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THE EFFECT OF PRACTICE ON EYE MOVEMENTS IN THE 1/D PARADIGM

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ABSTRACT OF THESIS

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Previous studies have demonstrated that observers may ignore highly salient feature singletons during a conjunction search task through focusing the attentional window (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), or by the suppression of bottom-up information (Treisman & Sato, 1990). In the current study, observers' eye movements were monitored while performing a search task in which a feature singleton was present and corresponded with the target at a chance level. With practice, observers were less likely to make an initial saccade toward the singleton item, but initial saccades directed at the target were likely throughout. Results demonstrate that, in an effort to ignore the singleton, observers were more likely to suppress bottom-up information than adjust the size of the attentional window.

KEYWORDS: Visual Search, Eye Movements, Conjunction Search, Attentional Window, Bottom-Up Suppression

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Name	Date

THESIS

Will Seidelman

The Graduate School

University of Kentucky

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Arts and Sciences
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By

Will Seidelman

Lexington, Kentucky

Director: Dr. Lawrence Gottlob, Professor of Psychology

2011

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SECTION ONE: INTRODUCTION

At any given moment, we are presented with more visual information than we can process and bring into consciousness. While processing the visual world around us, our eyes make rapid movements (saccades) three to four times a second to bring about the locus of perceptual attention to relevant areas. This movement also serves to direct the fovea to areas of interest, which allows for processing of fine detail. During fixations, the time between saccades, the eyes remain relatively stable and it is during this time that we are able to process visual information. The destination of each saccade is determined by a combination of visual scene properties (bottom-up, salience) and the goals of the observer (top-down information). For example, if you are looking for a quarter amongst other coins your eyes may first be drawn to a single penny due to its unique color and the sheen of the copper. However, your visual system can be adjusted to look for items with features similar to that of the quarter; this in turn increases the efficiency of the search. The goal of this study is to examine eye movements during a visual search for a conjunction of features to better understand the influence of bottom-up salience.

Bottom-Up Salience and Attention

Saliency is a measure of how distinct an item is relative to its surroundings, or the item's *local feature contrast* (Nothdurft H. , 1992; Nothdurft H. , 1993). An item's total salience is contingent on a wide array of stimulus dimensions (e.g., color, luminance, depth, orientation, etc.), and items distinct on one feature tend to become more salient when additional feature discontinuities are added (Nothdurft H.-C. , 2000; Callaghan, 1986). Salient items may also be thought of as "interesting" (Elazary & Itti, 2008), and if an item is sufficiently salient it will, in most scenarios, automatically attract attention.

This is evident in the observation that salient items seem to “pop out” from other items. According to many views of visual processing (e.g., Van Zoest, Donk, & Theeuwes, 2004; Itti & Koch, 2000), salience drives our ability to find certain objects when surrounded by other distracting items (visual search). However, salience may exert its influence for a short time period. For example, Kim and Cave (1999) had observers search a display containing four items for a circle (the target) among squares (distractors). In each trial, one distractor was a unique color. When the stimulus was presented for short durations (<60ms), observers were able to identify the target when it was placed near a salient distractor, but were unable to attend to the target when the distractor singleton was distant. This result was not found to be remedied by practice, leading to the conclusion that the salient item disrupted the deployment of attention at an early stage. Similar results were also obtained using abrupt onsets by Theeuwes (1995), with the exception that bottom-up interference was in effect until approximately 100ms.

Top-Down Attentional Selection

Even though the literature supports the notion that bottom-up information seems to play a vital role in visual search, a selection system based solely on bottom-up information would prove to be, in many cases, inflexible. Aside from a stimulus-based, bottom-up system, attention is also modulated or “guided” by the goals of the observer (see Figure 1 for an example). An extensive review of literature relating to guidance in search, along with a computational model, is presented in Wolfe (1994). Although the previously discussed work indicated that salience influences attention during a relatively short time window, different views have emerged as to what level of control salience exhibits initially in visual processing and selection.

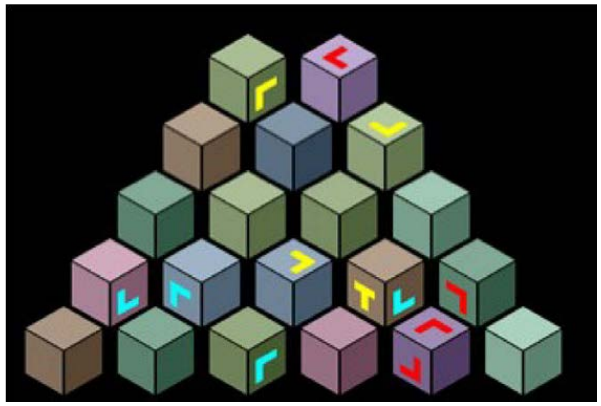

Figure 1. Figure from Wolfe **(2009)** demonstrating attentional guidance. If an observer is searching for a ‘T’ amongst ‘Ls’ in the image above, attention can be guided by providing information on color (yellow) or surface orientation (left-facing surface).

In one view, bottom-up information guides attention early in visual processing and it is during this time in which top-down control is not possible (Theeuwes, 1991; Theeuwes, 1992). This conclusion was derived from experiments where observers searched for a green circle surrounded by either green squares or red circles (i.e. feature search task). In one condition, a salient item on a non-critical search dimension was added to the display. For example, when searching for the green circle surrounded by green squares, a unique red square would be added. Even after extended practice, the addition of this unique item interfered with the search task, leading to the conclusion that complete top-down selectivity could not be achieved.

In a series of experiments, Yantis & Jonides (1996) demonstrated that strict bottom-up control early in visual processing is only achieved by the appearance of new perceptual objects (abrupt onsets). More specifically, a search target will capture attention if it abruptly appears in an array of objects that do not abruptly appear, which is often accomplished through pre-trial masking of the distractor items. The authors conclude abrupt onsets are able to capture attention due to the processing of new perceptual objects receiving higher priority than the updating of existing ones. The ability of abrupt onsets to capture attention has been reported in several studies with different methodologies (e.g. Schreij, Owens, & Theeuwes, 2008; Theeuwes, 1994; Yantis & Jonides, 1984).

Other findings suggest that attentional capture is contingent on how observers configure their attentional settings (e.g., Folk, Remington, & Johnston, 1992; Yantis & Egeth, 1999; Lamy, Tsal, & Egeth, 2003, Experiment 1). For example, Folk, Remington, and Johnson (1992) contested the idea that abrupt onsets necessarily attract attention. In what the authors titled the contingent involuntary orienting hypothesis, they proposed that task demands were influencing attentional settings in a way that made specific features of the onset item critical to the task. To demonstrate this, they had observers perform two search tasks: one where the target item was defined by a unique color and was surrounded by three distractor items, and one where the target was an abrupt onset but was the only object in the display. Immediately before the search display was presented, a spatial cue of four dots appeared around a possible location of the target item. The cue was either a color cue (four red dots placed around the cued location and four white dots placed around the other 3 possible locations) or an onset cue (four white dots placed around the cued location that abruptly appeared). In one condition the cue always appeared at the location of the target (valid cue), and in the other, the cue never appeared at the location of the target (invalid cue). When the cue matched the target type the invalid cue could not be ignored (e.g. onset cue with onset target); however, when the cue did not match the target it had little effect on the time required to identify the target. For example, when an onset cue was used to signal an onset target, attentional capture was reported. That is, subjects had “set” their attentional system to use sudden onset to locate a target. However, when an onset cue was used to signal a color target no attentional capture was reported. Therefore, observers had set color as the critical feature and were not distracted by the onset item.

In agreement with the contingent orienting hypothesis, Bacon and Egeth (1994) proposed the contingent capture hypothesis, asserting that observers configured their attentional settings into search modes for either unique items or specific features (i.e., singleton detection mode and feature search mode). In singleton detection mode observers adopt a strategy of searching for the most salient item regardless of the item’s unique feature channel. In doing so, salient distractors will capture attention and disrupt search. However, in feature-search mode, observers adopt a strategy of searching for a specific feature channel (e.g. color). In these instances the feature singleton does not disrupt search.

Finally, several studies have demonstrated the importance of an observer’s spatial attentional settings or *attentional window*. The notion of an attentional window is central to Treisman’s Feature Integration Theory (Treisman & Gelade, 1980), and the idea of a scalable spatial mechanism of visual attention under different names has been investigated for some time (c.f. attentional window is used in Ward, 1982; Treisman & Sato, 1990, a review of the use of the “spotlight” metaphor is presented in Yantis S., 1988, and a “zoom lens” model is proposed in Eriksen & St. James, 1986). Central to these theories is the notion that the attentional window can be scaled over the visual field, or focused on particular areas or items. Consider, for example, a large S comprised of multiple tiled T’s. Observers may either set a wide attentional window and perceive the

S, or focus the window on a singular T. Theeuwes (2004) argued attentional capture in visual search is contingent on the attentional window, and that it is set in a top-down manner based on task demands. If an observer sets a focused attentional window, salient objects in the periphery are suppressed and become unlikely to capture attention. However, if an observer sets a diffuse attentional window across a wide spatial area, salient items in the periphery are likely to capture attention. In support of this theory, Joseph, Chun, and Nakayama (1997) demonstrated that salient objects in the periphery are often not perceived when attention is focused.

Bottom-Up Influence in Conjunction Search

As we have seen, several theories exist on the influences of bottom-up and top-down information in search tasks. Although much of the previous work has focused on bottom-up influence in a feature search task, additional research has also been conducted on the influence of bottom-up information in a search for a conjunction of features. According to Wolf's Guided Search model, if distractors share bottom-up properties with the target, the bottom-up contribution is greatly reduced, although the weight can never set to zero (Wolfe J. M., 1994, p. 209). This allows for the possibility of highly salient items to be ignored if there is adequate top-down activation (e.g. specific knowledge of task demands). Additionally, Treisman and Sato (1990) reported that the suppression of irrelevant bottom-up information plays a role in conjunction search tasks. This finding led to a modification of their Feature Integration Theory, adding that feature inhibition may be used as an *optional strategy* to facilitate selective attention (Treisman & Sato, 1990, p.462).

In combination, Guided Search along with Feature Integration Theory, predict that irrelevant salient items in a conjunction search task may be ignored through bottom-up inhibition as well as top-down activation mechanisms. As a means to test this prediction, several studies have used a conjunction search task in which an additional distractor is added that is unique on some task-irrelevant feature channel (additional singleton paradigm). Using this paradigm, Theeuwes and Burger (1998) have shown that observers were only able to ignore a feature singleton if provided with advanced knowledge not only of what specific features to attend to (target features), but also which features to inhibit (distractor features). Similar results have also been demonstrated in cases where the exact spatial position of the target was known (Folk, Leber, & Egeth, 2002). Furthermore, in a paper titled "A salient distractor does not disrupt conjunction search", Lamy and Tsal (1999) had observers search for a green O (the target) amongst green Ts and red Os. On some conditions, a salient singleton item replaced one of the distractor items. This singleton was either a green X (unique shape), blue O (unique color), or blue X (unique shape and color). On trials where the target was present, none of the singleton items disrupted the search.[1] The authors, therefore, concluded that feature singletons may be ignored completely in a conjunction search task (for similar results see Gibson & Jiang, 1998).

One disadvantage to the additional singleton paradigm is that the observer is placed in a search task where the target will never share the unique feature of the singleton. Thus, there is an advantage to actively inhibit select feature channels more so than in a typical conjunction search task. Recent studies have introduced a new paradigm

[1] An effect of the salient item was detected in the target absent trials. For a discussion see Lamy and Tsal (2003, p. 97)

in order to better investigate the role of bottom-up processing in conjunction search by making the target item a feature singleton on a non-search-critical dimension in 1/(set size) of trials. For example, in a display consisting of all green items with 7 distractors and 1 target, the target would be a color singleton on 1/8 trials. For the remaining 7/8 trials, the color singleton would take the place of a distractor. The general finding amongst 1/d studies has been a decrease in time necessary to detect the target when the target is also the singleton (e.g., Yantis & Egeth, 1999; Todd & Kramer, 1994; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Proulx, 2007). Todd and Kramer (1994) demonstrated that the detection speed of the singleton target item is dependent on display size. In trials with a set size of 4 items, the position of the singleton item did not affect search. As display size increased, there was an increasing advantage in detecting the target when it was a singleton. The authors termed this phenomenon "attentional misguidance," as the search slope did not achieve the zero-slope criterion of prior attentional capture studies (e.g. Yantis & Jonides, 1984) [2]. Unlike attentional capture, the authors determined that observers were voluntarily allocating attention to the unique

[2] It is important to note a fundamental distinction between the explanations put forth for the target-singleton reaction time benefit found in 1/d studies. On the basis that results from these studies do not meet the attentional capture criteria of a 0 msec/item RT slope put forth by Yantis (1999), Todd and Kramer (1994) attribute the target-singleton reaction time benefit to a top-down search strategy that uses the unique item as a landmark to begin search. Theeuwes (2004) as well as Belopolsky (2007) consider this initial allocation of attention to be the result of bottom-up attentional capture. It is argued that the 0 msec/item RT slope attentional capture criteria is not met due to attentional capture not occurring on every trial. For the sake of consistency, I will refer to any initial allocation of attention to the singleton item as attentional capture. The debate as to whether or not true bottom-up driven attentional capture is taking place as opposed to top-down selection is beyond the scope of the current study. In the current case, results may be discussed without a distinction being made.

item. This became increasingly likely with the increase in salience of the unique object as additional items were added to the display.

Recent work from Proulx (2007), as well as Belopolsky et al. (2007), attempt to address possible explanations for the attentional misguidance phenomenon. Proulx (2007) demonstrated that the speeded detection of target-singleton items was not the result of intertrial priming. That is, the reaction time benefit in target-singleton trials was significant regardless of prior trial type. Belopolsky et al. (2007) suggest that the ability of the singleton item to capture attention is contingent on the size of the attentional window, which is set in a top-down manner. The researchers required observers to begin the search only after a *go / no go* signal was presented. The *go* signal was either presented at fixation (focused, small attentional window), or through a specific global arrangement of the stimulus items (diffused, large attentional window). See Figure 2 below for results of the experiment. In the diffused attention condition, the target was detected faster when it was a singleton item, results similar to that of previous 1/d studies. When observers' attention was focused at fixation this effect was eliminated. This lead the researchers to the conclusion that, by focusing the attentional window, attentional capture from the singleton was disrupted, and the probability of an initial shift of attention to the singleton decreased to that of any other item in the display.

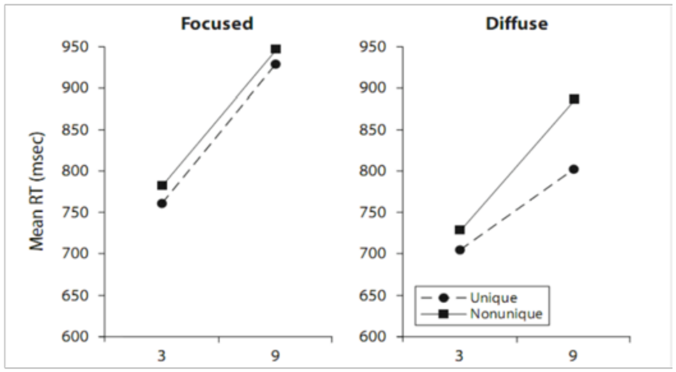

Figure 2. Results from Belopolsky et al., 2007. Speeded detection of the target singleton was present when a *go/ no-go* signal was presented at fixation (focused attention), but absent when the *go / no-go* signal was global (diffused attention).

Theeuwes and Godjin (2001) provide an explanation on how an attentional-window hypothesis may explain the difference in reaction times in a 1/d paradigm as opposed to that of a typical additional feature singleton conjunction search such as that used by Lamy and Tsal (1999). If a non-feature singleton is added to the display, pre-attentive salience will never define the target. As such, attention will proceed in a focused state and proceed serially throughout the display. When the possibility of a pre-attentive property to define the target is presented, observers adopt a diffused attentional window across the display. In doing so, selection is prioritized by salience resulting in attentional capture.

One must also consider that, although the salient item does have a possibility of corresponding with the singleton, the probability of that occurrence is inversely related to display size. As display size increases, an observer may be better off adapting to a focused attentional window in order to ignore the singleton. With the attentional windows being under top-down control, observers would be able to adjust the spatial size of the window during search. Theeuwes and Godjin (2001) suggest that the top-down setting of the attentional window "might be adjusted and optimized for a visual search task so that target detection is still fairly easy while interference is reduced to a minimum. So when the target of search is not a feature singleton that can be detected by parallel search observers may adopt the attentional window to a smaller size." Although observers have been shown to change attentional window size between tasks with separate task demands (Beloplsky & Theeuwes, 2010), it is unclear whether adjustments will be made with practice while holding task demands constant.

Increasing Performance by Adapting Attentional Settings

The current study was conducted in order to determine if, with practice, observers adapt attentional settings in order to suppress a distracting feature singleton in the 1/d paradigm. In order to investigate this, we monitored observers' eye movements throughout the task. Most models of saccadic programming rely on a combination of bottom-up and top-down information to determine oculomotor programming (Findlay & Gilchrist, 1998; Godijn & Theeuwes, 2002; Godijn & Theeuwes, 2003). According to these models, bottom-up (exogenous) and top-down (endogenous) information is integrated into a two-dimensional saccade map, with exogenous activation reaching the saccade map before endogenous. The notion of a saccade map is similar to that of other attentional models (c.f. the concept of an activation map in Guided Search, Wolfe J. M., 1994, a salience map in Itti & Koch, 2000, and a master map in Treisman & Gelade, 1980). According to Wolf's Guided Search model, the relationship between attentional deployment on the activation map and eye movements is cooperative in nature (Wolfe & Gancarz, 1996). The direction of an initial saccade would then serve as an indicator as to what location attention was first directed. In monitoring how often the initial saccade is directed toward the singleton item, we were provided with an indication of how often the singleton captured attention (Theeuwes, Kramer, Hahn, & Irwin, 1998).

The task used in this experiment is similar to that of several earlier studies (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Proulx, 2007; Yantis & Egeth, 1999, Experiment 3). Observers were presented with a display of 9 rectangles that were either red or green and vertical or horizontal. Observers searched for a predefined target item that differed from all of the distractor items in the display by 1 feature (e.g. if the target was a red vertical item the distracters were green vertical and red horizontal items). One item in the display was a luminous singleton, and the singleton coincided with the target every 1/9 trials. In order to measure changes in initial saccade direction across time, trials were grouped into four separate blocks. By blocking the target type, and giving a description of the target and distractors to the observer before each block (i.e. both the feature values as well as the probability of the target and singleton coinciding), observers were provided with an abundance of top-down information. In doing so, any practice-related decrease in attentional capture as a result of increased top-down guidance would be unlikely (Wolfe, Butcher, Lee, & Hyle, 2003). This leaves two possible mechanisms observers may utilize to ignore the distracting bottom-up information of the singleton: observers may begin to invoke a focused attentional window (Beloplsky & Theeuwes, 2010; Theeuwes J. , 2004; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), or suppress the unique feature of the singleton through a bottom-up inhibition mechanism (Treisman & Sato, 1990). These two predictions and their expected results are presented in the following:

H1$_1$: Attentional capture from the singleton is reduced with practice, and this is accomplished through focusing of the attentional window.

If observers begin to focus the attentional window, attentional capture by the singleton should be disrupted. The singleton would then be the initially attended item at a chance level, and would be examined as frequently as any other item in the display. Focusing the attentional window would also reduce the ability to detect the target item in the periphery, thus we would expect the probability of initial saccades to be directed toward the target to also decrease to chance levels. Therefore, after practice, the probability of attending to any particular item in the display should reduce to chance levels.

H2$_1$: Attentional capture from the singleton is reduced with practice, and this is accomplished through the suppression of bottom-up information while maintaining a diffuse attentional window.

Alternatively, if observers do not narrow the attentional window, they may inhibit the bottom-up feature information of the singleton item. If this were the case, we would expect a decrease in initial saccades toward the singleton item, much like the expected result of focusing the attentional window. However, with the attentional window diffuse, we would not expect the rate of initial saccades directed at the target to decrease. Instead, initial eye movements to the target item would either increase or stay constant across trials. Therefore, after practice, we should witness a decrease in the proportion of saccades initially directed at the singleton, while the proportion of saccades directed at the target should be high, and remain constant (or increase) throughout.

SECTION TWO: METHOD

Participants

Ten undergraduate psychology students (6 male, 4 female) participated. All participants had normal or corrected-to-normal vision and were provided with course credit for participation. One participant was removed from analysis due to failure to follow directions. In order to determine the desired sample size, an a priori power analysis with G*Power (Faul, Erdfelder, & Buchner, 2007), along with a pilot study of 3 participants were conducted. Other studies in both visual search (e.g., Gottlob 2006, Experiment 2; Wolfe 2004) as well as eye tracking studies (e.g., Theeuwes 1998; Walker 1997) have been performed with 10 or fewer participants.

Apparatus

Stimulus Presentation. The displays were controlled by a Windows-based computer connected to a 20 inch ViewSonic CRT monitor (model P225f) with a display resolution of 1024x768 and a refresh rate of 60 Hz. Stimulus displays were programmed using E-prime (Psychological Software Tools Inc., Pittsburgh, PA). Responses were recorded using a key press on a computer keyboard.

Eye Tracking. Participants' head movements were stabilized though the use of a chinrest, forehead rest and two stabilization rings rotated to rest on the participants' temples. The participants' eye movements were monitored using an ASL Eye-Trac 6 Chinrest Mounted eye tracker (Applied Science Laboratories, Bedford, MA). Eye position was sampled every 16.6ms with an estimated spatial error between actual gaze and computed gaze of less than 1º. Calibration was performed before each block of trials. Figure 3 demonstrates the eye tracking apparatus.

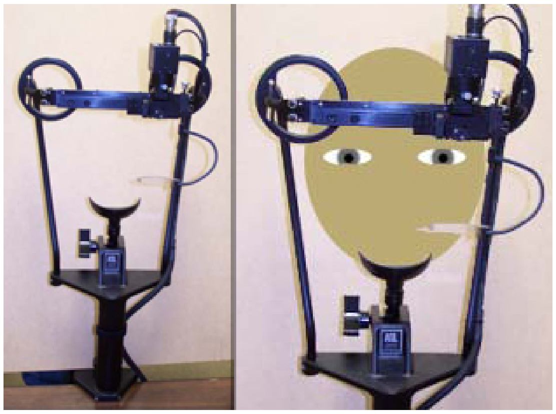

Figure 3. Eye tracking equipment with a mock up of participant head placement.

Stimuli & Procedure

Participants performed a visual search for an item (the target) defined by two critical features (i.e., hue and orientation), surrounded by two classes of similar items that differ on a single dimension. For example, if the target is defined as RED and HORIZONTAL, distractor classes were RED VERTICAL and GREEN HORIZONTAL. Set size remained constant at nine stimulus items in each display. Each display item contained a black letter; target items contained either a 'C' or 'Ɔ', and distractor items contained either an 'O' or 'D'. The internal letters were small to promote fixation on an attended item. On 9/10 of the trials, one item was a luminous singleton (red = 40.07 lx, green = 96.7 lx) in that it was brighter than the other letters (red = 1.9 lx, green = 4.3 lx). When presented, the singleton item coincided with the target on 1/9 trials. Figure 4 demonstrates a possible display for the target singleton, singleton present (160º separation), and singleton absent conditions.

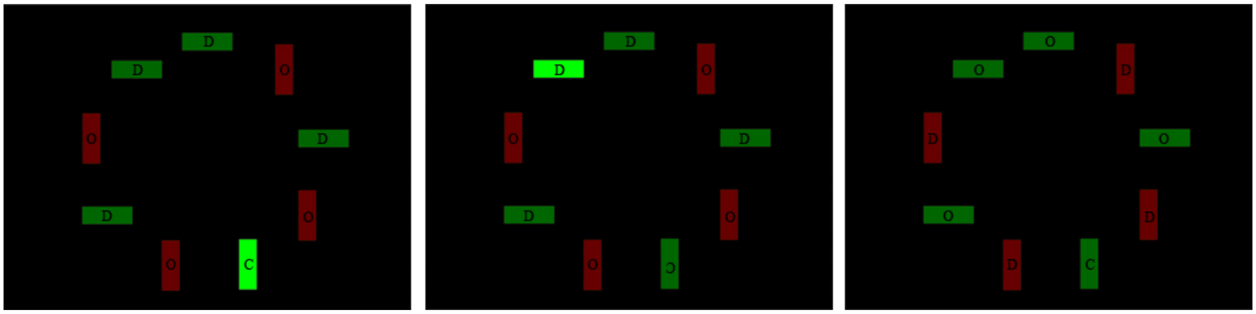

Figure 4. Sample stimulus displays from the three conditions. From left to right: Target Singleton, Singleton Present, and Singleton Absent. Internal letters are not to scale.

There were three different displays per trial (listed in sequential order): fixation display, search display, and feedback display. Each trial began with a fixation display (duration = 1 second) consisting of a black background with a white “+” located in the center of the screen. The following search display consisted of nine stimulus items placed at 40º intervals around the circumference of an invisible circle (radius = 31.9º) centered on fixation. Each distractor item had a length of 3.18º and a width of .9º. The order of events is presented in Figure 5.

Participants were informed of the target features (i.e. orientation and color) prior to each block. Participants were informed that one item in the display would be brighter than the others in 9 out of every 10 trials and that the target would be the bright item at random, or in other words, in 1 out of every 9 trials. Participants were instructed to keep their eyes on the fixation cross until the item display was presented, at which time they were to find the target as quickly and accurately as possible. After the target was detected, participants were to indicate, using a key press, the letter contained inside the item. Search display was terminated by key press of either ‘z’ if the target contained a ‘C’, or ‘m’ if the target contained a ‘Ɔ’. Visual feedback was provided after each trial indicating accuracy of their response. If participants noticed that they were making several incorrect responses, they were to slow down and attempt to increase their accuracy.

After participants were presented with the previous instructions, they performed one block of 30 practice trials. The target for the practice block was randomly selected from the four possible target combinations. Data from the practice trials was not recorded and eye movements were not monitored. After completion of the practice block, participants performed four experimental blocks consisting of 60 trials per block. The target item for each block was selected at random without replacement from the four possible targets. Target randomization was performed for each participant prior to the experiment. Participants were given the opportunity to take a 5 minute break before each block of trials, although none opted to do so. The experiment lasted approximately 45 minutes.

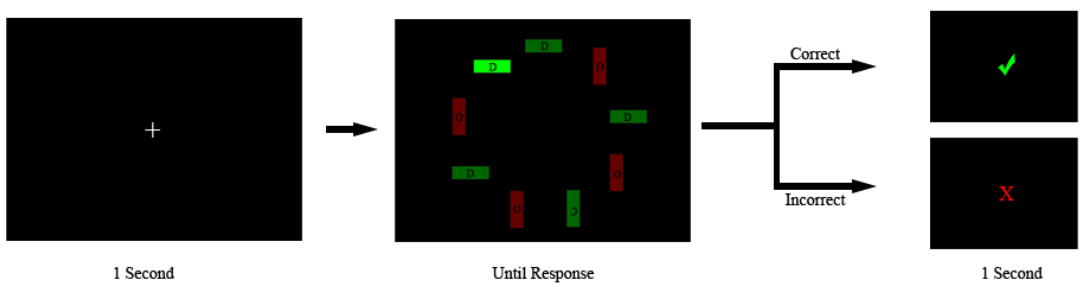

Figure 5. Order of events: A fixation and cue appears before each search stimulus. If a luminance singleton is present it will coincide with the target on 1/9 trials. Feedback is given after each trial. Displays are not to scale.

Design

The independent variable was the absolute angular distance between the target and singleton around the invisible circle on which the items were placed. As the nine items were equidistant from one another, the conditions were separations of 160 º, 120 º, 80 º, 40 º, or 0º (with 0º being the target singleton condition). The experiment utilized a single-factor, within-subjects design. Position of the target, distractors, and singleton were determined beforehand, and were pseudo-randomized to maintain an equal number of trials per block for each level of the independent variable. Distractor type was balanced at four items of each distractor type per display.

SECTION THREE: RESULTS

Discarded Data

Data were discarded on trials in which the participant either responded incorrectly (2% of trials), or did not begin a trial by fixating on the cross (7% of trials). Data were also discarded if a participant's initial saccadic latency was above 600 ms (5% of trials), or if the eye tracker lost tracking during any point of the trial (1.6% of trials). In all, 16% of the total data were discarded.

Analysis

A repeated measures design using the generalized linear mixed model was utilized, as implemented in PROC MIXED. PROC MIXED allows for the modeling of random effects (subject) variance components along with fixed effects. Data are fit by using the method of restricted maximum likelihood models (REML) instead of means square estimates used in traditional repeated measures GLM procedures. PROC MIXED was selected for this experiment primarily due to the procedure's improved handling of missing values and uneven group observations. All pairwise comparisons are adjusted with the Tukey–Kramer method.

Fixation Criteria

Fixations were defined using the default values provided by the ASL Data Analysis software (Eyenal). A fixation was calculated if gaze position had a standard deviation of no more than one-half degree on the x- and y- plane for a minimum of 6 samples (.09 seconds). A fixation ended when gaze position was further than 1 degree from the initial fixation point for a minimum of 3 samples (.045 seconds). The calculated fixation point is the average of all data points from the beginning to the end of the fixation. Any recorded values exceeding a visual angle of greater than 1.5 standard deviations from the initial point are not included in the average.

Reaction Time

First, reaction time (RT) analysis was performed (see Figure 6). Prior studies using this paradigm have demonstrated a RT benefit in detecting the target when the singleton coincides with the target as opposed to coinciding with a distractor (Beloplsky & Theeuwes, 2010; Proulx, 2007; Todd & Kramer, 1994; Yantis & Egeth, 1999). In the current experiment, the increased contrast between the target and the inner identifying letter in the target singleton condition may have influenced the reaction time measure. For this reason, the target singleton condition was removed from the current analysis. Instead, RT analysis was performed with the four remaining separation conditions as factors. If the singleton is capturing attention, we may detect a RT decrease as the separation between singleton and target increased. That is, if attention is being captured by the singleton, increasing the separation between the singleton and the target would lengthen the time required to locate the target. However, there was no main effect of separation $F(3, 24) = 1.93$, $p = .15$.

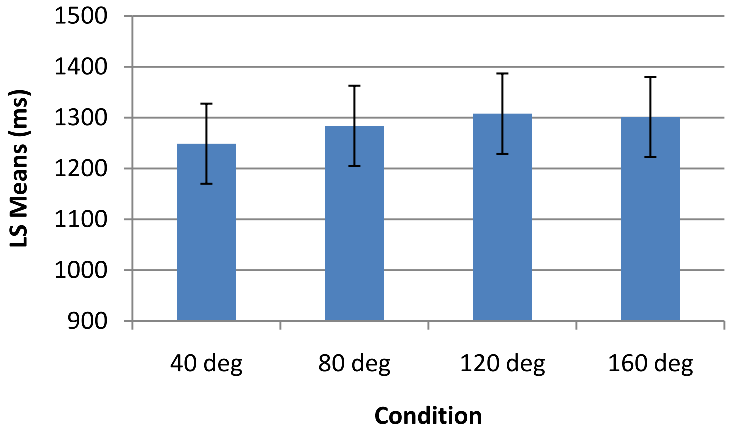

Figure 6. Reaction time means by condition. Means presented are estimated least-square means

Fixations Per Trial

Total Fixations. In the previous RT analysis, there was no main effect of separation between the non-target singleton trials. Prior studies have demonstrated that the average fixations per trial correlate highly with RT, and may serve as an additional measure of search efficiency (Shen, Reingold, & Pomplun, 2000). As with RT, if the singleton is capturing attention we would expect the average number of fixations per trial to increase as separation between the singleton and target increased. Unlike the RT analysis, all conditions, including the target singleton condition, were submitted to the analysis (see Figure 7). There was a main effect of separation, $F(4, 32) = 5.97$, $p < .001$. Pairwise comparisons revealed that participants made significantly fewer fixations in the target singleton condition than all other conditions except for the lowest (40º) separation condition, $t(32) > 3.37$, $p < .02$. There were no significant comparisons for non-singleton conditions, $t(32) < 2.4$, $p > .12$.

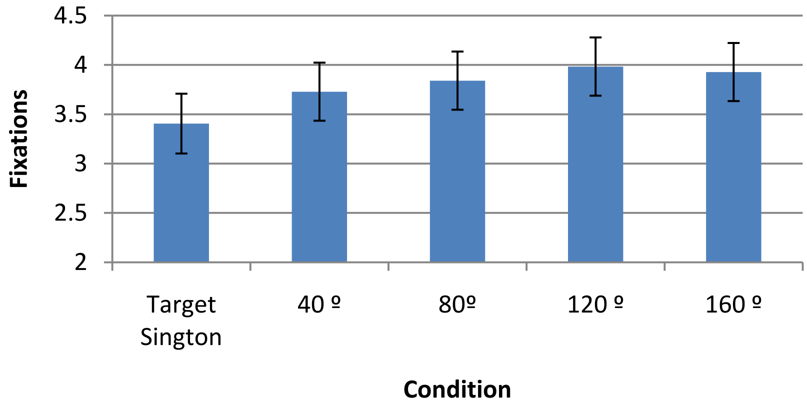

Figure **7**. Fixations per trial with standard error bars

Fixations After Singleton Capture. In order to better analyze the fixation effect found in the prior analysis, a follow-up analysis was conducted where singleton-directed and miss trials were analyzed separately. If the conclusions from the prior analysis were correct, initial saccades directed toward the singleton should require fewer fixations to land on the target when the singleton is proximal to the target as opposed to when it is distal. If an initial eye movement is instead directed at a distractor item that is not the singleton, the number of fixations required to land on the target should remain relatively stable in regards to the singleton's position (see Figure 8). When a participants initial saccade was directed toward the singleton there was a main effect of separation, $F(3, 23) = 3.5$, $p < .032$. Pairwise comparisons revealed that subjects required fewer fixations in the 40º separation condition ($\bar{X} = 4.03$) than in the 160º condition ($\bar{X} = 4.74$), $t(23) = 2.84$, $p < .043$. In trials where the initial saccade was directed toward a non-singleton item there was no effect of separation, $F(3, 23) = .07$, $p > .97$.

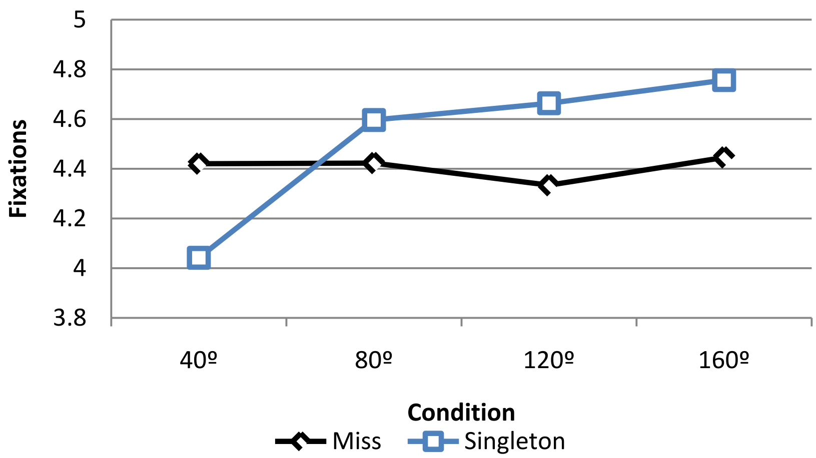

Figure 8. Average number of fixations in a trial by initial saccade destination with standard error bars

Initial Saccade Destination

Initial saccades moving past an area defined by a 3º circle centered at the fixation point were assigned to a particular stimulus item if the first fixation point had an angular deviation of less than 10º (1/4 of the distance between the items) from the linear path between the fixation cross and the center of the item. Similar angular deviation criteria have been used in previous oculomotor capture experiments (e.g. Godjin & Theeuwes, 2002 Experiment 1; Theeuwes & Godijn, 2003), although the current criterion is more conservative as to avoid falsely attributing a saccade to an item when it lands near the midpoint of two items.

In order to determine how location of the singleton affected attentional capture, as well as how often attentional capture was occurring, analyses were performed on the proportion of eye movements directed at a particular item for each condition (see Figure 9). For initial saccades that travelled directly to the target there was an effect of singleton location, $F(4, 32) = 20.34$, $p < .01$. Pairwise comparisons demonstrated that subjects were most likely to make an accurate eye movement to the target in the target singleton condition (61%) than all other conditions ($\bar{X}$ = 32%), t (32) > 6.72, p < .01. No other significant differences were found between conditions, *t*(32) < 2, p > .29. In non-target singleton conditions, participants directed initial saccades toward the singleton item in 22% of trials. In these trials there was no effect of separation, *F*(3, 24) = 1.12, p = .36. Additionally, subjects made initial eye movements toward distractor items that were neither the target nor the singleton on an average of 43% of trials. In these trials there was an effect of separation, *F*(4, 32) = 2.95, p = .035. However, pairwise comparisons did not achieve significance, *t*(32) < 2.73, p > .07. Due to the three measures lacking independence (i.e. the measures summed to 1), a comparison could not be made between the landing destinations.

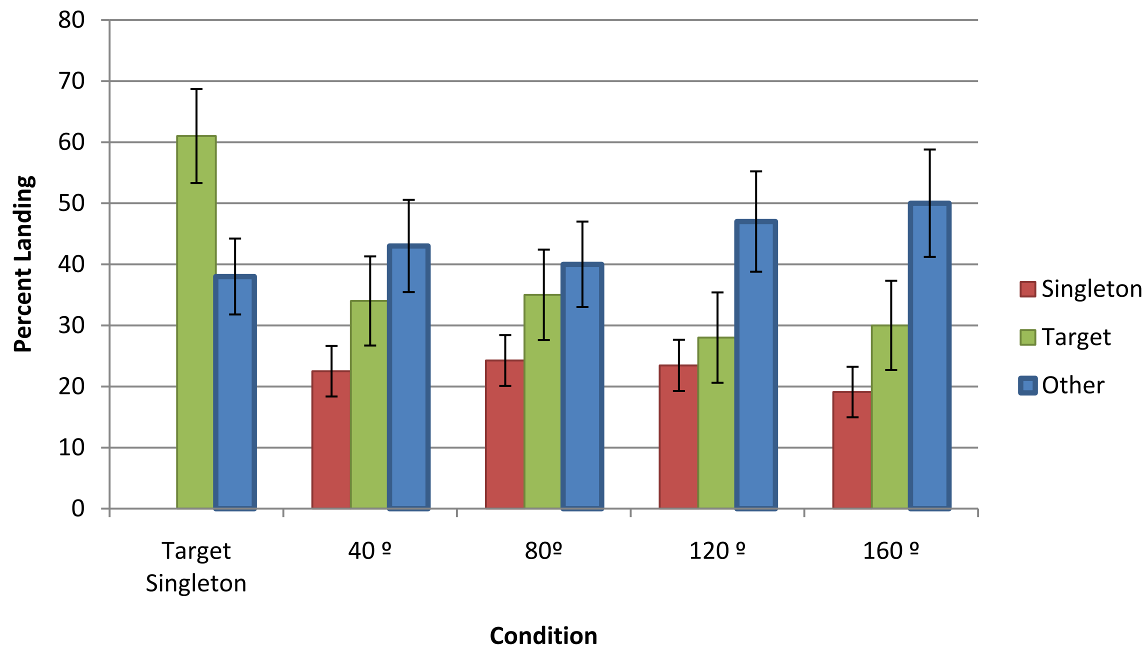

Figure 9. Initial saccade x condition with standard error bars

Practice Effect Analysis

Block as a Factor of Initial Eye Movement. Three separate repeated measures analysis were performed to investigate the effect of block on initial eye movement direction (see Figure 10). If participants were developing methods to ignore the singleton, attention capture from the singleton should decrease across blocks. The probability of an initial eye movement being directed toward a non-target singleton item did reduce significantly across blocks, $F(3, 24) = 3.46$, $p < .04$. Pairwise analysis revealed that participants were more likely to make an initial eye movement toward the non-target singleton item in the first block of trials than in the fourth block of trials, $t(24) = 3.03$, $p < .03$. If participants are focusing the attentional window we would expect initial saccades toward the target to be reduced to chance levels along with the singleton. In the final block of trials, participants made an initial saccade to the target item on 37.32% of trials. There was no significant difference in the percentage of initial eye movement direction across blocks for either target directed eye movements, $F(3, 24) = 1.07$, $p = .37$, nor initial eye movements directed toward non-singleton distractor items (miss), $F(3, 24) = .44$, $p = .72$.

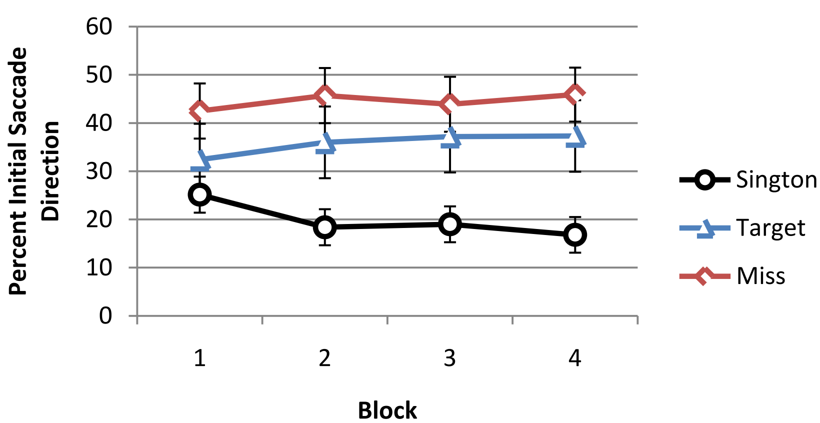

Figure 10. Practice effects on initial eye movement direction.

Saccadic Latency

Saccade Latency with Destination as a Factor. Initial Saccadic Latency was defined as the period of time between the presentation of the stimulus and first saccade away from the fixation cross. Initial saccades were classified as being directed toward one of three areas. In the non-target singleton condition, initial destination could either be toward: 1) the target area 2) the singleton area or 3) neither the target nor the singleton, which was classified as a miss. In the target singleton condition, initial destination could be either 1) target singleton or 2) elsewhere, which was classified as a miss.

As salience has been demonstrated to drive eye movements for only a short time period (Donk & Van Zoest, 2007), saccades directed at singleton and target singleton items may display lower latency than non-singleton target directed saccades. If so, the occurrence of a target singleton would result in an accurate and rapid saccade if the attentional window is left diffuse over the display. These instances may discourage the adoption of a focused attentional window, which would help explain why participants are maintaining a diffuse window throughout the task (see Figure 11). For non-target singleton trials, there was a main effect of initial direction, $F(2, 16) = 53.55$, $p < .001$, with saccades directed at the singleton requiring the lowest latency ($\bar{X}$ = 292 ms). Initial eye movement directed at neither the target nor the singleton required slightly longer latency ($\bar{X}$ = 305 ms), while saccades directed at the target required the highest latency ($\bar{X}$ = 339 ms). All pairwise comparisons were significant $t(16) > 3.17$, $p < .02$. In target singleton trials, there was no significant difference in latency for saccades directed toward the singleton or saccades directed at other non-target items, $t(8) = .35$, $p = .73$.

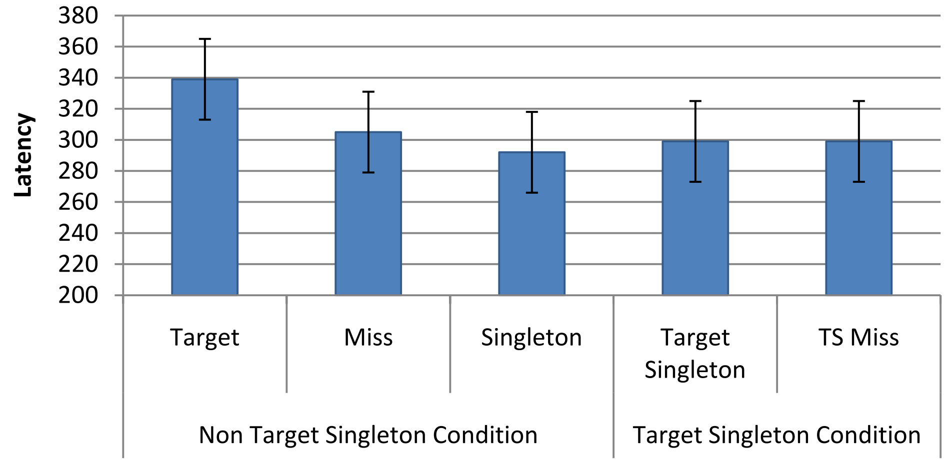

Figure 11. Saccadic latency with destination as a factor, bars are standard error bars

Initial Saccade Destination with Latency as a Factor

In order to perform the final analyses, trials were separated into 5 bins based on saccadic latency. These analyses were performed to better investigate the time course of singleton and target singleton directed saccades. In the prior analysis I hypothesized that participants were relying on the singleton item in order to make a rapid initial saccade. If this is the case, singleton directed saccades should generally be low latency while top-down directed saccades toward the target should display increased latencies. Finally, as saccades may be directed to the target singleton due to either top-down or bottom-up information, we would expect latencies to the target singleton to cover a wide range of latencies.

Singleton Directed Eye Movements. In non-target singleton trials, the percentage of eye movements that were erroneously directed toward the singleton item decreased as initial latency increased, $F(4, 29) = 11.06$, $p < .001$. Pairwise comparisons demonstrated that trials in the lowest two bins were significantly less likely to be directed toward the singleton than trials in the highest latency bin, t(29) > 3.17, p < .028. Thus, high latency saccades were far less likely to be salience driven (see Figure 12).

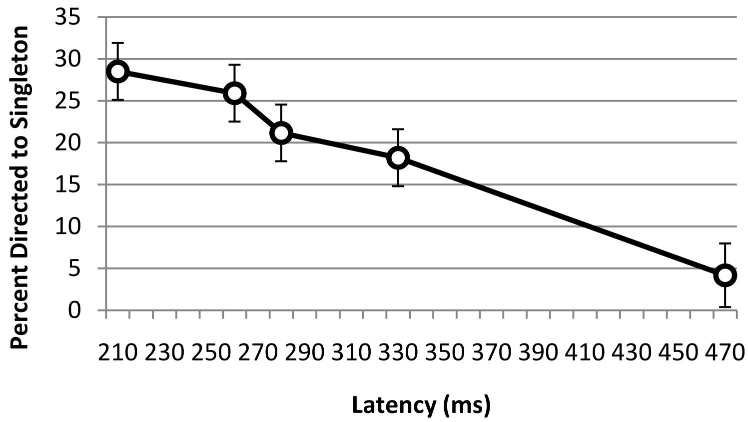

Figure 12. Percent of eye movements directed at the singleton as a function of saccadic latency. Bars indicate Standard Error.

Non-Singleton Directed Eye Movements. Saccadic latencies for each condition (target singleton and non-target singleton) were separated with the same bin procedure as described in the prior analysis. A repeated measure analysis was conducted with bin and condition as factors. A significant interaction revealed initial eye movement were more likely to be directed toward the target in the target-singleton condition for all but the highest latency bins, $F(4, 22) = 9.63$, p < .001. Pairwise comparisons revealed that these differences were significant for the four lowest latency bins, t(22) > 4.25, p < .01, but trials in the highest latency bins were not significantly different, t(22) = 2.1, p = .54. Consistent with the prior analysis, salience driven eye movements toward the target were executed accurately with low saccadic latency. Only in the highest latency trials were goal oriented saccades toward the non-singleton target able to achieve the same level of accuracy (see Figure 13).

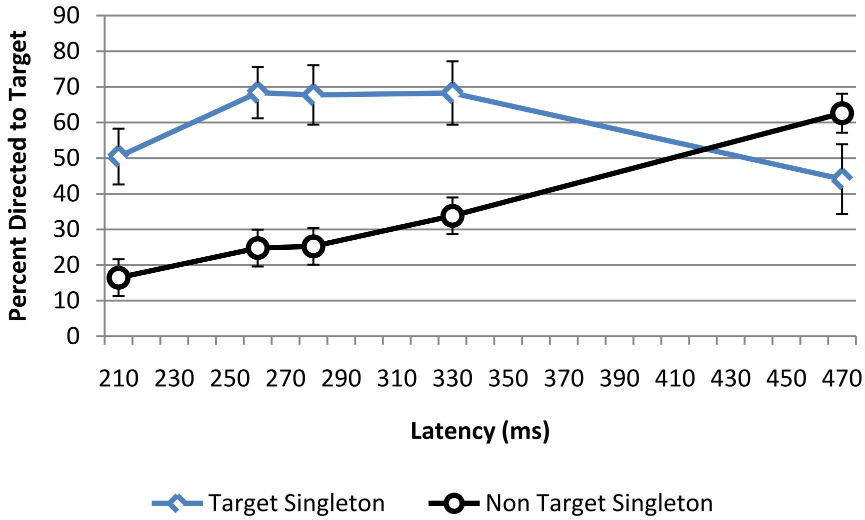

Figure 13. Percent of eye movements directed at the singleton as a function of saccadic latency and condition. Bars indicate Standard Error.

SECTION FOUR: DISCUSSION

General Discussion

In the current study, no reaction time differences were detected as the singleton separated from the target. Unlike previous studies, RT was not used as a means to compare search efficiency between target singleton and non-target singleton trials due to an increase in contrast in target singleton trials that may have affected RT. Instead, the average number of fixations per trial was used as a measure of search efficiency. Fixation data were in line with reaction time data from previous studies, and suggested that the target was found more efficiently when it was either the singleton or located near the singleton item. That is, fewer fixations were required to detect the target in the target-singleton and lowest separation (40º) conditions than higher separation conditions. Furthermore, in non target-singleton trials where the observers initially directed their gaze toward the singleton item, there was an increase in fixations required to detect the target when the singleton was distant from the target. This data indicated that, after the singleton captured attention, a serial search was executed through the remaining distractor items until the target was detected.

Analysis of the eye movement data yielded several reasons the fixation effects may have occurred. First, observers were almost twice as likely to make an accurate initial saccade toward the target item when it was a feature singleton. In conditions where the singleton was a non-target item, the singleton captured attention in approximately 22% of trials. These results are in agreement with predications from Proulx (2007), as well as Todd (1994), that the salient item was likely to capture attention, although goal-oriented eye movements toward the target were the most probable. Initial eye movements that were directed at neither the target nor singleton remained relatively stable between conditions. After practice, the ability of non-target singletons to initially capture the eyes was reduced. Specifically, the proportion of initial eye movements directed toward the singleton decreased across blocks. While practice affected the number of saccades directed at a singleton, the probability of an initial saccade being directed toward the target or a non-singleton distractor item did not change significantly across blocks.

Saccades directed toward the singleton item displayed relatively low latencies when compared with latencies of non-singleton target directed saccades. Time-course analysis demonstrated low latency saccades were likely to be directed toward the singleton, while the highest latency saccades were often target directed and seldom directed toward the singleton. However, eye movements directed toward the target when it was a singleton were likely regardless of latency. In accordance with saccade map theories (Findlay J. M., 1982; Godijn & Theeuwes, 2002), along with previous salience research (Donk & Van Zoest, 2007), rapidly accumulating bottom-up information allowed for the accelerated execution of singleton directed saccades. As top-down information takes longer to develop, target-directed saccades required additional time to execute.

Bottom-Up Suppression After Practice

The results indicate that, even when task demands are held constant, if a salient item is distracting to search, observers will develop a more-efficient attentional set that relies less on bottom-up information. My results show the singleton item was less likely to capture attention with increased practice within the search task, as evident from eye movement analysis that demonstrates observers made fewer eye movements toward the singleton item in the final block of trials than in the initial block of trials. These changes were obtained with observers who were provided with a high level of top-down knowledge as well as the singleton's probability of coinciding with the target item, and that the probability would be held constant throughout the experiment.

Prior to high amounts of practice, the singleton did not capture attention on every trial. This result was expected, as prior studies with the same paradigm did not produce a zero reaction time search slope with increasing display sizes (Beloplsky & Theeuwes, 2010; Todd & Kramer, 1994; Jondies & Yantis, 1988). After practice the singleton became less likely to capture attention, a prediction of the attentional window hypothesis ($H1_1$) as well as the bottom-up suppression hypothesis ($H2_1$). However, practice did not result in a decrease in the proportion of initial saccades toward the target item. One would assume that, in order to rapidly detect and attend to the target item, a diffused attentional set would be required. By adopting a focused attentional set, the probability of observers initially attending to the target would drop to chance levels along with the other items in the display. Therefore, the results indicate that participants were not adjusting the size of the attentional window, but were instead suppressing bottom-up information in order to ignore the singleton ($H2_1$).

One can account for these results in terms of Wolf's GS model and Treisman's FIT. In order to rapidly detect and orient to a target in the periphery, observers maintain a diffuse attentional window. If observers encounter bottom-up information that has a low probability of being indicative of the target, an attentional set is developed that inhibits bottom-up activation in the activation map. This would, in turn, lead to a decrease in the singleton's influence in the saccade map resulting in fewer initial eye movements being directed toward the singleton. As stated previously, in Wolf's Guided Search model the relationship between attentional deployment on the activation map and eye movements is cooperative in nature (Wolfe & Gancarz, 1996). As eye movements became less likely to be directed toward the singleton item after practice, we may then assume that the singleton item became less likely to be selected as the winner on the activation map. However, as the influence of bottom-up information can never be completely reduced (Wolfe J. M., 1994, Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), the singleton would still be occasionally selected, even after practice. As the target singleton is a source of bottom-up and top-down information, the likelihood of it being selected on the activation map would increase, as the bottom-up and top-down activation would be summated. This was supported in the current study where increased initial saccade accuracy was demonstrated in target-singleton trials. This rapid accumulation of bottom-up and top-down information would also account for the decrease in saccadic latency in target-singleton trials due to the summated information more rapidly reaching the criterion to initiate a saccade (Godijn & Theeuwes, 2002).

A similar explanation based on an observer's attentional set has been proposed previously. Todd and Kramer (1994) suggested observers adopt an attentional set that is vulnerable to attentional capture from the singleton as a way of structuring search when a large number of items are present. I believe the current results are in agreement with this conclusion, but provide additional insight into the flexibility of the observers' attentional set. As initial eye movements were less likely to be directed toward the singleton with practice, it would be hard to argue that observers' attentional sets were remaining constant throughout. Instead, practice encouraged the formation of attentional sets that relied less on the often distracting bottom-up information. Still, practice did not completely reduce the effect of this information, as the singleton was still initially attended at a higher than chance level. Thus, observers' did not develop an attentional set that would completely inhibit bottom-up information in task.

Even though capture by the singleton was reduced through bottom-up suppression, initial eye movements to the singleton were not reduced to zero. This finding implies that observers opted to develop an attentional set that assigned some level of weight to the singleton item. This may be due to target-singleton trials where relying on bottom-up information allowed for a low latency saccade to the target. I speculate that these target-singleton trials may have reinforced an attentional set that left the observer vulnerable to attentional capture, although the level of reinforcement was not as pronounced after practice. This may also explain why previous additional feature singleton conjunction search experiments did not report attentional capture by singleton items (e.g. Lamy and Tsal, 1999). In these studies there was incentive to completely maximize suppression of the singleton's unique feature. By making the target a unique item at chance level, observers were not able to develop the same level of suppression, resulting in occasional attentional capture.

Another question is raised as to why observers did not opt to scale the attentional window to disrupt attentional capture of the singleton. It is possible that developing a more stringent focused attentional set came at too high of a cost in reaction time to detect the target, even when it was not a singleton. Proceeding through a search with a attention focused may have proven slower than an attentional set that would occasionally allow for the singleton item to capture the observer's eyes. In other words, observers may have considered a speed-accuracy tradeoff where the speed increase outweighed the decrease in accuracy. Such slowdowns in the 1/d paradigm have been witnessed when observers are forced to develop a focused attentional set (Belopolsky et al., 2007, p. 936).

The notion that observers will maintain a diffuse attentional set in order to rapidly find what they are looking for also has practical implications. In instances where search is occurring through a large area of the visual field, observers are likely to maintain this diffuse attentional window. In doing so, the number of saccades to find an object, as well as time required is reduced. In such instances, the knowledge of what bottom-up features to inhibit is vital to ignoring salient items that may otherwise distract the observer. This is especially true in cases where certain salient features may be encountered with either the target or some other distracting object. In the current study this bottom-up adaptation occurred through practice, and was quite effective. It may be the case that there are other less time demanding means of encouraging observers to suppress certain bottom-up information, and future studies may explore different methods to accomplish this.

In conclusion, the current study demonstrated observers are actively adjusting attentional settings throughout the visual search task. With practice, observers begin to suppress bottom-up information in order to ignoring distracting salient items that would otherwise capture attention. I believe the current findings add insight into the changing nature of observer's attentional sets, and their reliance on different information sources when performing a visual search task. Future studies should take these changes into consideration when examining the interaction between top-down and bottom-up information.

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Applications of Statistics in Psychology. University of Kentucky, Department of Psychology, Summer 2010. Professor: Troy Bitson, Ph. D.

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Peer-Reviewed Proceedings Chapters:

Sublette, M., Carswell, C. M., Seidelman, W., Seales, W. B., & Clarke, D. (in press). A "White Space" Effect in Users' Anticipation of the Challenges Involved in Using Everyday Products. *Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting*. Las Vegas, NV: Human Factors and Ergonomics Society.

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Posters:

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Other Activities/Memberships:

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