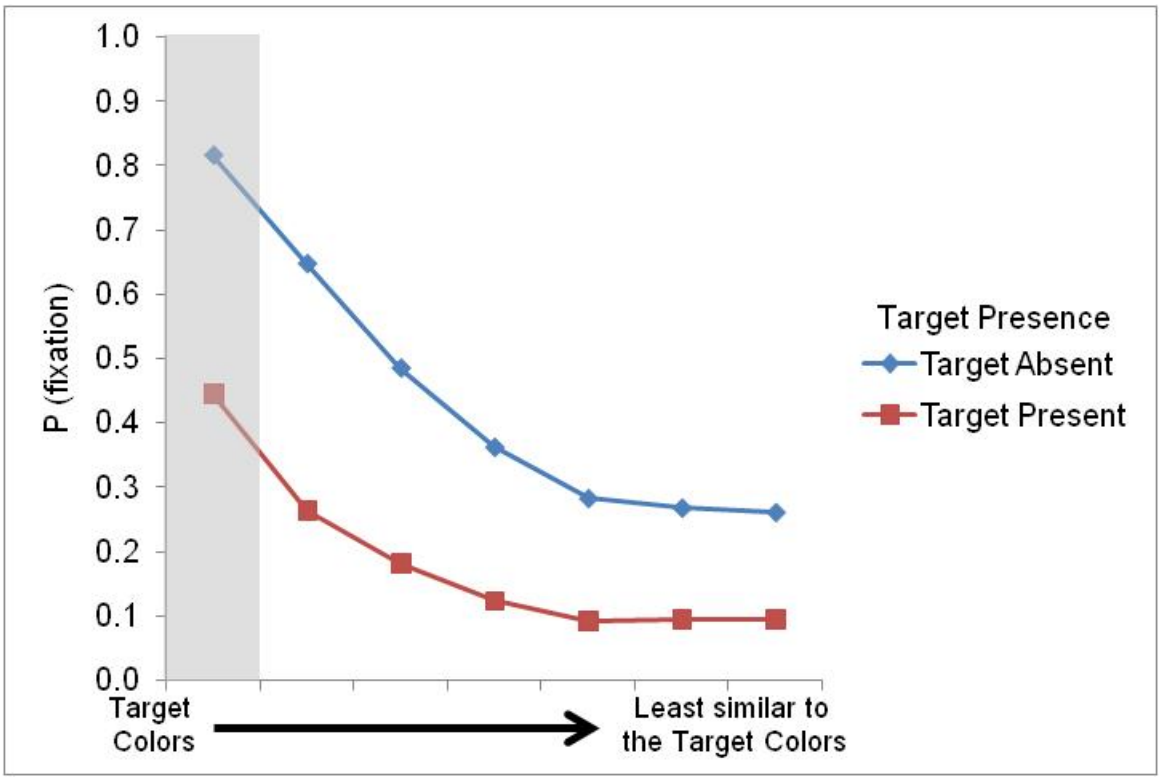

Figure 6: The probability of fixation for target absent and target present trials. These data are collapsed across both Target Sets.

Figure 7 reflects this same pattern across both Target Sets, in which the presence or absence of the target influenced the use of color resulting in a significant Target Set x Target Presence x Color Step interaction, $F(6,180) = 2.83$, $p = .012$. Finally, there was a numerical, but non-significant difference ($p = .104$) between the overall probability of fixation in the 4-step Target Set (.350) and the 1-step Target Set (.281).

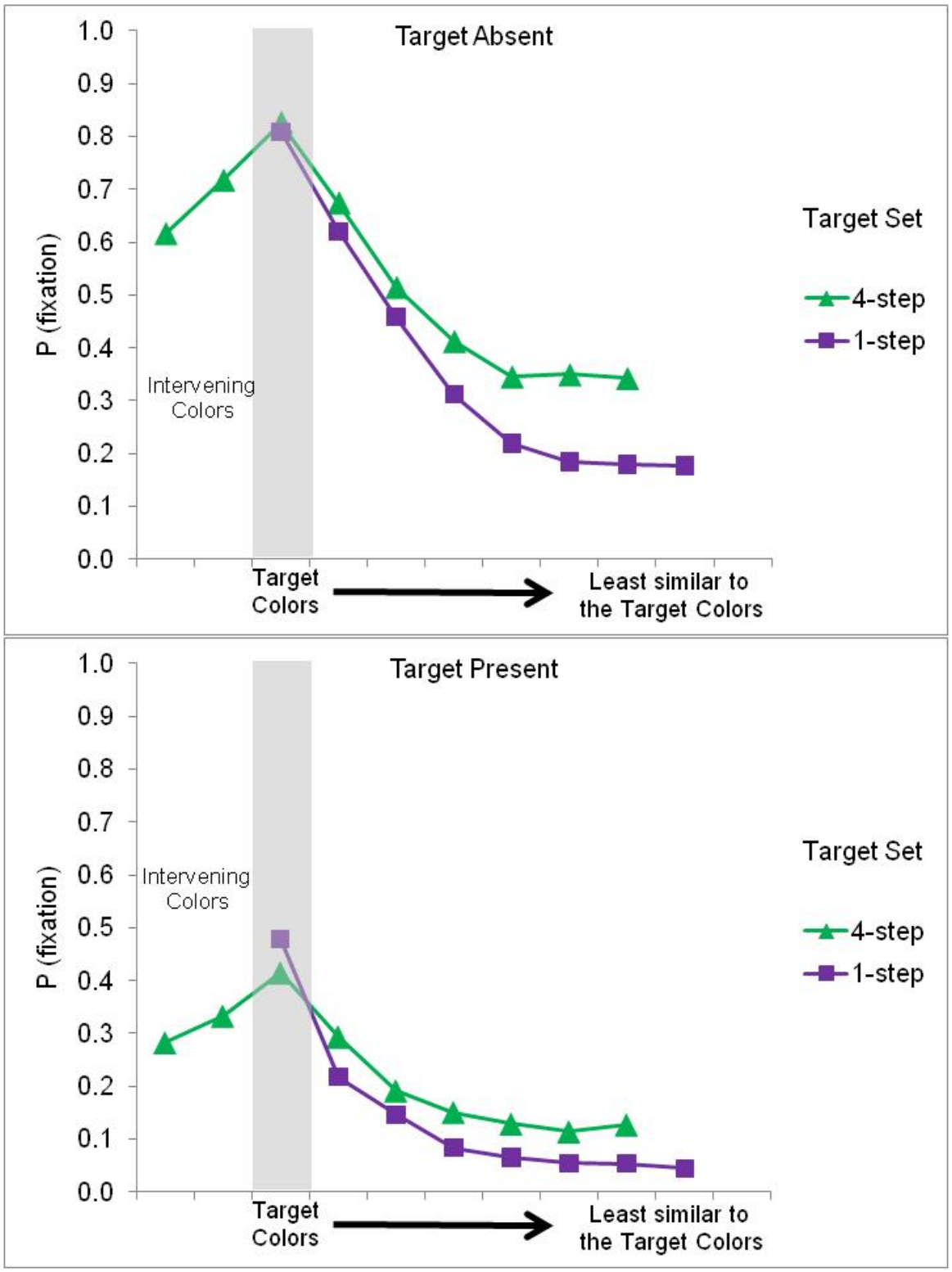

Figure 7: The probability of fixation for the 4-step and 1-step Target Sets. The top panel shows the target absent trails and the bottom panel shows the target present trials.

Experiment 1B included a search for a single target to assess the degree to which there was a cost or benefit associated with searching for two targets versus one. This will be explored in terms of reaction times, accuracy and fixation probabilities by adding the single target search as another level of Target Set to the ANOVAs listed above.

The results revealed that subjects in the single Target Set (1050 ms) responded significantly faster compared to the 1-step Target Set (1302 ms), $F(1,30) = 8.87$, $p = .06$, but only performed marginally better ($p = .069$) in terms of accuracy (Mean difference = .21). Not surprisingly, subjects in the single Target Set outperformed the 4-step Target Set in both accuracy and response times (ps < .001). Consistent with previous results, subjects responded significantly faster, were more accurate and fixated objects less frequently when the target was present compared to when it was absent in the Single Target Set (ps < .001)

Subjects fixated more objects in the 1-step Target Set (.281) compared to the single Target Set (.242), but this difference failed to reach significance ($p = .168$). However, Color Step and Target Set significantly interacted, $F(6,180) = 2.74$, $p = .014$, demonstrating more fixations on distractor colored objects two to six steps from the target in the 1-step Target Set versus the single Target Set (Figure 8).

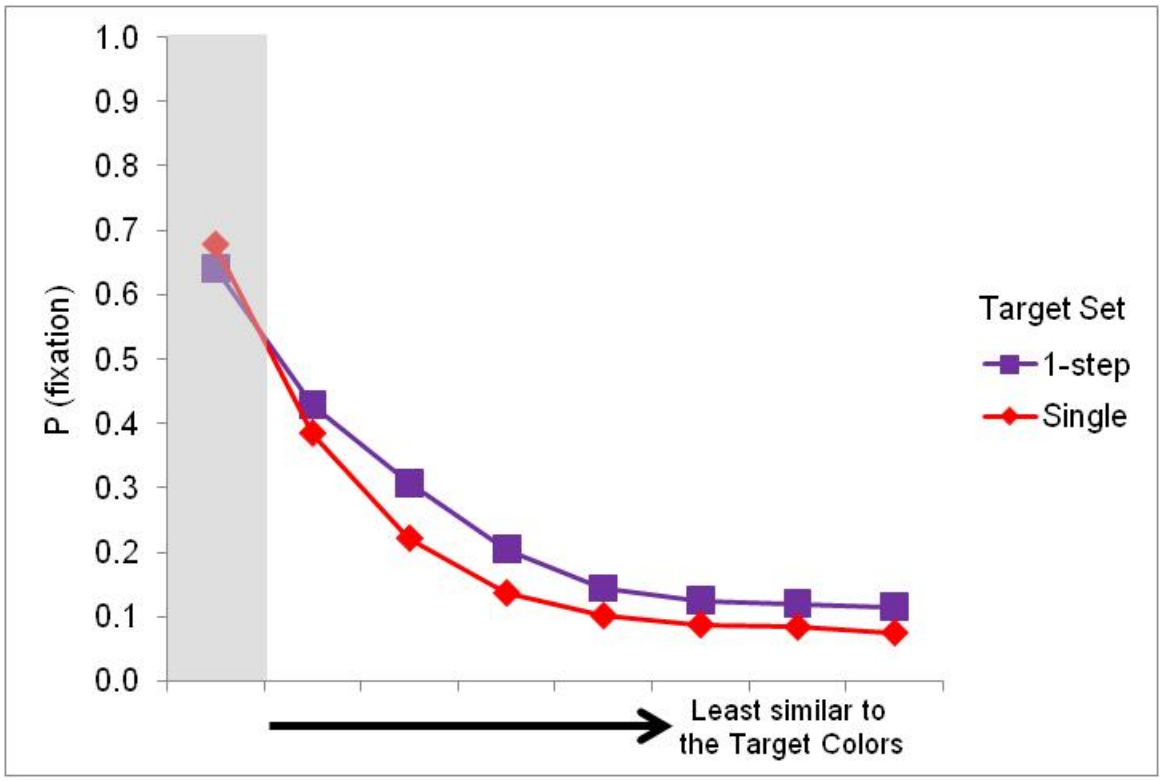

Figure 8: The probability of fixation for the single and 1-step Target Sets.

Subjects in the 4-step Target Set (.350) fixated significantly more objects than subjects in the single Target Set (.242), $F(1,30) = 6.53$, $p = .016$, and Target Set interacted with Color Step, $F(6,180) = 8.98$, $p < .001$, which was driven by a higher fixation frequency on all objects except the target colors (Figure 9).

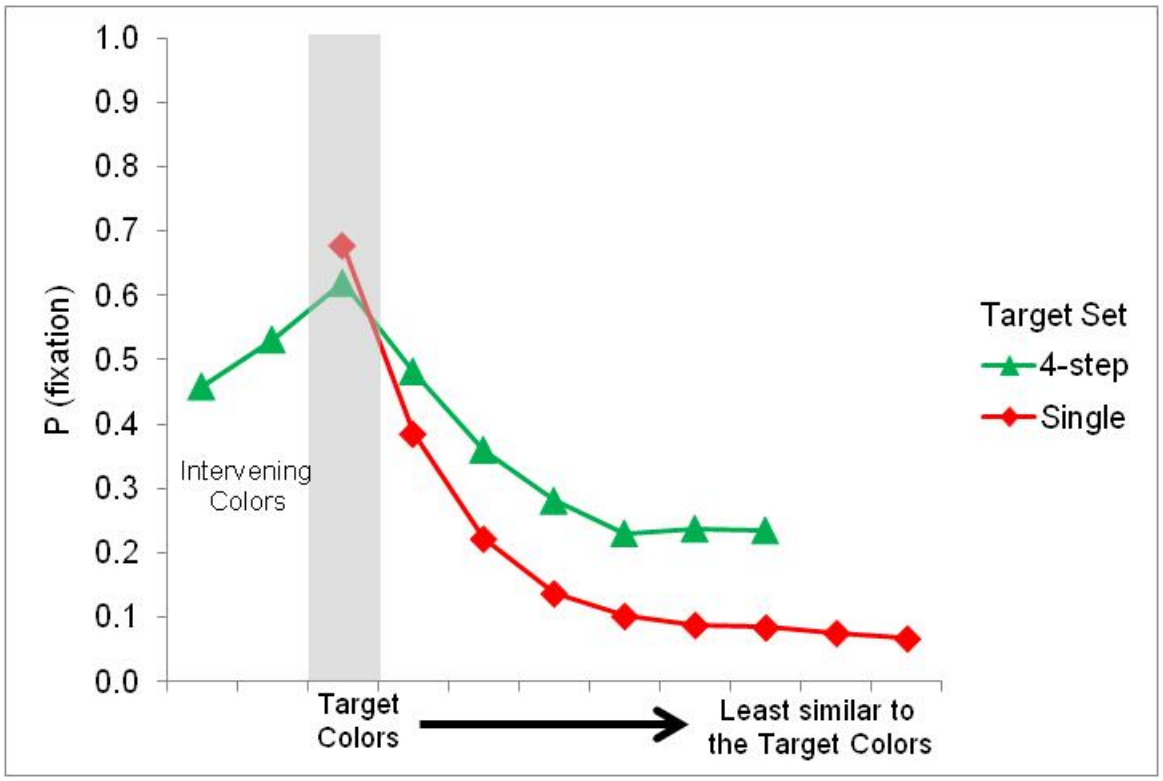

Figure 9: The probability of fixation for the single and 4-step Target Sets.

Color selectivity was weakened when the target was absent compared to when it was present resulting in a significant Target Presence x Color Step interaction, $F(6,180) = 51.73$, $p < .001$. This reduction in color selectivity was more detrimental in the 4-step Target Set compared to the single Target Set, exemplified by a Target Set x Target Presence x Color Step interaction, $F(6,180) = 2,17$, $p = .048$ (Figure 10).

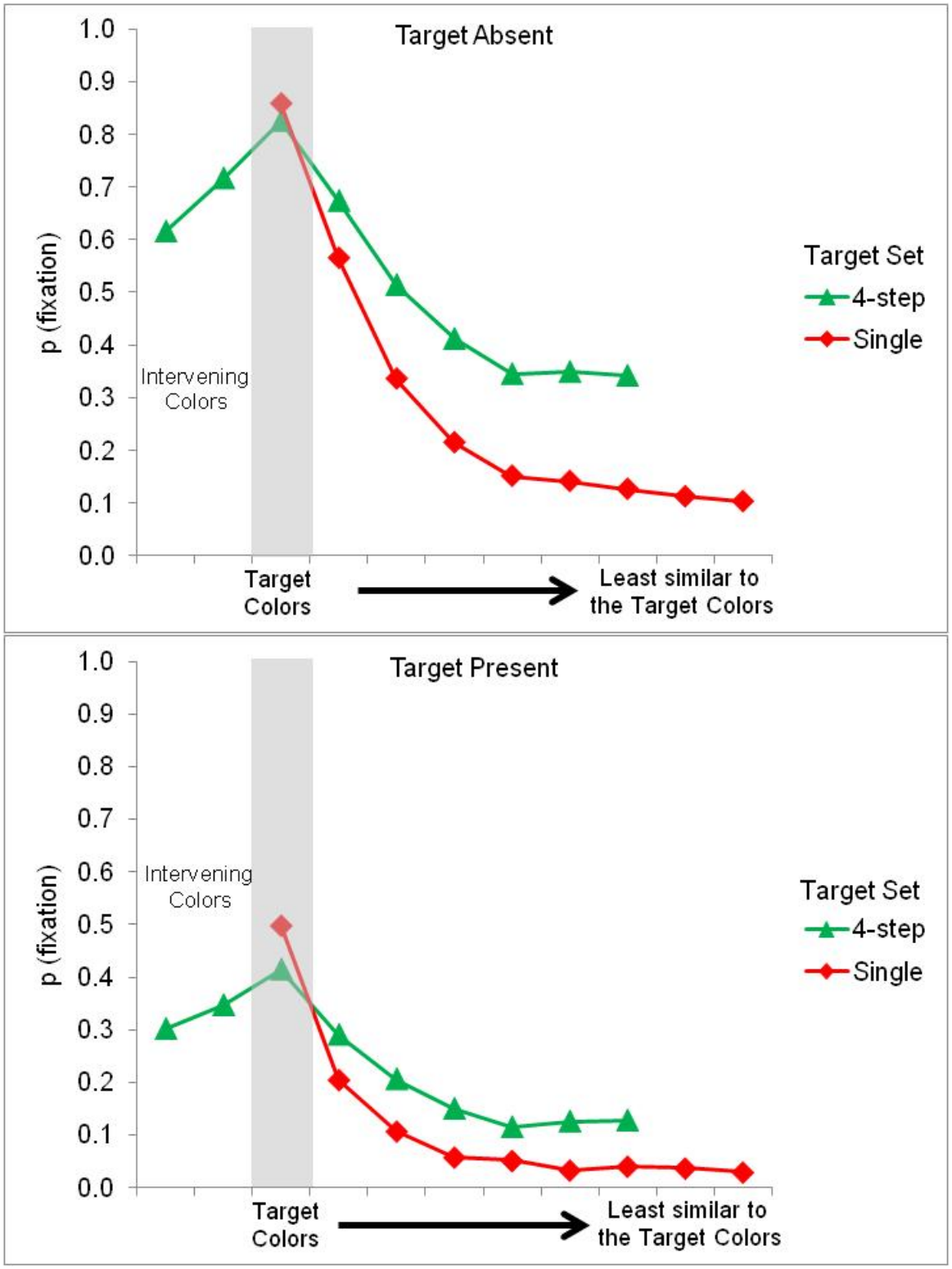

Figure 10: The probability of fixation for the single and 4-step Target Sets when the target was absent (top panel) and when the target was present (bottom panel).

To further assess this dual target cost, the fixation probabilities for the single Target Set data were subtracted from each of the dual Target Sets. The resulting differences were analyzed with a one sample t-test to determine if the value was significantly different from 0. The results confirmed, in terms of these difference scores, that search in both the 4-step, $t(13) = 3.43$, $p = .004$, and the 1-step, $t(13) = 4.57$, $p = .001$, Target Sets were less efficient compared single Target Set.

It is worth noting that although only the Ls were included in the analysis, subjects fixated the target Ts at a much higher frequency than the target colored Ls for all three Target Sets ($ps < .001$). This demonstrates that although color guidance was encouraged, guidance by shape occurred to some degree. See Table 1 for a summary of the fixations to these separate objects.

Target Set	Ts	Ls
Single	.88	.50
1-step	.89	.48
4-step	.93	.41

Table 1: The probability of fixation for target colored objects in the single, 1-step and 4-step Target Sets.

Individual Differences

The results reported thus far are based on the average performance across all 16 subjects for each experiment. Further inspection of the individual subject data suggests that these aggregate results may be a little deceiving. Recall that in the 4-step Target Set, three intervening colors exist between the two target colors in color space. In the figures above, these three colors are represented by the two points to the left of the shaded

vertical bar (which indicates the target color). Subjects in the 4-step Target Set demonstrated large individual differences in the pattern of fixations to these intervening colors. Figure 11 provides a plot of the differences between the probability of fixation to the target colors and the central intervening color. Large differences represent fewer fixations on the intervening color while small or negative differences reflect the same relative fixation frequency to the targets and the intervening colors.

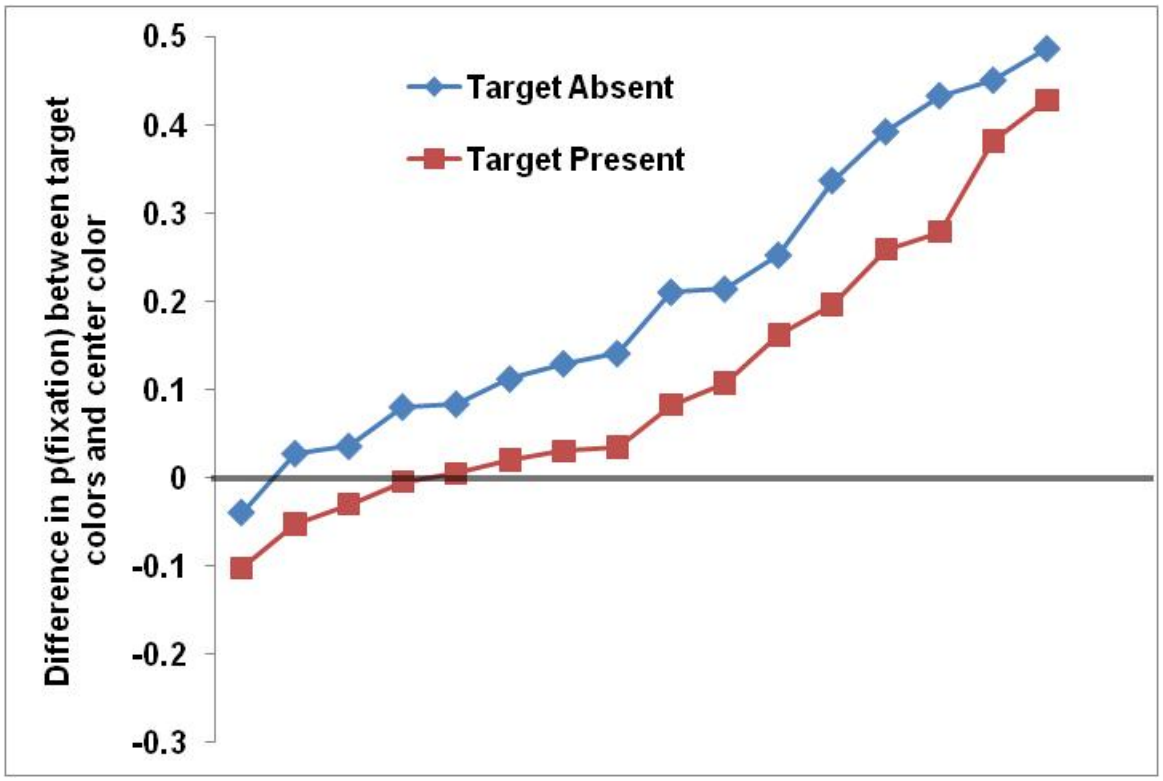

Figure 11: The individual differences for the 4-step Target Set. Each point represents the difference in fixation probabilities between the target colors and the intervening color. The line extending from 0 represents a subject that fixated the intervening color at the same frequency as the targets.

Discussion

Experiment 1 had two main goals: 1) to explore the source of the cost associated with searching for two colors simultaneously compared to a searching for a single target, and 2) to assess the cost related to increasing the separation in color space between the

two target colors. Previous results highlighted by Stroud et al. (submitted) demonstrated a reduction in color selectivity and a dual target cost with less controlled stimuli. Recall that the stimuli utilized by Stroud et al., were abstract representations of real world objects and thus contained manipulations across two separate feature dimensions. It is difficult to conclude to what degree the dual target cost was attributed to the manipulation of shape, color, or the combination of the two. Further, Stroud et al. included just two conditions: 1) single target search and 2) search for two targets separated by 8-steps in color space. Although the reduction was exemplified by significantly more fixations to non-target colors (compared to single target search), there was no way of assessing whether this was a result of the separation between the two targets or simply because there were two targets to search for compared to one.

The current project focused on the single dimension of color, utilizing well-controlled shape stimuli, and included variation of the separation between the two target colors in color space. These results demonstrate that subjects can effectively use color to guide search with varying success across all conditions. Subjects searching for a single target color performed exceptionally well locating the target quickly, accurately and with most fixations to the target color and to colors very similar to it. This color selectivity diminished not only with the addition of a second target, but also as a result of the similarity between the two targets. In all Target Sets, this color selectivity was weakened when the target was absent, most likely reflecting subjects broadening their search after the target was not initially located.

The significant interactions between Target Set and Color Step demonstrated two important findings. First, there is a clear cost associated with searching for two colors

compared to just one. Although subjects did not fixate significantly more objects in the 1-step target set compared to the single Target Set, the interaction between Target Set and Color Step reached significance (see Figure 8), reflecting diminished color selectivity when searching for two very similar colors rather than just one. Secondly, this reduction in color selectivity was even more pronounced when the targets were separated by three intervening colors in color space. What is surprising is that this 'split-target' cost was not a result of more objects fixated that resembled the target colors, but rather an increased fixation frequency on objects dissimilar from the target colors. This elevated fixation rate appears to be a direct result of the increased separation between the two targets in color space and will be explored further in Experiments 2 – 4.

In terms of guiding mechanisms, it appears that subjects in the 1-step Target Set may be representing the two colors as a single unitary template since search was only marginally affected by the increased number of targets. The results of the 4-step Target Set are not as clear, given the individual differences. If search is guided top-down via a single representation, consisting of a range of colors including both targets, observers should not be able to ignore the intervening colors as effectively as the aggregate data show. To investigate this further, the data from Figure 11 were separated based on the differences in the fixation probabilities between the targets and the center intervening color. The majority of subjects (approximately 12) appear to have represented the two dissimilar colors as two separate, discrete templates when the target was absent, represented by the collection of blue points above the black line in Figure 11. When the target was present, the pattern is less in favor of discrete templates, but the majority of the points still reside above the black line. These results, along with the results of the

probability of fixation, suggest that subjects initially search for target colored objects and if the target is not located, search is broadened. However, these extra fixations are not equally distributed across the 16 distractor colors. It appears that most subjects maintained separate representations and the increased fixations occurred on objects dissimilar to either target. Based on these data, the question regarding representation remains unresolved and the goal of Experiment 2 is to examine this further.

CHAPTER 3

EXPERIMENT 2

Introduction

The results of the 4-step Target Set from Experiment 1A showed that the three intervening colors between the two target colors received considerably fewer fixations compared to the target colors, suggesting that the two targets were represented separately. The individual subject data suggest that some subjects represented the two targets as a range, while others attempted to hold two separate object representations. Experiment 2 utilized the exact same stimuli from the 4-step Target Set in Experiment 1A, but in Experiment 2, subjects were presented with a 'range' of possible target colors instead of just the two separate target colors. The motivation behind specifying the target colors as a continuous range was to encourage subjects to search for the entire range of colors, and thus produce a pattern of fixations with equal attention devoted to the target colors and the three intervening colors. Since the same stimuli from Experiment 1 were used, the target colors were the colors on either end of the range stimulus. Subjects were not informed that only the outside colors appeared as targets, but were asked a number of questions regarding their knowledge of the stimuli after completing the experiment.

There are a number of possibilities for how subjects will perform in the current experiment. If subjects can actually represent the two targets as a range of colors, then fixations to the three intervening distractor colors should occur at the same frequency as fixations to the targets. On the other hand, subjects may choose to guide their search by the two outside colors of the range (which are the only target colors that ever appear) and ignore the three intervening distractor colors much like Experiment 1. However, a third

alternative may exist: subjects might initially search for the entire range, and later modify their search strategy after completing a number of trials when they determine that the only target colors that are present are the two outside colors. To investigate this possibility, the probability of fixation was plotted across the four quarters of the experiment. This analysis was not included in the current project, but is the subject of a separate undergraduate honors thesis. It is important to note that the subjects' responses to the questions following the experiment could reveal additional information of how the range was used throughout the experiment. If subjects report that they were largely unaware that the only targets present were the outside colors, then it is likely that the range was actually utilized. The results of Experiment 2 will demonstrate that there is a degree of flexibility associated with encoding these targets.

Method

Subjects

Six male and 10 female University of Massachusetts students, with ages ranging from 18 – 24 (M = 20.94, SD = 1.77) took part in Experiment 2. They were drawn from the same subject pool as Experiment 1.

Apparatus

The same eye tracker and equipment used in Experiment 1 were used for the current experiment.

Stimuli

The displays from the 4-step Target Set of Experiment 1A were used again for Experiment 2. The same target color pairs were used as target ranges with all 16 color pairs represented (See Figure 12 for an example target range). The target range stimulus

subtended roughly the same visual angle as the two separate target color stimuli used in Experiment 1A (see Figure 3).

Figure 12: An example of the target range stimulus specifying the possible target colors for Experiment 2. This range corresponds to the targets in Figure 3 for the 4-step Target Set. Even though subjects were presented with the entire range, the targets only appeared in the two outermost colors.

Design

The exact same design was implemented as in Experiment 1 with the inclusion of a 4-step range resulting in a 2 (Target Set: 4-step versus 4-step range) 2 (Target Presence: absent versus present) x 7 (Color Step: target – 7 steps) mixed factorial design.

Procedure

The current experiment was run exactly the same way as Experiment 1A. After the experiment was completed, subjects were asked a number of questions to see if they were able to determine if the targets only appeared as the outside colors. Subjects were shown the target range and asked the following questions: 1. Which colors did the T appear as? 2. Did you devise a strategy for searching? 3. Did you ignore any part of the range and search for specific colors? If subjects had trouble divulging a search strategy, then further questions were directed towards asking about specific uses of color, areas of the range and so on.

Results

The data from the current Experiment were compared with the data from the 4-step Target Set from Experiment 1A. Response times and accuracy were submitted to a 2 (Target Set: 4-step versus 4-step range) x 2 (Target Presence: absent versus present)

ANOVA with Target Set as a between subjects factor. The fixation probabilities were submitted to a similar ANOVA with Color Step added as a factor.

The responses to the questions following the experiment revealed that most subjects reported that the targets mostly appeared towards the end of the range, but not specifically the outer edge. Notice that the range in Figure 12 does not contain clear delineations between the colors, perhaps giving the impression that more than just the outside colors were present in the experiment. Despite the fact that the majority of subjects made this observation, no subject reported altering his or her strategy for searching throughout the entire experiment. Some went as far to express that they 'felt as though the target would eventually appear in the other colors.'

Accuracy and Response Times

Similar to previous results, subjects were more accurate and responded faster when the target was present. There was no significant difference between the 4-step and the 4-step range (mean difference = .08) for accuracy. Subjects responded faster in the 4-step Target Set (1747 ms) compared to the 4-step range Target Set (2219 ms), $F(1,30) = 9.00$, $p = .005$, and searched longer when the target was absent in 4-step range Target Set revealed through a significant Target Set x Target Presence interaction, $F(1,30) = 6.73$, $p = .015$.

Probability of Fixation

Consistent with Experiment 1, subjects were color selective and fixated more objects when the target was absent, as revealed through main effects of Color Step, $F(1,30) = 64$, $p < .001$ and Target Presence, $F(1,30) = 376.28$, $p < .001$, respectively. Subjects presented with the range fixated significantly more objects compared to

searching for the two separate targets, $F(1,30) = 12.10$, $p = .002$, and made more fixations when the target was absent in the 4-step range Target Set, resulting in a significant Target Set x Target Presence interaction, $F(1,30) = 7.90$, $p < .001$. Color step and Target Presence significantly interacted, $F(8,240) = 7.68$, $p < .001$, replicating the previous result that subjects fixated less objects and were more color selective when the target was present.

The 4-step range dramatically altered subjects' use of color, exemplified by a significant Color Step x Target Set, $F(8,240) = 13.28$, $p < .001$ interaction. When the target was absent, selectivity essentially broke down with the 4-step range resulting in a significant Target Set x Target Presence x Color Step, $F(8,240) = 10.85$, $p < .001$, interaction. Planned comparisons conducted on the intervening colors revealed that subjects fixated significantly more objects when given the 4-step range, both when the target was present ($p = .04$) and when the target was absent ($p = .022$) (Figure 13).

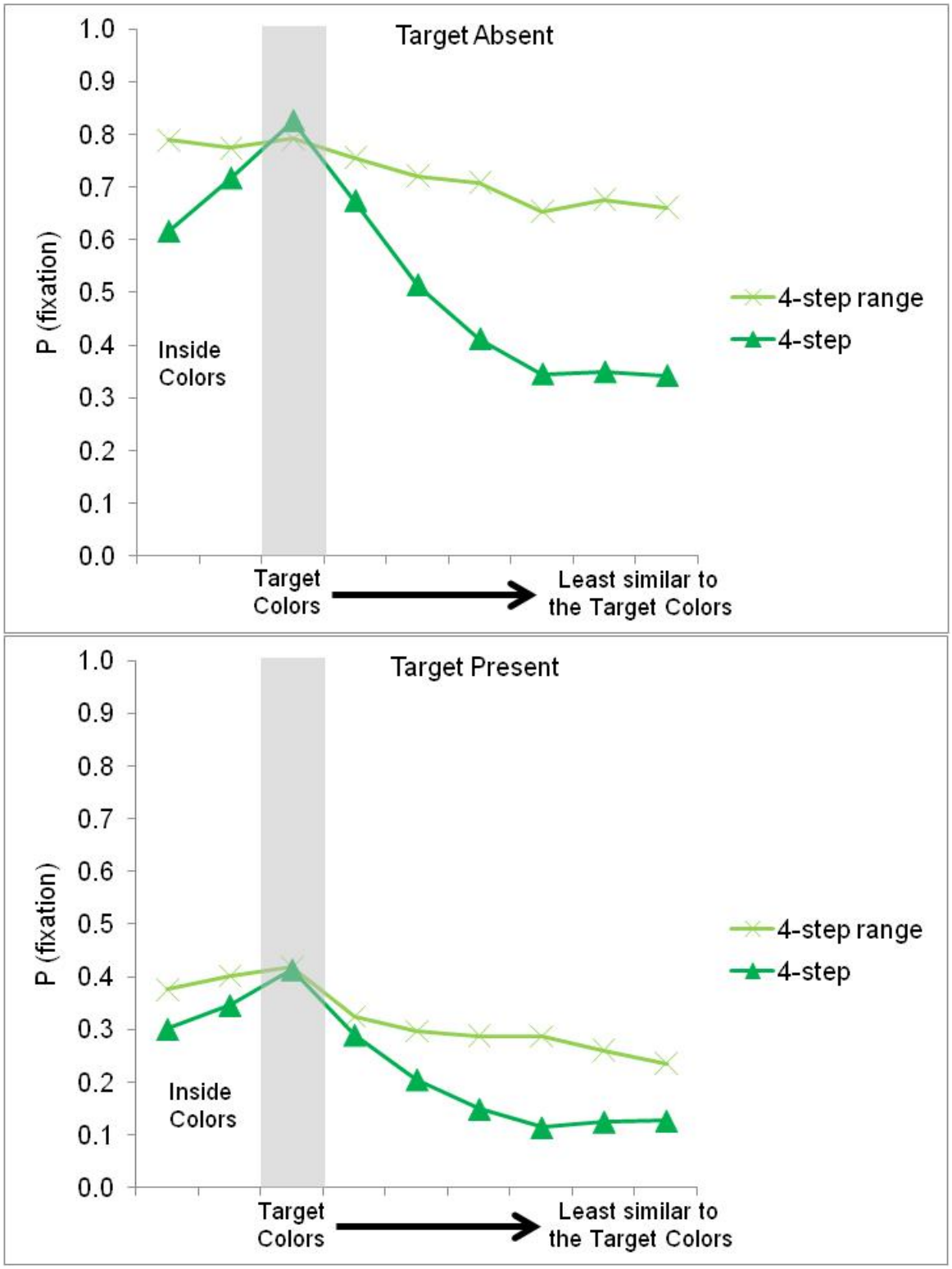

Figure 13: The probability of fixation for the 4-step and 4-step range Target Sets when the target was absent (top panel) and when the target was present (bottom panel).

Individual Differences

Similar to Experiment 1A, the individual subject data were inspected for the 4-step range Target Set to assess the degree to which subjects may have utilized a template range versus two discrete target templates. Once again, the fixation probabilities for the middle intervening color were subtracted from the mean of the target colors to yield a difference score. These difference scores for the 4-step range were plotted along with the scores from the 4-step Target Set to provide a direct comparison between the two Target Sets (Figure 14).

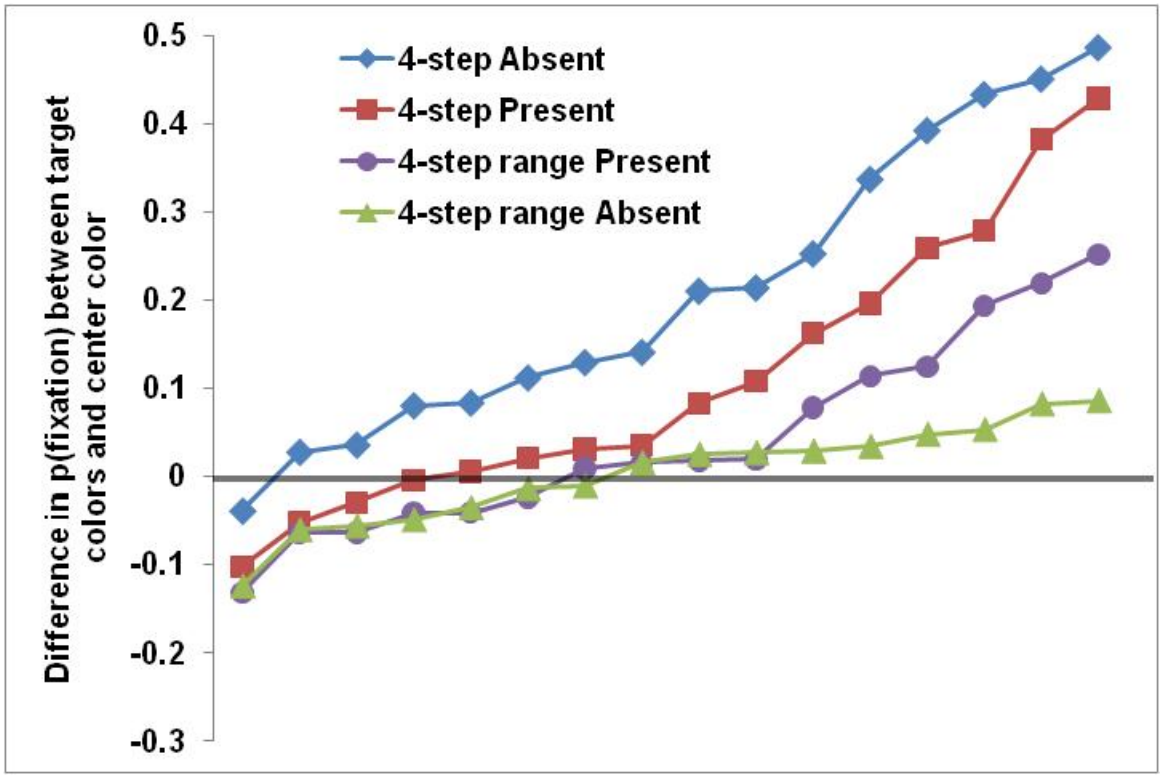

Figure 14: The individual differences for the 4-step range and 4-step Target Sets.

Discussion

Experiment 2 was aimed at investigating if subjects could utilize a range of target colors as an effective template for guiding search when with the target color was

specified by a range stimulus. It was suspected that the range stimulus presented to the subjects as a search target would produce the greatest effect on the three intervening colors that are between the two targets in color space. Subjects viewed the exact same stimuli as the 4-step Target Set in Experiment 1A, but were given a 'range' of colors to search for instead of two separate templates. In terms of response times and accuracy, performance only differed slightly between the two Target Sets. However, the fixation probabilities revealed that search was markedly affected when subjects were given the target range.

Overall, subjects given the 4-step Range fixated significantly more objects, indicating a reduction in color selectivity. What was more interesting is specifically how the range affected subjects' use of color during search. Recall from Experiment 1 how color selectivity was weakened as the distance in color space between the two targets increased, from 1-step to 4-steps. This reduction in selectivity was greatest on colors that were least similar to either target color. In the current experiment, the three way interaction between Color Step, Target Set and Target Presence demonstrated a similar decrement in color selectivity.

When the target was present, subjects did in fact fixate the intervening colors at a higher frequency than when the target was specified as two separate objects. However, the difference in fixation probabilities for the objects least similar to the targets was much greater compared to the difference for the intervening colors. When the target was absent, subjects fixated every object at about the same frequency, indicating almost a total breakdown in search selectivity. These results suggest that search is initially guided by the target range, and if the target is not located, then mechanisms of search break

down, resulting in increased fixation rates on almost every object. The individual differences supported this notion as well. Compared to Experiment 1, Figure 14 shows that the proportion of subjects with difference scores close to 0 when searching for the range is greater than subjects searching for the discrete targets. However, these data can be misleading since subjects presented with the range fixated nearly every color at a greater frequency and not just the intervening colors.

Subjects had difficulty utilizing the presented range stimulus to effectively guide search. The target color range did cause a decrease in selectivity for the intervening colors, but it also created a much larger cost for objects dissimilar to either target color. Thus, it appears that for colors that are separated by 4-steps in colors space, it is not likely that subjects are utilizing a single template to guide search. Based on this notion, two questions remain: 1) What leads to the diminished color selectivity reflected by the increased fixation frequency on colors dissimilar to the targets? 2) Can a template range be maintained for two similar colored targets if there are fewer intervening distractor colors included? The goal of Experiment 3 is to investigate these notions further.

CHAPTER 4

EXPERIMENTS 3A and 3B

Introduction

The results of Experiment 1 revealed insight about color selectivity as well as how two colors are represented to guide search. Two interesting results emerged thus far regarding selectivity: the cost for searching for 2 colors at once and an additional cost when the targets were less similar to one another. It appears that this cost is directly related to the degree of separation in color space between the two targets. However, the generalizability of the results is limited. The results of Experiment 1 were only based on two different target sets that contained either very similar or fairly dissimilar colors (Figure 3). The data suggest that dissimilar colors (separated by 4-steps) are represented as two separate templates rather than a unitary range. Although searching for two similar colors produced a decrement in search, compared to searching for just one, it is impossible to make any claims regarding representation since no intervening colors existed. This leads directly into the main motivation for Experiments 3A and 3B.

The current experiment further examined this split target cost by utilizing targets that are separated by only 2 steps in color space (containing 1 intervening color). This condition presents a level of similarity that is in between the 1-step and 4-step Target Sets. The results will be able to speak to the nature of both the split target cost as well as representation in addition to what was found in the previous experiments. The results of the previous experiments suggest that as the similarity between the colors decreases, the proportion of fixations to objects dissimilar to either target color increases. However, these results are limited to only two levels of target similarity. The current experiment

will provide a more complete picture of the split target cost with the intermediate level of similarity between the targets. If the split target cost is directly related to the similarity of two target colors, then the fixation probabilities for the 2-step Target Set to colors dissimilar to either target should be increased compared to the 1-step Target Set, but not as high as the 4-step Target Set. The current experiments included a dual target condition (3A) as well as a range condition (3B) analogous to the previous experiments.

Method

Subjects

Thirty-two additional University of Massachusetts students, recruited from the same subject pool as the previous experiment, took part in these experiments. Sixteen subjects participated in Experiment 3A (Mean age = 20, SD = 2.70) while the remaining sixteen participated in Experiment 3B (Mean age = 19.38, SD = 0.89).

Design

As in Experiments 1 and 2, both dual target and range Target Sets were utilized in the current experiments, resulting in two levels of Target Set: 2-step and the 2-step range. The experiments together produced a 2 (dual versus range) x 2 (absent versus present) x 7 (color) step mixed factorial design.

Apparatus and Stimuli

The same equipment and settings were used for the current experiment. While new stimuli were generated for the current experiment, the same parameters were invoked except the target colors were separated by 2 steps with just 1 intervening color.

Procedure

The same procedure as before was used in the current experiment.

Results

The data from Experiment 3A were combined with Experiment 1 to assess the dual and split target costs across the four Target Sets. Response times and accuracy were analyzed in the same fashion as Experiment 1 yielding a 4 (Target Set: 4-Step versus 2-Step versus 1-step versus single) x 2 (absent versus present) repeated measures ANOVA with Target Set as a between subjects factor. Fixation probabilities were submitted to a 4 (Target Set) x 2 (Target Presence) x 7 (Color Step) mixed analysis of variance. As with Experiment 1, only color steps common across all 4 Target Sets were included. Planned comparisons were aimed at comparing the 2-step Target Set with the 4-step Target Set, particularly on the intervening colors.

For Experiment 3B, the 2-step range Target Set was compared with the 2-step Target Set to evaluate the same predictions regarding representation as two separate targets versus one unitary range. Planned comparisons were conducted on the single intervening color between the two Target Sets. Finally, the 2-step range and the 4-step range Target Sets were compared to determine how the range representation was influenced by the separation between the two target colors in color space.

Experiment 3A

See Figure 15 for a summary of the response times and accuracy across all 4 Target Sets. The overall comparison replicated the previous two experiments revealing faster response times, $F(1,60) = 102.86$, $p < .001$, and less errors, $F(1,60) = 55.13$, $p < .001$, when the target was present. Comparisons revealed that subjects searching for the

single target responded significantly faster compared to each of the dual-target sets (ps < .006). Response times increased as the similarity between the targets decreased, but to a higher degree when the target was absent. This was supported by significant interactions between Target-set and Target-presence for each dual target set compared to the single target (ps < .05). There was no difference between the 2-step and 4-step Target Sets. For accuracy, the same pattern shown in response times was demonstrated for target present trials, but the interactions failed to reach significance due to the ceiling effect when the target was absent (mean target absent error rate = 1.2%).

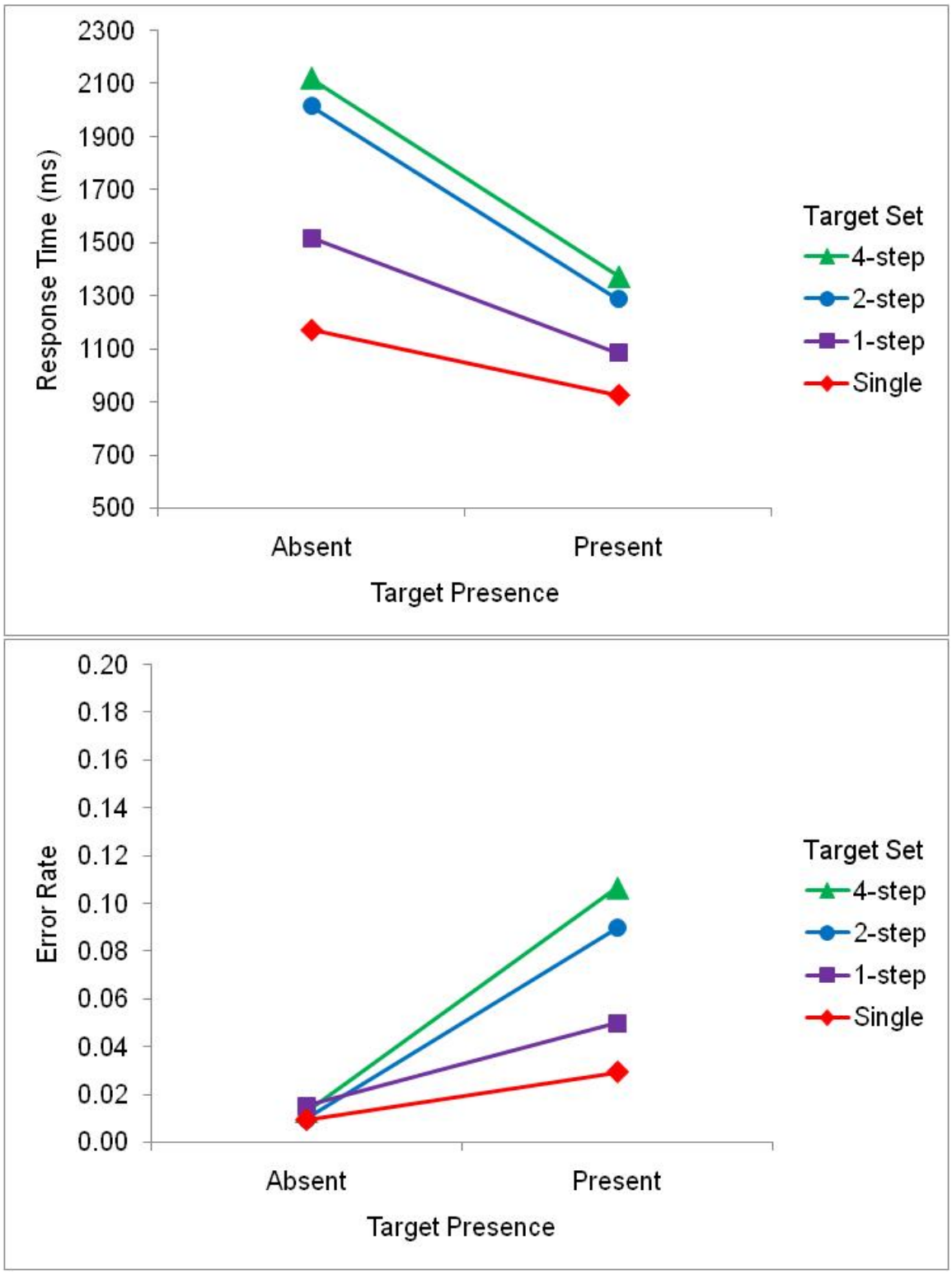

Figure 15: The response times (top panel) and accuracy (bottom panel) across all 4 Target Sets. Note the scale for accuracy only extends to .20 in order to show the separation between the Target Sets.

Figure 16 presents the fixation patterns for all 4 Target Sets. While the main focus of the current experiment is between the 2-step and 4-step Target Sets, it is important to note that, with all of the Target Sets included, the 3-way interaction between Target Set, Target Presence and Color Step reached significance, $F(18,360) = 2.170$, $p = .004$. The primary comparison of interest for the current experiment was between the 2-step and 4-step Target Sets to further explore the effect that separating targets in color space had on the fixation probabilities.

Color was used differently to guide search between the two Target Sets as revealed through significant interactions between Color Step and both Target Presence, $F(7,210) = 33.30$, $p < .001$, and Target Set, $F(7,210) = 3.23$, $p = .003$ as well as the interaction between all three factors, $F(7,210) = 2.11$, $p = .043$. The two Target Sets included in this comparison contain intervening colors in between the targets in color space. Refer to the data points to the left of the shaded region in Figure 16 for the fixations to these intervening colors. For both target absent and present trials, subjects fixated the common intervening color more in the 2-step Target Set, although the t-tests were not significant ($ps > .20$). Turn now to the data points to the right of the shaded region in Figure 16. These represent the fixations to the distractors that are outside the target colors on the color wheel. The results showed that subjects in the 2-step Target Set fixated more objects dissimilar to the targets compared to the single target and 1-step Target Sets, but not as much as in the 4-step Target Set. This illustrates the split target cost by showing that the increased fixation frequency on these distractor colors dissimilar to either target is a function of the similarity between the target colors.

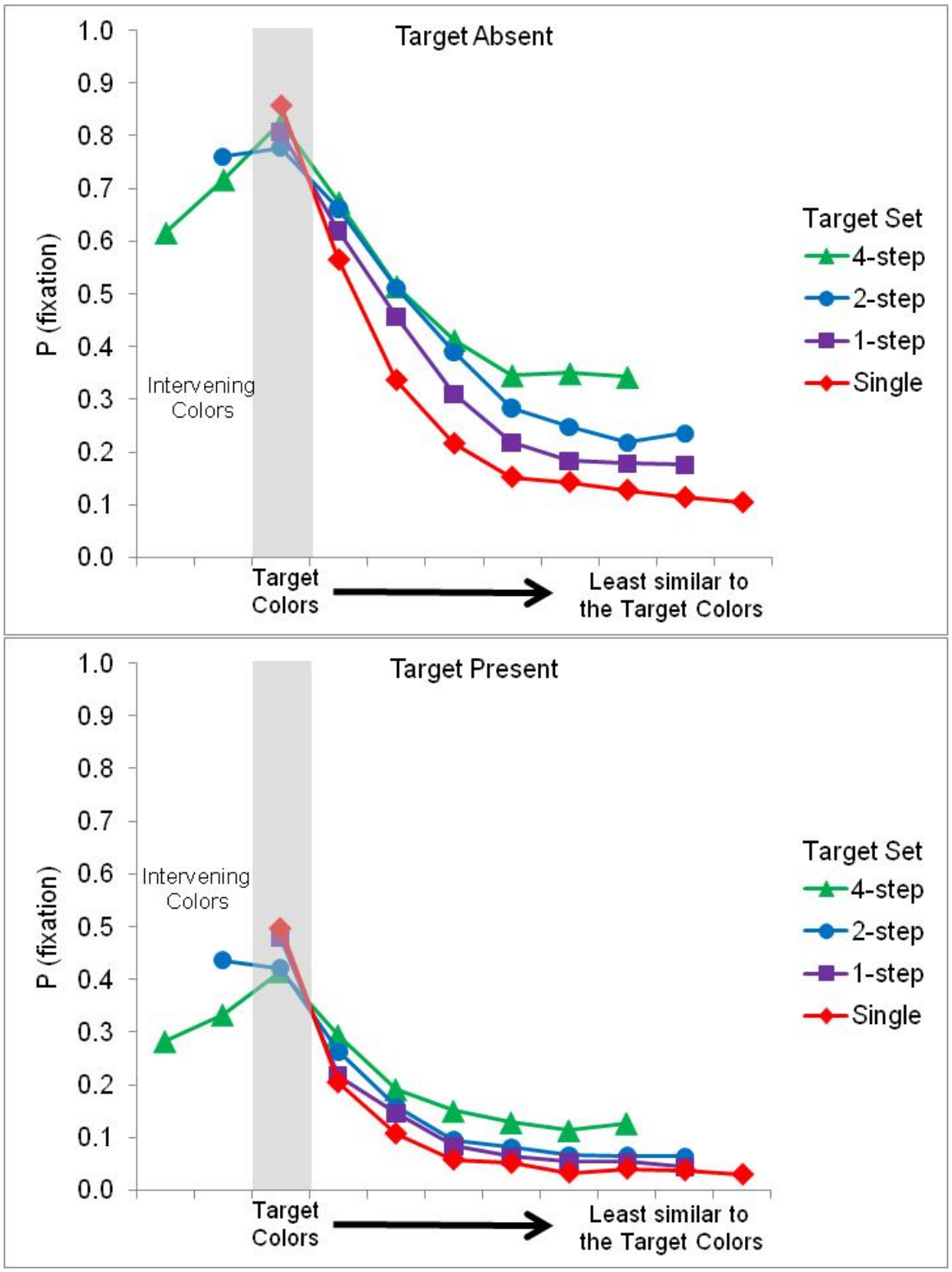

Figure 16: The probability of fixation for all 4 Target Sets for both target absent (top panel) and present (bottom panel) trials. The green and blue lines represent the three way interaction between Target Set, Target Presence and Color Step for the comparison between the 2-step and 4-step Target Sets.

Experiment 3B

There was no reliable difference between the 2-step and the 2-step range Target Sets for both accuracy and response times (ps < .20). Subjects responded faster and were more accurate when the target was present (ps < .001), and the Target Set x Target Presence interaction failed to reach significance for both measures (ps > .25).

Subjects fixated more objects on target absent trials compared to target present trials, $F(1,30) = 234.38$, $p < .001$, and more objects similar to the targets, $F(8,240) = 122.87$, $p < .001$. The only significant interaction was between Target Presence and Color Step, $F(8,240) = 27.71$, $p < .001$, replicating the fact that subjects are more color selective when the target is present. Fixations to the intervening color did not significantly differ between the two Target Sets for both target absent ($p = .784$) and present ($p = .144$) trials. The three-way interaction between Target Set, Target Presence and Color Step failed to reach significance ($p = .250$), which suggests that color was not used differently between the dual target and range Target Sets. However, comparisons revealed that subjects given the range target specification fixated significantly more objects than those shown two separate target objects, both when the target was present, $F(1,30) = 4.64$, $p = .039$, and when it was absent, $F(1,30) = 1.31$, $p = .034$ (See Figure 17).

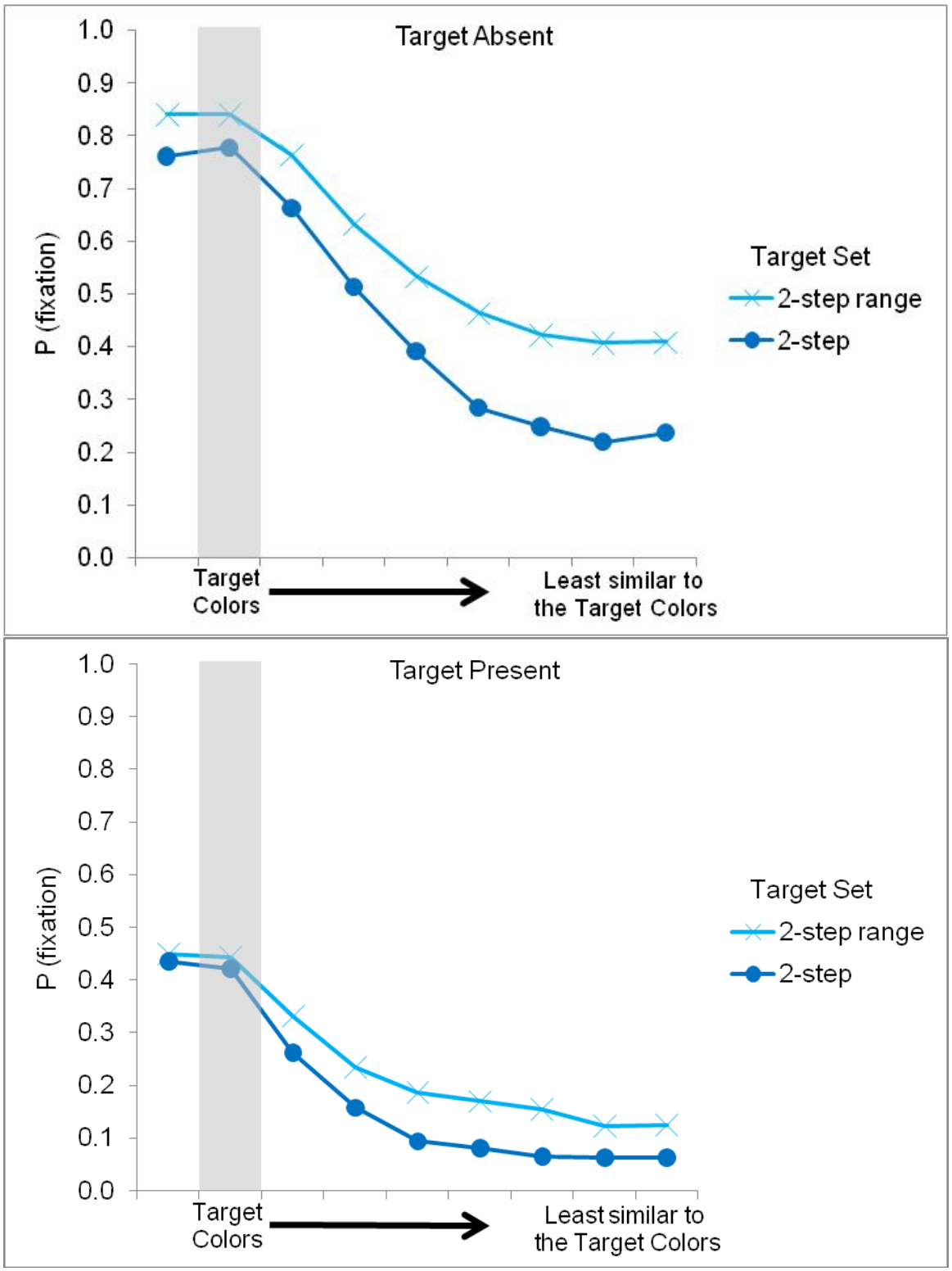

Figure 17: The probability of fixation for the 2-step and 2-step range Target Sets for both target absent (top panel) and present (bottom panel) trials.

The 4-step range and 2-step range Target Sets were compared to investigate the effect that the increased number of colors represented in the range had on the objects fixated. Figure 18 shows that the 4-step range was more difficult to maintain compared to the 2-step range. Similar to the comparison between the 2-step and 4-step Target Sets, color selectivity was dramatically altered as the number of intervening colors increased. Color Step, once again, significantly interacted with Target Set, $F(7,210) = 11.39$, $p < .001$, and Target Presence, $F(7,210) = 7.23$, $p < .001$. Finally, the range stimulus had varying affects on search depending on the presence or absence of the target. When the target was present, color selectivity was somewhat preserved for both Target Sets, but when the target was absent, subjects given the 4-step range fixated almost every object with the same frequency. This was supported by a significant three-way interaction between Target Set, Target Presence and Color Step, $F(7,210) = 7.32$, $p < .001$).

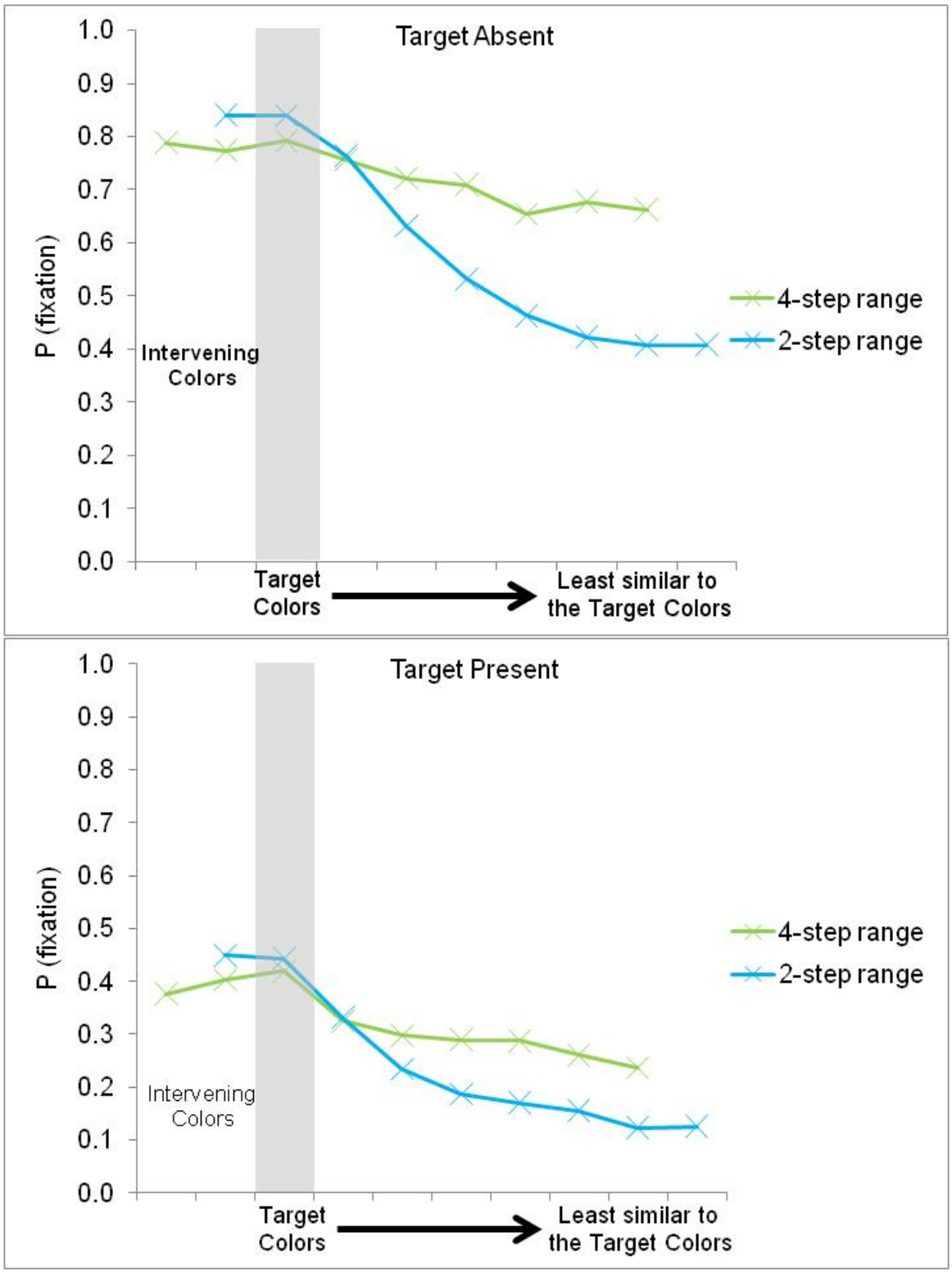

Figure 18: The probability of fixation for the 2-step range and 4-step range Target Sets for both target absent (top panel) and present (bottom panel) trials.

Individual differences were evaluated as was done with the 4-step Target Set to examine whether subjects are maintaining two separate target representations or a unitary template range. Figure 19 provides a summary of these results for both the 2-step and 2-step range Target Sets. The results suggest that in both conditions (dual target and range), the majority of subjects fixated the single, intervening color at the same frequency as the target colors. Together, this pattern favors a range representation of the two similarly colored targets.

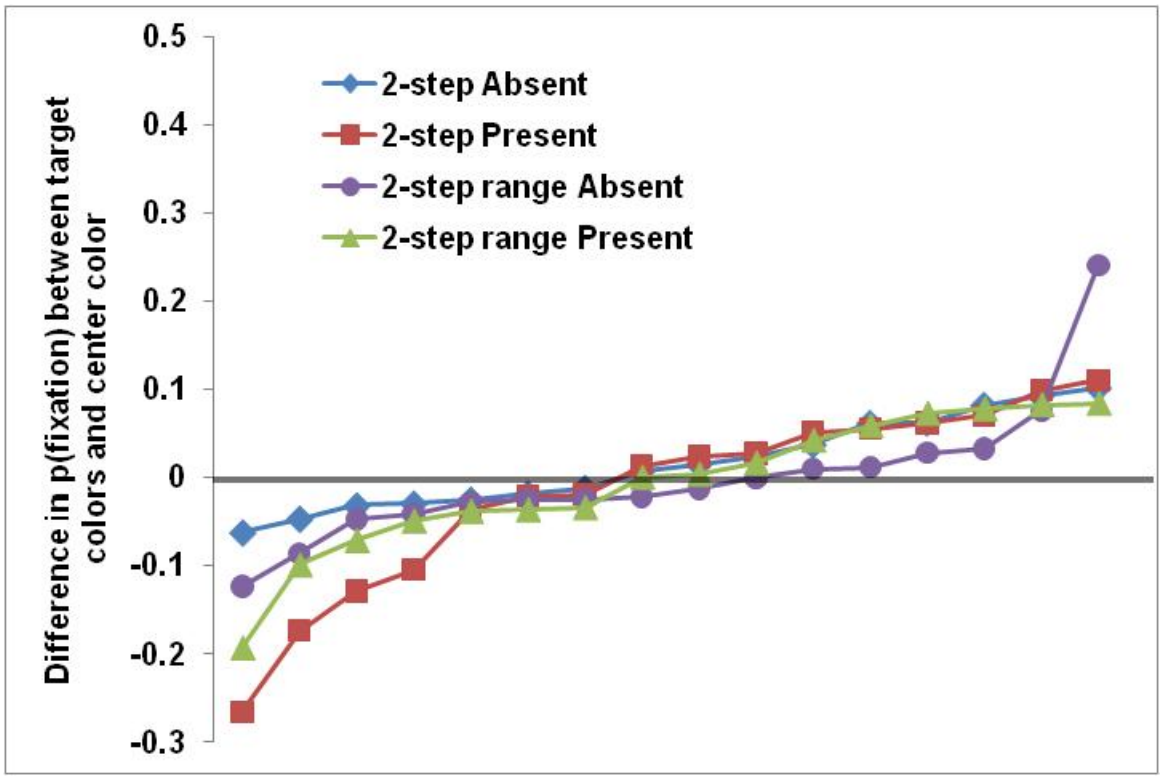

Figure 19: The individual differences for the 2-step and 2-step range Target Sets.

Intermediate Summary

The first three experiments utilized well-controlled shape stimuli to explore the degree to which observers can limit their fixations based on multi-target representations defined primarily by color. Subjects can effectively use color to guide search, as in earlier studies. In all Target-sets, this color selectivity was weakened when the target was

absent, most likely reflecting a broadening of search after the target was not initially located. The present results confirmed previous findings demonstrating a cost for searching for two colors at once. When searching for a single color, subjects exhibited a high degree of color selectivity by directing saccades mainly to objects of the target color and of other similar colors. The addition of a second target had varying effects depending on the similarity between the two target colors. A cost was observed even for two very similar colors (1-step separation) and the cost increased as the dissimilarity between the two target colors increased. However, it was the source of this cost that is the most intriguing.

What is surprising in the current data is that this 'split-target' cost was not a result of more fixations to objects that were similar to the target colors, but rather to an increased fixation frequency on objects very different from the target colors (See the right side of Figure 16). In terms of guiding mechanisms, it appears that subjects in the 1-step Target-set may be representing the two colors as a single unitary template, since search was only marginally affected by the increased number of targets. However, going from 1-step to 4-steps, there appears to be a trend towards representing the targets as discrete templates, as evidenced by the fixations to the intervening colors. For the 2-step Target-set, subjects had trouble ignoring the single intervening color and fixated it at about the same rate as the targets, suggesting that subjects constructed a representation that included a range encompassing both target colors as well as the feature values in between them. When subjects were presented with a 2 step range stimulus specifying the target color values, the results were somewhat similar to the dual target condition. When the target was present, the target and intervening color were fixated at the same frequency in

both conditions. However, when the target was absent, there appeared to be a cost for all color steps. This suggests that subjects may be representing the two similarly colored targets as a range, but the actual "range" held in working memory guiding search may be different than the rainbow stimulus presented to subjects in Experiment 3. The difference between the two might create another potential source of interference, possibly contributing to the cost observed as a result of the given range.

The results of the 4-step Target-set showed that the three intervening colors received considerably fewer fixations compared to the target colors, suggesting two separate, discrete templates. When subjects were presented with the range stimulus specifying target colors, search was disrupted greatly across all color steps. Thus, it appears that when the two targets are similar, they may be represented as a unitary range, but when they are dissimilar, search is guided by two separate templates. However, the split target cost suggests that these discrete templates cannot be maintained effectively. If the two templates are guiding search concurrently (the simultaneous hypothesis), then perhaps the extra fixations are due to interference between the conflicting templates. If, instead, one template controls search and is then replaced by the other (the alternating hypothesis), then this cost might reflect switching costs from these repeated individual searches? This, as well as implications for representation will be discussed in more detail in the final chapter.

CHAPTER 5

EXPERIMENT 4

Introduction

The previous experiments revealed the degree to which observers can limit their fixations based on multitarget representations defined within the single dimension of color. Experiments 1A, 1B and 3A manipulated the color differences between the targets in dual target search, compared to a baseline search for a single target color. In Experiments 2 and 3B, the target colors were specified with unitary ranges that spanned either four or two color steps, respectively. Collectively, this series of experiments varied the information given to subjects about possible targets, in an attempt to reveal the templates utilized to guide fixations during search. The purpose of the next set of experiments is to test the limits of selectivity by manipulating additional aspects of the stimuli involved in search. Previous research has shown that the saccadic system is quite flexible (Pomplun, Reingold, & Shen, 2001, 2003; Shen, Reingold, & Pomplun, 2000, 2003; Williams, & Reingold, 2001) and the goal of the following experiment is to investigate how the guiding template or templates are shaped by the various targets and distractors the observer encounters while performing repeated search trials. In other words, search behavior will be manipulated through the characteristics of the distribution of colors in the displays as opposed to the information provided to the observers.

The previous experiments suggested that the guiding template is influenced by the similarity between the two search target colors. When the targets were similar to one another (the 2-step Target Set), the majority of subjects appeared to construct a template with a single range containing the targets and the one intervening color. As the targets

decreased in similarity (the 4-step target set), search seemed to be guided by separate templates for each target, as evidenced by a greater ability to fixate fewer intervening colors. To what extent is this template shaped by the actual exposure to distractors with these intervening colors? One possibility is that the exposure leads to a more specific template that excludes those colors, resulting in the ability to ignore those distractors. An alternative account is that the intervening distractors interfere with the ability to shape the template, leading to a greater frequency of fixations on those intervening distractors.

The current experiment aims to test if a range representation might be conjured if subjects do not encounter any distractors with these intervening values for the first half of the experiment. During the second half of the experiment, intervening colors will be presented in the same way as Experiment 1A. If the target template can be 'molded' into a range, then the intervening colors should be fixated at rates similar to the targets. Specifically, this question was investigated in the current experiment by comparing the probability of fixation to the intervening colors between the second half of both experiments. If the proportion of fixations in the second half of the current experiment is not significantly different from latter half the 4-step Target Set, then apparently exposure or practice (across a short interval) does not allow observers to 'hone' in on the two target representations.

The current experiment may also address the split target cost revealed in the previous experiments. The split-target cost, as described previously, is the increase in the frequency of fixations to objects dissimilar to the targets as a function of the separation, in color space, between the two target feature values. Is this cost mediated by exposure to these intervening colors? It could be that the presence of the intervening colors, which

attract more fixations than the outside colors (as a result of attention driven by both targets) equally distant from the targets in color space (see Figure 16), tax the system and contribute to this cost. With no intervening colors present, a range template would be the most efficient as it requires maintaining just one guiding template. However, if intervening distractor colors are present, then a range stimulus is not efficient, and the system is faced with more feature values to ignore, increasing the difficulty of the task. This interference could result in an overall decrement in performance as evidenced by fixations on the highly dissimilar colors. Alternatively, the absence of the intervening colors may facilitate selectivity by limiting the number of distractors that are highly similar to the targets, which may influence the template utilized to guide search. Less strain on the system, coupled with fewer distractors competing with the template, may perhaps lead to a higher degree of color selectivity and the absence of the split target cost. This question was explored by comparing the probability of fixation to the dissimilar distractor colors from the first half of the current experiment with the first half of the 4-step Target Set from Experiment 1A.

Only the 4-step Target Set was used in this experiment because it is the condition from the previous experiments in which the targets were least similar to one another. If the results of the current experiment demonstrate large differences based on this specific degree of separation between the target colors, then similar experiments should be conducted with additional target sets.

More broadly stated, the current experiment is aimed at exploring the following questions: 1) If subjects are effectively holding two templates in memory in order to guide search, how much are these templates affected by the properties of the stimuli

encountered across trials? 2) If there are no distractors with colors between the two target colors, will subjects be more likely to represent the target colors as a single range, and if so, will this make it easier or harder to avoid other distractor colors? The current experiment will attempt to address both issues in light of the information the observer encounters throughout the experiment.

Method

Subjects

Sixteen additional subjects from the same pool as the previous experiments participated in Experiment 4 (Mean age = 19.63, SD = 1.41).

Apparatus

The same equipment and settings as the previous experiments were utilized for the current experiment.

Stimuli

The stimuli for the current experiment were constructed in the same manner as Experiment 1. The task was the same as the previous experiments, which was to locate the target T amongst Ls for a total of 256 experimental trails (50% with the target present) preceded by 5 practice trials. The main manipulation involved presenting intervening distractor colors exclusively during the second half of the experiment. The first 128 trials only contained objects drawn from 13 out of the 16 possible colors from the color wheel: the two target colors and the remaining 11 distractor colors outside the targets. Because these trials do not contain any intervening colors, the total pool of possible objects to create the stimuli was reduced. As a result of this, the additional objects were evenly distributed across the remaining 13 distractor colors. Subjects were

not made aware of the composition of the stimuli. To allow a direct comparison with Experiment 1A, the second half of this experiment contained the exact same trials as the second half of the 4-step Target Set from Experiment 1A. The purpose of this condition is to test whether repeated trials with no intervening colors will affect subjects' selectivity on subsequent trials. That is, after not being exposed to the intervening colors, are those feature receptors effectively 'turned off' or 'enhanced'?

Procedure

The procedure was the same as Experiment 1.

Results and Discussion

The results of 4-step Target Set from Experiment 1A were included in the data analysis, reflecting the condition that has a common occurrence of intervening colors. This 4-step Target Set contains intervening colors on 86.5% of the trials (SD = 1.41%). For the purposes of the current experiment, the condition from Experiment 1 will be referred to as 'Intervening' and the condition from the current experiment will be considered 'No-intervening' to focus on the most important aspect that is being compared. The No-intervening condition represents the extreme in regard to manipulating the presence of the intervening distractor colors. If significant results are found in regard to selectivity based on the current manipulation, these results would warrant further experiments with different levels of proportions of intervening colors.

Accuracy and response times were submitted to a 2 (Target Presence: absent versus present) x 2 (Target Set[1]: intervening versus no-intervening) mixed analysis of variance, with Target Set as a between-subjects factor. In order to compare the effects of

[1] Note that the factor of Target Set is used differently in this experiment. The target colors were the same for both levels of this factor and Target Set refers to the presence or absence of intervening colors during the 1st half of the experiment. Target Set was used to remain consistent across all experiments.

exposure to the intervening colors, the first and second halves of the experiments were analyzed separately.

Consistent with all previous analyses, subjects committed more errors, but responded faster when the target was present (ps < .001). There was no significant difference for response times between the two Target Sets for the first half of the trials. However, subjects were slightly more accurate in the no-intervening (Mean error rate = 7.1%) compared to the intervening (4.5%) Target Set, $F(1,30) = 5.25$, $p = .029$, especially when the target was present, resulting in a significant Target Set x Target Presence interaction $F(1,30) = 1.30$, $p = .047$. For the second half of the experiment, accuracy and response times did not significantly differ between the two Target Sets. There was a significant Target Set x Target Presence interaction, $F(1,30) = 5.54$, $p = .025$, for response times only as a result of faster responses for the no-intervening Target Set when the target was present. While these results provide some evidence that exposure to the intervening colors alters performance, they might simply be due to the individual differences as a result of the between-subjects manipulation of Target Set. Analysis of the patterns of eye movements will reveal whether these small differences in RT and accuracy affected color selectivity.

To evaluate the hypotheses regarding the influence the intervening colors had on selectivity, the fixation probabilities were be analyzed in a 2 (Target Set) x 2 (Target Presence) x 5 (Color Step) mixed ANOVA. As with the measures above, the two halves of the experiment were compared separately. Only the colors common between the two Target Sets were included each analysis. The results showed the same consistent finding that subjects fixated significantly more distractors similar to the targets, and fixated more

objects overall when the target was absent (ps < .001). Target Set and Target Presence significantly interacted both for the first half, $F(6,180) = 10.41$, $p < .001$, and the second half, $F(8,240) = 21.86$, $p < .01$, which, again is a reflection of an increased fixation frequency on dissimilar colored objects during target absent trials. With regard to selectivity, there were no significant main effects or interactions involving Target Set for either the first half (all ps > .91) or the second half (all ps > .45). There appears to be evidence that fewer intervening colors were fixated in the second half for the intervening Target Set when the target was present, but the comparison did not reach significance, $F(1,30) = 1.46$, $p = .236$. See Figure 20 for a summary of these results.

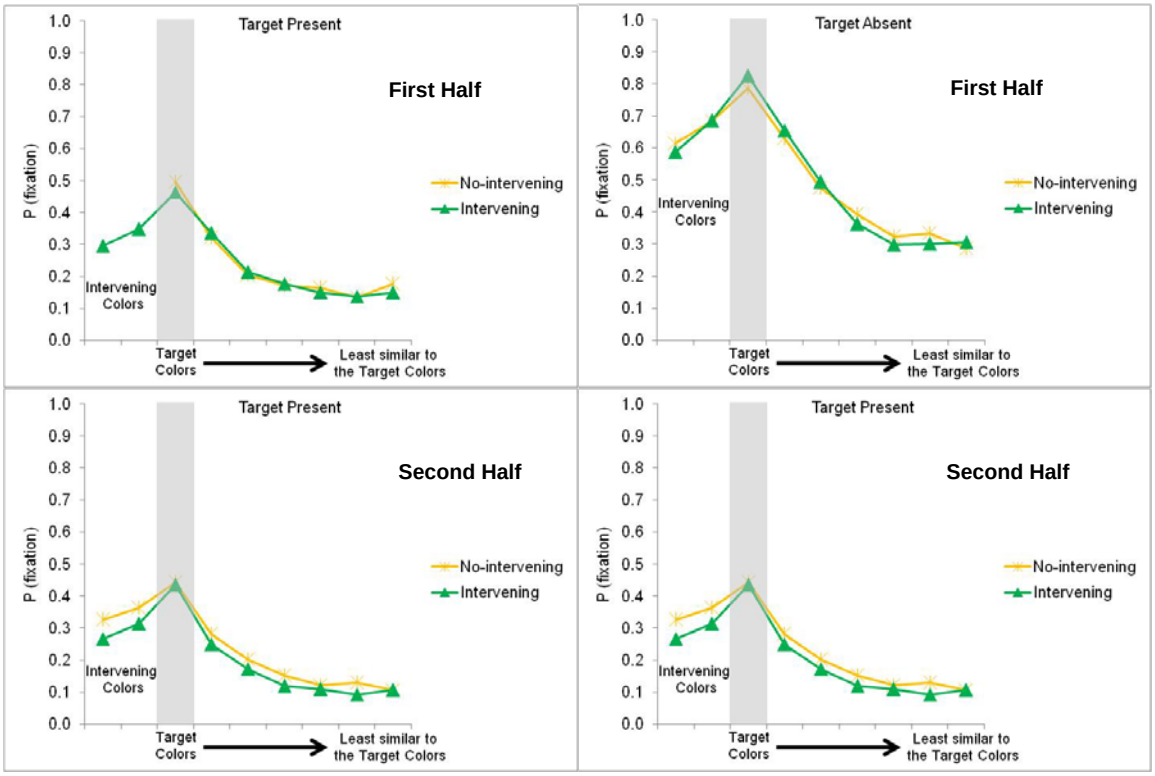

Figure 20: The probability of fixation for the Intervening and No-intervening Target Sets. The top panel represents the first half of each experiment and the bottom panel is the second half.

These results suggest that the intervening colors have, at best, a minimal influence on shaping the guiding template. The accuracy and response time data revealed that performance was somewhat limited for subjects exposed to the intervening colors, but there was no converging support for this in the eye movement data. The statistical significance associated with these effects was rather weak, and it is more likely that the results represent spurious effects due to individual differences between the groups. The probability of fixation results suggest that exposure to the intervening colors may provide some benefits in shaping the target template. The comparison involving the first half of trials showed no evidence that the absence of the intervening colors moderates the increased fixations to the dissimilar distractors characteristic of the split-target cost. Lack of a significant difference in fixations on dissimilar colors between the two experiments suggests that this cost may rather be associated with an inability to maintain an effective template, as opposed to interference or competition from the objects present in the display. The analysis of the second half of trials suggests that there is some advantage for viewing intervening colors on previous trials. In particular, there is a noticeable decrease in the fixation rate on the three intervening colors, but the statistical evidence is not strong enough to support this conclusion. Further experiments are needed to support these claims since they involve null results. Finally, these results also do not provide enough convincing support to perform similar tests based on the 2-step Target Set or with additional varied proportions of the intervening colors.

CHAPTER 6

EXPERIMENT 5

Introduction

The final experiment of this study will also be aimed at investigating the flexibility of the system involved in target representation guiding search. Three hypotheses were outlined in the introduction as possible ways that multiple targets may be represented. To test these hypotheses, the previous experiments included manipulations that required subjects to search for targets that defined at the beginning of each trial. The results suggest that representation depends on a number of factors, including the similarity between the feature values that define the targets. The previous experiment showed that prior exposure to specific distractor colors has a minimal effect on shaping the target template. The current experiment is focused on an additional aspect of representation. When two target templates are active in memory to guide search, the attentional system could either facilitate processing of items that match the target features (Duncan, et al. 1997), inhibit items with conflicting features (Cepeda, Cave, Bichot & Kim, 1998; Ruff & Driver, 2006), or perhaps use a combination of both mechanisms (Dosher & Lu, 2000). The purpose of Experiment 5 is to examine to what extent features can be activated or inhibited, by including a condition in which subjects are presented with a set of feature values that are <u>not</u> the targets. That is, subjects will either be presented with a subset of the colors that are likely to be targets or a subset of the colors that will never be targets. One key question of interest is whether search is driven more by top-down guidance (through the target or distractor representations) or bottom-up factors (the characteristics of the stimuli). In order to explore these two processes that

influence search, the analyses will be focused on the fixations to the colors that are not included as specified targets or distractors.

Method

Subjects

Thirty-two additional subjects recruited from the University of Massachusetts community took part in Experiment 5. The subjects in the target condition had a mean age of 19.81 years (SD = 1.05), and the subjects in the distractor condition had a mean age of 19.75 years (SD = 1.07).

Apparatus and Stimuli

The current experiment utilized the same materials and equipment as the previous experiments. The task remained the same: responding to the presence or absence of a target T amongst distractor Ls. The stimulus displays were constructed slightly differently for the current experiment compared to the previous experiments. See Figure 21 for a schematic of the target and distractor colors. The same stimuli were used for both conditions, but the information provided to subjects differed between conditions with the addition of the factor of Instruction Set. For this factor, the first level (Target) consisted of presenting subjects with four square color patches that occupy four contiguous colors from the same ring of stimulus colors used in previous experiments. Although subjects were only shown four target colors to search for, the targets appeared equally across eight different colors. These eight colors consisted of the four specified colors as well as the two colored objects immediately to the left and right of that set on the ring of stimulus colors. For the second level (Distractor), a different set of subjects were presented with four color patches that represented colors that never appeared as targets. These specified

distractor colors were on the opposite end of the color ring from the four specified target colors. The targets never appeared in any of these four specified colors, nor did targets appear in any of the two colors to the left or the two colors to the right of this specified range. For both subject groups, distractors appeared in each of the 16 colors an equal number of times throughout the experiment.

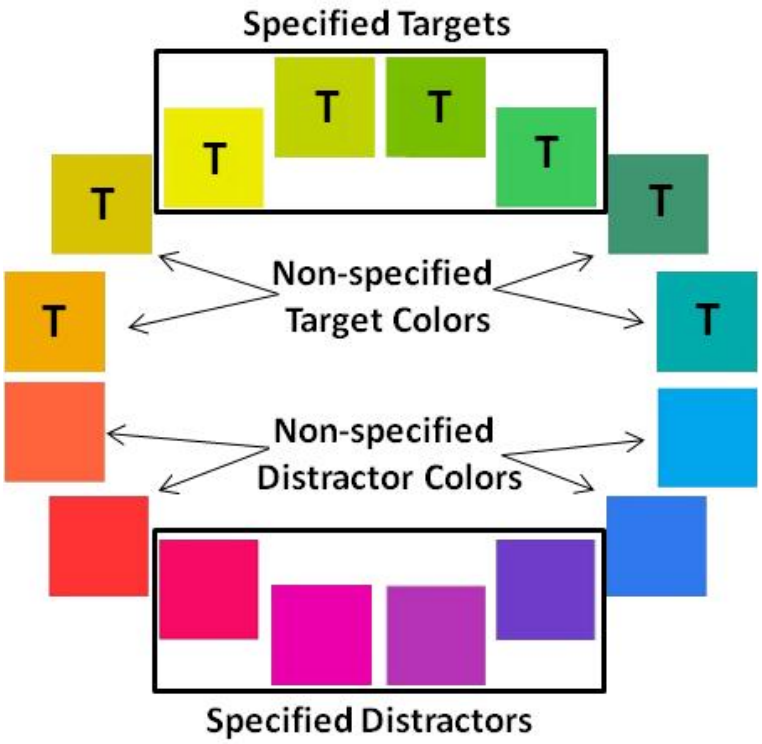

Figure 21: A schematic of the target and distractor colors used in Experiment 5. For both subject groups, each target appeared in any of the 8 colors labeled with a T, while each distractor appeared in any of the 16 colors. Subjects given the Target Instruction Set were presented with only the 4 Ts outlined in the upper box as possible targets. Subjects given the Distractor Instruction Set were presented with just the 4 colors in the lower box as colors that will never be targets.

Design

The main manipulation in this experiment is the information given to the subjects, which is included in the factor of Instruction Set described in the previous section. Also, the factor of Color Step from the previous experiments will be grouped differently to

focus on the different pairings of colors by category. This new factor will be referred to as Color Category, which includes the following four levels: the 4 colors specified in the Target Instruction set (level 1; Specified Targets), the 4 colors specified in the Distractor Instruction set (level 2; Specified Distractors), the colors between the target and distractor set that sometimes appear as targets, but are not specified in the Target Instruction set (level 3; Non-specified Target Colors) and the colors between the target and distractor set that only appear as distractors, but are not specified in the Distractor Instruction set (level 4; Non-specified Distractor Colors). The resulting design is a 2 (Instruction Set: Target versus Distractor) x 2 (Target Presence: Absent versus Present) x 4 (Color Category: Specified Targets versus Specified Distractors versus Non-specified Target Colors versus Non-specified Distractor Colors) mixed factorial design with Instruction Set as the only between-subjects factor.

Procedure

The experiment followed the exact same procedure as the previous experiments with the exception of the instructions. Before the experiment, subjects in both conditions were given the same instructions: to locate the T as with the previous experiments. Subjects were then informed of the nature of the color patches viewed before each trial. In the Target Instruction condition, subjects were specifically told that "the targets will most likely appear in any of the 4 colors." For the Distractor Instruction condition, subjects were informed that the "targets will never appear in any of the 4 colors." Each subject completed 256 experimental trials preceded by 5 practice trials.

Results

Accuracy and response times were analyzed based on the two factors of Instruction Type and Target Presence. There were no significant main effects or interactions for these two dependent measures, with the exception of faster responses and lower error rates on target present trials ($Fs > 90$). Therefore, there is no evidence that varying the instructions given to the subjects had an effect on speed or accuracy at finding the target.

The two subject groups produced similar patterns of fixations, and it appears that there was little effect of Instruction Type. As a result of the small differences between the two conditions, the data are presented within a restricted range in the graphs below in order to show the effects and possible trends more clearly (see Figure 22). The fixation probabilities were analyzed in a 2 (Instruction Type: Target versus Distractor) x 2 (Target Presence: Present versus Absent) x 4 (Color Category: Specified Targets versus Specified Distractors versus Non-specified Target Colors versus Non-specified Distractor Colors) repeated measures ANOVA. As with the previous experiments, the analyses were conducted on the distractor L objects only, so that the fixation rates reflected only search guidance based on color without guidance based on shape. This overall comparison revealed main effects for Target Presence, $F(1,30) = 1355$, $p < .001$, and Color Category, $F(1,30) = 11.72$, $p < .001$. There were no other significant main effects or interactions. Since there were several manipulations testing different aspects of search, this section is broken up into subsections focusing on separate aspects of the experiment.

Instruction Type

The data in Figure 22 suggest that there may be a subtle effect of instruction type, especially when the target was present, which may reflect events earlier in the search trial. Comparisons focused separately on the absent and present data demonstrated no significant main effects or interactions involving Instruction Type. Although the data suggest a reliable difference between the two Instruction Types when the target was present, the effect failed to reach significance ($p = .203$). The results of these comparisons as well as the overall results suggest that there was no affect for presenting subjects with information about which colors to search for versus which colors to avoid.

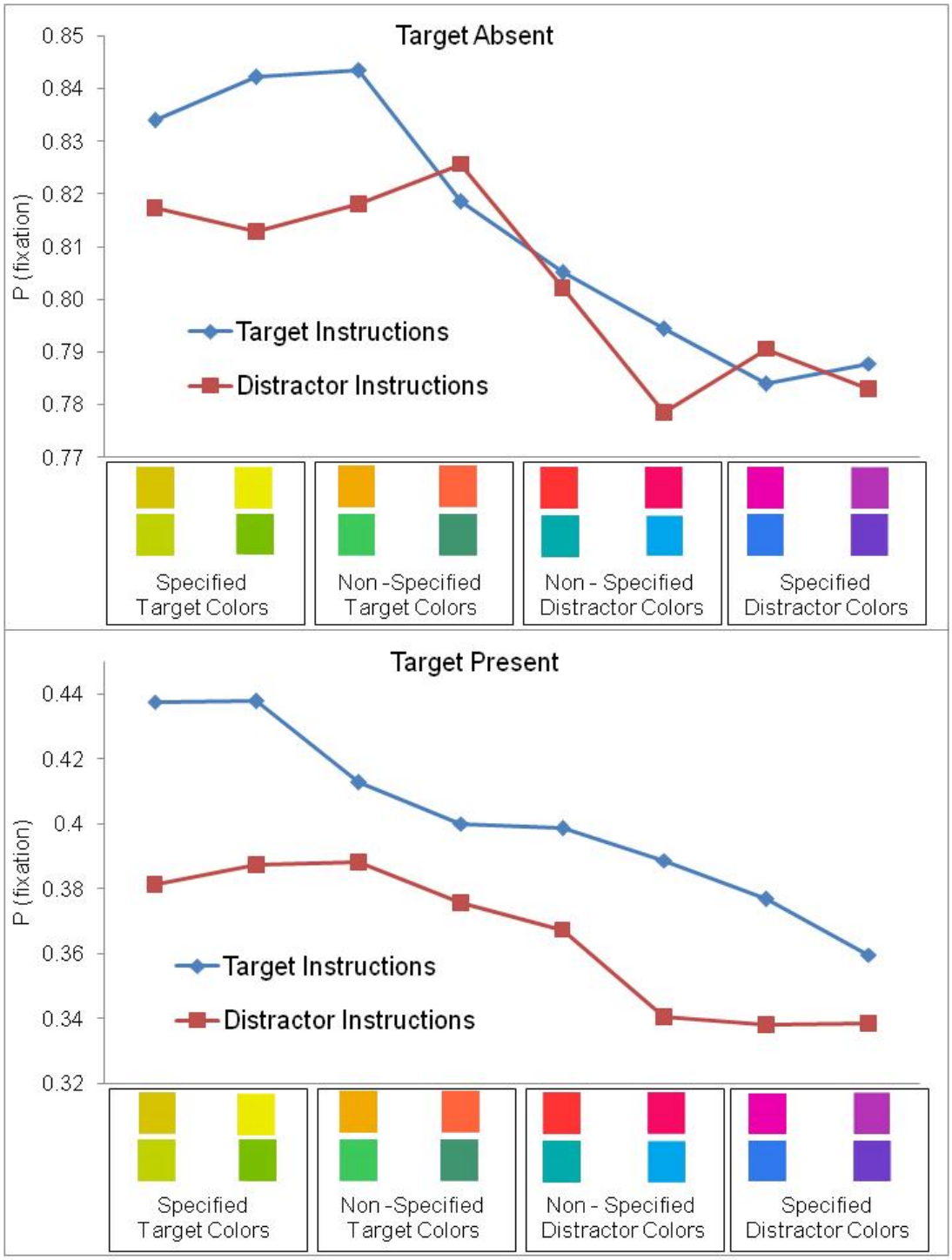

Figure 22: The probability of fixations for Experiment 5 with the top panel for target absent and the bottom panel for target present. The x-axis shows the different levels of color category. As with previous figures, the data for all 16 subjects are presented together, even though each subject searched for a different set of colors. The colors along the x-axis were arbitrarily selected to show the relative distance in color space between the distractors. Note that the y-axis scales are adjusted in order to illustrate the differences between the two Instruction Types better.

Color Selectivity

With regard to the main effect of Color Category found in the overall comparison, subjects fixated more target colored objects compared to distractor colored objects, both when the target was present and when it was absent. The fixation probabilities were collapsed across the colors that sometimes appeared as targets (the four points on the left side of Figure 22, or "possible target colors") and the colors that always appeared as distractors (the four points on the right side of Figure 22, or "never-target colors"). T-tests were conducted to observe if more target colored distractors were fixated within each of the Instruction Type conditions. When provided with information regarding colors to ignore (Distractor Instruction condition), subjects fixated significantly more possible target colors than never-target colors on both target absent, $t(15) = 4.374$, $p = .001$, and target present, $t(15) = 3.897$, $p = .001$, trials. When given information about the colors to search for (Target Instruction condition), subjects fixated more possible target colors compared to never-target colors both when the target was absent, $t(15) = 2.067$, $p = .056$, and present, $t(15) = 2.176$, $p = .046$. Given that the results for the Target Instruction condition were only marginally significant, this is weak evidence that information about the distractors to avoid could lead to stronger guidance. However, since this was a between-subjects design, this may simply be due to differences between the groups.

Specified target and distractor colors

On Figure 22, the two leftmost points on each line (specified target colors) represent the fixations to the target colored distractors that were either specified as target colors (the blue line) or furthest from the specified distractor colors (the red line). The

data suggest that the subjects who were provided with the information about the target colors fixated the specified target colors at a higher frequency when the target was present, but this difference only reached marginal significance based on a comparison ANOVA between the two sets of instructions, $F(1,30) = 3.284$, $p = .08$. Similar comparisons were conducted between the Target Instructions and the Distractor Instructions, specifically comparing the specified target colors and the specified distractor colors (the first and last box in Figure 22). However, each of these comparisons resulted in non-significant results (all ps > .560), giving no statistical evidence that specifying the target or distractors biased fixations towards specific distractor colors.

Discussion

The current experiment was aimed at exploring two main questions: 1) To what extent attention is guided toward items that match the target representations, or to what extent attention is guided away from those that match the distractor representations, and 2) to what extent selectivity is guided by the distribution of the colors that the target T's have been paired with over the previous trials. The first question was explored by comparing the boundaries between the specified and unspecified colors. If search was guided primarily by the representation of the target colors given in the instructions, then a sharp decrease in fixations should have been observed between the specified and non-specified target colors in the Target Instruction Set compared to the Distractor Instruction Set. The target present data in Figure 22 suggest that this may be what is occurring, but there is no statistical support for this claim. Similarly, if search was guided by the representations of the distractor colors given in the instructions, then a decrease in fixations should have been observed at the boundary between the specified distractors

and the unspecified distractors in the Distractor Instruction Set compared to the Target Instruction Set. Unfortunately the analyses do not provide enough convincing evidence to favor either of these explanations. Instead, the data seem to reflect a weak influence of the distribution of colors to the target objects.

To evaluate whether search was driven more by the information provided to subjects or the colors viewed across the experiment, the fixation probabilities between the eight target colors and the eight non-target colors were compared. These comparisons showed that in all conditions, the eight target colors were each fixated at a higher frequency compared to the eight colors that always appeared as distractors ($ps < .03$). To further investigate the influence of the colors viewed, the non specified targets and distractors were compared (the two inside boxes in Figure 22). The results showed that more fixations were made on non specified target colors compared to non specified distractor colors, $F(1,30) = 9.82$, $p = .004$. Comparisons were aimed at the specified versus non specified colors for both Instruction Set conditions separately when the target was present and when it was absent. Although the collapsed data yielded a significant result, none of the comparisons showed reliable differences (all $ps > .261$) . This result alone suggests that the guiding representation was perhaps developed from the information about the distribution of target and distractor colors gathered across trials throughout the experiment.

The results of the current experiment are consistent with a number of interpretations. This section will be devoted to outlining various possible explanations for these results, as well as ways to address each issue. Before discussing the specifics, it is important to take a closer look at the overall number of objects fixated for target absent

and present trials. Recall that each display contained exactly 10 objects. If subjects were to abandon all color information and adopt a search strategy that involves fixating every object until the target was located, roughly half of the objects would be fixated when the target is present (assuming that search would end when the target was fixated), and all items would be fixated when the target was absent. While the actual fixation rates do not correspond precisely to these predictions, subjects did fixate approximately 80% of the items when the target was absent and 40% when the target was present. Thus there is a fairly low level of color selectivity in this task, which could have arisen because of the instructions or because subjects were able to learn something about the target color distribution across many trial. To test between these two explanations, a condition should be run with no instructions using the same stimuli.

Each of the previous experiments involved presenting subjects either with a maximum of two discrete objects or one unified range. The current experiment involved presenting subjects with four discrete objects as the search set, which resulted in almost a total collapse in selectivity. It is entirely possible that building a template that includes four target objects creates too much of a disruption, by means of interference or cognitive load, which would lead to a seemingly unguided search strategy. This account would explain why a similar pattern of results is observed across both Instruction Sets. Keeping the original purpose in mind of testing whether subjects can effectively search for or ignore a given target set, the most appropriate way to address this concern would be to include a condition with fewer objects in the target sets.

Another aspect of the current experiment that diverges from the previous experiments is that the information provided to the subjects was not a completely

accurate description of the stimuli that the subject encountered. That is, even though four possible target colors were presented, the target could appear in any of eight different colors. In the subject group that was given information about what target colors to expect, subjects may have chosen to ignore these instructions given that the information proved to be false for 50% of the trials. Ignoring the instructions would result in either searching through every object (as discussed previously) or creating a template based on the actual colors viewed. The subjects who were given information about which objects to ignore were less likely to have noticed the limitations in the instructions they received, because the colors designated as distractor colors never appeared on target objects.. The instructions stated that a specified number of objects would 'never be the targets,' and although they left out some other important facts, these instructions proved to be correct as far as they went. The best way to determine whether the inaccuracies in the instructions affected attentional performance would be to include a condition in which the targets present throughout the experiment match the information provided to the subjects and only appear within those sets of colors.

The last issue involved in this experiment is in regard to the identity of the target sets that were presented. In the previous experiments involving discrete targets, subjects were given clearly defined objects to search for before each trial. In the current experiment, subjects viewed color patches rather than a concrete image of the search target. This is similar to the range experiments, in which subjects were presented with a rectangle containing the feature values included in the target set. In both the range experiments and Experiment 5, color selectivity was compromised, which may be partially attributed to subjects not viewing the target shape. The obvious way to

investigate this further would be to repeat Experiment 5, but present the targets as colored T shapes at the beginning of each trial, as was done in some of the earlier experiments. It is less clear how the information about possible distractors should be presented; perhaps as colored L shapes.

To summarize, there are at least three possible explanations for the weak color selectivity in Experiment 5: 1) cognitive overload/interference from four discrete objects, 2) incongruence between the instructions and displays, and 3) abstractly specified target or distractor information. There are a couple of different ways of approaching future studies. Since the search set for the previous experiments was manipulated between-subjects, it is possible to take advantage of the already collected data sets. Experiment 5 contains possible target colors spanning eight color steps, which represents the maximum possible separation between the two extreme values on the color wheel. Conversely, the 1-step Target set from Experiment 1A corresponds to the minimum degree of separation between the two targets. As a logical first step towards addressing all three issues discussed about the current experiment, a condition involving information about the distractors to ignore should be run with the 1-step Target Set. Subjects will be presented with exactly the same stimuli from Experiment 1A, but with different instructions. Rather than searching for the two Ts that are targets, subjects will be given the two colors that are on the opposite side of the color wheel, with instructions to ignore them. This experiment will address all three concerns by providing only two objects to search for, instructions that accurately describe the upcoming stimuli, and exposure to the target shape before each trial. The results will also represent a condition toward the extreme in terms of the minimum color distance between the targets. If the results provide clear

interpretations based on two similar targets, further experiments will be conducted with varying similarities between the targets.

CHAPTER 7

GENERAL DISCUSSION

The current project had several aims under the main goal of investigating the mental representations that guide visual search for multiple targets. The final chapter is separated into three sections and will proceed as follows. The first section will summarize the results of the five experiments. The next section will be devoted to exploring the implications of the current findings with respect to representation and visual search. The final section will be concerned with discussing the limitations of the present study, and more importantly, what questions still remain leading to future research.

Summary of Results

The five experiments included in this project involved manipulations of different aspects of search, with monitoring of eye movements. Several consistent patterns emerged across all experiments. In every condition, subjects responded faster, committed fewer errors, and fixated fewer objects when the target was present. This is expected for the non-eye movement measures since search should conclude after the target is located. The fixation data revealed that subjects used the provided target information in different ways to direct search depending on the manipulations involved in each experiment. What was even more consistent across these experiments was the result that subjects fixated the target object approximately 90% of the time compared to just 50% for the target-colored distractors. These differences reflect shape guidance to a certain degree.

The first three experiments focused on the effects of manipulating the relationships between the two possible target colors. These first three experiments had three main goals: 1) to evaluate the cost associated with searching for two colors compared to one, 2) to explore the effects of increasing the separation between two target colors in color space, and 3) to investigate the nature of the target representations guiding search.

With respect to the first aim, the present results replicated previous findings demonstrating costs for searching for two targets compared to one, while bringing new information to light regarding what may contribute to this dual target cost. Response times and accuracy revealed a pattern consistent with a cost as a function of the similarity between the two targets. As the targets decreased in similarity, the time to find the target and chances of making an error increased. The pattern of eye movements revealed the source of this cost in terms of selectivity.

The results showed that subjects exhibited a high degree of color selectivity when searching for just a single target color (Experiment 1B). Subjects focused their attention and directed the majority of their saccades to objects of the target color and distractors similar to the target. The addition of a second target had varying effects, depending on the similarity between the two search target colors. A cost was observed even for two very similar colors, as well as two colors that were markedly different (Experiment 1A). What was surprising is that this cost was a result of increased fixations on dissimilar colors, most likely reflecting unguided search. If search was guided in an efficient manner, it would seem more logical to direct fixations towards objects similar to either target to increase the probability of finding the target. Given that the cost appeared

greater (meaning more fixated objects) when the two possible target colors were less similar to one another, the results suggest that there is not only a cost associated with searching for two colors compared to one, but this cost appears to be directly related to the similarity between the colors. This finding leads directly into the second aim.

Previous research showed increased fixations on colors dissimilar to both targets when the two search targets differed maximally (eight color steps) based on the ring of 16 colors (Stroud, et al., submitted). The present research included three levels of color similarity in order to reveal a more complete picture of this reduction in color selectivity. Experiment 1 included the 1-step and 4-step dual target conditions as instances in which the target colors were similar and dissimilar to one another, respectively. Similar to Stroud et al., the results revealed that the dissimilar targets in the 4-step Target Set led to increased fixations on colors dissimilar to either target, relative to the 1-step Target Set. Given these two 'extreme' values in terms of similarity between the search targets, the cost appeared to be a function of this similarity. This suspected 'split-target' cost representing the separation (or split) in color space between the two target colors motivated the inclusion of the additional dual target conditions to determine the extent this cost was directly related to the color similarity between the targets.

The 2-step condition was included to provide an instance in which the level of similarity between the targets was in-between the two dual target conditions in Experiment 1. Further, the 2-step condition included one distractor color in between the two targets in color space, which contrasted with the 4-step condition that contained three intervening distractor colors (discussed below). The results of the 2-step condition demonstrated a similar cost, again due to additional fixations to distractors dissimilar to

either target. This cost was greater than the 1-step condition, but not as severe as the 4-step condition. The 2-step data further strengthen the split-target cost by showing a direct relationship between the similarity between the two targets and the proportion of fixations to dissimilar colored objects. These results raise the question of how subjects are representing these two target colors to guide search, which was the third aim of this project.

The fixation patterns of the dual target conditions suggested that the two colors may be represented as either discrete templates or a single unified target range template. The individual subject data were examined and revealed large differences in regard to the fixations to the intervening distractor colors (in-between the two targets in color space). In the 2-step Target Set (with one intervening color), the majority of subjects fixated the intervening distractor color at approximately the same frequency as the target. This supports the notion that the two targets are represented as a range. However, in the 4-step Target Set (with three intervening colors), most of the subjects fixated the intervening target colors less frequently compared to the two targets. This pattern is more consistent with the two targets being represented as discrete templates. These results motivated the next experiments that manipulated the information provided to the subjects as search targets.

Subjects in Experiments 2 and 3 viewed the exact same stimuli as the dual target conditions for the 2-step and 4-step conditions, but were presented with single 'rainbow' stimuli before each trial to specify the possible target colors. The purpose behind these experiments was to try to force subjects to utilize a range representation to guide search, and help resolve some of the debate left by the dual target conditions as seen in the

individual subject data. The results showed that the range stimuli disrupted search across both 2-step and 4-step conditions compared to the regular dual target search conditions in the earlier experiments. However, the range stimulus affected search in the 4-step condition to a greater degree than the 2-step condition. In the 2-step condition, there was no difference in the fixation patterns to the target and intervening color between the dual target and the range condition, with only a moderate increase in fixation rate for distractor colors very different from the target. In the 4-step condition, selectivity was almost eliminated. These results suggest that when the targets are similar, they may be represented as a template range, but when the targets are dissimilar, two individual templates may be maintained.

Experiments 4 and 5 were aimed at questions involving the flexibility of the target representation by focusing more on manipulations of the stimuli that the observers encountered. Experiment 4 manipulated the information available to subjects. This experiment was aimed at determining to what extent exposure to the color values in between the two target colors (in color space) shaped the guiding template or templates. If subjects did not view distractors with any of these intervening colors as they learned the search task, then perhaps they would represent the two target colors as a range of values including the targets and the colors in between. If this was the case, then fixations to the intervening colors should occur at the same frequency as fixations to the targets for the second half of the experiment. The results did not support this conclusion, and revealed that the lack of exposure to the intervening colors had little to no effect on shaping the target template. That is, in the second half of the experiment, the fixation probabilities to the targets and intervening colors was not statistically different between

the two experiments. The implications these results have for representation and visual search will be covered in subsequent sections.

The final experiment explored to what extent subjects' representations are flexible by presenting them with either information about which targets to search for or which distractors to ignore. The results revealed that color selectivity was almost entirely eliminated and the manipulation regarding the target instructions had little effect on search. It appears that subjects adopted a strategy of fixating nearly every object in each display regardless of the instructions. The explanation for these results is unclear and requires future research. Both the results and subsequent research designs are the focus of the next two sections.

Implications for Multi-target Representation

Three hypotheses were outlined in the introduction regarding representation of multiple targets. The simultaneous hypothesis purports that two targets are represented concurrently, guiding search in a parallel fashion. The alternating hypothesis also predicts that two separate templates are maintained, but search is conducted for one target at a time. The final hypothesis, the range hypothesis, suggests that one template is used comprised of the two search targets including all feature values contained between the targets. The first two hypotheses are advantageous because the templates contain only the features included in both targets to guide search. They are disadvantageous because they require the maintenance of multiple templates, potentially introducing interference and adding to the cognitive load. The range hypothesis requires only a single template, but the template would include many nontarget features. The results of the current

experiments reveal that the nature of representation may be based on a number of different factors.

When two targets are similar colors, as in the 1 step Target Set, the fixation patterns are similar to search for just a single target. This suggests that the two colors may be represented as a single template. However, with no distractors containing feature values between the two targets, it is impossible to determine which hypothesis is supported. The 2-step target set represents an instance in which the targets are similar to one another, but also contain a non-target feature value between the targets. In this case, subjects treated the intervening color the same as the two targets and fixated all three at the same frequency. This suggests that all three colors were included in the search template. This supports more of a range account, rather than discrete templates. When subjects were presented with the rainbow stimulus representing the range of possible target colors in Experiment 3, the fixation patterns to these three colors were not significantly different than in trials with the target colors specified as two discrete objects. However, the range target specification produced more fixations on the distractors least similar to the target colors. Taken together, the results further suggest that subjects may be utilizing a range representation for two similar colored objects. The extra fixations on dissimilar colored distractors with the rainbow target specification may be because subjects are using a range representation, but in a form that is different from the template provided, causing interference. Along the same lines, subjects may be utilizing a range representation with greater weights assigned to the target colors since only the outer most colors actually appeared as targets. In the range provided, each color

within the range is equally represented, which again may cause interference or some disruption in the search process.

The results for the 4 step Target Set revealed something much different. In the discrete target conditions, subjects ignored the intervening colors at approximately the same frequency as colors falling outside of the range that were the same number of color steps from the targets. This pattern of fixations is consistent with discrete target representations of each target. When subjects were provided with a range template in Experiment 3, color selectivity diminished drastically. These results are consistent with either of the two hypotheses outlined above and rules out the possibility of a range representation for the target template. However, there is not enough evidence to support either the alternating or the parallel hypothesis over the other. The results do lend to a number of possibilities for future research outlined in the next section.

The results of Experiments 1 – 3 reveal an interesting picture regarding representation and search. It appears that as the similarity of the two targets decreases, there is a corresponding transition from representing targets as a unitary template to discrete templates. In terms of search, the split-target cost revealed that as the two targets decrease in similarity, there is an increase in fixations to objects dissimilar to both targets. This implies that the discrete templates utilized for a pair of dissimilar targets are imperfect, resulting in less effective search guidance. The nature of this cost should be explored further to investigate if it is a result of interference between the target templates, switching between templates over time, or some other underlying mechanism.

The latter two experiments contributed to the entire project by revealing some further limits to search for multiple targets. Experiment 4 demonstrated that with

dissimilar target colors, subjects most likely use the same representation of two discrete target colors regardless of their exposure to intervening distractor colors. That is, the guiding template is most likely not shaped by the objects encountered during search. Experiment 5 tested this further by not only manipulating the instructions provided to subjects, but also including a mismatch between what was told to subjects and what they actually viewed. The obvious lack of guidance in Experiment 5 can be attributed to a variety of things. The experiment presented subjects with four discrete search templates, whereas in previous experiments the maximum number of search targets was two. It may be that this number of target colors is too much for the system to handle, resulting in cognitive overload. Without an efficient method of guiding search, subjects may default to fixating nearly every object in each display. The second possibility is that subjects may have noticed that the actual targets appeared in a wider range of colors than indicated by the instructions. As a result in this mismatch, subjects may have ignored the instructions and again chosen to fixate almost every object. Both of these possibilities are the subject of future research discussed in the next section.

To summarize, when two targets are similar, a range representation of some sort is most likely utilized. As targets decrease in similarity, there is not only evidence for representation of the two target colors as discrete templates, but also for a decrease in search efficiency. Regardless of the exact nature of representation, search in these experiments appears to be guided more by the instructions as opposed to the objects viewed across trials.

Future Research

More work is necessary to answer the question of how we represent multiple objects to guide search. The results of the 4-step Target Set suggested that two separate templates are held in working memory in order to guide search. An important next step would involve trying to replicate this condition with an equally difficult working memory task. That is, if two discrete templates are maintained in working memory, then similar search behavior should be observed for search for a single target accompanied by a visual working memory task that requires maintaining a single color. This experiment will also allow a test of the split target cost by varying the similarity of the color held in working memory with the target color. As the similarity between the memory patch and the search target decreases, then fixations to distractors least similar to the targets should also increase. The results of this experiment would help support the discrete template account for dissimilar target search, but it would not address the seemingly unitary template used for two similar targets.

Recall that the results of the 2-step Target Set suggested that subjects utilized a range template that included both the targets and the intervening color. The results of Experiment 3, in which subjects were presented with a range of possible target colors, revealed similar fixation patterns to the targets, but more fixations to distractors very dissimilar to the target. Two new experiments will contribute to this debate. In the current project, subjects were presented with a range, but targets only appeared in the outside two colors. One possible contribution to the increased fixations was due to the mismatch between the range and the actual stimuli encountered. A logical follow up would consist of presenting subjects with the same range specification, but allowing all

three colors within the range to appear as targets. This may allow subjects to 'hone in' on the target colors and could reduce the extra fixations to the dissimilar distractor colors. The other issue proposed was the possibility that the range stimulus presented to subjects does not match the range representation that subjects would naturally develop. Although a range was presented with equal representation to each color, a range that matched the stimuli may be more appropriate. Subjects would view the same stimuli used in the current experiments, but the colors that actually appear as targets would be depicted more saliently within the range. If search proceeds efficiently with the 'weighted range,' then it would be evidence that this type of representation is used, and also that the properties of the displays may contribute to the representation as well.

The final two experiments, which included manipulating the distribution of distractors encountered over the course of many trials, give rise to a number of necessary follow up experiments. The logical next step is to investigate why selectivity was reduced to such an extent in Experiment 5. Recall that subjects were presented with four colors to search for, while the targets actually appeared in eight colors. This mismatch may have encouraged subjects to ignore the instructions and fixate nearly every object. To resolve this, subjects could simply be presented with all eight colors in the target set. If the results are similar, then it may be an issue of cognitive load and an inability to efficiently hold eight colors. Recall that subjects exhibited a high degree of color selectivity when searching for two colors as in Experiments 1 – 3, while selectivity nearly vanished when required to search for four separate colors in Experiment 5. It is therefore important to include a condition in which subjects are required to search for three separate colors. If cognitive load is responsible, then reduced color selectivity should be

seen in search for three colors, but not as severe as four. These experiments will extend the current findings to cover search for more than just two objects.

The current project revealed a number of findings regarding search for multiple colors. In terms of guidance, the results suggest that two similar colors may be represented as a single template, but the exact nature of this representation requires further research. For two dissimilar colors, search becomes less guided and the targets are most likely represented as two separate templates. In a general sense, this project is focused on search for objects within the dimension of color. It is important to investigate if similar results can be generalized to other dimensions such as orientation, size, or even depth. Converging multidimensional results would solidify this notion of a split target cost and contribute both theoretically and in an applied sense. The results will help refine models of visual search by stressing the importance of the similarity between the search targets. With increased dissimilarity comes an added search cost. In the applied realm, whenever search is needed for multiple items that contain different colors, the results show that it is important to consider the similarity of the colors of the targets. In theory, it may seem logical to search simultaneously for distinctly different objects, but the results of the current project argue against that strategy. If it is impossible to create a scenario in which search can be guided toward two similar colors, then search should be split into separate phases for each individual target.

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