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Leveling the Viewing Field: The Impact of Target Prevalence on Searcher's Functional Viewing Field

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LEVELING THE VIEWING FIELD: THE IMPACT OF TARGET PREVALENCE ON SEARCHER'S FUNCTIONAL VIEWING FIELD

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To my mother, for always encouraging me to pursue my dreams.

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ABSTRACT

It is well known that target prevalence impacts various cognitive processes. In visual search, rare search targets are more difficult to detect than common targets. The present research investigated novel questions about target prevalence, focusing on observers' functional viewing field (FVF) during passive search tasks. The FVF is the area in a display where attention is focused and item processing is enhanced. According the FVF framework (Hulleman & Olivers, 2017), the size of the FVF is modulated by the ease of target detections, such that visual search involving difficult target detection reduces the FVF. Although this would suggest that low target prevalence searches should be conducted with a "narrow" FVF, recent evidence from eye-movement analyses (Papesh & Guevara Pinto, 2019) seems to indicate the opposite: Relative to high-prevalence conditions, low-prevalence search yields a wider FVF. It is possible that this effect is due to expectations of target frequency learned during high target prevalence conditions. Three experiments were conducted to test hypotheses regarding the interaction of target prevalence and target expectations in modulating the FVF. Using a dual-task paradigm, where observers passively searched for targets at center of the display while simultaneously processing probes in their periphery, Experiment 1 examined the effects of target prevalence on the FVF size. Experiment 2 manipulated observers' trial-by-trial expectations about target presence, revealing the consequences of expectations for the FVF in isolation from effects of target prevalence. Lastly, Experiment 3 directly contrasted prevalence and expectations within the same experimental design. The results showed that the size of FVF is modulated by direct experiences (i.e., target prevalence) and externally generated expectations (i.e., trial-by-trial cues), but the interaction between the two remains unclear. The implications of these findings expand our theoretical understanding of how target prevalence influence search behaviors, particularly those that extend beyond search miss rates.

CHAPTER 1. INTRODUCTION

In visual search, rare targets are missed more frequently than common targets (Wolfe, Horowitz, & Kenner, 2005). This is known as the low-prevalence effect (LPE), and it has been replicated multiple times inside and outside of the laboratory (e.g., Rich, Kunar, Van Wert, Hidalg-Sotelo, Horowitz, & Wolfe, 2007; Mitroff & Biggs, 2014), particularly in high-risk visual search tasks such as baggage checks (Wolfe, Brunelli, Rubinstein, & Horowitz, 2013), medical screening (Evans, Birdwell, & Wolfe, 2013) and ID matching (Papesh & Goldinger, 2014; Papesh, Heisick, & Warren, 2018). For instance, about 30% of cancers go undetected in mammography screening due to the overall low prevalence of abnormalities during screening procedures (estimated to be about 0.3%; Bird, Wallace, & Yankaskas, 1992; Evans, Birdwell & Wolfe, 2013). Similarly, the likelihood for a transportation security officer to find a "threatening" target (e.g., guns, knives) in an airport security check is extremely low (less than 0.000005% in 2017, according to the Transportation Security Administration[1]), although they encounter non-threatening targets (e.g., water bottles) more regularly. It is important to note that, although the LPE is often investigated in visual search, it has also been reported in non-visual search tasks, such as in *haptic* exploration of artificial tactile maps (Ishibashi, Watanabe, Takaoka, Watanabe, & Kita, 2012) and in short-term memory "searches" (e.g., Theios, Smith, Haviland, Traupmann, & Moy, 1973). Such findings reflect the broad impact of target prevalence on cognitive processes.

The LPE is typically examined in visual search by having observers search for target items among arrays of distractors (e.g., searching for "tools" among objects from other

[1] The real prevalence estimate may actually be higher, as this percentage is based only on the number of threating items found at US airport security checkpoints, ignoring the items that may have gone undetected.

categories). In some conditions, targets are only present in 2-25% of the trials (low-prevalence), while in others, targets are presented in 50-90% of the trials (high-prevalence). The hallmarks of the LPE involve higher low-prevalence miss rates and a decrease in search times (particularly in target-absent trials; Wolfe et al., 2005; Rich et al., 2007). The latter finding suggests that, under low prevalence conditions, observers preemptively terminate the search before the target is located. These effects of target prevalence are robust, and hard to overcome, as observers continue to miss low-prevalence targets even when they are forced to slow down their search or when they work with a partner on the same search task (Wolfe, Horowitz, Van Wert, Kenner, Place, & Kibbi, 2007).

1.1 SOURCES OF PREVALENCE-RELATED ERRORS

Early accounts of the LPE in visual search attributed the elevated miss rates and decreased RTs to a prepotent motor response (Fleck & Mitroff, 2007), suggesting that participants developed a bias for the “target-absent” key when target prevalence was low, as most responses were performed using that key during low-prevalence search experiments. Importantly, this implied that “miss” errors may be corrected if observers are allowed reverse any responses made in haste. Indeed, Fleck and Mitroff (2007) showed that, when observers were given the opportunity to correct their responses, the LPE was eliminated (a strong LPE, of course, was observed in participants’ *initial* decisions). However, Van Wert, Horowitz, and Wolfe (2009), and others (e.g., Wolfe et al., 2007), have failed to replicate these results despite using the same methodology, showing that even when observers are given the opportunity to correct their responses (or when they are forced to provide two responses), they still miss infrequent targets more frequently than common targets. This suggests that although a prepotent

motor response may inflate miss rates for rare targets, it is not the sole cause of prevalence-related errors.

Wolfe and Van Wert (2010) have proposed a formal model of visual search that explains errors due to target prevalence, which they referred to as the Multiple-Decision Model (MDM). According to the MDM, observers select individual items from the display in a sequential manner (left panel, Figure 1), based on preattentively defined activation maps regarding each item's similarity to the search target (see Wolfe, 1994, for an explanation of how these maps are produced). Once an item has been selected for processing, the observer completes an internal two-alternative forced choice (2-AFC) decision, determining whether the selected item is (or not) the target (central panel, Figure 1). If the observer determines that the item is the target, then a target-present response is made and the search ends. However, if the observer determines that the attended item is not the target, then the item with the next highest activation is selected for processing and the 2-AFC decision is made again. A second mechanism accumulates evidence from the display simultaneously, as the observer is selecting items and performing the corresponding 2-AFC decisions. This second process reflects the observer's quitting threshold and it is expressed as a drift diffusion signal where evidence is accumulated to determine whether the search should be terminated (right panel, Figure 1). If the signal reaches the quitting threshold before the target is selected for processing, then the observer terminates the search and a target-absent response is made. Thus, under this model, a correct target-present response can only be made if the target is selected for processing before the quitting threshold is reached. Moreover, although both the internal 2-AFC decision and the quitting threshold exist in parallel, they are independent from one another, where the internal decision is modeled using signal detection theory (SDT) and observer's quitting threshold is modeled as a drift diffusion process.

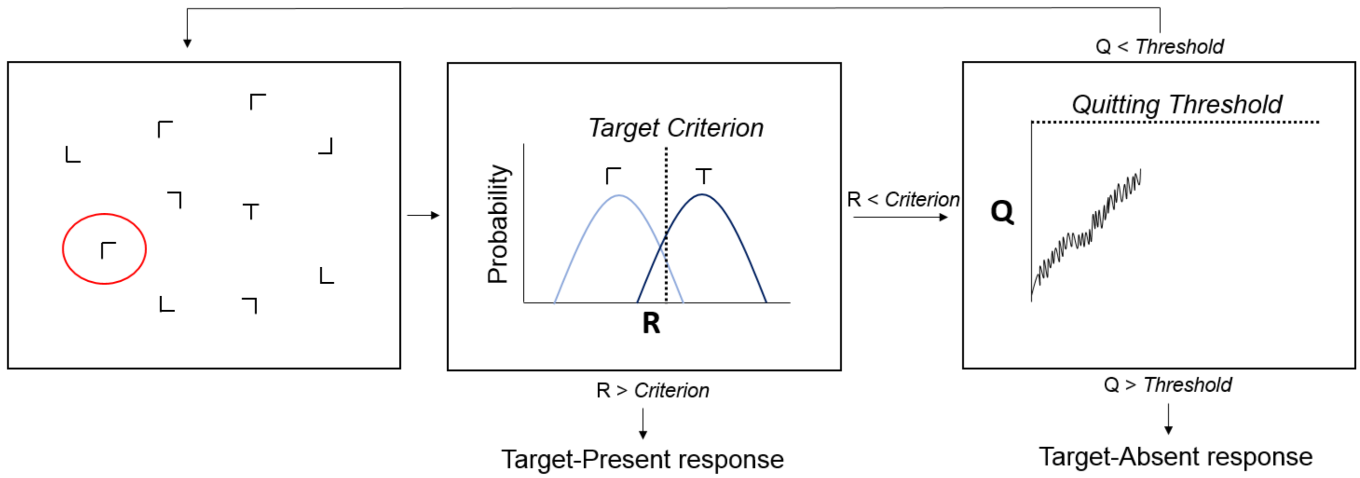

Figure 1. The Multiple-Decision Model of visual search described in Wolfe, J. M., & Van Wert, M. J. (2010). An item is selected for processing (red circle, left panel) and a 2AFC decision is made to determine whether the item is the target (central panel). If the response signal for the selected item (R) surpasses the target identification criterion, then a target-present response is made. If not, a new item will be selected unless a target-absent response is made when a quitting signal (Q) exceeded its threshold (right panel).

The independence of the two mechanisms outlined in the MDM proposes that miss rates during low prevalence search can arise due to either process. More specifically, each process allows for a specific type of search error. For instance, low target prevalence involves a conservative shift of the target-identification criterion, requiring additional evidence for any selected item to be perceived as the target before a target-present decision is made. This shift makes it harder for observers to identify the target as such after it has been selected for processing (i.e., identification errors). Additionally, low target prevalence also produce a decrease in the observer's quitting threshold, resulting in miss errors attributable to early search termination (i.e., selection errors) This explains both the higher miss rates for rare targets and the decrease in RTs during target-absent trials, suggesting that under low target prevalence conditions, observers do not search *exhaustively*, but terminate search before selecting every possible item in the display.

There is ample evidence that low target prevalence reduces observers' quitting-thresholds. Particularly, it has been shown that, relative to high-prevalence searches, low-prevalence searches result in fewer items fixated (Rich et al., 2007; Schwark, Sandry, Macdonald, & Dolgov, 2012) and shorter RTs during target-absent trials (Wolfe, Horowitz, & Kenner, 2005; Wolfe et al., 2007). More recently, researchers have also found support for a conservative shift in the decision criterion. For example, when selection errors are minimized, as in dual-target search tasks, where observers simultaneously search for a rare target (present only in 5% of trials) and a common target (present in 45% of trials), observers continue to miss the rare target, even though overall prevalence is relatively high (50% target prevalence; Godwin, Menneer, Riggs, Cave, & Donnelly, 2015; Hout, Walenchok, Goldinger, & Wolfe, 2015). This effect persists even when rare targets are fixated directly; And if observers do respond target-present when fixating the rare target in dual-target search tasks, it takes them longer to make that decision.

Furthermore, observers also detect fewer targets during low-prevalence conditions in "passive" search tasks, in which item selection is not determined by the observer. For instance, observers in Hout et al. (2015) completed a rapid serial visual-presentation (RSVP) search, where each item is presented one at a time for short durations (e.g. 100 ms) and a target present/absent response is not made until *all* items in the search set are presented. Selection errors in this type of search are completely eliminated, given that all items have to be viewed before any response is possible. Nonetheless, rare targets were still missed more frequently than common targets (Hout et al., 2015), suggesting that identification errors are an integral part of the LPE. Peltier and Becker (2016) also replicated the LPE in both active (i.e., array-based) and passive RSVP search, however, they suggested that identification errors account for a much

smaller proportion (15-20%) of the overall miss rate for rare targets, relative to selection errors (80-85%). Van Wert and Wolfe (2010) described this conservative shift in the target-identification criterion as a result from observers trying to equate the miss and false-alarm errors based on the implied ratio of target-present to target-absent trials. This criterion shift is not accompanied by a decrease in sensitivity, however. In fact, some studies have found higher sensitivity during low-prevalence searches relative to high-prevalence searches (e.g., Wolfe et al., 2007), but it is typically attributable to an extremely low rate of false-alarms in the low-prevalence condition[2].

1.2 THE FUNCTIONAL VIEWING FIELD FRAMEWORK

While the Multi Decision Model of visual search (Wolfe & Van Wert, 2010) makes clear distinctions between the sources of prevalence-related errors, the role of attention allocation is seldom discussed in the context of the low-prevalence effect. Instead, it is implied that, like in any other type of visual search, attention is focused in foveal vision and is guided by a set of task-relevant features regardless of task parameters (Wolfe, 1994, 2007; Wolfe & Van Wert, 2010). This guided search process assumes that the entire search display is preattentively processed in parallel, with a subsequent serial selection process in which items matching the target template are inspected further. Young and Hulleman (2013) have found that the serial

[2] Peltier and Becker (2016) suggested that the internal decision component of the MDM is better modeled by a second drift diffusion process rather than as a SDT process, as it would allow predictions about the latencies of such internal decisions. During low target prevalence conditions, this would result in a bias to identify any selected item as a “distractor” because evidence would start accumulating closer to the “distractor” boundary. This predicts both slow target identifications and fast distractor rejection decisions. This prediction was supported by their data, as dwell times for distractors decreased in low, relative to high, target prevalence search conditions. Aside from these additional predictions about distractor dwell times, a diffusion-drift model of the internal 2-AFC decision makes the same predictions as the original MDM (with a SDT component).

search process can be more or less efficient depending on target detection difficulty. Specifically, when target detection is difficult (e.g., conditions with low discriminability between targets and nontargets, excessive visual clutter, target ambiguity, etc…) the amount of information that can be processed in parallel during serial search is limited. Young's and Hulleman's (2013) observers searched for a tilted line among vertical lines (easy search), for a letter T among letter L's (medium-difficulty search), and for a specific box among similar boxes (hard search; see Figure 3). Importantly, displays appeared using gaze-contingent windows, which allowed observers to clearly process the display immediately surrounding any given fixation (i.e., information presented foveally or parafoveally), but prevented them from peripherally processing the rest of the display. Young and Hulleman also manipulated the size of the window, such that the window surrounding each fixation was small (2.4º), medium (4.9º), or large (9.7º). As the gaze-contingent window decreased in size, search performance (indexed by RTs) was impaired. Young and Hulleman also found a search difficulty and window size interaction, revealing that the effect of window size was largest during blocks of "easy search" trials and weakest during blocks of "hard search" trials. They suggested that this arose due to a "narrowing" of observers' *functional visual field* (FVF) when the search task was difficult: When observers could not easily identify the target in the array, attention was narrowed to facilitate target detection, rendering the artificial "narrowing" of the gaze-contingent window redundant and less disruptive.

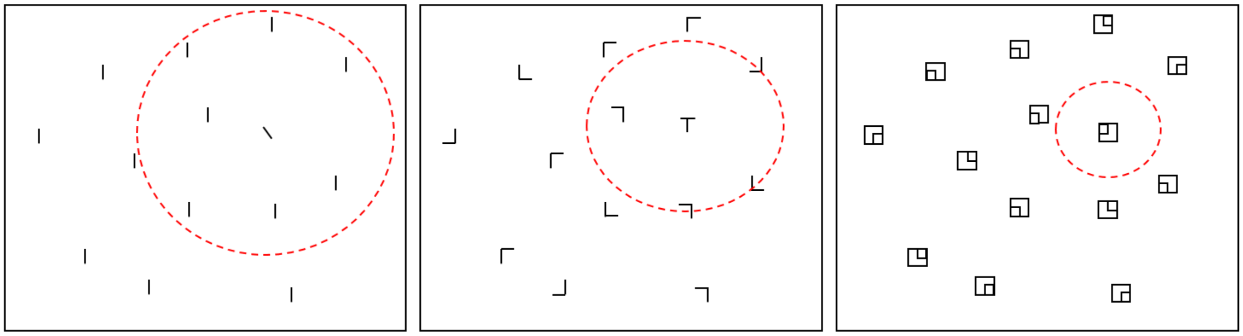

Figure 2. Examples of the search tasks used in Young and Hulleman (2013). The left panel depicts an easy search task with a large gaze-contingent window (dotted red line). The central panel depicts a moderately difficult search task with a medium-size window. The right panel depicts a difficult search task with a small window. None are drawn to scale.

The FVF refers to the area of the display attended by the observer, where items fall in foveal or parafoveal vision, and are thus processed at higher resolution (Sanders, 1970; Hulleman & Olivers, 2017). Items falling outside of the FVF are processed peripherally and at lower resolution, implying that not all elements in a visual display are processed equally within a single fixation. This is not a particularly new concept, as it has been previously described using different terms, such as the area of visual conspicuity (Engle, 1977), useful field of view (Ball, Beard, Roenker, Miller, & Griggs, 1988), perceptual span (O'Regan, Lévy-Schoen, & Jacobs, 1983; Rayner, 2009), zooming-lens (Eriksen & St. James, 1986), or the attentional window (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). The FVF framework proposed by Hulleman and Olivers (2017) differs from previous conceptualizations of attention through its elegant simplicity, emphasizing the *ease* of target detection as the primary factor impacting the size of the FVF during visual search: As targets become harder to detect, the FVF decreases in size. This reduction in observers' FVF during difficult searches is thought to be a functional response that 1) may reduce the amount of interference produced from other items processed in parallel when an item is being inspected, 2) may increase the "resolution" with which the inspected item is processed, or 3) a combination of both.

Multiple studies support the relationship between target detectability and FVF size. For instance, Drew, Boettcher, and Wolfe (2017) recently found that the FVF changes as a function of memory set size in “hybrid” search. In hybrid search, observers memorize a set of target objects, and later search for any of them in visual arrays (in this way, they are simultaneously searching memory and the display). Search performance, indexed by both target detection and RTs, decreased with larger memory set sizes (MSS). Importantly, Drew et al. reported that the FVF decreased from approximately 10º for a MSS of 1 to approximately 6° of for a MSS of 100 objects. Note that the size of FVF is also related to the *number of fixations* made during search. For instance, at large MSS, observers make more fixations to find targets, reflecting a narrower FVF. Meanwhile, at small MSS, distractors near any given fixation can be more easily rejected without foveal processing, as they fall within a larger FVF, reducing the need for additional fixations. Similarly, Young and Hulleman (2013) also found that during natural search (i.e., no gaze-contingent window) observers made more fixations in “difficult” search blocks relative to “easy” search blocks. This finding confirms that small gaze-contingent windows barely impair performance during difficult searches because those searches are already conducted with a relatively small FVF. Lastly, it is important to note that the difficulty with which targets are found in visual search, and consequently the FVF size, is inherently dependent on observers’ level of expertise with the search task. For instance, Manning, Ethell, Donovan, & Crawford (2006; see also Crawford, Litchfield, & Donovan, 2017) demonstrated that expert searchers (e.g., radiologists) are not only faster than novices at finding nodules in x-ray images, but that they also make fewer fixations prior to locating a target, reflecting a wider FVF. Similar findings have been reported with expert chess players (Reingold, Charness, Pomplun, & Stampe, 2001), who make fewer fixations than novices when identifying the “best” possible move in chess arrays.

Furthermore, methodologies have been developed to examine FVF size while eliminating the need for overt eye movements. For instance, Williams (1982, 1985, 1989) asked participants to complete a foveal character classification task at the center of screen while simultaneously monitoring the orientation of lines (horizontal or vertical) presented in their periphery. Importantly, the perceptual load of the central task was manipulated, so that participants had to discriminate between zero, two, or six characters. Across multiple experiments, the results consistently showed that detection of peripheral lines was slower and more error-prone as the central task load increased. In terms of the FVF, Williams (1982) suggested that this reflected a 2º difference across each load condition. Similarly, Ball et al. (1988; see also Sekuler & Ball, 1986) employed a dual-task procedure in which observers had to discriminate central faces while simultaneously identifying the location of a peripheral face. Observers determined whether a central face was present or absent on any given trial (easy condition), whether a face was "happy" or "sad" (medium condition), or whether two simultaneous faces were the same (difficult condition). The results showed that observers' ability to localize the peripheral probe decreased as the central task became more difficult, reflecting a clear trade-off between foveal processing demands and the size of the FVF. More recently, Guevara Pinto and Papesh (2019) asked participants to passively search for real-world objects in a central RSVP search using precise (e.g., single picture targets) or imprecise target cues (e.g., multiple-picture or categorical targets). In a subset of trials, however, observers were also tasked with detecting and identifying peripheral probe items briefly presented during the ongoing RSVP search. Relative to trials involving precise target cues, trials with imprecise target cues were associated with worse peripheral task performance, reflecting a narrowing of the FVF when target detection was difficult

This evidence demonstrating that difficult target detection reduces the FVF suggests that target prevalence should also impact FVF size. Difficult target detection is at the core of low target prevalence search: Research has extensively shown that, relative to common targets, rare targets are missed despite being directly fixated (e.g., Godwin et al., 2015; Hout et al., 2015; Peltier & Becker, 2016). Moreover, even when rare targets are identified as targets, observers require more time to make those decisions. Other work has shown that processing rare targets may impose additional cognitive demands, relative to processing common targets. For example, Shapiro, Raymond, and Arnell (1994; see also Crebolder, Jolicœur, & McIlwaine, 2002) examined the impact of target frequency in an attentional blink (AB) paradigm. The AB, where detection of a target precludes detection of a second target in a RSVP search task, has been proposed to be due to limited-capacity resources being consumed by the first target (Chun & Potter, 1995). Shapiro et al. demonstrated that when targets are drawn from large set of possible items (decreasing the frequency with which any individual target is presented), a stronger AB effect is produced, relative to when targets are drawn from a small set of items. Moreover, using pupillary responses to index cognitive processing, Papesh and Guevara Pinto (2019a) demonstrated that rare targets not only produce a stronger AB than common targets but they indeed consume more attentional resources after they have been detected.

Finding rare targets is more challenging than finding common targets, therefore it is possible for low target prevalence search to incidentally reduce the size of observers' functional viewing field. This prediction has been indirectly supported by examining initial fixation patterns prior to search trials. Menneer, Godwin, Liversedge, Hillstrom, Benson, Reichle, & Donnelly (2017) noted that, when observers searched under high target prevalence conditions, their initial fixations were more often located towards the center of the search display, relative to low target

prevalence conditions. They argued that this tendency to initially look at the center of the display during high target prevalence searches is consistent with a larger FVF, where a single, central fixation allows observers to cover more areas of the search display than a non-central fixation. However, Papesh & Guevara Pinto (2019b) recently used the methods described by Young and Hulleman (2013) to assess the FVF from fixation patterns made during search: For every trial, an artificial circle with a radius of 1º of visual angle was drawn around each fixation. This radius was then gradually increased by 1º until either 51% (target-present trials) or 85% (target-absent trials) of items in the display fell inside any circle (items were only counted once, regardless if they fell within multiple circles). Once that criterion was reached, the final circle radius determined the FVF size. When observers frequently encountered targets throughout the search task, the FVF was reliably reduced by over 0.6º, relative to when targets were rare. While such results are in contrast with predictions from the FVF framework, they are not surprising given that calculating the FVF size from fixation patterns is inherently dependent on the number of fixations made during search. Numerous studies have already reported greater number of fixations made during high-prevalence searches (e.g., Godwin et al., 2015; Peltier & Becker, 2016; Schwark et al., 2013), consistent with a smaller FVF relative to low-prevalence conditions. Still, the analyses on initial fixation patterns by Menneer et al. suggest the contrary, but this discrepancy in results is probably attributable to dynamic changes in FVF size within single trials. Hulleman and Olviers (2017) recognized that while their framework assumes a “fixed” FVF, it is possible that the FVF may be altered on-line during search to accommodate specific task demands, but that further research is required to test this. Thus, it is possible for observers to start high-prevalence searches with a wide FVF but subsequently reduce it to conduct an exhaustive search. Meanwhile the FVF may not change in size throughout the search at low

target prevalence. This dynamic nature of the FVF is interesting, often cited as a major point of criticism to FVF framework (e.g., Itti, 2017; Kristjánsson, Chetverikov, & Brinkhuis, 2017), and yet testing it is outside of the scope of the present investigation. Therefore, the present study focused on examining the influence of target prevalence on the FVF by using a passive search task which do not require overt eye movements.

How could the relatively *easy* high-prevalence search then reduce the FVF? Perhaps a different mechanism, independent of target detectability, may also modulate the size of the FVF. In experiments with target prevalence manipulations, observers may not be explicitly aware of how difficult it is to find rare targets, but instead they may be aware of how often targets are found throughout the search task. It is possible that the frequency with which targets are detected modulates the size of the FVF. Specifically, frequently detecting targets (i.e., high-prevalence conditions) may cause observers to develop expectations of the likelihood that a target will be found in any given trial (Godwin, Menneer, Riggs, Taunton, Cave, & Donnely, 2016). These internal expectations develop as observers learn the statistical regularities of the search task, and once established, they are difficult to overrule, as they are independent from expectations produced by external cues or explicit instructions (Lau & Huang, 2010; Ishibashi, Kita, & Wolfe, 2012; cf. Schwark, Sandry, MacDonald, & Dolgov, 2012). If observers expect a target to be present on a given trial, as indicated by their prior search history, it is possible that they adopt a smaller FVF, reducing interference from peripheral processing to improve detection of the expected target. Thus, adopting a smaller FVF during high-prevalence conditions may be a functional response to observers' expectations of target detection frequency.

Visual search research on observers' expectations has often focused on contextual expectations, examining how semantic information about the target (e.g., toothbrush) is

integrated with the search context (e.g., bathroom) to efficiently allocate attention to important locations within the search context (e.g., sink; Malcolm & Henderson, 2010; Spotorno, Malcolm, & Henderson, 2014; Torralba, Oliva, Castelhano, & Henderson, 2006; Võ & Wolfe, 2012, 2013). Recent research, however, has demonstrated that expectations about search difficulty impact how observers allocate attention in preparation for search trials. For instance, Schmidt and Zelinsky (2017) manipulated observers' expectations by having participants search for a specific target (e.g., teddy bear) among either objects of the same object category (i.e., high target-distractor similarity) or among objects of different categories (i.e., low target-distractor similarity). Importantly, target previews among these two conditions were identical, and contralateral delay activity (CDA) was measured to index the amount of target details loaded into visual working memory (VWM) in preparation for search. A larger CDA amplitude was observed prior to the onset of the search array in blocks of high, relative to low, target-distractor similarity. This suggests that when observers expected a difficult search, they allocated resources to encode detailed target representations in VWM in order to compensate for the difficulty in target detection. However, a different attention allocation strategy is adopted when targets are not precisely defined (e.g., with picture cues) prior to search: When targets are only cued by categorical information, particularly superordinate-level categories (e.g., "food"), observers allocate resources to improve overall item processing, "narrowing" their attention to closely inspect each item and find the target (Guevara Pinto & Papesh, 2019). Similarly, it is possible that observers narrow their attention during high-prevalence conditions in preparation to more easily process and detect an expected target. The present investigation tested this hypothesis.

The present study had three main goals. The first goal was to establish the effect of target prevalence on the FVF in a passive search task (Experiment 1). The second goal was to establish

a relationship between observers' expectations of target likelihood and the FVF. If expectations modulate the FVF to facilitate target detection, then a smaller FVF should be observed in trials where observers expect a target to be present (Experiment 2). Lastly, the third goal was to examine whether the effect of target prevalence on the FVF is due to learned expectations of target likelihood (Experiment 3).

CHAPTER 2. EXPERIMENT 1: TARGET PREVALENCE AND FVF

The goal of Experiment 1 was to examine the effect of target prevalence on the FVF size in a search task that does not require overt eye movements. Adopting the methods from Guevara Pinto and Papesh (2019), the relative size of the FVF was assessed as a function of target prevalence, which was manipulated across three blocks (25%, 50%, and 75% target prevalence) of rapid serial visual presentation (RSVP) search trials. Importantly, in a small subset of critical trials (25% of trials per prevalence block), a small black shape was presented outside the central search sequence, in the participant's periphery, at two eccentricities off-center (6.5º and 12.5º). Participants were instructed to detect and identify these peripheral items without sacrificing accuracy on the central RSVP search. If high target prevalence reduces the FVF, then lower peripheral probe identification is expected during the high, relatively to low, prevalence block, particularly when probes are presented at larger eccentricities off-center.

2.1 METHOD

Participants.

A power analysis (within-subjects effect $\alpha = .05$, $\beta\text{-}1 = .95$) conducted on the Search Difficulty x Probe Distance effect size on probe identifications in Exp. 3 of Guevara Pinto and Papesh (2019; $\eta_p^2 = .029$) suggested 88 participants as necessary to reach the desired power. Thus, 96 undergraduate students ($M_{age} = 18.94$ years, $SD = 1.45$; 73 women) were recruited from the Psychology Department subject pool of Louisiana State University. Participants received partial course credit in exchange of their participation.

Stimuli and Procedure.

The stimuli were selected from the *Massive Memory* database (Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Oliva, 2010, cvcl.mit.edu/MM/stimuli.html), which

consists of over 4,000 color images of real-world objects from 240 categories (17 exemplars per category). Images were presented in full color against a white background (255, 255, 255). They were sized to fit within a 100 x 100 pixel square, and subtending 2.3° of visual angle (horizontally and vertically) at a viewing distance of 60 cm. For the secondary, peripheral detection task, ten black polygons served as search-irrelevant peripheral probes during critical trials. The shapes included an *arrow* (pointing up), *circle*, *cross*, *heart*, *hourglass*, *incomplete circle*, *pentagon*, *square*, *star*, and a *triangle*. Polygons matched the dimensions of the search items (100 x 100 pixels, subtending 2.3° of visual angle). Stimuli were presented on 21.5-inch monitors, with 1920 x 1080 screen resolution and 60-Hz sampling rates and experimental procedures were controlled using E-Prime 2.0 (Psychology Software Tools, 2006).

Procedure.

After providing informed consent, participants were instructed that they would complete three blocks of RSVP search trials, with 1-minute breaks in between each block. Additionally, participants were further instructed that, every so often, a black shape would appear in their periphery, outside the central RSVP stream. If this occurred, they were instructed to report noticing a shape in periphery and would also have to pick the shape out of a 5-item line-up. They were explicitly told, however, that their main task was searching for the target item in the central stream, and that they should not sacrifice accuracy on the primary task to detect peripheral probes. They were also told that missing peripheral probes would not result in any penalty, however, missing a target in the search task would result in a two second time-penalty.

At the beginning of each trial, participants were presented with the search target. They then self-initiated the search by pressing the space bar. A 1500 ms fixation cross was followed by the onset of the 24-item RSVP stream. Objects were presented sequentially for 75 ms each,

with a 35 ms blank ISI screen between each object (e.g., Guevara Pinto & Papesh, 2019; Potter, Wyble, Hagmann, & McCourt, 2014). During target-present trials, targets were presented in serial positions 4-21, and if a probe was presented, it was always presented at least 7 serial positions before the target. After the offset of the stream, participants indicated their target-present or target-absent response using the "f" or "j" keys (counterbalanced across participants). Immediately after, they provided their peripheral detection responses using the "v" and "n" keys (counterbalanced across participants). If participants reported detecting a peripheral probe, they were required to identify it from a 5-AFC lineup using the number pad (see Figure 3). Participants only received error feedback on the primary search task, which took the form of a 2-second time penalty. No feedback for either their probe detection or identification responses was provided.

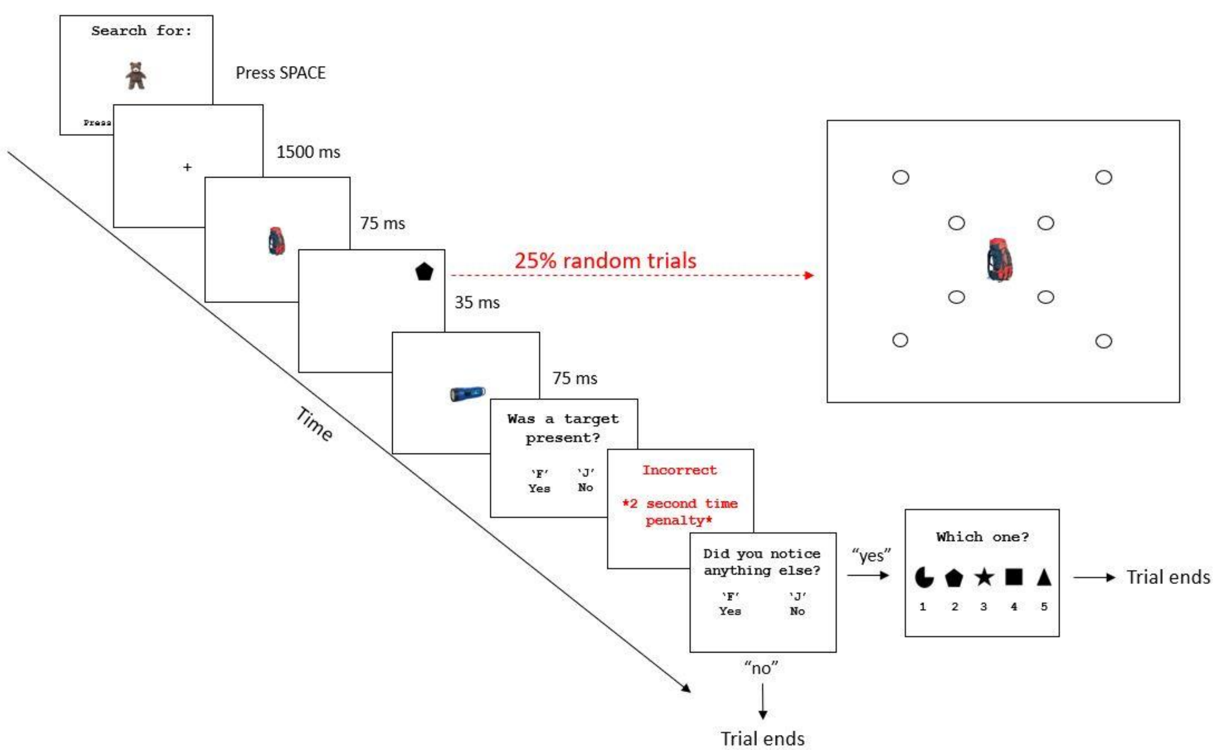

Figure 3. Trial schematic of Experiment 1. Each trial consisted of 24 objects each followed by a blank ISI screen. The box depicted to the right indicates the 8 possible spatial locations in which peripheral items could be presented.

Participants completed three blocks of trials, with 25%, 50%, and 75% target prevalence rates across blocks. The order of the blocks was counterbalanced across participants. Each block consisted of 40 transition trials followed by 120 experimental trials. Transition trials were not included in the analyses, but preceded experimental trials in order to allow for the observer's target-identification criterion to be set based on the current block's prevalence rate (Ishibashi et al., 2012; Peltier & Becker, 2016; Wolfe & Van Wert, 2010). Participants were not informed about the difference between transition and experimental trials, so they experienced both as a single block of trials. Both transition and experimental trials used the respective block's target prevalence rate (i.e., the high-prevalence block included 90 target-present experimental trials). Participants were given self-paced breaks in between each block.

Importantly, a peripheral probe was presented at random in 25% of both transition (10 trials) and experimental (30 trials) trials within *each* prevalence block. Peripheral probe frequency was controlled independently from each block's target prevalence so that observers did not monitor their periphery but instead focused on the central RSVP stream on every trial. During these critical trials, probes were presented during the 35 ms ISI on both target-present and target-absent trials. If the target was present, the probe always preceded the target by 7 objects (to avoid an AB effect; e.g., Martens & Wyble, 2010). Although targets appeared in any serial position from 4-21, peripheral probes were only presented in trials where the target was presented in serial positions 9-21 (to ensure the 7-object distance between the two). The distance at which probes appeared from center was also manipulated, so that items appeared *relatively near* the center of the screen (subtending 6.5° horizontally and 6.3° vertically off-center) or *relatively far* from the center of the screen (subtending 12.6° horizontally and 12.3° vertically off-center) with equal frequency (15 trials each). Probes could also appear in any of the four

screen quadrants, resulting in 8 potential spatial locations, randomly determined on every trial. If a trial included a peripheral probe, then the probe was randomly selected from all ten possible shapes. If detected, the probed appeared in a random position in the 5-AFC identification lineup, along with four randomly selected foils. On trials where participants incorrectly indicated noticing a peripheral item (i.e., a false alarm), 5 random foils were assigned to the identification line-up. Participants completed four practice trials (half target-present) prior the first block of trials. One practice trial included a peripheral probe to demonstrate the secondary, peripheral task.

2.2 RESULTS

For all experiments in this study, all proportion data were arcsine-square-root transformed prior to analysis to ensure normality. For clarity, raw values are used for descriptive statistics and graphs, but inferential statistics are based on the transformed data. Alpha level for all analyses was set at .05, and multiple comparisons were subjected to Bonferroni corrections. Greenhouse-Geisser corrected degrees of freedom were applied for any sphericity violations. Transition trials are not included in the analyses.

Search Accuracy.

A 3 (Target Prevalence: Low, Medium, High) x 2 (Trial Type: Target-Present, Target-Absent) repeated measures ANOVA was conducted on the proportion of correct trials. A main effect of Trial Type was observed, $F(1, 95) = 60.51$, $p < .001$, $\eta_p^2 = .39$, revealing higher search accuracy during target-absent trials, as well as a reliable interaction, $F(2, 190) = 24.76$, $p < .001$, $\eta_p^2 = .21$. The interaction is characterized by an increase in hit rates during target-present trials and a decrease in correct rejections during target-absent trials as target prevalence increased (see Figure 4), all *ps* < .05.

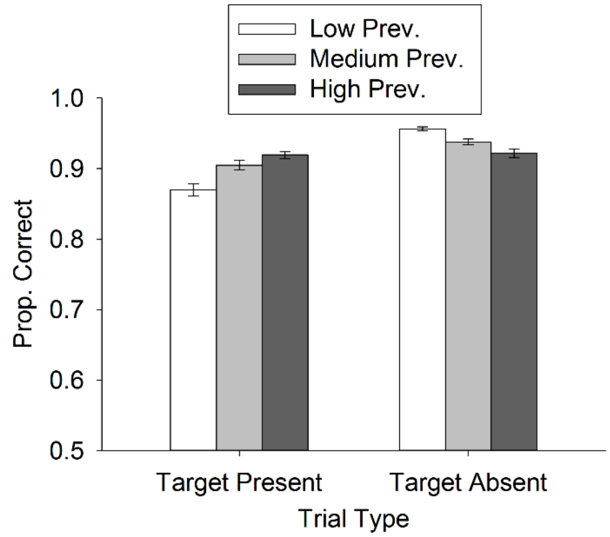

Figure 4. Search accuracy in Experiment 1. Error bars represent ± 1 SEM. The y-axis begins at chance.

Signal detection measurements of sensitivity (*d'*) and bias (*c*) were also calculated. While no effect of prevalence on *d'* was observed, $F(2, 190) = 0.058$, $p > .250$, $\eta_p^2 = .001$, target prevalence strongly influence *c*, $F(2, 190) = 16.59$, $p < .001$, $\eta_p^2 = .149$, such as the low prevalence condition yielded a more conservative bias (*M* = .28, *SE* = .03) relative to both the medium (*M* = .12, *SE* = .03), *p* = .001, and high prevalence conditions (*M* = .04, *SE* = .02), $p < .001$. No difference between the medium and high prevalence condition was observed, *p* = .133. These results replicate the classic low-prevalence effect during RSVP search observed in previous literature (e.g., Hout et al., 2015; Peltier & Becker, 2016).

Peripheral Probe Detection.

Analyses of Probe Detection were limited to only trials where a correct visual search response was made. A 3 (Target Prevalence) x 2 (Probe Distance) repeated measures ANOVA failed to yield any reliable results (see left panel in Figure 5).

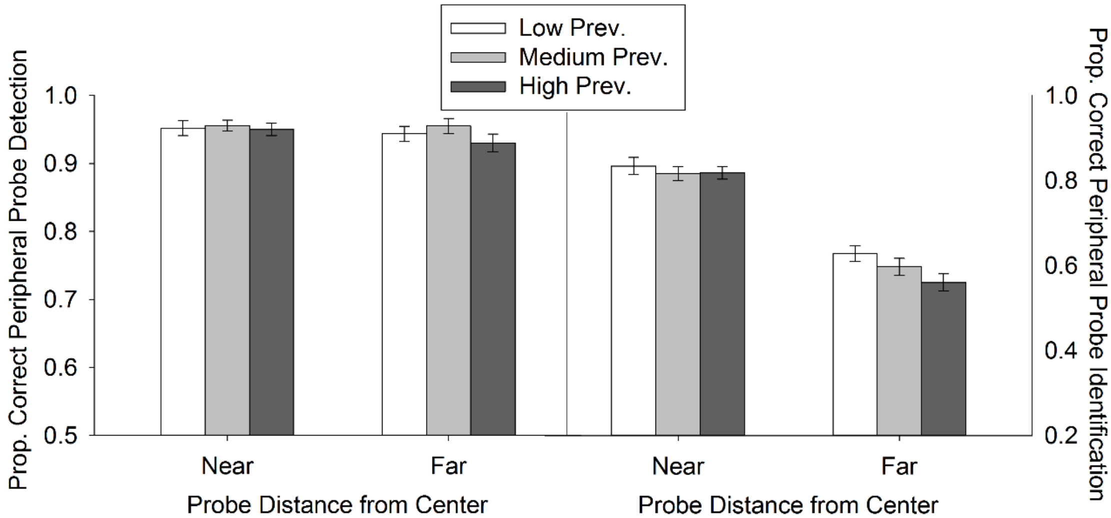

Figure 5. Peripheral probe detection (left panel) and identification (right panel) in Experiment 1. Error bars represent ± 1 SEM. The y-axes begin at chance.

Peripheral Probe Identification.

The proportion of correct identifications was examined in a 3 (Target Prevalence) x 2 (Probe Distance) ANOVA, revealing reliable main effects of Target Prevalence, $F(2, 190) = 5.64$, $p = .004$, $\eta_p^2 = .056$, Probe Distance, $F(1, 95) = 279.56$, $p < .001$, $\eta_p^2 = .746$, and a reliable interaction, $F(2, 190) = 3.67$, $p = .027$, $\eta_p^2 = .037$. While effect of Probe Distance reveals better probe identification on trials where the probe was presented near the central RSVP stream (*M* = .82, *SE* = .01) than far (*M* = .59, *SE* = .02), $p < .001$, the effect of Target Prevalence needs to be interpreted within the context of the reliable interaction: There were no differences across prevalence conditions on trials where the probe was presented near the RSVP stream, all *p*s > .250. However, when the probe was presented far from the center, probe identification rates were higher both in the low (*M* = .63, *SE* = .02) and medium prevalence (*M* = .59, *SE* = .02) conditions relative to the high prevalence condition (*M* = .55, *SE* = .02), $p < .001$ and $p = .004$, respectively. This indicates that the size of the FVF was reduced when search targets were

frequently found. The low and medium prevalence conditions were not different from one another ($p > .250$; Figure 5, right panel).

2.3 DISCUSSION

Experiment 1 was designed to test whether target prevalence influences the size of the FVF during passive visual search. To test this, observers searched for targets in a central RSVP stream across prevalence blocks, while simultaneously perceiving probes in their periphery. The results seem to indicate the FVF is smaller at high, relative to low, prevalence conditions, supporting recent findings (Papesh & Guevara Pinto, 2019b). This was reflected by a Target Prevalence x Probe Distance interaction, demonstrating that when observers frequently detected search targets, there were less likely to identify probes presented far away in the periphery. Contrary to the proposals of the FVF framework (Hulleman & Olivers, 2016; Young & Hulleman, 2013), these findings not only suggest that other factors besides ease of target detectability can modulate the FVF, but also that difficult target detection does not always result in a small FVF. Importantly, as target prevalence decreases the FVF is increased, despite target detection being lower at low-prevalence. No differences in signal detection measurement of sensitivity (*d*') were observed across conditions, suggesting that maybe the effect of prevalence on the FVF is due to changes in observers' bias to expect targets at high-, relative to low-, prevalence. Experiment 2 then tested the effect of target expectations on the FVF.

CHAPTER 3. EXPERIMENT 2: TARGET EXPECTATIONS AND FVF

The goal of Experiment 2 was to test whether observers' expectations about target probability impact the size of the FVF while keeping a moderate level of overall target prevalence (i.e., 50% prevalence). Previous work has demonstrated that using external cues to indicate the likelihood of whether a target will be present in a given trial significantly increases search RTs during target-absent trials in low-prevalence conditions (e.g., Lau & Huang, 2010; Ishibashi et al., 2012). Although miss rates are generally unaffected by cues, longer search times are consistent with a smaller FVF, where observers inspect a larger number of individual items when cued to expect a target in the display. More recently, Wendt, Kähler, Luna-Rodriguez, and Jacobsen (2017) demonstrated that observers' expectations can impact how attention is spread across a search array. Participants searched for target numbers (e.g., 3 or 7) in an array of numbers presented in a vertical line across the center of the display. Importantly, search trials were randomly intermixed with Eriksen flanker trials or same-different discrimination trials. During flanker trials, participants were presented with a vertical array of letters, instead of numbers, and had to identify the letter in the central position. For same-different discrimination trials, participants were also presented with a vertical array of letters but had to indicate whether all the letters in the array were the same or different. The results showed that when observers *expected* a same-different trial but instead got a search trial, the search target was located equally fast regardless of its location in the array. However, when observers expected a flanker trial but got a search trial they were faster at locating the target if it was presented in the central location of the array. Wendt and colleagues suggest that these findings are due to how attention allocation differs across the flanker and same-different tasks: Same-different judgments requires processing of all items in the array, thus attention is allocated "globally" across the entire array when

observers expected to make same-different judgments. Conversely, the Eriksen flanker task requires observers to selectively process the central item, while simultaneously inhibiting the peripheral or "flanker" items. Therefore, observers allocated attention to the central location in preparation for flanker trials, facilitating target processing in this location when a search trial was unexpectedly presented. Similarly, it is possible that in order to improve detection of expected targets, observers adopt a "narrow" spread of attention (i.e., small FVF), selectively allocating attention to the expected target location. If so, observers would then be less likely to identify peripheral probes on RSVP search trials when they are cued that a target will likely be present, and in particular when probes are presented far in the periphery.

3.1 METHOD

Participants.

One-hundred and five undergraduate students (M_{age} = 19.02 years, *SD* = 1.26; 75 women) were recruited from the Psychology Department subject pool of Louisiana State University. Participants received partial course credit for their participation.

Stimuli and Apparatus.

Search and peripheral probe stimuli were identical those used in Experiment 1. Additionally, a high-pitch tone (1250 Hz) and a low-pitch tone (250 Hz), both with 250 ms durations, were used as cues to indicate the likelihood of a target being present in any given trial. Tones were played through either Sennheiser HD 280 pro headphones or Onn HD headphones at a volume of 70 dB. Experimental procedures were controlled using E-Prime 2.0 (Psychology Software Tools, 2006).

Procedure.

The experimental design was similar to Experiment 1. Participants completed three blocks of RSVP search trials, all at 50% target prevalence, each consisting of 72 trials (half target-present). Participants were told about the peripheral probe task, but instructions emphasized primary task performance.

The search and response parameters of Experiment 2 were identical to Experiment 1, with the exception of the tone cues provided prior to RSVP stream onset. Participants received instructions prior to the experiment indicating which tone (high- or low-pitch) was the High-Probability Cue and which one is the Low-Probability Cue, along with auditory samples of each tone. Additionally, participants also completed a tone-discrimination task *before* and *after* the experiment, in which a single tone was played for 250 ms and they had to press the "f" or "j" keys to indicate whether the tone was the high- or low-probability cue. The tone-discrimination task consisted of 3 trials per tone, and participants received feedback on all answers.

At the beginning of each search trial, participants were presented with the search target. After participants dismissed the search target, a fixation cross appeared for 1500 ms. In 2/3 of the trials (48 trials per block, 144 trials total), a high- or low-pitched cue tone was played 250 ms *after* the onset of the fixation cross, cueing the likelihood that a target was present within the upcoming RSVP stream: One tone indicated that a target was very likely to be present in the current trial, while the other indicated that a target was unlikely to be present in the trial (assignment of cue to likelihood was counterbalanced across participants). The remaining third of trials in each block did not include a tone cue.

During each 72-trial block, high target-probability cues were played in 21 out of the 36 target-present trials, while low target-probability cues were played in only 3 target-present trials.

Similarly, high target-probability cues were played in 3 out of the 36 target-absent trials, while low target-probability cues were played in 21 target-absent trials. This rendered both cues 87.5% valid.[3] There were 12 No Cue target-present trials, and 12 No Cue target-absent trials. Peripheral probes were presented in 25% of trials per block (i.e., 18 trials per block), equally divided among high- and low-probability cue trials, and No Cue trials. Probes were again randomly presented at two levels of eccentricity (near or far) from the central RSVP stream on an equal number of trials (9 trials per block).

Prior to the first block of trials, participants practiced 12 search trials (4 No Cue, 4 High-Probability Cue, and 4 Low-Probability Cue trials). No Cue practice trials were evenly divided between two target-present and two target-absent trials. However, all High-Probability Cue practice trials were target-present, while all Low-Probability Cue practice trials were target-absent with the goal of reinforcing the association between each tone cue and target likelihood.

3.2 RESULTS

All participants showed perfect tone-discrimination accuracy both before and after the experiment.

Search Accuracy.

Search accuracy was examined in a 3 (Cue Type: High-Probability, Low-Probability, No Cue) x 2 (Trial Type: Target-Present, Target-Absent) repeated measured ANOVA. A marginal effect of Trial Type was observed, $F(1, 104) = 3.70$, $p = .057$, $\eta_p^2 = .034$, as well as reliable interaction, $F(1.604, 166.79) = 5.05$, $p = .012$, $\eta_p^2 = .046$. As shown in Figure 6, the interaction

[3] Note that 100% valid cues were not ideal in the present design as observers could disengage from the RSVP search when cued and potentially monitor the periphery for probes. Highly reliable cues (87.5%), however, informed participants how to efficiently allocate their attention in preparation for the upcoming search trial without highlighting the correct search response.

revealed higher search hits on target-present trials in which High-Probability cues were presented (*M* = .92, *SE* = .01), followed by No Cues (*M* = .90, *SE* = .01) and lastly by Low-Probability cues (*M* = .86, *SE* = .02), all *p*s < .05 (see Figure 9). In contrast, correct rejections in target-absent trials were lower when High-Probability cues (*M* = .86, *SE* = .02) were presented relative to both Low-Probability cues (*M* = .94, *SE* = .01), *p* = .014, and No Cues (*M* = .93, *SE* = .01), *p* < .001.

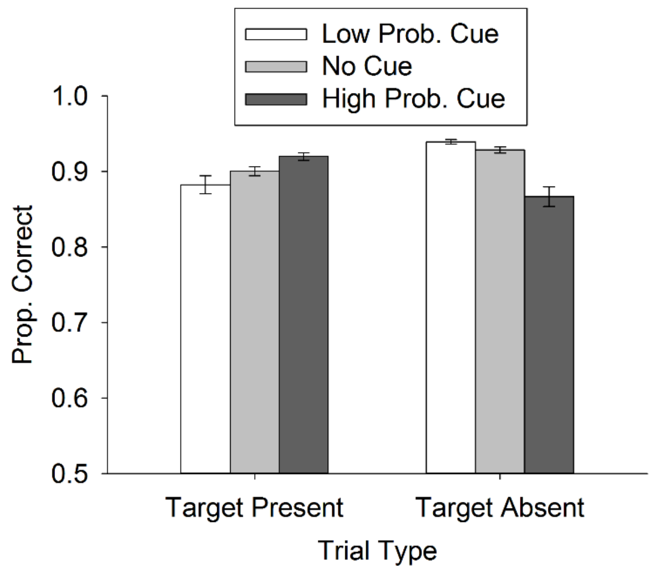

Figure 6. Search accuracy in Experiment 2. Error bars represent ± 1 SEM. The y-axis begins at chance.

As in Experiment 1, signal detection measurements were also calculated. However, no effect of Cue Type was observed on either *d'*, $F(1.87, 186.72) = .595$, $p > .250$, $\eta_p^2 = .006$, or *c*, $F(1.64, 166.09) = .203$, $p > .250$, $\eta_p^2 = .002$, although Low-Probability cues numerically produced a more conservative bias (*M* = .07, *SE* = .05) than No cues (*M* = .06, *SE* = .05) and High-Probability cues (*M* = .02, *SE* = .04).

Peripheral Probe Detection.

The proportion of correct peripheral probes detected was analyzed in a 3 (Cue Type) x 2 (Probe Distance) repeated measures ANOVA. No reliable main effects, or interaction, were observed (see Figure 7, left panel).

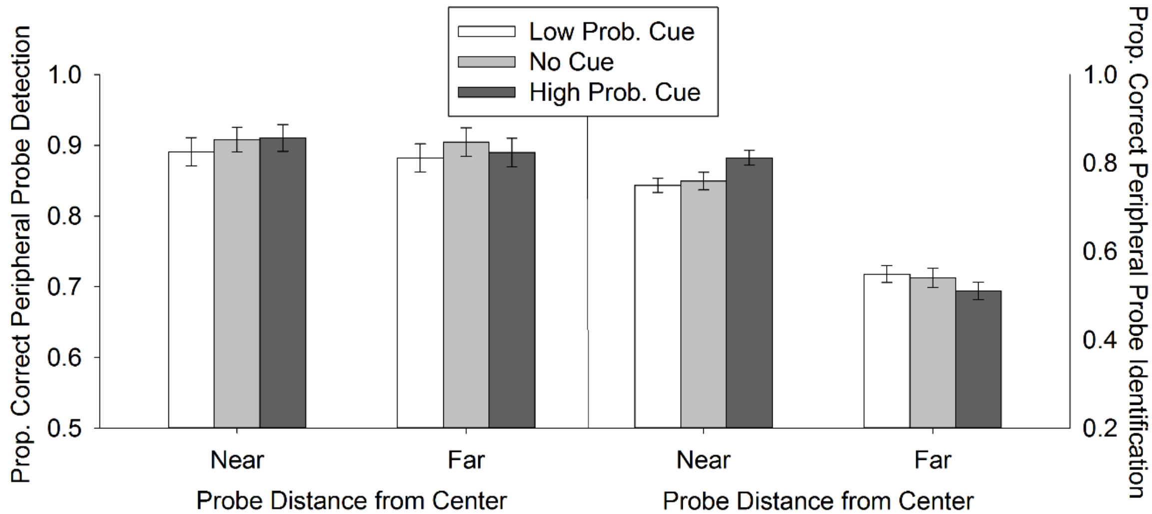

Figure 7. Peripheral probe detection (left panel) and identification (right panel) in Experiment 2. Error bars represent ± 1 SEM. The y-axes begin at chance.

Peripheral Probe Identification.

A 3 (Cue Type) x 2 (Probe Distance) repeated measures ANOVA revealed main effects of Cue Type, $F(1.86, 193.82) = 5.41$, $p = .006$, $\eta_p^2 = .049$, and Probe Distance, $F(1, 104) = 262.23$, $p < .001$, $\eta_p^2 = .716$, and a reliable interaction, $F(1.87, 194.35) = 5.20$, $p = .008$, $\eta_p^2 = .048$. As in Experiment 1, overall probe identification decreased when probes were presented far ($M = .54$, $SE = .02$), relative to near ($M = .78$, $SE = .02$) the central RSVP stream, $p < .001$. However, the interaction showed that the effect of Cue Type was only reliable when probes were presented *near* the center: Probe identification increased following a High-Probability cue ($M = .81$, $SE = .02$) relative to Low-Probability cues ($M = .74$, $SE = .01$), $p < .001$, and No cues ($M = .75$, $SE = .02$), $p = .018$. Low-Probability cues and No cues were not significantly different from

each other, $p > .250$. No differences across cue types were observed when probes were presented far from the central RSVP stream (see Figure 7, right panel), although High-Probability cues yielded numerically lower identification rates (*M* = .52, *SE* = .02) than Low-Probability cues (*M* = .55, *SE* = .02), $p > .250$. This pattern of results differs from the one observed in Experiment 1, but it is still suggestive that the FVF is modulated by target expectations: When observers were cued to expect a search target, the FVF narrowed, increasing processing adjacent to the RSVP stream. Conversely, when cued not to expect a target, the FVF increases in size, losing resolution within it and limiting processing of probes presented near the RSVP stream.

3.3 DISCUSSION

Experiment 2 tested whether externally-cued target expectations impact the size of the FVF. Based on the results of Experiment 1, it was predicted that when observers expected a target to be present in the upcoming trial, they would adopt a smaller FVF, thereby improving item processing and target detection. Narrowing the FVF would also cause them to be less likely to identify distant probes. While the Cue Type x Probe Distance interaction for probe identification was reliable, the results showed that observers were more likely to identify peripheral probes presented *near* the central RSVP stream when they expected a search target to appear. Although this pattern of results was not explicitly predicted, it nevertheless supports the hypothesis that expectations modulate the FVF, as High-Probability cues directed attention towards the central RSVP stream and improved nearby probe identification.

It is possible that using external cues to alter observers' expectations may have also altered the *subjective* experience of the search task by prompting them to "check" whether the cues were valid. For instance, observers may have adopted a generally smaller FVF than observers in Experiment 1, facilitating close inspection of the RSVP stream to determine the

relative validity of the cues (as they were not 100% valid). Such a small FVF may have impaired overall identification peripheral probes far from the center search task, regardless of Cue Type. Indeed, relative to Experiment 1, observers in Experiment 2 were, on average, 6% less likely to identify probes presented *far* from the center, $t(197) = 2.58$, $p = .011$, but did not reliably differed from observers in Experiment 1 in identifying probes near the central RSVP, $p = .07$. This suggests that perhaps the use of external cues may have unintentionally produced a smaller FVF in Experiment 2, limiting observers' ability to process probes far from the central search stream and thus occluding any effect of Cue Type at this level of eccentricity.

Nonetheless, the present findings have two important implications. First, they again indicate that the ease of target detection is not the only factor capable of influencing the FVF, as described by Hulleman and Olivers (2017). Importantly, the FVF framework assumes that changes in the FVF size are a result of the demands of the search task itself, rather than within observer's control. Here we find that the FVF is altered prior to the onset of the search task, based on external cues influencing observers' expectations of target likelihood. Second, and more relevant to the present investigation, they suggest that observers' expectations can directly impact the FVF. This provides a testable, explanatory mechanism for why the FVF was reduced in size during high-prevalence searches in Experiment 1. It is hypothesized that under high-prevalence conditions, observers incidentally learn to expect a target on any given trial, thus adopting a narrow FVF in order to more easily detect the upcoming target, even if detection is not as difficult as in low-prevalence conditions.

CHAPTER 4. EXPERIMENT 3: CONTRASTING TARGET PREVALENCE WITH TARGET EXPECTATIONS

The goal of Experiment 3 was to evaluate whether the effect of target prevalence on the FVF observed in Experiment 1 was due to different expectations of target likelihood across prevalence conditions. To test this, the modulating effects of *learned* and *cued* expectations on the FVF size were compared. Previous research has demonstrated that observers develop internal estimates of target prevalence throughout a search task based on direct experience, which are independent from expectations produced by external cues (Godwin et al., 2016). Although external cues do not override internal expectations to mitigate the elevated miss rates observed in low-prevalence conditions, they have a strong impact on other search behaviors. For instance, Lau and Huang (2010) examined RTs in low-prevalence search. They cued participants to whether the current trial had a high- or low-likelihood of being target-present, while keeping the actual target prevalence constant throughout the search block. The results showed that high-likelihood cues slowed down search RTs in target-absent trials, suggesting that participants searched more exhaustively when they expected a target. Ishibashi et al. (2012) found a similar effect in the opposite direction: When participants were cued *not* to expect a target during high-prevalence conditions, search RTs were shorter than when observers held no expectations about target likelihood.

That expectations affect search times (Ishibashi et al., 2012; Lau & Huang, 2010) suggests that observers' expectations may influence the "selection" component of the Multiple-Decision Model of visual search (Wolfe & Van Wert, 2010). Specifically, when targets are expected, observers may increase their quitting-threshold to exhaustively search, item-by-item. When targets are not expected, they may decrease that threshold, and instead globally "scan" the display. These effects on the selection stage do not necessarily impact the item identification

criterion (recall that the MDM proposes that each scrutinized item is subject to a 2-AFC decision about its status as a potential target). For example, Godwin et al. (2016) found that expecting a target increased search RTs, but did not affect verification times once targets were fixated. This suggests that the identification criterion may require direct experience, rather than top-down expectations, to be affected.

Experiment 1 established that FVF size is affected by accumulated task experience, and Experiment 2 established that FVF size is also affected by externally-cued expectations. Experiment 3, therefore, sought to explore how FVF may be impacted by the congruency between cued expectations and expectations accumulated via direct experience. That is, if the effect of target prevalence on FVF is due to learned expectations of target-likelihood, it is possible for external cues to be redundant with target prevalence, limiting their effect on the FVF. For example, high-probability cues may not be very effective under high-prevalence conditions, as observers may have already adopted a small FVF based on their previous experiences in the search task. On the other hand, if observers rarely encounter targets throughout the task, but are cued to expect a target in the upcoming trial, they may adopt a small FVF. This effect is predicted based on research showing that increasing target expectations in low-prevalence search increases search times (e.g., Ishibashi et al., 2012; Lau & Huang, 2010).

Specifically, it is predicted that high-probability cues should only reduce the size of the FVF, impacting peripheral processing, when observers are not already expecting the target to be present. As such, high-probability cues should only affect participants in the low- and medium-prevalence conditions; high-prevalence conditions should be unaffected. Similarly, observers should naturally adopt a larger FVF in low-prevalence conditions, making low-probability cues redundant and thus ineffective at modulating the FVF. At medium- and high-prevalence,

however, low-probability cues should impact the perception of peripheral probes. A reliable three-way interaction between Target Prevalence, Cue Type, and Probe Distance would support these predictions.

4.1 METHOD

Participants.

One hundred and fifty-five undergraduate students[4] (M_{age} = 19.21 years, SD = 1.39; 101 women) were recruited from the Psychology Department subject pool of Louisiana State University. Participants received partial course credit for their participation.

Stimuli.

The search stimuli, peripheral probes, and cue tones were the same as those used in Experiment 2. Experimental procedures were be controlled using E-Prime 2.0 (Psychology Software Tools, 2006).

Procedure.

The procedure was similar to Experiment 2. Participants completed three blocks of trials (25%, 50%, and 75% target prevalence), each including 42 transition trials and 120 experimental trials. Block order was counterbalanced across participants. Target probability cues were manipulated within each block, with an equal number of trials using High-Probability and Low-Probability Cues (24 trials each). The remaining experimental trials in each block were No Cue trials (72 trials; see Table 1 for a breakdown of the trial distribution)[5].

[4] The sample size for Experiment 3 was increased relative to the previous experiments with the goal to increase statistical power, given that a third variable was added to the experimental design, reducing the total number of observations per cell.

[5] This trial distribution rendered both cues (High- and Low-Probability Cues) as 87.5% valid across all blocks regardless of the actual prevalence of any block.

Table 1. Experimental trial break-down per Cue Type for Experiment 3.

Block Target-Prevalence	Trial Type	Experimental Trial Count Total	Cue Type	Cue Type Count
25%	Target-Present	30 trials	High-Probability	21
			Low-Probability	3
			No Cue	6
	Target-Absent	90 trials	High-Probability	3
			Low-Probability	21
			No Cue	66
50%	Target-Present	60 trials	High-Probability	21
			Low-Probability	3
			No Cue	36
	Target-Absent	60 trials	High-Probability	3
			Low-Probability	21
			No Cue	36
75%	Target-Present	90 trials	High-Probability	21
			Low-Probability	3
			No Cue	66
	Target-Absent	30 trials	High-Probability	3
			Low-Probability	21
			No Cue	6

Presentation of peripheral probes was also manipulated within blocks, with probes presented in a random subset of 25% of experimental trials (30 trials per block). Therefore, 10 experimental trials per Cue Type included a peripheral probe, equally and randomly presented near and far from the central RSVP stream (15 trials per eccentricity). Participants first completed the 6 trials of the tone discrimination task (3 per tone) and then practiced 12 search trials (4 No Cue, 4 High-Probability Cue, and 4 Low-Probability Cue trials). No Cue practice trials were evenly divided between two target-present and two target-absent trials. All High-Probability Cue practice trials were target-present trials, while all Low-Probability Cue practice

trials were target-absent. The overall target prevalence of the practice trials was 50% regardless of the prevalence of the first block. At the end of the experiment, participants completed six more trials of the tone discrimination task.

4.2 RESULTS

Prior to data analyses, four participants were dropped for failing to report detecting any peripheral probes throughout the search task. All remaining participants showed perfect tone discrimination accuracy both before and after the experiment.

Search Accuracy.

Search accuracy was examined in a 3 (Target Prevalence: Low, Medium, High) x 3 (Cue Type: High Probability, Low, Probability, No Cue) x 2 (Trial Type: Target-Present, Target-Absent) repeated measured ANOVA on the proportion of correct trials. Main effects of Trial Type, $F(1, 150) = 53.66$, $p < .001$, $\eta_p^2 = .263$, and Cue Type, $F(2, 300) = 10.16$, $p < .001$, $\eta_p^2 = .063$, were observed, as well as a trending effect of Target Prevalence, $F(2, 300) = 2.82$, $p = .061$, $\eta_p^2 = .018$. The effect of Trial Type revealed better performance during Target Absent trials (*M* = .93, *SE* = .003) relative to Target Present trials (*M* = .89, *SE* = .006). The other main effects are interpreted within the context of a reliable Target Prevalence x Trial Type interaction, $F(1.84, 275.87) = 4.26$, $p = .018$, $\eta_p^2 = .028$, a Cue Type x Trial Type interaction, $F(1.81, 271.89) = 14.46$, $p < .001$, $\eta_p^2 = .088$, and a reliable three-way interaction, $F(3.53, 528.83) = 3.39$, $p = .013$, $\eta_p^2 = .022$. As shown in Figure 8, as target prevalence increased, participants were better able to correctly respond "target present" and less able to correctly respond "target absent." Similarly, hits increased during target-present trials when observers received a High-Probability cue (*M* = .89, *SE* = .007) or No Cue (*M* = .88, *SE* = .006) as opposed to a Low-Probability cue (*M* = .84, *SE* = .02), both *p*s < .001. However, search hits between High-Probability cues and No cues only

differed in the low target prevalence block, *p* = .004, indicating that when observers were not readily expecting a target to be present, High-Probability cues improved target detection. Comparatively, in the high-prevalence block, where observers were already expecting targets, High-Probability cues were redundant and thus less effective. During target-absent trials, performance did not reliably differ across Cue Types regardless of Target Prevalence.

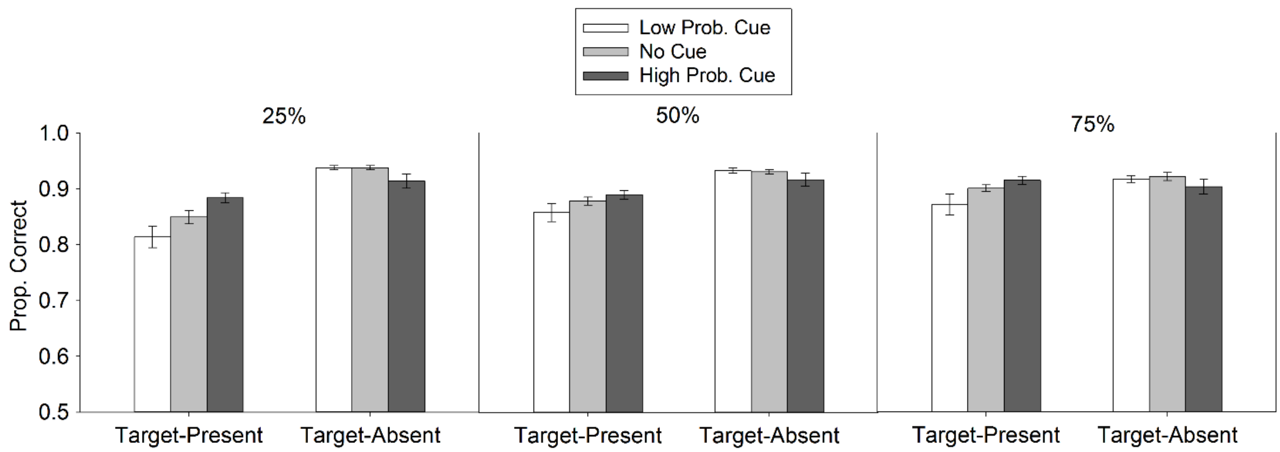

Figure 8. Search accuracy in Experiment 3. The left panel indicate the results for the low-prevalence block, the middle panel indicate the results for the medium-prevalence block, and the right panel indicate the results for the high-prevalence block. Error bars represent ± 1 SEM. The y-axis begins at chance.

Additionally, a main effect of Cue Type on *d'* was observed, $F(2, 300) = 30.08$, $p < .001$, $\eta_p^2 = .167$, indicating lower sensitivity in trials with No cues ($M = 3.19$, $SE = .08$) relative to trials cued by both High- ($M = 3.8$, $SE = .11$) and Low-Probability cues ($M = 3.67$, $SE = .10$), both *p*s < .001. No differences in sensitivity between High- and Low-Probability cues was observed, $p > .250$. As for *c*, a main of Cue Type was also observed, $F(1.85, 2.76.97) = 66.68$, $p < .001$, $\eta_p^2 = .31$, and interpreted in the context of a reliable Target Prevalence x Cue Type interaction, $F(3.63, 543.95) = 9.26$, $p < .001$, $\eta_p^2 = .058$. When No cues were presented, a conservative bias was observed during the low- ($M = .11$, $SE = .04$) relative to the high-prevalence block ($M = -.21$, $SE = .04$), $p < .001$, replicating the results from Experiment 1.

Response bias also differed from medium-prevalence (*M* = -.06, *SE* = .03) relative to the high-prevalence block, $p < .001$, and but not from the low-prevalence block, $p = .067$. Comparatively, a more conservative bias was observed in both the high- (*M* = .30, *SE* = .06) and medium-prevalence blocks (*M* = .22, *SE* = .03) relative to the low-prevalence block (*M* = .07, *SE* = .04) on trials were Low-Probability cues were presented, both *p*s < .001. No differences in bias were observed across prevalence blocks when High-Probability cues were presented, all *p*s > .250.

Peripheral Probe Detection.

As with the previous experiments, analyses for detection of peripheral probes were limited to trials in which correct search responses were made. The proportion of correct peripheral probes detected was analyzed in a 3 (Target Prevalence) x 3 (Cue Type) x 2 (Probe Distance) repeated measures ANOVA. Only a main of Probe Distance was observed, $F(1, 150) = 7.738$, $p = .007$, $\eta_p^2 = .047$, which revealed that peripheral probe detection decreased when probes were presented far (*M* = .88, *SE* = .02) relative to near (*M* = .90, *SE* = .01) the central search stream, $p = .002$.

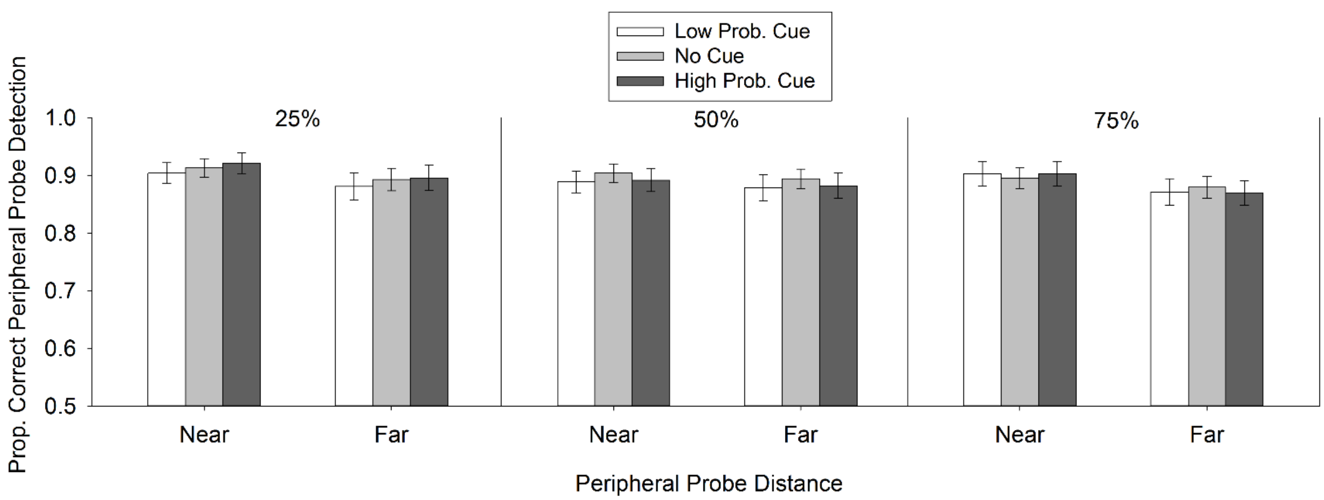

Figure 9. Peripheral probe detection in Experiment 3. The left panel indicate the results for the low-prevalence block, the middle panel indicate the results for the medium-prevalence block, and the right panel indicate the results for the high-prevalence block. Error bars represent ± 1 SEM. The y-axis begins at chance.

Peripheral Probe Identification.

A 3 (Target Prevalence) x 3 (Cue Type) x 2 (Probe Distance) repeated measures ANOVA revealed main effects of Target Prevalence, $F(2, 300) = 3.70$, $p = .026$, $\eta_p^2 = .024$, Cue Type, $F(1.82, 273.39) = 3.19$, $p = .047$, $\eta_p^2 = .021$, and Probe Distance, $F(1, 150) = 225.45$, $p < .001$, $\eta_p^2 = .60$. As expected, probe identification was lower when probes were presented far (*M* = .53, *SE* = .02) relative to near (*M* = .74, *SE* = .02) the central stream, $p < .001$. Probe identification was also lower during the high-prevalence block (*M* = .61, *SE* = .02) relative to both the medium- (*M* = .65, *SE* = .01) and low-prevalence blocks (*M* = .65, *SE* = .02), $p = .007$ and $p = .027$, respectively. Target Prevalence and Probe Distance did not interact. As in Experiment 2, the effect of Cue Type revealed better probe identification following High-Probability cues (*M* = .65, *SE* = .02) than Low-Probability cues (*M* = .62, *SE* = .02), $p = .017$, although no Cue Type x Probe Distance or Cue Type x Target Prevalence interactions were observed. The three-way interaction was also not reliable.

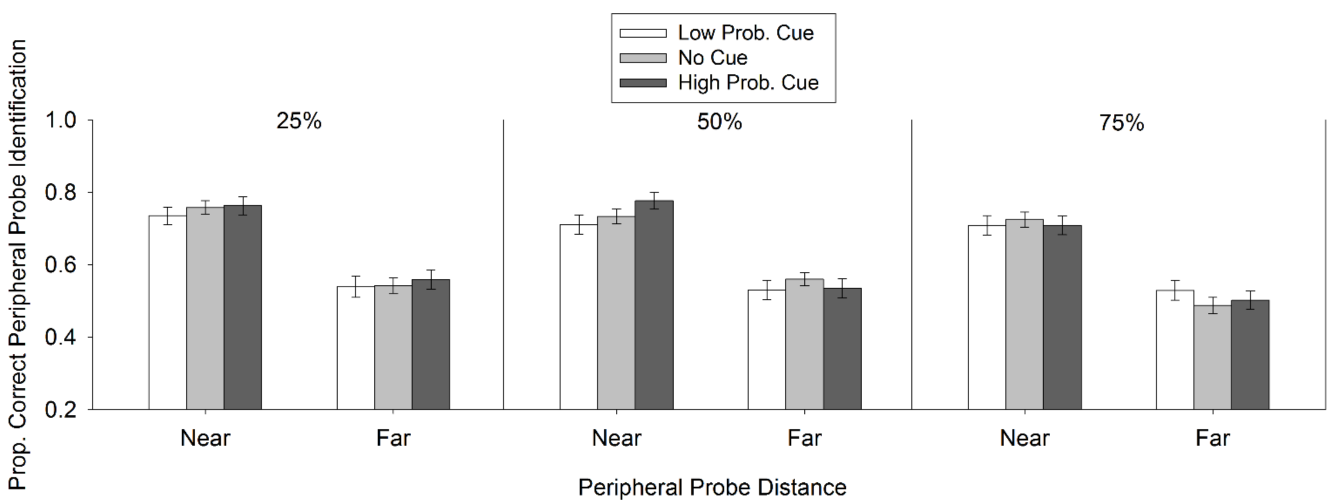

Figure 10. Peripheral probe identification in Experiment 3. The left panel indicate the results for the low-prevalence block, the middle panel indicate the results for the medium-prevalence block, and the right panel indicate the results for the high-prevalence block. Error bars represent ± 1 SEM. The y-axis begins at chance.

4.3 DISCUSSION

The goal of Experiment 3 was to test whether target prevalence modulates the size of the FVF by influencing observers' expectations of target likelihood. Observers searched across three blocks of trials, each with varying target prevalence (i.e., 25%, 50%, and 75%), while cues indicating both a high, and low, target-probability were presented within each block. Moreover, observers were again tasked to detect and identify probes in their periphery, and it was predicted that the impact of cues on the FVF size would depend on their congruency with observers' learned expectations: High-probability cues would be ineffective in reducing the FVF (i.e., increase perception of peripheral probes near the center, decrease perception of probes far away) during the high-prevalence block, where observers learn to expect targets. Similarly, low-probability cues would be not influence probe-processing during the low-prevalence block, where observers learn not to expect a target on most trials. The results, however, do not support this prediction. Instead, the cues influenced identification of peripheral probes across prevalence blocks. Moreover, target prevalence also influenced identification of probes, with the high target prevalence block yielding the lowest peripheral probe identification rate, regardless of the type of cue presented. This pattern of results indicates that the effects of target prevalence and cue type on the FVF occurred independent of each other.

Replicating Experiment 1, observers in Experiment 3 were less likely to identify probes during the high-prevalence condition, but this effect did not interact with the effect of probe distance. In post-hoc analyses restricted to No Cue trials (consistent with the design of Experiment 1), the Target Prevalence x Probe Distance interaction trends in the predicted direction, $F(2, 300) = 2.55$, $p = .078$, $\eta_p^2 = .017$, with lower identification rates for far-away probes in the high-prevalence condition ($M = .49$, $SE = .02$) relative to both the low- ($M = .54$,

SE = .02) and medium-prevalence conditions (*M* = .56, *SE* = .02), *p* = .026 and *p* = .001, respectively. No differences were observed in trials where probes were presented near the central RSVP, all *p*s > .250, consistent with the pattern of results observed in Experiment 1. The effect of target prevalence on probe identification did not interact with cue type either, indicating that it may not be caused by target expectations.

Previous work has demonstrated that although target expectations do not impact miss rates in conditions of uneven prevalence (e.g., 25% and 75%), they reliably influence search RTs at various levels of target prevalence (Godwin et al. 2016; Ishibashi et al., 2012; Lau & Huang, 2010). However, cued expectations strongly affected target detection in this experiment, such that high-probability cues improved detection of RSVP targets, particularly in the low-prevalence condition. As in Experiment 2, when observers were cued to expect a target, they were also more likely to identify peripheral probes, relative to when they were cued *not* to expect a target. While this may suggest a larger FVF following high-probability cues, the effect of cue type on peripheral identification seems to be limited to the medium-prevalence (50%) condition, particularly when probes were presented near the center (see Figure 12). Although the three-way interaction was not reliable, this pattern of results is consistent with the one observed in Experiment 2: At 50% target-prevalence, expecting a target improves processing near the attended location, facilitating perception of both, search targets and peripheral probes.

Overall, Experiment 3 replicates the general patterns of results observed in the previous experiments, as both target prevalence and cued target expectations impacted the identifications of peripheral probes. However, it seems that the modulating effects of target prevalence and target expectations on the FVF operate independent from each other. Specifically, when targets are frequently encountered in passive search tasks, the FVF decreases in size, limiting stimuli

processing in the periphery, relative to conditions were targets are rarely encountered. Comparatively, when observers are cued to expect a target in the search stream, their attention seem to narrow to improve detection of the likely target, incidentally improving detection of other nearby stimuli. It is important to also note that both effects seem to be relatively small: In Experiment 1, the effect size (i.e., η_p^2) for the reliable Target Prevalence x Probe Distance interaction on probe identification was .037, while the size of the Cue Type x Probe Distance interaction in Experiment 2 was .048. Such small effects may have not been able interactively modulate the FVF in Experiment 3.

CHAPTER 5. GENERAL DISCUSSION

The primary aim of the present investigation was to explore how the low-prevalence effect (LPE) (e.g., Godwin et al., 2015; Rich et al., 2008; Schwark et al., 2012; Wolfe et al., 2005, 2007) impacts cognition beyond inflating visual search miss rates. Particularly, the present study examined how target prevalence impacted the size of observers' functional viewing field (FVF) during a passive visual search task. The FVF is the area in a visual display where attention is directed and items are processed at higher resolution (Sanders, 1970; Young & Hulleman, 2013). Hulleman and Olivers (2017) recently proposed that the size of the FVF during visual search is strongly modulated by the difficulty of detecting targets: When targets are hard to find in the display, the FVF is reduced in size to closely examine the selected items and minimize interference from the periphery. Recent studies have supported this proposal (e.g., Drew et al., 2017; Guevara Pinto & Papesh, 2019), making it reasonable that any manipulations that reduce the detectability of targets may incidentally reduce the size of the FVF.

5.1 OVERVIEW OF PRESENT INVESTIGATION

In low-prevalence search, targets are more difficult to detect, even when directly fixated (Godwin et al., 2015; Hout et al., 2015; Peltier & Becker, 2016). This is thought to occur because low-prevalence conditions induce a conservative shift in the target identification criterion described by the Multiple-Decision Model of visual search (Wolfe & Van Wert, 2010). This shift in the identification criterion requires observers to gather greater evidence before deciding that a selected target is indeed the item they are searching for. Consequently, it was suggested that low-prevalence conditions should reduce the FVF size, relative to conditions where targets are frequent, to facilitate closer inspection of targets that are more challenging to identify. Menner et al. (2017) provided some support for such notion, demonstrating a stronger central fixation

tendency at the start of the search during high-, relative to low-, prevalence search. This was thought to be consistent with a narrow FVF when targets are rare. Yet, Papesh and Guevara Pinto (2019b) calculated the actual FVF size from fixation patterns and observed the contrary: High target prevalence produced a larger number of fixations, reducing the overall FVF size, relative to low-prevalence search. Such discrepancy in results could be explained by dynamic changes in the FVF as the search progressed (e.g., Itti, 2017; Kristjánsson et al., 2017), where observers adopt a wide FVF at the start of the search but subsequently reduce it to more closely examine a selected item.

The first goal of the present study was to clarify how target prevalence influences the FVF by controlling for on-line changes in FVF size. To accomplish this goal, Experiment 1 employed a paradigm designed to assess the relativ*e* size of the FVF while observers searched for target objects among real-world distractors in a rapid serial visual presentation task (RSVP; Guevara Pinto & Papesh, 2019). Specifically, observers were occasionally presented with peripheral probes during RSVP search for another object, and asked detect and identify them after the offset of the stream. These probes were presented either near or far from the central RSVP stream, and target prevalence was manipulated across three blocks of trials (25%, 50%, and 75% target-present). The results replicated the typical LPE observed in RSVP search (Hout et al., 2015; Peltier & Becker, 2016) and demonstrated that observers' ability to identify peripheral probes decreased as target prevalence increased, but only if probes were presented far from the RSVP stream. These results were consistent with those of Papesh and Guevara Pinto (2019b), indicating that high target prevalence reduces the FVF size during passive visual search. However, they are in contrast with the predictions from the FVF framework (Hulleman & Olivers, 2017; see also Meneer et al., 2017), as the FVF is larger during low-, relative to high-,

prevalence search, despite targets being more difficult to detect when target prevalence decreases.

Experiments 2 and 3 were designed to explore the mechanisms that allow target prevalence to modulate the FVF. Previous work on target prevalence has demonstrated that observers incidentally learn the statistical regularities with which targets are presented in search tasks (e.g., Godwin et al., 2016). It was predicted that, if observers learn to expect targets on most trials during high-prevalence conditions, then it is possible that they “narrow” their attention when targets are frequent, reducing the FVF in preparation to closely examine each item in the search set and more easily detect the target. Experiment 2 examined whether expecting a target in a given trial reduced the FVF. The design was similar to that of Experiment 1, except that target prevalence was consistently 50% across search blocks and observers were given pre-trial auditory cues indicating the likelihood (high vs low) of encountering a target in that trial. The results showed that high-likelihood cues improved target detection and increased the identification of peripheral probes presented near the search stream. These results support the hypothesis that expecting targets reduces the FVF, although the pattern of results differs from that observed in Experiment 1. Whereas the effect of target prevalence on peripheral probe identification in Experiment 1emerged only in trials with far away probes, the effect of external cues in Experiment 2 impacted probe identifications in trials where probes were presented near the center. It is possible that this discrepancy is due to observers adopting a smaller FVF, overall, in Experiment 2 than in Experiment 1. This might have been unintentionally caused by the validity of cues in Experiment 2: Both high- and low-probability cues were only 87.5% valid, which may have encouraged observers to adopt smaller FVFs to scrutinize the RSVP search stream and assess cue reliability. This type of behavior would be consistent with previous work

indicating that target cueing is not an all or nothing process but is graded proportionally to the reliability of cues (e.g., Cort & Anderson, 2013; Geng & Behramnn, 2005; Jonides, 1980), such that the benefit (in search times) for valid cues is reduced when cues are not 100%. Adopting a smaller FVF might have improved resolution near the RSVP stream, but limited observers' ability to perceive probes at the furthest distance, regardless of whether they were cued to expect a target (although probe identification at the furthest distance was numerically lower following high-probability cues). The pattern of results differed, yet the results of Experiments 1 and 2 seem to point toward a similar conclusion: The FVF size is reduced in size when targets are frequently encountered, or are likely to be encountered, limiting observers' ability to process visual information in their periphery.

The secondary goal of the present investigation was to understand *how* target prevalence impacts the FVF. Experiments 1 and 2 confirmed that high-prevalence conditions (or expectations) cause observers to adopt a small FVF, which narrows attention to the search stream and facilitates target detection. If observers employ this attention allocation strategy based on direct experience, then that would make the external cues used in Experiment 2 redundant in some situations. For example, cues indicating a high target-likelihood would be redundant with expectations learned in high target prevalence conditions. Experiment 3 was designed to test this prediction by directly contrasting the effects of target prevalence and cued expectations on FVF size. Observers searched through RSVP streams across three blocks of low, medium, and high target prevalence (25%, 50%, and 75%, respectively) while cues indicating high and low target-likelihood were randomly presented in subsets of trials intermixed with trials with no cues. Observers were again tasked with not only finding the target object but also detecting and identifying randomly-presented peripheral probes. Results generally replicated those observed in

Experiments 1, with peripheral probe identification decreasing at far distances during high-prevalence conditions, as well as those in Experiment 2: Higher probe identification at short distances following high target-likelihood cues. However, these two effects failed to interact with one another. Specifically, it was predicted that cued expectations would only be effective in impacting processing of peripheral probes if they were not redundant with the expectations learned throughout the task (i.e., target prevalence). The results showed that both main effects of prevalence and cued expectations observed in Experiment 3 were similar in size ($\eta_p^2 = .026$ and $\eta_p^2 = .021$, respectively), suggesting that they were equally effective at impacting identification of peripheral probes. Yet this seem to indicate that they both operate independent from each other, making it unclear whether the influence of target prevalence and external cues on observers' field of view arise from the same underlying mechanism.

5.2 THEORETICAL IMPLICATIONS AND FUTURE DIRECTIONS

The present investigation demonstrated that target prevalence influences the size of observers' functional viewing field (FVF), emphasizing the pervasiveness of prevalence effects across various stages in cognitive processing. The results from Experiment 1 showed that when targets are frequently found in visual search, observers are less able to process information presented far in their periphery, relative to search conditions in which targets are rarely found. A similar pattern of results emerged in Experiment 3, indicating that high-prevalence conditions narrow the FVF to facilitate target detection. In addition, Experiment 2 demonstrated that target expectations also modulate the FVF, such that expecting a target on a given trial narrows attention to improve target detection.

These results carry strong implications for the recent FVF framework of visual search (Hulleman & Olivers, 2017), as they indicate that multiple factors may impact the size of the

FVF. Mainly, high target prevalence and expectations of high target likelihood reduce the FVF size, although target detection is easier when targets are frequent as well as when they are expected. Reducing the size of the FVF has been thought to be a functional response that improves target detection (Young & Hulleman, 2013) by minimizing interference produced from parallel processing in the periphery and (or) increasing processing resolution at the attended region. The present study examined the relative size of the FVF by measuring observers' ability to process probes presented near the central RSVP search stream and far away in the periphery. Interestingly, high target prevalence decreased identification of probes presented *far* from the center, while high target-probability cues increased probe identifications *near* the search stream. It is thus possible that target prevalence impacts the FVF by minimizing parallel processing in the periphery while cued expectations improve processing resolution where attention is directed. The FVF framework assumes that the processing resolution within the FVF is inherently dependent on the FVF size (e.g., higher resolution at smaller sizes), yet further research is required to determine whether both, size and resolution, can be impacted differently by diverse factors. It may be useful to consider how the different factors that influence the FVF are related to the mechanisms of attentional control. For instance, Awh, Belopolsky, and Theeuwes (2012) proposed a trichotomy in attentional control, one where selective attention is influenced by bottom-up processes (e.g., target discriminability), top-down goals (e.g., target expectations), and past selection history (e.g., target prevalence). This view has received considerable support (e.g., Anderson, 2016; Failing & Theeuwes, 2018; Wang & Theeuwes, 2018), with various studies demonstrating that all three mechanisms impact selective attention independently from one another. It is likely then that the FVF, a consequence of visual selective attention, is differentially impacted by these different mechanisms.

The FVF framework differs from other models of visual search (e.g., Duncan & Humphreys, 1989; Triesman & Gelade, 1980; Wolfe, 1994, 2007) by suggesting that the entire visual display is not processed in parallel from a single fixation, but instead parallel processing is limited to the size of the FVF. Additionally, it puts *ease* of target detection as the primary factor impacting the FVF size. Note that the results from the present study do not necessarily imply that Hulleman's and Olivers' framework of visual search is incorrect. On the contrary, they add to this view by suggesting that the ease of target detection is not the only factor capable of modulating the size (or resolution) of the FVF during search, but that the *frequency* and *likelihood* with which targets are detected also influences observers' visual field. Such findings open the possibility for the FVF to be susceptive to other types of manipulations, improving our understanding of how visual search, in general, is conducted. However, the results of the present investigation do highlight situations where target detection is easy and yet the FVF is reduced in size, implying that target detectability is not an absolute determinant of FVF size. Furthermore, while the present investigation indicates that observers may have some level of control over the size of the FVF, it is important to remember that the temporal dynamics of such control remain unknown. Do observers adjust the FVF before, at the beginning, or during, their search? Experiment 2 demonstrated that trial-by-trial changes in the FVF are possible, however, the present investigation limited transient changes during search by employing a task that did not require eye movements. Understanding if (and how) the FVF changes during search will provide a better understanding of the mechanisms that give rise to such changes, particularly those that are under the observers control.

Comparatively, the effect of target prevalence on behavior may not be within the observer's control or even awareness. Still, a smaller FVF in conditions where targets are

frequently encountered would be consistent with search profiles observed in low- and high-prevalence searches, where high-prevalence search typically yields longer target-absent RTs than low-prevalence search (e.g., Rich et al., 2007; Wolfe et al., 2005, 2007). These longer RTs are accompanied by more fixations around the display (e.g., Godwin et al., 2015; Peltier & Becker, 2016; Schwark et al., 2013). A smaller FVF would inherently require observers to make more fixations to find the target, consequently producing longer RTs, particularly if the target is not present in the display. The shorter search times associated with low-prevalence search have typically been discussed within the context of the Multiple-Decision Model of visual search (MDM; Wolfe & Van Wert, 2010). The MDM proposes that observers make two separate, yet simultaneous, decisions during visual search: Deciding whether a selected item is the target, and deciding when to stop searching. More specifically, as selected items are compared to a target identification criterion, a quitting signal accumulates towards a threshold that terminates the search (see Figure 1). Importantly, when target prevalence decreases, observers' quitting-thresholds also decrease, prompting searchers to quickly end the search even if the target has not yet been located. As a result, observers do not search exhaustively during low-prevalence conditions, but instead seem to do a "global" scan of the search array, making only a few, rapid fixations to process the entire display. This would be consistent with a broader spread of attention, or FVF, when targets are rare. The present investigation supports this, suggesting that the FVF is inversely related to target prevalence. At low-prevalence, a large FVF may be adopted, where observers process a greater number of items in the display, albeit at *lower* resolution (potentially increasing target misses through identification errors; e.g., Hout et al., 2015; Pelteri & Becker, 2016). At high-prevalence, conversely, the FVF is reduced but the resolution within is increased, potentially decreasing target identification errors.

Despite demonstrating a modulating effect of target prevalence on the FVF size, the present investigation was unable to determine the cause of such effect. It was hypothesized that observers adjust their FVF after they incidentally learn to expect (or not to expect) targets in the search task, narrowing attention only when targets are frequently found. However, the results of Experiment 3 did not support this prediction, indicating that target prevalence may impact the FVF through a different mechanism. While it would be easy to accept this conclusion, further research is required to understand what causes target prevalence to modulate the FVF, and whether learned expectations are completely irrelevant in this process. Still, the present investigation produced important implications for the MDM of visual search. First, it suggests the item selection process may be influenced by task parameters. Particularly, when target prevalence is uneven (e.g., 25% or 75%), item selection may not be as strongly guided by the target template across the *entire* display (Wolfe, 1994, 2007) as when target prevalence is even (50% target-present). Instead, item selection may be limited by the size of the FVF. For instance, at low-prevalence, selection may involve a global scan, where multiple items are processed in parallel as potential targets (see top panels, Figure 11). This would possibly widen the signal distribution for distractor items, as the variability in distractor-target similarity across items would increase, without impacting the target discriminability. This was recently suggested by Hulleman, Lund, and Skarratt (2020), who demonstrated that when search is conducted with a larger FVF, search performance is more likely to be affected by variance in distractor similarity, relative to conditions where a small FVF is adopted. Conversely, selection at high-prevalence may involve a more serial process, where every item in the display is closely examined, one-by-one until the target is found (bottom panels, Figure 11).

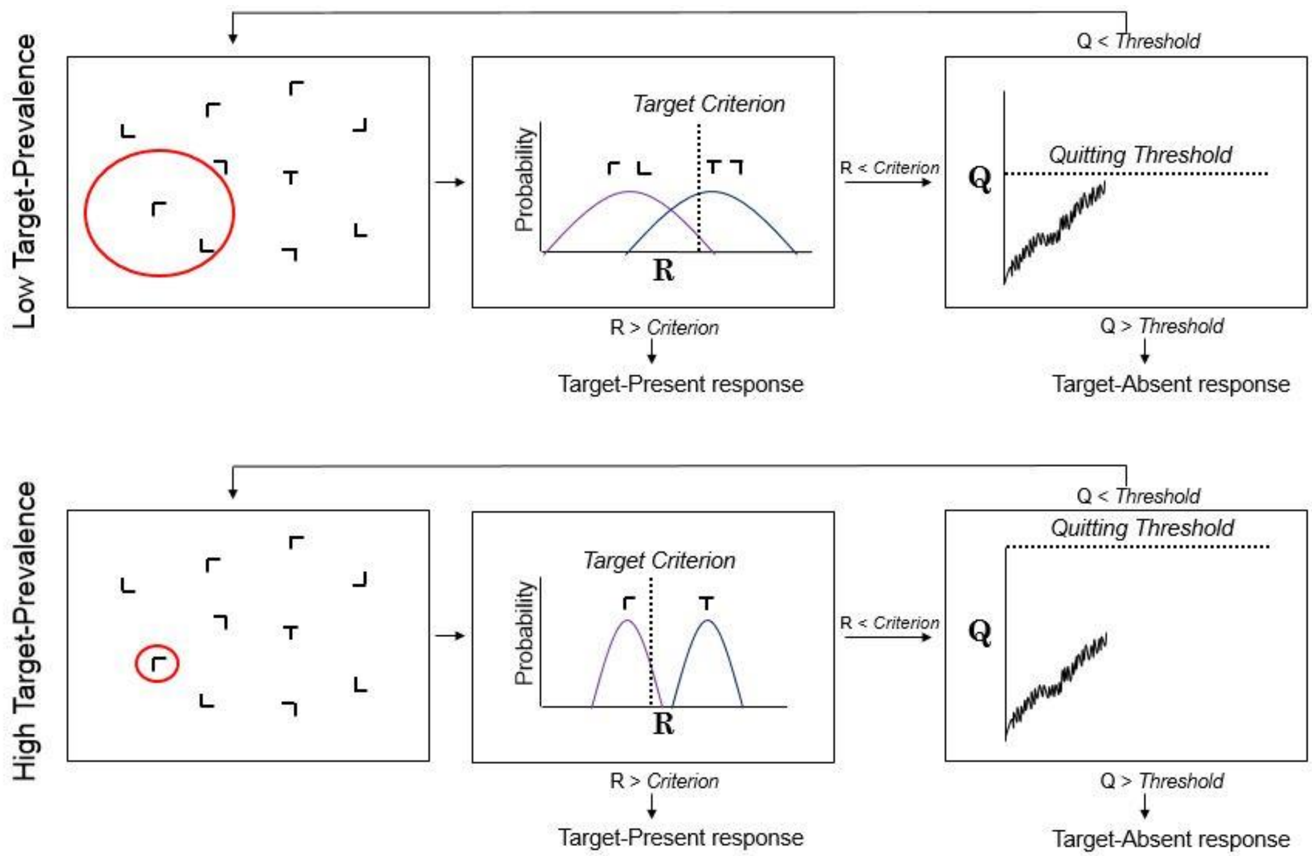

Figure 11. Modified Multiple-Decision Model of visual search with item selection varying as a function of low (top panels) and high (bottom panels) target prevalence levels.

Second, and more theoretically interesting, observers' quitting-thresholds and FVF may influence each other. When quitting-thresholds are lowered, observers are less likely to search exhaustively, and thus they may adopt a broader FVF to "cover" more items in shorter time. When quitting-thresholds are raised, however, observers may adopt a small FVF to search exhaustively across the display, ensuring that each item is closely examined. Therefore, the changes in the FVF size may be a functional response to changes in the observers' quitting-thresholds. However, the opposite could also be true: If the FVF is relatively large, observers may lower their quitting-thresholds as they may "feel" they are covering all items in the display from just a few fixations. Meanwhile, a small FVF would prompt observers to raise the threshold and search more exhaustively as only one or two items could be examined at a time. Whether

quitting-threshold impact the size of the FVF (or vice versa) is an interesting question, one that future studies should attempt to answer in order to clearly comprehend how visual search is conducted at various levels of target prevalence.

Lastly, the goal of studying low target prevalence in visual search has always been to use our theoretical understanding reduce elevated miss rates in applied domains, such as airport security screening (e.g., Wolfe et al., 2013) and radiology (e.g., Bird et al., 1990; Evans et al, 2013). The insights from the present investigation may help advance future research toward this goal. Low-prevalence search seems to be conducted with a wide spread of attention, potentially increasing both selection (e.g., Rich et al., 2007; Schwark et al., 2012; Wolfe et al., 2005, 2007) and target identification errors (e.g., Hout et al., 2015; Peltier & Becker, 2016) by lowering the processing resolution within the FVF or biasing observers to believe they have processed the entire display and thus prematurely stop searching. On the other hand, high-prevalence search may be reducing both types of errors by adopting a narrow FVF, improving item processing and encouraging exhaustive searches. To improve detection of rare targets, researchers could attempt to make the search behaviors at low-prevalence similar to those observed at high-prevalence. Specifically, by prompting observers to adopt a small FVF when targets are infrequent, it may be possible to reduce the elevated miss rates associated with low-prevalence. One way to do this could be to artificially limit observers' FVF using gaze-contingent windows during low-prevalence search similar to those employed by Young and Hulleman (2013). A gaze-contingent window would force observers to closely examine each item in the display and search more exhaustively, relative to normal "free" viewing conditions.

Implementing gaze-contingent windows in applied domains is unlikely, as it would require eye-trackers in many occupational settings. A much simpler alternative would be to bias

observers to adopt a *local* processing style. According to the *global precedence effect* (Navon, 1977; Poirel, Pineau, Jobard, & Mellet, 2008; Poirel, Pineau, & Mellet, 2009), observers naturally adopt a broad spread of attention, facilitating perception of holistic, or global, stimulus features over individual, or local, ones. However, observers can be biased to attend to local features using Navon's (1977) task, where a large percept, such a letter, is constructed from smaller, individual percepts and observers are tasked to respond to either the large (global processing) or small (local processing) percept while ignoring the other. Previous work using Navon's task to induce local processing styles have shown performance impairments on tasks that require holistic processing (e.g., Macrae & Lewis, 2002; Wen & Kawabata, 2018) while improving performance on tasks that benefit from featural processing (e.g., Weston & Perfect, 2005). Similarly, observers could perhaps be biased to adopt a local processing style, reducing the FVF, to attend to each individual item, rather than globally scanning the array, during low-prevalence search. Future studies should examine this possibility, as it would both provide an opportunity to mitigate miss rates in applied domains and expand our understanding how target prevalence influences cognitive processes.

5.3 CONCLUSION

In conclusion, the present investigation examined how target prevalence impacts the spread of attention during visual search, reflected in the relative size of the functional viewing field (FVF). The results showed that, relative to low-prevalence conditions, high-prevalence search decreased the size of the FVF. Expectations of target presence also modulated the FVF size. However, there was no evidence that target prevalence impacted the FVF through learned expectations, and further research is needed to determine what causes this effect. Nonetheless, these findings have strong theoretical implications for visual search models of target prevalence

(e.g., Van Wert & Wolfe, 2010) and attention allocation (e.g., Hulleman & Olivers, 2017), as both need to incorporate the negative relationship between target prevalence and the FVF. More generally, this investigation contributes to the increasingly diverse study of the low-prevalence effect (Evans et al., 2013; Horowitz, 2017; Ishibashi et al., 2012; Mitroff & Biggs, 2014; Papesh & Goldinger, 2014; Wolfe et al., 2005, 2007) by demonstrating that target prevalence may impact cognition in ways that move beyond elevated search miss rates.

APPENDIX A. INSTITUTIONAL REVIEW BOARD APPROVAL

ACTION ON EXEMPTION APPROVAL REQUEST

Re: **IRB#** E11793

LSU

Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu
lsu.edu/research

To: Juan Pinto
Psychology

From: Dennis Landin
Chair, Institutional Review Board

Date: August 6, 2019

Title: Leveling the Viewing Field: The Impact of Target-Prevalence on Searcher's Functional Viewing Field

New Protocol/Modification/Continuation: New Protocol

Review Date: 8/6/2019

Approved_____X_____ **Disapproved**___________

Approval Date: 8/6/2019 **Approval Expiration Date:** 8/5/2022

Exemption Category/Paragraph: 3a

Signed Consent Waived?: No

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable):

By: Dennis Landin, ____DLandin____ Chairman

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc. Approvals will automatically be closed by the IRB on the expiration date unless the PI requests a continuation.**

** All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX B. INFORMED CONSENT FORM

Approval #E11793 Exp. Date: 8/5/2022

Consent Form

1. Study Title: Leveling the Viewing Field
2. The purpose of this research project is to examine how people search for objects in a visual display while simultaneously attending to items in the periphery. Participants will search for a target object among a series of rapid images at the center of a computer screen, which may or may not be present. Additionally, participants will also be asked to detect different shapes in the periphery of the screen as they are conducting their search. The study session will take 60 minutes.
3. Risks: There are no more than minimal risks of harm involved in this study.
4. Benefits: The data from this study will further research on human perception.
5. Investigators: The following investigators are available for questions about this study, M-F, 8:00a – 4:30p: Dr. Megan Papesh (mpapesh@lsu.edu; 225-578-4138), Juan Guevara Pinto (jgueva3@lsu.edu; 225-578-4138)
6. Performance Site: Louisiana State University and Agricultural and Mechanical College
7. Number of subjects: 400
8. Subject Inclusion: Individuals between the ages of 18 and 65 with normal or corrected-to-normal vision and normal color vision.
9. Right to Refuse: Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.
10. Privacy: Results of the study may be published, but no names or identifying information will be included in the publication. Subject identity will remain confidential unless disclosure is required by law.
11. Signatures: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. For injury or illness, call your physician, or the Student Health Center if you are an LSU student. If I have questions about subjects' rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, or www.lsu.edu/research. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of this consent form.

Subject Signature: ____ Date ______________

The study subject has indicated to me that he/she is unable to read. I certify that I have read this consent form to the subject and explained that by completing the signature line above, the subject has agreed to participate.

Signature of Reader: ______________________________________ Date: ______________

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VITA

Juan D. Guevara Pinto, born in Tegucigalpa, Honduras, earned his Bachelor of Science degree in Psychology in 2014 from Georgia Southern University in Statesboro, Georgia. He then earned his Master of Arts degree in Psychology in 2017 from Louisiana State University in Baton Rouge, Louisiana. In May 2020, Juan is anticipating to graduate from Louisiana State University with his Doctor of Philosophy degree in Cognitive and Brain Sciences. His research interests focus on studying the interaction between attention and memory, examining how previous experience influence the deployment of attention but also how attention allocation impacts how information is encoded in memory.