Experience-guided Attention and Eye Movements: Coupled or Independent?

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Abstract

Daily activities often occur in familiar environments; locations that were important in the past remain significant in the future, making it crucial for us to fine-tune attention based on learning. Indeed, researchers have demonstrated that people can acquire an implicit spatial preference for locations that frequently contained a search target in the past (location probability learning), resulting in both faster response and more frequent eye movements toward those locations. In this dissertation, I presented three empirical studies that investigated experience-guided attention and its relationship with eye movements. Study 1 showed that location probability-guided attention is independent of goal-driven oculomotor control. Study 2 used eye tracking to restrict the visible regions to a location opposite from the fixation, necessitating saccades away from the attended locations. Participants still acquired an attentional preference toward the high-probability region, suggesting that the spatial alignment between attention and eye gaze is unnecessary for location probability learning. Study 3 examined the role of peripheral vision to learning. I simulated peripheral vision loss using gaze-contingent eye tracking. Results showed that implicit location probability learning was impaired in the absence of peripheral vision. Together, this dissertation provides evidence that experience-guided attention is a high-level process independent of oculomotor movements and is implicitly supported by peripheral vision.

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1. Introduction

The visual world around us is far more complex than what we can process at one time. Attention allows us to select important sensory input and ignore irrelevant input. Although it is possible to attend to an object without directly looking at it (i.e., via covert attention; Posner, 1980), visual selection is usually achieved by a sequence of eye movements that bring task-relevant information to the fovea. For example, when looking for Waldo in a photograph of a state fair, we may direct our eyes first to the hotdog stand, then to the amusement park, until we spot the hidden Waldo. The alignment of visual attention and eye movements raises an important question: what role do eye movements play in visual attention? The importance of eye movements in selection leads some researchers to propose that brain mechanisms underlying oculomotor movements also support visual attention (Rizzolatti et al., 1987). This *premotor theory of attention* is contrasted with *the modular theory of attention*, which postulates that attention is a high-level cognitive function detached from the oculomotor circuit (Posner & Dehaene, 1994).

This dissertation investigates one form of visual attention - experience-guided attention - particularly its relationship with eye movements, and its reliance on peripheral vision. Before embarking on the three empirical studies, I first review the relationship between visual attention and eye movements. Although several articles have reviewed this relationship (e.g., Hunt et al., 2019; Kowler, 1995; Smith & Schenk, 2012), those studies focused primarily on goal-driven or stimulus-driven attention. Increasing evidence has shown that visual attention has multiple drivers, including task goals, perceptual salience, and previous selection history (Addleman & Jiang, 2019; Awh et al., 2012; Theeuwes, 2019). A unique aspect of this dissertation is its focus on the relationship between eye movements and experience-guided attention. Unlike goal-driven attention, prior experience often guides attention implicitly, independent of the observer's task goals. These experience-related changes in attention emerge even though the physical salience of stimuli has not changed with experience, distinguishing experience-guided attention from stimulus-driven attention. These differences raise the possibility that experience-guided attention may interact with eye movements in unique ways, relative to goal-driven or stimulus-driven attention.

Following the introductory literature review, I will present three empirical studies. These studies examined one form of experienced-guided attention – location probability learning, a learned attentional preference for locations that frequently contained a search target in the past. I ask three questions. First, does looking away from high-probability target locations disrupt location probability learning? Second, can location probability learning persist when eye movements are forced away from the attended location? Third, what role does peripheral vision play in location probability learning? The final chapter of the dissertation discusses the theoretical implications of these findings and explores possible future research directions. I conclude that experience-guided attention represents a high-level process partially independent of oculomotor movements and that is implicitly facilitated by peripheral vision.

1.1 The tripartite model of attention

For decades, psychological and neuroscientific studies have emphasized two drivers of spatial attention: top-down goals and bottom-up stimulus salience (Egeth & Yantis, 1997). For example, when driving, we may voluntarily attend to the traffic lights because they are relevant to the task. We may also inadvertently attend to a bright neon billboard in our peripheral vision in a bottom-up manner. This dichotomy of attention between goal-driven (or voluntary, endogenous) and stimulus-driven (or involuntary, exogenous) attention not only accounts for behavioral findings in attentional cueing but also is supported by neuroscientific findings. Goal-driven attention relies primarily on the dorsal parietal regions, whereas stimulus-driven attention relies primarily on the ventral parietal regions of the brain (Corbetta & Shulman, 2002).

However, the dichotomous model of attention has left out an important third source of attention: previous experience. Locations that were important in the past tend to remain important in the future, making it possible to fine-tune attention based on learning. In the 1990s, some dichotomous models conceptually grouped previous experience with goal-driven attention (J. M. Wolfe, 1994), whereas other models grouped it with bottom-up attention (Desimone & Duncan, 1995). The theoretical uncertainty largely derives from the implicit (unconscious) nature of experience-guided attention. The tendency to search for people on the street rather than in the sky, for example, is often unconscious, distinguishing it from goal-driven attention. At the

same time, previous experience does not change the sensory salience of stimuli, making experience-driven attention distinct from bottom-up attention. With increasing evidence of experience-driven attention, researchers have replaced the dichotomous model of attention with a tripartite model. Experience-guided attention is considered a third driver of attention, encompassing multiple mechanisms related to reward, statistical learning, and cue-target association (Addleman & Jiang, 2019; Awh et al., 2012; Jiang, 2018; Theeuwes, 2019).

1.1.1 Goal-driven and stimulus-driven attention

The dichotomous model of attention postulates that spatial attention is either goal-driven, voluntarily directed toward important objects or locations, or stimulus-driven, involuntarily captured by physically salient stimuli. These two forms of attention are commonly assessed using the Posner cueing paradigm. In the endogenous cueing task, participants first view a "cue" that is typically a symbol presented at the center of the display. The cue, such as a left arrow, informs the participants about the probable location of the upcoming target stimulus (e.g., on the left side of the screen). After a variable stimulus onset asynchrony (SOA), the target stimulus appears either at the cued location ("valid" trials) or at a different location ("invalid" trials). Response time to the target's onset (detection task) or feature (discrimination task) is faster on valid trials than invalid trials, demonstrating goal-driven attention (Posner, 1980).

The exogenous cueing task is similar except for the nature of the cue. Instead of using a central symbolic cue, the exogenous cueing task typically flashes a bright stimulus in the visual periphery, triggering an involuntary shift of spatial attention to its location (Jonides, 1981; Posner & Cohen, 1984; Yantis, 1993). The cue is uninformative, meaning that it does not predict the target's location at above-chance levels. Nonetheless, at short SOAs between the cue and the target, participants are faster at responding to a target stimulus in the cued location than in other locations. This facilitatory effect at short SOAs typically changes into an inhibitory effect at longer SOAs. When the SOA between the peripheral cue and the target exceeds 500ms, participants are often slower responding to a target in the cued location than in a different location, demonstrating "inhibition of return" (Lupiáñez et al., 2006; Müller & Rabbitt, 1989; Posner & Cohen, 1984).

Although both the endogenous and exogenous cueing paradigms have revealed a cue validity effect, these cues yield characteristically different effects. First, within a given trial voluntary shifts of attention take longer to develop than involuntary shifts. Exogenous cueing produces a validity effect at SOAs as short as 100-120ms, but endogenous cueing takes 300ms or longer to develop (Cheal et al., 1991; Liu et al., 2007; Nakayama & Mackeben, 1989; Pinto et al., 2013; Remington et al., 1992). Second, endogenous cueing is effective only when the cue is predictive of the upcoming target location. Exogenous cueing, by definition, occurs when the cue is uninformative and it summons attention involuntarily (Pinto et al., 2013; Yeshurun & Carrasco, 1998). Third, inhibition of return occurs only in the context of exogenous cueing. It is not observed in endogenous cueing tasks (Peelen et al., 2004). These differences support the idea that different mechanisms subserve goal-driven versus stimulus-driven attention.

Research on visual search tasks has similarly distinguished between bottom-up and top-down search mechanisms. When a search target differs from distractors in a simple feature, such as finding a red rose among green leaves, the target "pops out" from distractors. Search is considered "parallel" (Treisman, 1988) or "efficient" (J. M. Wolfe & Gray, 2007), requiring little focal attention. In contrast, when the target differs from distractors in a combination of features, such as finding a red vertical line among red horizontal and green vertical lines, search is "serial" or "inefficient". The efficiency of search is indexed by the slope of the linear function relating RT to the number of items (set size) on the display. Whereas feature search tasks produce slopes under 10ms/item, conjunction search tasks yield much steeper search slopes, sometimes in the range of 100ms/item (J. M. Wolfe, 1998). The distinction between feature and conjunction searches corresponds roughly to stimulus-driven versus goal-driven attention.

Neuroimaging studies support the dichotomy of attention as stimulus- or goal- driven. Goal-driven attention activates the intraparietal sulcus, the superior parietal lobule, and the frontal eye fields, regions that comprise the dorsal attention network (Corbetta et al., 2000; Corbetta & Shulman, 2002; Hopfinger et al., 2000; Kastner et al., 1999). In contrast, stimulus-driven attention activates the temporal parietal junction and the ventral frontal regions that comprise the ventral attention network (Corbetta et al., 2000; Perry & Zeki, 2000). Multi-unit recordings in monkeys have placed electrodes simultaneously in several brain regions. By

examining the time course of neural activity (e.g., activation in the parietal cortex before the frontal cortex), these studies have sourced stimulus-driven attention to the lateral intraparietal area and goal-driven attention to the frontal eye fields (Buschman & Miller, 2007; Ibos et al., 2013).

Although it is meaningful to distinguish between stimulus- and goal- driven attention, these two forms of attention interact. Physically salient distractors capture attention, interfering with goal-driven attention (Theeuwes, 1992; Yantis & Jonides, 1990). Conversely, the potency of bottom-up capture of attention is contingent on whether the salient stimulus falls within a general task set. According to the "contingent capture" account (Folk et al., 1992), salient stimuli capture attention if they share some properties with what the observer is looking for. For example, when participants search for a unique color, a cue that contains a unique color tends to capture attention. Conversely, when participants wait for the presentation of a suddenly appearing target, a cue that contains a sudden onset tends to capture attention. Posner's exogenous cueing paradigm is an example of such contingent capture – the target is a sudden onset, so the sudden brightening of a stimulus, such as a peripheral box captures attention to trigger spatial orienting. To what degree salient stimuli capture attention involuntarily remains a heated debate (Luck et al., 2021).

1.1.2 Experience-guided attention

Traditionally, the dichotomous model of attention has considered one's previous experience as a form of top-down attention (J. M. Wolfe & Gray, 2007). The tendency to search for the microwave in the kitchen rather than the bedroom, for instance, is explained as reflecting top-down knowledge of where microwaves are typically found. However, observers are frequently unaware of using previous experience to modulate attentional allocation. Because experience-guided attention tends to affect search in an implicit manner, its impact on behavior is notably different from the more deliberate, goal-driven attention. This difference has led some researchers to place experience-guided attention in the camp of bottom-up influences. For example, Desimone and Duncan (1995) consider trial-by-trial repetition priming a form of bottom-up attention. To incorporate these and other forms of experience into models of attention,

more recent theories of attention consider experience to be a third driver of attention, complementing the influences of task goals and physical salience (Addleman & Jiang, 2019; Awh et al., 2012; Failing & Theeuwes, 2018; Jiang, 2018; Todd & Manaligod, 2018).

Among the most influential tripartite models of attention is the integrated priority map theory (Awh et al., 2012). This theory makes three claims. First, spatial attention is affected not only by task goals and physical salience, but also by previous experience. Second, experience-guided attention is an umbrella term that captures several learning-based attentional effects, including selection history, cue-target association, and reward learning. Third, regardless of the source of attention, all three drivers affect the weights assigned to locations on an integrated attentional priority map. Locations that receive the highest weights are prioritized, regardless of whether the weights come from task relevance, salience, or learning. As reviewed next, the first two claims of this theory have strong support, whereas the third claim is questionable.

1.1.2.1 Variety of experience-guided attention

Selection history refers to one's previous experience attending to certain locations or features. This experience tends to increase attentional priority for previously attended locations or features, and decrease attentional priority for previously ignored locations or features. An example of a short-term selection history effect is intertrial repetition priming. For example, participants in Maljkovic and Nakayama (1994, 1996) searched for a uniquely colored target among distractors and reported the shape of the target. Response was faster when the target on trial N had the same color as the target on trial N-1, a phenomenon known as intertrial feature priming. Likewise, response was faster when the target on trial N happened to be in the same location as the target on trial N-1, a form of intertrial location priming. Intertrial priming also applies to the repetition of distractors - repeating distractor features or locations reduces interference from these distractors (Kristjánsson & Driver, 2008). The effect is short-lived. The strongest intertrial priming comes from the immediately preceding trial. The effect dissipates rapidly as trial lag increases, becoming undetectable by 8 trials (Maljkovic & Nakayama, 1994, 1996). As noted earlier, although Desimone and Duncan (1995) consider this effect a form of

bottom-up attention, intertrial priming does not change the physical salience of stimuli and is better considered a selection history effect.

Selection history can also induce durable changes in attention, as demonstrated by location probability learning (LPL; Druker & Anderson, 2010; Geng & Behrmann, 2005, 2005; Jiang et al., 2013). In the standard LPL paradigm, participants search for a target T among distractor Ls and identify the target's orientation. Unbeknownst to them, the target is disproportionately likely to appear in one visual quadrant (e.g., 50% of the time) relative to the other quadrants (e.g., 16.7% of the time in each of the other three quadrants). Although most participants are unaware of the biased target distribution and cannot identify the high-probability quadrant, their search speed is faster when the target appears in the high-probability quadrant rather than in a low-probability quadrant (Jiang et al., 2013). Other studies have found that people can also learn to deprioritize locations that frequently contained a distractor in the past (Ferrante et al., 2018; Goschy et al., 2014; B. Wang & Theeuwes, 2018a).

Besides learning the target's location probability, participants can also acquire cue-target associations in visual search. An example of a cue-target association is contextual cueing (Chun & Jiang, 1998). In this paradigm, participants search for a T target among L distractors. Unbeknownst to them, some displays occasionally repeat. After just a few repetitions, participants become faster finding the target among repeated displays relative to nonrepeated ones (Chun & Jiang, 1998). In this paradigm, the spatial layout of distractors serves as the "cue", or context, for the target. Repetition allows participants to acquire associative learning between the distractor layout and the target. Contextual cueing does not occur when the spatial layout of a search display is repeated but the target's location is randomized, suggesting that emergence of contextual cueing relies on consistent associations within the search display, rather than just perceptual familiarity with the layout. Many cues can provide the context for the target, including repeated distractor shapes, the semantic category of distractor words, repeated motion trajectories of distractors, auditory cues, and temporal sequences (for a review, see Sisk et al., 2019). Similar to location probability learning, contextual cueing does not depend on the deliberate use of the cue. Participants often cannot identify repeated displays (Chun & Jiang, 1998, 2003). In fact, informing participants about the display repetition does not increase the size

of the effect, suggesting that the effect is largely independent of goal-driven attention (Chun & Jiang, 2003).

A third category of selection history effects is reward-driven attention. A well-known, though controversial, paradigm is value-driven attentional capture. In an early instantiation of this paradigm (Anderson et al., 2011), participants first searched for a target that could be either red or green among other colored distractors. Participants received a higher monetary reward for rapidly responding to the red target, and a lower reward for responding to the green target. Subsequently, they searched for a unique shape among other shapes, in the absence of monetary reward. In this testing phase, the distractor could be red, green, or other colors. The presence of a red distractor slowed participants more than did the presence of a green distractor, suggesting that a highly rewarded feature may capture attention. Although the literature has seen many reports of value-driven attentional capture (for a review, see Anderson, 2016), this effect is small in magnitude (typically 10ms or less when comparing high- and low- reward values) and not easily replicable. Some studies reported that features of previous search targets capture attention, regardless of monetary reward (Sha & Jiang, 2016).

Other studies have reported increased priority to locations previously associated with high monetary reward. In Chelazzi et al. (2014), participants searched for a target among distractors arranged in 8 locations around a circle. They received high, medium, or low monetary reward depending on the location of the target. Subsequently, when searching for two possible targets arranged in a circle, participants tended to find the target in the previously high-reward location first. This finding led Chelazzi et al. (2014) to propose that reward modulates the attentional priority map, such that highly rewarded locations receive greater priority in subsequent tasks. Unlike contextual cueing and location probability learning, however, the reward-based attentional effect of Chelazzi et al. (2014) appears to depend on explicit awareness. Using a variant of this task, Sisk et al. (2020) showed that highly rewarded locations were prioritized only in participants who were aware of the reward-location contingency. Unaware participants showed no preference for high-reward locations, suggesting that reward affects priority via goal-driven attention.

The important role of explicit awareness in some forms of experience-guided attention, such as reward-guided attention, suggests that not all selection history effects are distinct from goal-driven attention. Some of these effects of prior experience directly influence task goals and should be considered a form of goal-driven attention. Others, however, reflect implicit learning and are not goal-driven. Accumulating evidence has shown that in such cases, experience-guided attention may be qualitatively different from goal-driven attention.

1.1.2.2 Implicit, experience-guided attention versus goal-driven attention

The best characterized case of implicitly learned attention is location probability learning (LPL). As reviewed above, LPL refers to a learned attentional preference for locations that frequently contained a search target in the past. Unlike goal-driven attention (e.g., endogenous cueing of the Posner task), location probability learning induces a persisting change of attention that does not rapidly adjust to a change in the target's location probability. For example, in Jiang et al. (2013), participants first acquired a spatial bias toward one quadrant (e.g., the upper left) in a training phase that lasted about 500 trials. Subsequently, the target's location became unbiased, meaning that the target was equally likely to appear in any quadrant. Although the previously learned bias was no longer "valid," participants continued to show faster RT when the target appeared in the previously high-probability quadrant. This effect persisted over several hundred "extinction" trials, and was strong even when the training and testing phases were separated by more than a week. Thus, unlike the flexibility shown by goal-driven attention, implicitly learned attention is persistent and insensitive to outcome devaluation.

A second unique feature of implicit learned spatial attention is that it relies on a viewer-centered spatial reference frame. That is, the frequently attended location is referenced relative to the viewer rather than to the external environment. In an early demonstration of this unique characteristic (Jiang & Swallow, 2013), participants were first trained to develop a spatial bias toward one region of a computer screen placed flat on a desk (e.g., the target most often appeared in the east corner of the screen). Subsequently, participants changed their sitting position by 90º, resulting in a viewpoint change in the relative location of the screen corners and in their perspective. After the viewpoint change, participants no longer favored the east corner of the

screen. Instead, they preferred to search in a corner in the same visual field as the previously high-probability corner. In contrast, when given explicit instruction to prioritize the east corner of the screen, participants can do so by mobilizing goal-driven attention. Interestingly, when older adults were tested in this task, they showed a strong viewer-centered persistence of location probability learning comparable to that shown by the young adults. In contrast, their ability to follow explicit task instructions to prioritize the east corner was lower than that of young adults, demonstrating age-related decline in goal-driven attention but no decline in implicitly learned attention (Twedell et al., 2017).

Finally, perhaps because the underlying mechanism is implicit learning, implicitly learned attention is preserved under high working memory load. Imposing a secondary working memory task during visual search does not interfere with location probability learning, even though it interferes with goal-driven attention (Won & Jiang, 2015). This is reminiscent of the findings for older adults, noted above – LPL is preserved even when goal-driven attention declines in older adults (Twedell et al., 2017). Similarly, LPL is largely preserved in individuals with a neurological or neurodevelopmental disorder, as in Parkinson's patients (Sisk et al., 2018), children with an autism spectrum disorder (Jiang, Capistrano, et al., 2013), and patients with hemifield neglect (Geng & Behrmann, 2002).

1.1.2.3. Priority map and habitual attention

How does prior experience affect the allocation of spatial attention? In the past decade, two views have emerged. According to the integrated priority map view, prior experience, such as reward history, alters the weights assigned to various locations. This is depicted as a change in the priority map of Chelazzi et al. (2014; Figure 1.1A). On this account, experience changes *where* one may shift attention toward. An alternative account conceptualizes experience-guided attention as a habit (Jiang, 2018; Jiang & Sisk, 2019). Much like typical motor habits, habitual attention affects *how* people shift attention. On this account, spatial attention includes both a static, map-like “where” component and a dynamic, action-like “how” component. Frequently finding a target in one visual-spatial region reinforces not only where we are likely to attend, but

also the direction of attentional shift that lands on the target. Figure 1.1B illustrates both the where and how components of spatial attention (Jiang, 2018).

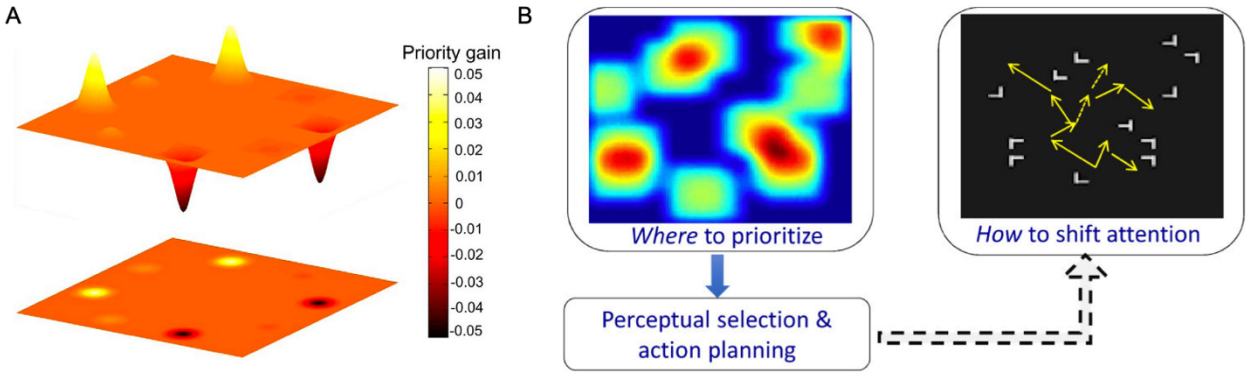

Figure 1.1 *Two views on how prior experience affects spatial attention. (A). Previous experience may change the weights assigned to locations on an attentional priority map (Chelazzi et al., 2014). (B). Experience may also change the direction of attentional shift, as indicated by the arrows (Jiang, 2018).*

According to the priority map account, the priority map sums the bottom-up and top-down signals for different objects or locations, determining which objects or positions are selected for recognition and action. The highest peak of activation on the map corresponds to the spatial location that is most likely attended next. If past experiences change where to attend through the priority map, then experience-driven attention should interact with goal-driven attention. However, as discussed above, location probability learning is independent of goal-driven attention. The habitual attention view emphasizes the dynamic component of attention. Every time when an observer successfully detects a target, the directions of attentional shifts that lead to the target are reinforced, increasing the likelihood that such vectors of attentional shifts would occur again. Thus, past experiences not only influence which locations in space are prioritized, but also change how we shift spatial attention. This distinction is reminiscent of Goodale and Milner (1992)'s division of vision between the "where" and "how" systems.

The habitual attention view raises the question about what roles eye movements play in visual attention. Could it be that visual attention depends on moving one's eyes toward the target? In the next section, I review the relationship between attention and eye movements.

1.2 Visual attention and eye movements

To bring visual information to the region of the retina with the highest acuity – the fovea – we execute a series of eye movements, including smooth pursuits, large saccades, and microsaccades (Brenner et al., 2007; Martinez-Conde et al., 2009; Robinson, 1965). Among these, saccadic eye movements are closely related to visual attention. Saccades refer to rapid, ballistic movements of the eyes with speeds up to 800 degrees/s (Munoz & Everling, 2004). When executing saccades, our brain converts the target's position relative to the fovea to a motor signal, which activates the extraocular muscles to move the eyes toward the target (Purves et al., 2001). This process is time-consuming, leading to a ~200ms delay between the onset of a visual stimulus and the initiation of a saccade. Still, the flexibility of saccading to any location makes saccades an important tool for orienting attention overtly in visual space.

In the mid 1980's, neurophysiological evidence began to emerge that supported a close relationship between attention and eye movements. Guided by the *premotor theory of attention* (Rizzolatti et al., 1987), neuroimaging studies began to examine whether the same neural circuits were involved in eye movements and covert attention. The premotor theory postulates that spatial orienting results from the activation of the oculomotor system. Shifts of spatial attention are achieved by planning eye movements and other motor activities, such as hand movements (Craighero & Rizzolatti, 2005; Rizzolatti et al., 1987; Rizzolatti & Craighero, 1998). This theory further proposes that the same neural circuits underlie spatial attention and saccade preparation. Spatial attention reflects the activation of brain regions that transform spatial information to movements. The activation of these regions increases motor readiness to respond to a specific location, and facilitates processing of information in that location. Consistent with the premotor theory of attention, eye movements and attentional orienting are both associated with activation of the frontal eye fields (FEF) and the lateral intraparietal area (LIP) (for a recent review, see Bisley & Mirpour, 2019).

In contrast to the premotor theory, work by Posner and others has emphasized covert attention, or attentional shift in the absence of saccadic eye movements. According to the *modular theory of attention* (Posner & Dehaene, 1994), attention is a high-level cognitive function that operates independently of the basic sensorimotor circuits. Posner et al. (1982) proposed that attentional shifts can either be overt, employing the oculomotor system to bring relevant items to the fovea, or covert, shifting the focus of attention without changing gaze direction. One demonstration of covert attention is the antisaccade task, which requires participants to saccade toward the location on the contralateral side of a visual target (Hallett & Adams, 1980). Humans and nonhuman primates can perform the antisaccade task (Amador et al., 1998; Bell et al., 2000; Fischer & Weber, 1997; Hallett & Adams, 1980), suggesting that it is possible to dissociate attention from eye movements. Nonetheless, the greater ease in attending to the saccade target (as in the "prosaccade" task), relative to making an antisaccade, hints at a close relationship between attention and eye movements (Bell et al., 2000; Schall, 2004).

Taken together, the strong connection between attention and eye movements has led vision scientists to ask whether eye movements are necessary for attention. The two contrasting theories are *the premotor theory* and *the modular theory of attention*. In the following section, I review findings on the relationship between eye movements and each form of attention, including goal-driven, stimulus-driven, and experience-guided attention.

1.2.1 Eye movements, goal-driven, and stimulus-driven attention

The majority of research on the relationship between attention and eye movements focuses on transient drivers of attention, including current task goals and perceptual salience. Because eye movements can facilitate selection, the debate about the relationship between transient attention and eye movements has largely focused on addressing the necessity of eye movements in attention. Specifically, do people obligatorily attend to where the eyes move to, and conversely, is it at all possible to attend to a location that one cannot look at (e.g., either due to paralysis of the eyes or because the location is out of the eyes' reach)? And do eye movements and covert attention rely on the same neural mechanisms? As reviewed next, studies from

behavioral, neuropsychological, and neuroimaging approaches have provided evidence for both a connection and partial independence between attention and eye movements.

1.2.1.1 Behavioral evidence

Accumulating evidence shows that people obligatorily attend to locations targeted for eye movements. Hoffman and Subramaniam (1995) presented participants with an array of four letters at the 3, 6, 9, and 12 o'clock locations. Participants needed to detect whether the array contained the letter T or the letter L while simultaneously saccading to one of the four locations. Participants more accurately responded to the letter if it was at the location of the saccade goal than if it was in one of the other three locations. This finding suggests that saccade preparation triggers attentional orienting. Another study showed that the converse is also true – attending to a location facilitates saccadic preparation toward that location. In Kowler et al. (1995), a single numeral appeared among letters, capturing attention in a bottom-up manner. In alternating blocks, participants were instructed to either saccade toward that location or to the contralateral side. Kowler et al. found that eye movements toward the numeral had shorter latencies and higher accuracy than eye movements toward a contralateral location. Together, these findings illustrate a tight coupling between visual attention and eye movements. Preparing a saccade results in preferential attention to the location of the saccade target. Conversely, attending to a location facilitates saccadic eye movements toward that location.

But is it possible to attend to a location that cannot also be looked at, either because of paralysis of the oculomotor system or because the location is out of the eyes' reach? Craighero et al. (2004) designed an "eye abduction" paradigm to test attentional effects in locations that can or cannot be reached by the eyes. Craighero et al. (2004) placed the computer screen 40º to the left or to the right of the participant's sagittal plane, preventing participants from making oculomotor preparation or execution farther into the temporal hemifield, while allowing intact eye movements toward the nasal hemifield. In an attentional cueing task, participants first viewed a central cue (a thin line pointing to the left or to the right) that informed them about the probable location of the upcoming target. The target stimulus (a filled circle) then appeared either in the cued location (with a 70% probability) or the opposite side (with a 30% probability),

equidistant from fixation. When the target was in the nasal hemifield, meaning that it was possible for the participants to look directly at it, the results showed a standard attentional cueing effect – faster target detection in the cued location than in the opposite location. Critically, when the target was in the temporal hemifield, meaning that its location could not be gazed at, the attentional cueing effect disappeared. Response was no faster in the cued location than in the opposite location. Thus, if the participants cannot prepare or execute an eye movement toward a location when it is outside of the eyes' reach, they also cannot preferentially attend to it, consistent with the premotor theory of attention. Unfortunately, these findings were not replicated in subsequent studies (Casteau & Smith, 2020; Smith et al., 2012). The replication studies found that covert, goal-driven attention to a location does not always depend on the preparation or execution of an eye movement toward that location.

The studies reviewed above examined endogenous (goal-driven) cueing of spatial attention. But does exogenous orienting also depend on saccade preparation and/or execution? Though two early studies by Smith and colleagues showed that eye abduction weakened exogenous cueing (Casteau & Smith, 2020; Smith et al., 2010), supporting the premotor theory of attention, other recent studies contradicted this finding. In Hanning et al. (2019), participants turned their head ~35º to the left of the monitor, making it impossible to execute a rightward saccade that exceeded 8º. The researchers flashed a peripheral cue – a white circle – for 50ms at one of four locations (-10º, -6º, 6º, or 10º) relative to the central fixation point. This was followed by a 50ms presentation of a target stimulus – a noise patch tilted to the left or right – at any of the four locations. Hanning et al. found that detection sensitivity was greater when the target appeared at the location of the peripheral cue, even when this location was out of the oculomotor range (i.e., the 10º position). Extending this finding, Hanning and Deubel (2020) found that a peripheral cue presented at a location outside of the oculomotor range interfered with target detection at other locations. Regardless of the differences in experimental setting and parameters in Smith and colleagues' and Hanning and colleagues' studies, the presence of an exogenous cueing effect in some studies argues against the strong version of the premotor theory.

Together, these studies show that although eye movements may contribute to spatial attention and modulate the size of attentional cueing, both endogenous (goal-driven) and

exogenous (stimulus-driven) attention can be allocated to places outside of the eyes' reach. Covert attention is at least partially independent of oculomotor preparation or execution.

1.2.1.2 Neuropsychological evidence

Neuropsychological patients with damaged oculomotor systems, caused by either cortical or subcortical lesions or oculomotor muscle palsy, provide another test for the premotor theory of attention (Craighero et al., 2001; Gabay et al., 2010; Heide & Kömpf, 1998; Masson et al., 2020; Posner et al., 1982; Rafal et al., 1988; Sereno et al., 2006; Smith et al., 2004). If covert attention depends on intact eye movements, then these patients should be impaired at shifting spatial attention. As reviewed next, although some of these patients exhibit attentional deficits, others benefit from attentional cueing even when they cannot move their eyes.

Smith et al. (2004) and Gabay et al. (2010) showed that endogenous attention does not require intact eye movements in neuropsychological patients. Smith et al. (2004) tested a patient who never made voluntary eye movements since birth due to chronic ophthalmoplegia. In this study, a central arrow, pointing left or right, was presented for 100ms. This was followed by an asterisk (target) appearing in the cued (80%) or the contralateral (20%) location. Even though the patient could not make voluntary eye movements, this participant showed a significant cue validity effect, suggesting that endogenous attention does not depend on voluntary eye movement. Gabay et al. (2010) tested patients with Duanes retraction syndrome, a condition that resulted in reduced ocular motility of one eye. As in Smith et al.'s task, a central arrow validly predicted the upcoming target on 80% of the trials. All patients tested showed a validity effect in detecting the target. Thus, contrary to the premotor theory and to an early study by Craighero et al. (2001), endogenous attention does not depend on eye movements.

Exogenous cueing, on the other hand, seems to be impaired in patients with a deficit in eye movements (e.g., Gabay et al., 2010; Rafal et al., 1988; Sereno et al., 2006; Smith et al., 2004). Recent studies, however, did not replicate the strong dependence of exogenous attention on eye movements. Masson et al. (2020) found an exogenous attentional effect in patients without the ability to saccade. Patients with either horizontal or vertical congenital gaze paralysis (due to hypoplasia of brainstem) performed a peripheral attentional cueing task. After one of two

peripheral boxes (the cue) brightened, a target dot appeared with equal probability in one of the two boxes (40% in each box), and was absent on the remaining 20% of trials. Participants were instructed to press a button upon detecting the target dot. All patients showed an attentional cueing effect in their paralyzed orientations. Thus, exogenous covert attention did not require oculomotor processes.

In summary, although some patients with impaired oculomotor functions exhibit attentional deficits, both endogenous (goal-driven) and exogenous (stimulus-driven) attention are found to be intact in some patients with impaired eye movements. Thus, covert attention in neuropsychological patients is at least partially independent of oculomotor preparation or execution.

1.2.1.3 Brain imaging evidence

The eye abduction paradigm and neuropsychological studies have focused on a strong prediction of the premotor theory: covert attention depends on overt eye movements. As reviewed above, evidence for this prediction has been inconsistent at best. The premotor theory also makes a second, less controversial prediction: eye movements and covert attention rely on similar neural mechanisms. This prediction has received overwhelming support from fMRI studies on humans (Astafiev et al., 2003; Beauchamp et al., 2001; Corbetta et al., 1998; de Haan et al., 2008; Nobre et al., 2000; Perry & Zeki, 2000).

In an early study, Corbetta et al. (1998) asked participants to shift spatial attention either without eye movements (covert orienting) or with eye movements (overt orienting). In the covert task, participants maintained central fixation while shifting attention to the left visual field to detect a visual probe (an asterisk). In the overt task, they shifted fixation to the location of the probe. These two tasks produced substantial overlap in neural activity, including areas of the parietal cortex (the intraparietal sulcus - IPS), transverse occipital sulcus, the frontal cortex (including medial frontal gyrus and precentral sulcus - PreCS), and the temporal cortex (superior temporal sulcus - STS). Differences between the two tasks were also noted, with the covert attention task producing greater activity in the PreCS and IPS and the overt attention task producing greater activity in the medial occipital cortex. Subsequent studies uncovered largely

overlapping brain activations for eye movements and covert spatial orienting (e.g., Nobre et al., 2000; Perry & Zeki, 2000).

Thus, fMRI studies have converged on the finding of largely overlapping brain activation induced by covert spatial orienting and overt eye movements. Although these findings support the premotor theory of attention, they cannot be used to support the strong claim that attention depends on eye movements. First, in most fMRI studies, the overt eye movement condition requires participants to attend to the saccade goal. Because attention is involved in both the overt and the covert conditions, the common brain activation may be explained by the need to shift attention in both cases, regardless of whether eye movements are involved. Second, as a correlational measure, fMRI cannot tell us which of the activated regions are necessary for brain function. A region, such as the occipital cortex, could be activated by both the overt and covert orienting task, yet this region may not be needed for either task. Presumably participants could still carry out spatial shifting even when this area was damaged. Finally, the spatial resolution of fMRI is on the order of millimeters. Within a single voxel, there are tens of thousands of neurons. An overlap in brain activation, as revealed in fMRI, needs not imply that the same neurons are involved in covert orienting and overt eye movements. A definitive answer to this question requires the recording from single neurons, as reviewed in the next section. Thus, although fMRI studies have revealed close connections between eye movements and spatial attention, these findings have not provided compelling evidence for the premotor theory.

1.2.1.4 Neurophysiological evidence

Single-unit recording from nonhuman primates provides superior spatial resolution at the level of individual neurons, as well as excellent temporal resolution on the order of milliseconds. These studies have shown that although covert attention and overt eye movements tend to activate neurons in the same general area of the brain, the specific population of neurons involved in these two functions diverges (Messinger et al., 2021; Thompson, 2005). For example, Thompson (2005) recorded single neurons in the FEF while monkeys performed a covert popout search task. In this task, a visual array appeared at six (or eight) isoeccentric locations spaced equally around the central fixation. The target was a unique colored object or a

unique shape (e.g., a Landolt C among O distractors). The monkeys were required to maintain fixation and push a lever in the direction of the singleton target (or the gap in the C stimulus). Some neurons were visually responsive - they showed increased activity after the onset of the target stimulus. Other neurons were not visually responsive. Instead, they increased their activity before saccade but not upon target presentation. The visually responsive neurons appear to correspond to the detection of the popout target (covert orienting), and the saccade-related movement neurons correspond to eye movements. They increase activity before saccades and are inhibited by the onset of the popout target. Thus, orienting to a popout target and saccade production appear to be mediated by two separate populations of neurons in the FEF.

Using neurofeedback training, Schafer and Moore (2011) also found a dissociation between attention and eye movements in neurons in the FEF. Monkeys were trained to increase (or decrease) the firing rates of FEF neurons in the arcuate sulcus while maintaining fixation. On each trial, monkeys received feedback (pure tones in high or low pitches) based on the firing rate of multi-unit activity in the FEF. Monkeys were trained to increase firing rates to a high threshold (up condition), or decrease firing rates to a low threshold (down condition). Subsequently, the monkeys performed an overt search task, during which they made a saccade toward an oriented bar (target) surrounded by other objects. Search was more accurate when the target appeared in the response field of the FEF neurons in the up condition relative to the down condition. Despite this change in response accuracy, the monkeys were equally likely to saccade toward the response field of the FEF neurons in the up and down conditions. Consistent with Thompson (2005), these findings suggest that FEF neurons in the arcuate sulcus modulate attention selection but not eye movements.

Despite the partial independence between neurons corresponding to covert attention and eye movements, stimulation of neurons in the FEF can induce shifts of attention. In an influential study, Moore and Fallah (2001) stimulated neurons within the FEF of monkeys at a level that was below the threshold of eye movements. That is, the stimulation was too weak to trigger an eye movement. The monkeys' task was to detect a luminance change in a peripheral target while maintaining fixation. Even though the microstimulation did not trigger an eye movement, it affected the monkey's behavior. Monkeys detected smaller luminance changes when the target

was located within the FEF neurons' movement field. This finding was replicated in subsequent studies (e.g., Moore & Armstrong, 2003; Moore & Fallah, 2004). Cavanaugh & Wurtz (2004) extended this finding to neurons in the superior sulcus (SC). When monkeys were required to detect directional changes of visual motion, their performance was enhanced by the sub-threshold stimulation of SC neurons whose movement field corresponded to the target's location. These stimulation studies demonstrate that activation of neurons associated with oculomotor control can induce attentional shifts. They are consistent with behavioral studies in humans, demonstrating that eye movements influence attention. However, as is the case with behavioral studies, the microstimulation data cannot tell us whether eye movements are necessary for attention.

1.2.1.5 Brief summary

Previous studies on the relationship between eye movements and attention have revealed a close connection between the two. These two processes engage largely overlapping regions of the brain in human fMRI studies. Behavioral studies have shown that people preferentially attend to the location of a saccade goal, suggesting that eye movements influence attention. In addition, micro-stimulation of neurons involved in oculomotor movements affects spatial orienting. However, evidence for a strong claim of the premotor theory – that attention depends on eye movement - remains elusive. Eye abduction paradigms have uncovered cases in which people can attend to locations outside of the eyes' reach, and neuropsychological patients with an eye movement deficit can still benefit from attentional cueing. Together, these findings support a weaker version of the premotor theory – that eye movements are related to spatial attention. They are also consistent with components of the modular theory of attention, namely, covert attention is a high-level cognitive process that is, at least in part, abstracted from oculomotor movements.

1.2.2 Eye movements and experience-guided attention

The studies reviewed above have focused exclusively on goal-driven (endogenous) or stimulus-driven (exogenous) attention. They have left out the relationship between eye movements and a third driver of attention – previous experience. As reviewed earlier, increasing

evidence shows that spatial attention can be experience-driven. Because this third form of attention may be qualitatively different from goal-driven and stimulus-driven attention, it may interact with eye movements in distinct formats. In addition, if visual attention is a dynamic system that metaphorically moves around, it is possible that eye movements, particularly oculomotor habits, underlie experience-guided attention. In the next section, I review the relationship between eye movements and experience-guided attention.

1.2.2.1 Experience affects both covert attention and overt eye movements

Selection history not only affects which features or locations are likely attended in the future, it also affects eye movements. This was first demonstrated in intertrial repetition priming. McPeek et al. (1999) asked participants to make a single saccade toward a color singleton presented among distractors. The display contained either a red diamond among several green diamonds, or a green diamond among several red diamonds. Saccade latency was shorter when the target color on trial N matched that on trial N-1, than when the target color switched. In other words, intertrial priming was observed not just in search RT, but also in saccade latency. In another study, Belopolsky and Van der Stigchel (2013) showed that the eye movement trajectory was sensitive to the location of a previous trial's distractor. In this study, participants were required to make a saccade in a pre-specified direction. These saccades tended to be curved away from the location of an irrelevant distractor presented on the preceding trial. Likewise, location probability learning not only affects search RT but also the direction of the first saccadic eye movement. In Jiang et al. (2014), participants searched for a T target among L distractors. The target's location was biased toward a high-probability quadrant in a training phase and was unbiased in a testing phase. Eye tracking showed that participants were more likely to direct the first saccadic eye movement at trial onset to the high-probability quadrant, and this tendency was maintained in the unbiased testing phase.

Cue-target association studies have also revealed a change in eye movement as a result of learning. Studies on contextual cueing showed that the faster RT on repeated search trials was accompanied by fewer fixations and a higher proportion of direct saccade toward the target (Harris & Remington, 2017; Manelis & Reder, 2012; Peterson & Kramer, 2001). Zhao et al.

(2012) examined the eye movement trajectories and found that the scan path of the eyes was more directed toward the target in the repeated condition than in the nonrepeated condition. Thus, implicit cue-target association learning affects both search RT and eye movements.

Reward, too, affects saccade programming, trajectory, and speed (Bucker et al., 2015; Hickey & van Zoest, 2012; Kawagoe et al., 1998; Liao & Anderson, 2020; Milstein & Dorris, 2007; Yamamoto et al., 2013). In Hickey and van Zoest (2012), participants saccaded toward a target that could appear above or below the fixation while ignoring a distractor presented on the left or right side of the fixation. Participants received monetary reward that varied from trial-to-trial. Following a high reward trial, if the distractor on the next trial happened to be the same color as the target on the previous high-reward trial, short-latency saccades showed a tendency to be curved toward the distractor. In other words, when a color was momentarily associated with high reward, it may bias eye movements on the immediately following trial.

1.2.2.2 Dissociation between eye movements and experience-guided attention

Although previous experience can affect both covert attention and overt eye movements, several studies have revealed a dissociation between the two. First, repeated eye movements are not necessary for the acquisition of location probability learning. The learned spatial bias was just as strong when participants maintained central fixation during training, either because the display was presented too briefly for eye movements (Addleman et al., 2018; Jiang & Swallow, 2013), or because an eye tracker confirmed the maintenance of central fixation (Geng & Behrmann, 2005).

Second, several studies showed possible differences in the underlying mechanisms for a change in eye movements and a change in covert attention. Lin et al. (2016) compared the effects of a trained color-target association in two tasks: a visual search task that allowed for eye movements and a flanker task that did not involve eye movements. In the search task, participants searched for a target that was always presented inside a specific-colored circle, establishing an association between that color and the target. In a subsequent testing phase, the color of the circle was no longer predictive of where the target was. Nonetheless, participants continued to be faster if the target happened to be inside the previously trained color. But if the

testing phase involved a flanker task in which participants responded to the target at fixation, the color of the surrounding distractors – same or different from the trained color – did not influence response. Although this study did not directly test eye movements, the difference between findings for the search task versus the flanker task suggests that the trained color affected overt eye movements more than covert attention.

A more direct test for the dissociation between eye movements and attention came from Kim and Anderson (2019a). In the training phase of Experiment 1, participants received monetary reward for shifting their gaze in the direction opposite to a colored square (the antisaccade task). With training, antisaccades were faster and more accurate in response to the more highly rewarded color. In a subsequent testing phase, participants saccaded toward a shape-defined target (the prosaccade task). One of the previously trained colors appeared as a target or distractor. Saccades were faster when the target was in a previously high-reward color; and conversely, saccades were slower when the distractor was in the previously high-reward color, reflecting value-driven learning in orienting attention. In the training phase of Experiment 2, participants repeatedly oriented away from a colored square without rewards. In the same prosaccade test as in Experiment 1, in contrast, participants saccaded slower when the target was rendered in a previously learned color, and saccades were faster when the distractor was in the learned color. The opposing results across these two experiments suggest a dissociation between attention driven from monetary reward and eye movements learned from instrumental conditioning.

Finally, studies have found important distinctions between different forms of experience-driven attention. Whereas selection history effects are often implicit, reward-based attention is sometimes explicit (Sisk et al., 2020). Consistent with this difference, Anderson et al. (2017) found that patients with depression maintained intact attentional effects induced by (implicit) selection history effects, but showed impaired attention in (explicit) reward-based attention. Using fMRI, Kim and Anderson (2019b) found that selection history effects were associated with activation in sensory-processing areas, whereas reward-based attention activated other areas, including the caudate tail. Thus, although reward-driven attention may be independent of

eye movements (Kim & Anderson, 2019a), it remains possible that other forms of experience-guided attention depend on eye movements.

1.3 Summary

This chapter of literature review summarized (1) the multifaceted nature of attention, and (2) the tight coupling and partial independence between attention and eye movements. Although psychological and neuroscientific studies have emphasized the dichotomous view of attention as goal-driven or stimulus-driven, the emerging literature demonstrates that previous experience can bias attention in a manner that is neither goal-driven nor stimulus-driven. In the visual domain, attention selection is usually achieved by a succession of eye movements toward the target. The strong connection between attention and eye movements raises the question of whether eye movements are necessary for visual attention. Researchers proposed two contrasting theories – the premotor theory and the modular theory. Accumulating evidence from behavioral, neuropsychological, neuroimaging, and neurophysiological studies found both a tight coupling and partial independence between visual attention and eye movements. However, these studies primarily focus on goal-driven and stimulus-driven attention. It remains unclear whether oculomotor movements play an important role in experience-guided attention.

The relationship between eye movements and experience-guided attention may take several forms. First, previous experience not only affects covert attention, but also overt eye movements. In line with this account, as reviewed earlier, all forms of experience-guided attention, such as selection history effects, cue-target associations, and reward history, are found to influence eye movements. Second, eye movements may be necessary for the formation of an attentional habit. For example, the tendency to preferentially attend to high-probability target locations may reflect an oculomotor habit of moving one's eyes toward those locations. On this account, when eye movements are prevented, preferential attention to the high-probability locations should also cease. Empirical data, reviewed above, do not support this prediction. Finally, an oculomotor habit that's spatially incompatible with selection history may interfere with experience-guided attention. On this account, compelling participants to frequently saccade

in a direction away from a search target should weaken location probability learning. This possibility has not been tested in previous studies and is the focus of the first two studies.

The first two studies of this dissertation aimed to investigate the robustness of one form of experience-guided attention – location probability learning – under conditions characterized by atypical eye movements. When a visual search target appears more often in one region of space, participants are faster finding it in the high-probability locations. Study 1 examined the impact of a spatially incompatible oculomotor signal on location probability learning, by combining an oculomotor task with a visual search task. Study 2 tested whether spatial alignment between eye movements and attention was necessary for the acquisition of location probability learning, by forcing eye movements away from the current gaze. In both studies, I demonstrated that location probability learning was robust, suggesting that attentional learning reflects a high-level cognitive process that is partially abstracted away from oculomotor movements, in line with the modular theory of attention. Therefore, these two studies enrich the theoretical understanding of experience-guided attention and oculomotor movements.

Following an investigation of the relationship between experience-guided attention and eye movements, Study 3 examines the role of peripheral vision in supporting implicit LPL. Although the central fovea has higher acuity, the visual periphery, being much larger than the central fovea, is more likely to contain visual targets. It remains unclear how peripheral vision affects attention learning. Study 3 addressed this question by using gaze-contingent eye tracking to simulate peripheral vision loss in a location probability learning task. The study tested whether central vision alone was sufficient for implicit LPL, or whether learning depended on having peripheral vision.

Taken together, this dissertation focuses on the relationship between eye movements and attention, particularly experience-guided attention. Chapters 2, 3, and 4 present three empirical studies. In Chapter 5, I synthesize these studies and other recent findings and discuss the mechanisms underlying experience-guided attention.

2. Study 1: Independence of implicitly guided attention from goal-driven oculomotor control

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Independence of Implicitly Guided Attention from Goal-driven Oculomotor Control

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Preface

Location probability learning – the acquisition of an attentional bias toward locations that frequently contained a search target – shows many characteristics of a search habit. To what degree does it depend on oculomotor control, as might be expected if habit-like attention is grounded in eye movements? Here, we examined the impact of a spatially incompatible oculomotor signal on location probability learning (LPL). On each trial of a visual search task, participants first saccaded toward a unique C-shape, whose orientation determined whether participants should continue searching for a T target among L distractors. The C-shape often appeared in one, "C-rich" quadrant that differed from where the T was frequently located. Experiment 1 showed that participants acquired LPL toward the high-probability, "T-rich" quadrant, an effect that persisted in an unbiased testing phase. Participants were also faster finding the target in the vicinity of the C-shape, but this effect did not persist after the C-shape was removed. Experiment 2 found that the C-shape affected search only when it was task-relevant. Experiment 3 replicated and extended the findings of Experiment 1 using eye tracking.

Thus, location probability learning is robust in the face of a spatially incompatible saccade, demonstrating partial independence between experience-guided attention and goal-driven oculomotor control. The findings are in line with the modular view of attention, which conceptualizes the search habit as a high-level process abstracted from eye movements.

Keywords: spatial attention, visual search, selection history effects, location probability learning, oculomotor control

Introduction

The visual world is more complex than what we can process at one time. Attention allows us to select relevant sensory input for further processing. Although it is possible to attend to an object without directly looking at it, selection is often achieved by a sequence of eye movements that bring task-relevant information to the fovea. The importance of eye movements in selection leads some researchers to propose that the brain mechanisms underlying oculomotor control also support visual attention (Rizzolatti et al., 1987). This *premotor theory of attention* can be contrasted with the *modular theory of attention*, according to which attention is a high-level cognitive function detached from the oculomotor circuit (Posner & Dehaene, 1994). To date, research on the relationship between attention and oculomotor control has primarily focused on transient drivers of attention, such as perceptual salience and current task goals. These studies have found both a close connection and partial independence between eye movements and attention (for reviews, see Hunt et al., 2019; Kowler, 1995; Smith & Schenk, 2012). However, increasing evidence has shown that visual attention is also sensitive to one's previous experience, often without the participants' awareness (Addleman & Jiang, 2019; Awh et al., 2012). The abundance of selection history effects raises the question about whether experience-guided attention relies on oculomotor control, as predicted by the premotor theory, or whether it is independent of eye movements. We address this question in the context of a well-characterized selection history effect – location probability learning.

Location probability learning (LPL) refers to the acquisition of a spatial attentional bias toward locations that contain a visual search target disproportionately often. In studies of LPL, participants search for a target, such as a letter T, among distractors (e.g., letter Ls) presented in

random locations. Unbeknownst to the participants, across multiple trials, the target appears more frequently in one region of space than in other regions. Although often unaware of the target's location probability, participants respond more quickly to the target when it is in the high-probability rather than the low-probability locations (Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Jiang, 2018; Jiang, Swallow, et al., 2013). LPL is not restricted to the learning of the target's location probability. If a distractor, such as a visually salient singleton, frequently occurs in one region, participants acquire a spatial attentional bias away from that region (Britton & Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; B. Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019).

The spatial attentional bias acquired through LPL differs from goal-driven attention in several ways. These unique features suggest that LPL reflects the development of a search habit (Salovich et al., 2018). First, like traditional motor habits, LPL is insensitive to outcome devaluation. After participants have acquired an attentional bias toward one region, the attentional bias persists in that region for several hundred trials after the target's location probability becomes unbiased (Jiang, Swallow, et al., 2013). Second, LPL yields a viewer-centered, rather than environment-centered, bias of spatial attention. In Jiang and Swallow (2013), participants were first trained to develop a spatial bias toward one region of a computer screen placed flat on a desk (e.g., the east corner of the screen). Subsequently, they changed their sitting position by 90º, resulting in a viewpoint change in the relative location of the screen corners and their perspective. After the viewpoint change, participants no longer prioritized the east corner of the screen. Instead, they preferred to search in a corner in the same visual field as the previously high-probability corner. Third, LPL demonstrates a key feature of habits – automaticity. Although explicit awareness can increase the size of LPL (Jiang, Swallow, et al., 2014; Vadillo et al., 2020), LPL is robust even when participants lack awareness of the target's location probability (Jiang et al., 2018). Imposing a secondary working memory load interferes with goal-driven attention but not with LPL (Won & Jiang, 2015). These features lead Jiang (2018) to propose a multiple-levels framework of attention, according to which spatial attention has both a map-like, *where* component and a dynamic, action like *how* component. Frequently

finding a target in one region reinforces not only where to attend, but also the direction of the attentional shift that lands on the target.

By emphasizing the dynamic aspect of attention, the habitual attention account raises the possibility that eye movements play a crucial role in the acquisition and maintenance of LPL. Might it be that LPL simply reflects a tendency to move one's eyes toward the high-probability locations? Empirical data on the role of eye movements in LPL have yielded mixed answers. On one hand, LPL not only speeds up search but also changes the direction of the first saccadic eye movement. Following training, participants are more likely to direct the first saccadic eye movement toward the high-probability locations, and this tendency persists after training (Jiang, Won, et al., 2014). This finding suggests that LPL results in both an overt eye movement habit and a covert spatial attentional bias. Other studies, however, suggest that the covert spatial bias does not depend on an overt eye movement. For example, participants can acquire LPL while maintaining central fixation, either with the enforcement of an eye tracker or because the display was presented too briefly for eye movements (Addleman et al., 2018; Geng & Behrmann, 2005; Jiang & Swallow, 2013). This finding suggests that much like endogenous or exogenous attention, experience-guided attention shows partial independence from eye movements.

Although LPL can emerge in the absence of an overt eye movement, this finding does not imply complete independence of LPL from oculomotor control. When people maintain central fixation, the oculomotor system is in a neutral state – it does not conflict with the emerging search habit. A stronger test of the independence of LPL from oculomotor control would come from a study design that pits the two factors against each other. Suppose the search target most often appears in the lower right. If people always have to look in a different direction first, such as toward the upper left, this can introduce an oculomotor signal incompatible with the habit of searching in the lower right. The premotor theory of attention predicts that the spatially incompatible oculomotor signal should interfere with the development of LPL. In contrast, if the search habit underlying LPL is a relatively high-level mechanism, then LPL may remain robust in the presence of an incompatible oculomotor signal. The three experiments reported here tested these competing hypotheses.

Experiment 1

To introduce a spatially incompatible oculomotor signal, we combined the standard LPL task with a secondary task that required an immediate saccadic eye movement. On each trial, participants viewed 12 white letters that included one rotated T and 11 Ls, along with a black C-shaped object. The task they performed depended on the orientation of the C-shape. Because the C-shape was presented briefly and its gap was small, accurate identification of its orientation necessitated an immediate eye movement toward the C-shape. On the occasional trials in which the gap pointed up (9% of the trials), participants pressed the spacebar to end the trial. These trials served as a probe to ensure that participants had followed instructions to look at the C-shape (Kowler, 1995). On the other trials when the gap pointed down, participants made no response to the gap, but instead had to find the T and report its orientation.

To introduce spatial incompatibility between LPL and the initial saccade, in a training phase, we presented the C-shape in a "C-rich" quadrant 70% of the time and in each of the other quadrants 10% of the time. The task goal, therefore, required participants to frequently saccade toward the C-rich quadrant. The target T, however, appeared frequently in a different, "T-rich" quadrant on 50% of the trials. Because the T-rich quadrant rarely contained the C-shape, the search habit toward the T-rich quadrant would need to form following a spatially incompatible, goal-directed oculomotor signal. By examining search RT across different target quadrants in the training phase, we could determine whether the spatially incompatible C-task interfered with LPL. Furthermore, we examined the persistence of any spatial attentional biases in an unbiased testing phase. The C-shape was removed in the testing phase. In addition, the target T was equally probable in all four quadrants. We examined whether participants were faster finding the target in the previously T-rich quadrant, as might be expected if the search habit had persisted. We also tested whether there was a search advantage in the previously C-rich quadrant, as might be expected if frequently saccading toward it had produced a lasting oculomotor habit.

Because the oculomotor signal toward the C-rich quadrant was both goal-driven and spatially incompatible with the emerging search habit, Experiment 1 allowed us to simultaneously address the role of goal-driven attention and oculomotor control in experience-guided attention. The relationship between goals and habits is complex. A learned habit, such as

a tendency to drive home after work, can sometimes override a momentary goal (e.g., stopping by a pharmacy), suggesting partial independence between habits and goals. However, goals can also interfere with the spontaneous emergence of a habit (for a review, see Wood & Rünger, 2016). Consequently, both endogenous orienting and saccade toward the C-rich quadrant could interfere with LPL. Any preservation of LPL under these stringent conditions would suggest that LPL is a robust effect, partially independent of task goals and oculomotor control.

Method

Testing platform. Experiment 1 was conducted using an online platform (Pavlovia.org) during a period when in-person testing was halted due to COVID-19. The online platform was validated by a recent publication that revealed LPL in online testing (Ivanov & Theeuwes, 2021). In addition, we conducted a pilot experiment to validate online testing. This pilot experiment was identical to Experiment 1, except that the C-shape was omitted, rendering it a standard LPL task. The 24 participants in the pilot experiment acquired an LPL (18% of RT saving) that was comparable in size to previous in-person studies (10-25% of RT savings in Jiang, Swallow, et al., 2013). Further details about the pilot experiment can be found on Open Science Framework (https://osf.io/9vdpw/).

Sample size determination. We prespecified 24 participants as the targeted sample size in each experiment. This sample size was determined based on Experiment 1 of Jiang, Swallow, et al. (2013), which reported an effect size of 2.68 in Cohen's *d* for LPL. Assuming comparable effect sizes, G*Power analysis (Faul et al., 2007) showed that 5 participants were needed to reach a power of .95 at an alpha-level of 0.05 in a two-tailed test. The pilot experiment online had a smaller effect size (1.75 in Cohen's *d*), necessitating a minimal sample size of 7. Taking into consideration of noise in online data collection, reduced power in a dual-task design, and the need to counterbalance quadrant assignments across participants, we aimed to collect data from 24 participants.

Participants in all three experiments reported here were between the ages of 18 and 45 years of age and were naïve to the purpose of the study. They were fluent in English and had normal or corrected-to-normal visual acuity and normal color vision. Participants in Experiments

1 and 2 provided informed consent online, after which they launched the experiment on Pavlovia.org and completed the experiment on their own laptop or desktop computers. Participants in Experiment 3 received informed consent in person and completed the experiment with eye tracking. Participants were students from the University of Minnesota who volunteered their time for extra course credit or cash reward.

Participants in Experiment 1 included 18 females and 6 males with a mean age of 20.8 years (*SD* = 2.7 years).

Equipment

Stimuli in the online experiments were presented on the participants' own laptop or desktop computers with an unrestrained viewing distance. We used MATLAB (www.mathworks.com) to generate condition files for PsychoPy. Stimulus presentation was controlled by PsychoPy (Peirce et al., 2019) and converted into JavaScript for testing on Pavlovia.org. Stimulus size was specified in pixels.

Materials and procedure

The experiment contained four phases: practice, training, testing, and recognition test.

Each practice trial started with a small fixation point at the center of the display. After 500ms, an array of white letters along with a black C-shape was displayed. The black C-shape (15 × 15 pixels) contained a gap (5 pixels) pointing either up or down and was presented for just 300ms. The search items included one rotated white letter T (40 × 40 pixels; rotated 90º to the left or right) and 11 rotated Ls (40 × 40 pixels; each randomly rotated 90º, 180º, 270º, or 0º) and were presented until participants made a response. The location of all the items was selected randomly from a 10 × 10 invisible matrix that subtended 600 × 600 pixels, with the constraint that there were three search letters in each quadrant. The orientation of the target T was selected randomly, with the constraint that both responses (left/right) occurred equally often. Participants were instructed to immediately move their eyes to the C-shape and identify its gap direction. On trials when the gap pointed up, participants pressed the spacebar to terminate the trial. On the remaining trials when the gap pointed down, participants were asked to make no response to the

C-shape, but instead to find the letter T and press either the left or the right arrow key to report the orientation of the T. The search display was erased upon the keypress response. Correct responses received a brief feedback ("Correct!" printed in green for 200ms). Incorrect responses to the letter T received a longer feedback ("Incorrect!" printed in red for 2s). Incorrect responses to the C-shape led to a 2s feedback with a full screen of colorful blobs along with the word "Incorrect" printed in red. Participants were instructed to aim for 100% accuracy in the C-task and to respond as accurately and as quickly as possible in the T-task. The practice phase contained 12 trials with just the C-shape, where participants pressed the spacebar for upward Cs (6 trials) and made no response to downward Cs (6 trials). This was followed by 24 trials that combined the C- and T-tasks. These included 12 trials with an upward C-shape and 12 practice trials with a downward C-shape. To ensure that participants understood what they were asked to do, after practice, we asked participants to answer two short questions about how to respond to the C-shape and the letter T. All participants correctly answered these questions.

The training phase contained 6 blocks of trials with 66 trials in each block. The trials were similar to the dual-task trials participants experienced during practice. In each block, probe trials with an upward C-shape occurred 6 times, leaving the majority of the trials with a downward C-shape that signaled visual search.

The testing phase contained 3 blocks of trials with 60 trials in each block. In this phase, the C-shape was no longer presented. Participants searched for the letter T and reported its orientation on all trials.

Finally, the recognition phase asked participants to answer a few questions that gauged their awareness of the spatial distribution of the C-shape and the target T.

Design

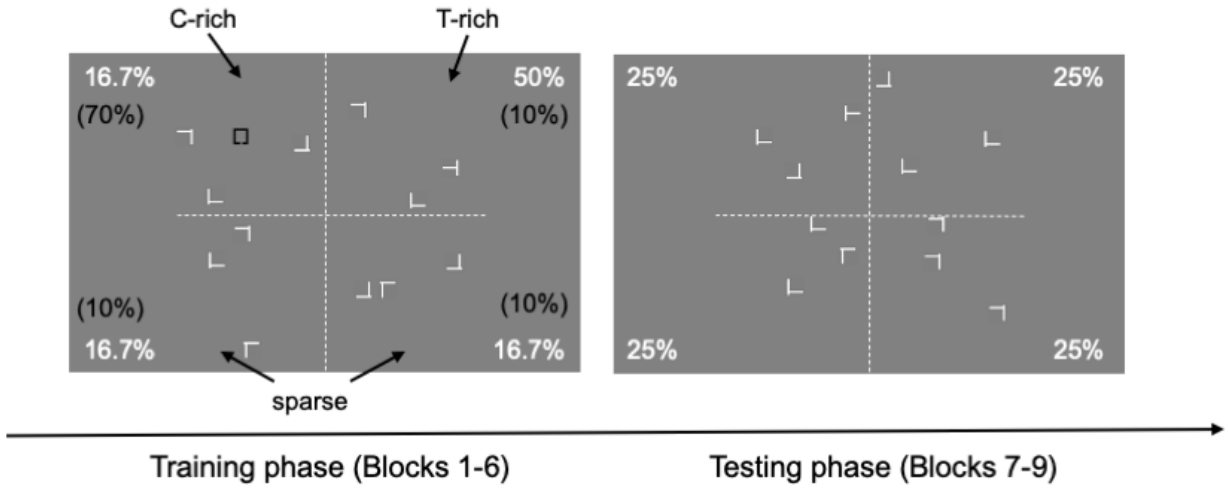

Figure 2.1 *A schematic illustration of stimuli and design used in Experiment 1. During training (Blocks 1-6), a black C-shaped object was presented concurrently with the T-and-L items, but it offset after 300ms, leaving the T and Ls on the display. Participants performed a combination of a Go/No-Go task to the C-shape and a T-among-Ls search task. Participants first saccaded toward the black C-shape to identify the direction of its gap. On 9% of the trials in which the gap pointed up, participants pressed the spacebar to terminate the trial. On 91% of the trials in which the gap pointed down, participants made no response to the gap, but proceeded to search for a target T and reported its orientation. The C-shape appeared most often (70% of the time) in one quadrant, the "C-rich" quadrant. The target T appeared most often (50% of the time) in another quadrant, the "T-rich" quadrant. The other two quadrants were considered "sparse" quadrants. The testing phase (Blocks 7-9) did not include the C-shape. The T's location was unbiased in the testing phase (i.e., 25% in each quadrant). Items are not drawn to scale. The dashed lines and the numbers illustrating the target's location probability are for illustrative purposes only.*

To introduce spatial incompatibility between the oculomotor task toward the C-shape and the search task, in the training phase we manipulated the location probability of the C-shape and the T. On search trials (i.e., when the C-shape pointed down), the target T appeared in a T-rich quadrant 50% of the time and in each of the other three quadrants 16.7% of the time. The C-

shape appeared in a different, C-rich quadrant 70% of the time and in each of the other three quadrants 10% of the time. On probe trials (i.e., when the C-shape pointed up), the target T also appeared in the T-rich quadrant 50% of the time and in each of the other quadrants 16.7% of the time. The C-shape was presented in the C-rich quadrant 66.7% of the time, the T-rich quadrant 16.7% of the time, and in each of the other two quadrants 8.3% of the time [1]. Because the trial terminated after the probe response, there was no search on these trials. The designation of the specific quadrants to T-rich, C-rich, and sparse was counterbalanced across participants.

In the testing phase, the target T appeared in each quadrant 25% of the time. In addition, the C-shape was removed.

Participants were not informed of the location probability of the letter T or the C-shape, nor were they alerted to the transition from the training to the testing phase.

Recognition

The recognition phase contained the following questions. First, participants were asked whether they thought the target T was equally likely to appear in all locations, or whether it was more often found in some locations than others. After this first response, participants were informed that the target was more likely to appear in one visual quadrant. They were asked to select the quadrant where the target T most often appeared. Finally, we asked participants to choose the quadrant that most often contained the C-shape.

Results

C-task. In the training phase, participants correctly made a Go response to upward C-shapes 93.1% of the time (*SE* = 1.4%). The false alarm rate to a downward C-shape was 2.9% (*SE* = 0.5%), yielding an overall accuracy of 96.8% (*SE* = 0.5%). The high level of accuracy suggests that participants successfully oriented toward the C-shape.

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[1] Because each block contained just 6 probe trials, we could only approximate the C-shape's spatial distribution on these trials to be close to the 7:1:1:1 ratio used on search trials. The closest approximation was used in this experiment, yielding a distribution of 6.7:1.7:0.8:0.8 distribution across the C-rich, T-rich, and sparse quadrants).

Visual search: T-task. On trials when the C-shape pointed downward, participants correctly responded to the T's orientation 97% of the time. Mean accuracy was unaffected by whether the T was in the T-rich quadrant (M = 97.3%, SE = 0.5%), the C-rich quadrant (M = 96.9%, SE = 0.6%), or the sparse quadrants (M = 96.9%, SE = 0.4%), $F(2, 46) = 0.96$, $p = .391$, $\eta_p^2 = .040$. In the following search RT analysis, we removed probe trials (i.e., Go trials with an upward C-shape) as well as trials with an incorrect search response. Figure 2.2A displays mean RT across blocks.

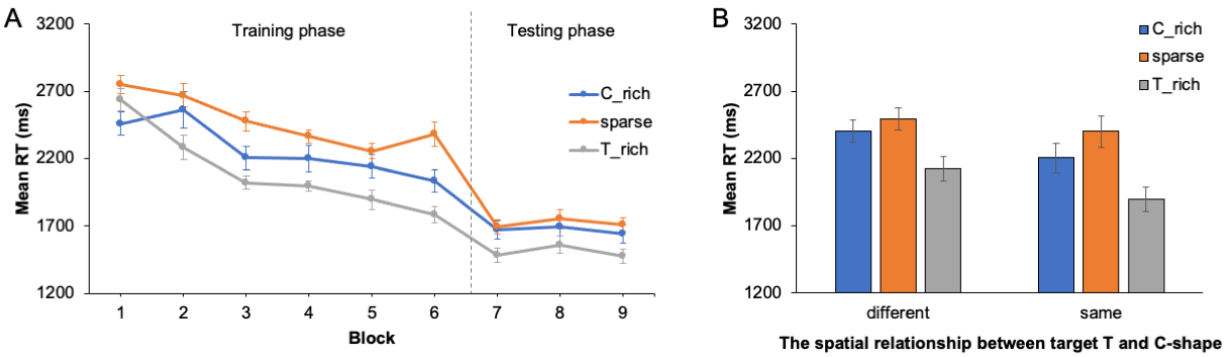

Figure 2.2 *Mean RT in Experiment 1. (A) Search RT across blocks. The target T was presented more often in the T-rich quadrant in the training phase (Blocks 1-6) but had an unbiased spatial distribution in the testing phase (Blocks 7-9). The C-shape appeared more frequently in the C-rich quadrant in the training phase. It was omitted from the testing phase. (B) Training phase RT as a function of whether the target T and the C-shape were located in the same quadrant, and where the target T was. Error bars show ±1 within-subject SE of the mean.*

Training phase. An ANOVA using target location (T-rich, C-rich, or sparse quadrants) and training block (1-6) as factors showed a significant main effect of target location, $F(2, 46) = 17.79$, $p < .001$, $\eta_p^2 = .436$. The main effect of block was also significant, with faster RT in later blocks than earlier ones, $F(5, 115) = 17.18$, $p < .001$, $\eta_p^2 = .428$. These two factors interacted, driven by a larger effect of target location in later than in earlier blocks, $F(10, 230) = 2.53$, $p = .007$, $\eta_p^2 = .099$.

To understand how target's location affected RT, we computed mean RT when the target was in the T-rich, C-rich, or the sparse quadrants. We performed three planned pairwise *t*-tests using a critical alpha level of 0.0167, adjusted for multiple comparisons. RT was significantly faster in the T-rich quadrant than the sparse quadrants, $t(23) = 6.43$, $p < .001$, Cohen's $d = 1.312$, demonstrating location probability learning. RT was also faster in the C-rich quadrant than the sparse quadrants, $t(23) = 3.46$, $p = .002$, Cohen's $d = 0.706$, showing an effect of overtly orienting to the C-rich quadrant at trial onset. RT was faster in the T-rich quadrant than in the C-rich quadrant, $t(23) = 2.41$, $p = .025$, Cohen's $d = 0.491$, but this effect missed the critical alpha level. Thus, both the task goal of overtly orienting to the C-rich quadrant and LPL affected search RT.

To further examine how overt orienting toward the C-shape influenced search, we examined how the spatial relationship of the T and C-shapes affected search RT. We divided trials based on whether the C-shape and the T occurred in the same or different quadrants, and which quadrant the T was in. As shown in Figure 2.2B, this analysis revealed a significant main effect of spatial relationship, with faster RT when the T and C-shape appeared in the same rather than different quadrants, $F(1, 23) = 20.28$, $p < .001$, $\eta_p^2 = .469$. The main effect of the target quadrant was significant, $F(2, 46) = 20.22$, $p < .001$, $\eta_p^2 = .468$, with faster RT when the T appeared in the T-rich rather than the other quadrants. These two factors did not interact, $F(2, 46) = 1.14$, $p = .328$, $\eta_p^2 = .047$. Thus, if the target T happened to appear in the same quadrant as the C-shape, search was faster, suggesting that overt orienting to the C-shape modulated the allocation of attention in the ensuing search task.

Testing phase. The testing phase examined whether the search advantage in the T-rich and C-rich quadrants persisted after both the C-shape and the probability cue were removed. An ANOVA on target location (previously C-rich, T-rich, or sparse quadrants) and block (7-9) showed a significant main effect of target location, $F(2, 46) = 10.97$, $p < .001$, $\eta_p^2 = .323$, no main effect of testing block, $F(2, 46) = 0.504$, $p = .607$, $\eta_p^2 = .021$, and no interaction, $F(4, 92) = 0.172$, $p = .952$, $\eta_p^2 = .007$.

Follow-up planned *t*-tests showed that RT was faster in the previously T-rich quadrant than both the C-rich quadrant and the sparse quadrants, $t(23) = 3.12$, $p = .005$, Cohen's $d = 0.637$ comparing T-rich with C-rich, and $t(23) = 4.88$, $p < .001$, Cohen's $d = 0.996$ comparing T-rich with sparse. Thus, LPL induced a persisting spatial bias toward the previously high-probability T-rich quadrant. In contrast, RT was not faster in the previously C-rich quadrant than the sparse quadrants, $t(23) = 1.14$, $p = .268$, Cohen's $d = 0.232$. We conducted a Bayesian analysis for null results (Dienes, 2014; Morey & Rouder, 2011). This analysis produced the Bayes Factor B_{01}, which indexed how much more likely the observed data came from the null model relative to the alternative model. Values greater than 3 favor the null hypothesis, whereas values less than 0.333 favor the alternative hypothesis. In our study, the Bayes factor B_{01} (null vs. alternative hypothesis) was 3.47 in the comparison between C-rich and sparse, providing evidence in favor of the null hypothesis (Dienes, 2014; Morey & Rouder, 2011). Thus, once the task goal of saccading to the C-shape was removed, there was no longer any attentional preference for the C-rich quadrant.

Recognition test

Most participants – 17 out of 24 – successfully identified the C-rich quadrant during the recognition test, $\chi^2(1) = 26.89$, $p < .001$, suggesting that they were aware that the C-shape frequently appeared in one specific region. In contrast, just 5 of the 24 participants indicated that they thought the target's location was biased. On the forced-choice task, 8 of the 24 participants (33%) correctly identified the T-rich quadrant as the high-probability quadrant, a level that was not higher than chance, $\chi^2(1) = 0.89$, $p = .346$. This was numerically below the rate of explicit recognition in a previous study (42.2% in Jiang et al., 2018). However, because the recognition test used just a single forced-choice trial, it may have underestimated the degree of explicit awareness (Vadillo et al., 2020). The Appendix A contained additional analysis that split participants into aware and unaware participants based on their forced choice response. This analysis did not find evidence of increased LPL in aware relative to unaware participants.

Discussion

Experiment 1 provided strong evidence that experience-guided attention can be acquired in the presence of a spatially incompatible oculomotor signal. The accurate responses to the C-shape suggests that participants had followed the task goal of orienting to the C-shape. In addition, search RT was faster when the target appeared in the vicinity of the C-shape, confirming that participants attended to locations around the C-shape. Despite the C-shape appearing frequently in a region away from the target's high-probability region, participants successfully acquired LPL of the T-rich quadrant. The magnitude of LPL was comparable to that observed in previous studies (15% of RT saving in the present experiment, relative to 10-25% of RT savings found in Jiang, Swallow, et al., 2013). The effect persisted through the unbiased testing phase, ruling out short-term repetition priming as an adequate account of LPL. The presence of LPL in the face of a spatially incompatible saccadic eye movement suggests that LPL is relatively independent of oculomotor control.

The persistence of LPL in the testing phase could be contrasted with a lack of durable attentional preference for the C-rich quadrant, suggesting that frequently saccading to the C-shape was insufficient for inducing an automatic attentional bias. Thus, whereas repeatedly finding a target in a location produced LPL, frequently saccading toward a location based on instruction did not.

The robustness of LPL in Experiment 1 was striking, but the experiment design left two questions unanswered. First, although participants showed a spatial bias toward the C-rich quadrant during training, it is unclear whether this reflected endogenous orienting toward the C-rich quadrant, or exogenous orienting toward a singleton stimulus. The C-shape was unique in both color and shape, making it a candidate stimulus for exogenous orienting. This could lead to attentional capture and LPL of the C-shape. Previous studies showed that people learn to bias attention away from a singleton distractor (Britton & Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; B. Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019), suggesting that salient distractors may have briefly captured attention but are then suppressed (Gaspelin et al., 2015). The inhibitory effect may have counteracted any attentional preference for the C-rich quadrant, resulting in a lack of a persisting attentional preference in the testing

phase. To understand whether exogenous orienting had taken place in Experiment 1, it is important to repeat this experiment but render the C-shape task-irrelevant. Experiment 2 aimed to do this. Second, the online testing platform used in Experiment 1 prevented us from recording participants' eye movements. Although saccades were likely made toward the C-shape given its small size and short duration, we did not have eye data to corroborate this assumption. When in-person data collection resumed, we conducted Experiment 3 as a replication of Experiment 1 with the addition of eye tracking.

Experiment 2

This experiment was the same as Experiment 1, except that participants were not asked to perform any task on the C-shape. Instead, they performed a single task of finding the letter T. The C-shape was therefore a task-irrelevant singleton distractor. This design allowed us to examine whether the C-shape may have triggered exogenous orienting, as well as a learned attentional bias away from the C-rich quadrant.

The C-shape had several properties that made it a candidate stimulus for exogenous attention. In addition to having a common onset with the search items, it was the only black item on the display, the only stimulus with a curved line, and the only stimulus that abruptly offset after 300ms. If the C-shape was effective in capturing attention, we may expect search RT in the C-rich quadrant to be faster than in the sparse quadrants, at least early in the experiment. As training progressed, participants may develop a spatial attentional bias away from the C-rich quadrant, resulting in slower search RT in the C-rich relative to the sparse quadrants. However, other features of the C-shape may render it an ineffective stimulus for automatic attentional capture. First, because the C-shape was black and the other items were white, its luminance was low, reducing its visual salience. Second, the C-shape always differed from the target letter in color and shape, making it easy for participants to adopt an attentional set that did not include any features of the C-shape (Folk et al., 1992). Over time, participants may habituate to the C-shape and minimize attentional capture (Kelley & Yantis, 2009). If this is the case, then performance should be comparable between the C-rich and the sparse quadrants.

Method

Participants. Twenty-four new participants, including 20 females and 4 males with a mean age of 19.8 years (*SD* = 1.3), completed Experiment 2. The experiment was conducted using the same online platform as in Experiment 1.

Materials, procedure, and design. The experiment was identical to Experiment 1 except that participants were not asked to perform any task on the C-shape. In fact, the instructions did not mention the C-shape. Because the C-shape was task-irrelevant, there were no probe trials. Therefore, each of the 9 blocks contained 60 trials, all of which required visual search.

Recognition. The recognition test was similar to that of Experiment 1, except that participants were first asked whether they had noticed the C-shape. Participants made a forced-choice response among three options: (a) Yes, and I found the black C distracting; (b) Yes, but it did not bother me at all; and (c) No, I did not notice any black letters. Following this question, participants answered the same two recognition questions about the letter T's spatial distribution as those used in Experiment 1.

Results

Participants were equally accurate when the target was in the T-rich (*M* = 98.3%, *SE* = 0.3%), C-rich (*M* = 98.1%, *SE* = 0.3%), and the sparse quadrants (*M* = 97.8%, *SE* = 0.4%), $F(2, 46) = 1.34$, $p = .272$, $\eta_p^2 = .055$. In the RT analysis, we excluded incorrect trials. Figure 2.3A shows the mean RT across blocks.

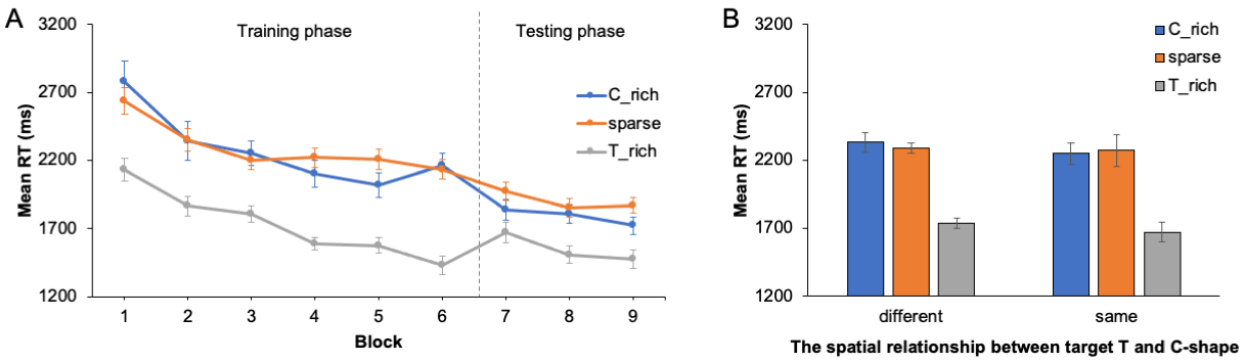

Figure 2.3 *Results from Experiment 2. (A) Search RT across blocks. The target T's location was biased toward the T-rich quadrant in Blocks 1-6 (training phase) and was unbiased in Blocks 7-9 (testing phase). The C-rich quadrant frequently contained the task-irrelevant C-shape in the training phase. The C-shape was removed in the testing phase. (B) Search RT in the training phase as a function of whether the target T and the C-shape appeared in the same quadrant or in different quadrants, and as a function of where the target T was. Error bars show ±1 within-subject SE of the mean.*

Training phase

An ANOVA using training block (1-6) and target location (T-rich, C-rich, or sparse) as within-subject factors showed a significant main effect of block, with faster RT as training progressed, $F(5, 115) = 15.04$, $p < .001$, $\eta_p^2 = .395$. The main effect of target location was also significant, $F(2, 46) = 37.46$, $p < .001$, $\eta_p^2 = .620$, an effect that did not interact with block, $F(10, 230) = 1.31$, $p = .227$, $\eta_p^2 = .054$.

To understand how RT differed across quadrants, we conducted three planned contrasts comparing the mean RT when the target was in the T-rich, C-rich, or the sparse quadrants. The critical alpha for these tests was $p < .0167$ to control for multiple comparisons. We found that RT was significantly faster in the T-rich quadrant than both the C-rich, $t(23) = 6.14$, $p < .001$, Cohen's $d = 1.253$, and the sparse quadrants, $t(23) = 12.46$, $p < .001$, Cohen's $d = 2.543$. RT did not differ between the C-rich and the sparse quadrants, $t(23) = 0.17$, $p = .870$, Cohen's $d = 0.034$, Bayes Factor B_{01} (null vs. alternative) = 6.29 in favor of the null hypothesis. This finding shows that participants developed a spatial bias toward the T-rich quadrant, but not toward the C-rich or the sparse quadrants.

If the C-shape had captured attention, then search should be faster if the target T appeared in the same, rather than a different, quadrant as the C-shape. To determine if this was the case, we separated trials based on whether the target T was in the same quadrant as the C-shape and which quadrant the target T was located (T-rich, C-rich, or sparse). This analysis (Figure 2.3B) revealed just a significant main effect of target location, $F(2, 46) = 26.20$, $p < .001$, $\eta_p^2 = .533$. The main effect of the T-C spatial relationship was not significant, $F(1, 23) = 1.86$, $p = .186$, η_p^2

= .075, meaning that RT was not faster when the T happened to be in the same quadrant as the C-shape than when they occurred in different quadrants. A Bayesian analysis for null hypothesis showed a Bayes factor B_{01} (null vs. alternative) of 4.64, providing evidence in favor of the null hypothesis. These two factors did not interact, $F(2, 46) = 0.08$, $p = .922$, $\eta_p^2 = .004$. Thus, there was no evidence that the C-shape effectively captured attention.

Testing phase

To find out whether participants had acquired a persisting spatial bias either toward or away from the C-rich quadrant, we examined the search RT data in the testing phase after the C-shape was removed and when T's spatial distribution was unbiased. An ANOVA on testing block (7-9) and target location (previously T-rich, C-rich, or sparse quadrants) as factors showed a significant main effect of block, $F(2, 46) = 4.88$, $p = .012$, $\eta_p^2 = .175$, with faster RT in later blocks than earlier ones. The main effect of target location was significant, $F(2, 46) = 15.02$, $p < .001$, $\eta_p^2 = .395$, but it did not interact with block, $F(4, 92) = 0.481$, $p = .750$, $\eta_p^2 = .020$.

Follow-up tests showed that search RT was significantly faster in the previously T-rich quadrant than both the C-rich and the sparse quadrants, $t(23) = 3.40$, $p = .002$, Cohen's $d = 0.694$ comparing T-rich with C-rich, and $t(23) = 5.58$, $p < .001$, Cohen's $d = 1.140$ comparing T-rich with sparse quadrants. The C-rich and sparse quadrants did not differ, $t(23) = 1.78$, $p = .088$, Cohen's $d = 0.363$. Bayesian analysis for null hypothesis yielded a Bayes factor B_{01} (null vs. alternative) of 1.51, a value that did not strongly support either the null hypothesis or the alternative. Thus, we were able to detect a persisting spatial bias toward the previously T-rich quadrant, but there was a lack of clear evidence for a persisting attentional bias toward the C-rich quadrant.

Across Experiment Comparisons

Other than the task-relevance of the C-shape, Experiments 1 and 2 were conducted under comparable conditions. To determine how this factor affected performance, we conducted an exploratory analysis that contrasted the two experiments. This comparison focused on the testing phase, which was identical other than what participants had experienced up to that point. We

performed an ANOVA using target location (previously T-rich, C-rich, or sparse) and testing block (7-9) as within-subject factors, and experiment (Experiments 1 vs. 2) as a between-subject factor. This analysis showed a significant main effect of target location, $F(2, 92) = 25.77$, $p < .001$, $\eta_p^2 = .359$, showing faster RT when the target appeared in the previously T-rich quadrant relative to the other quadrants. The main effect of testing block was not significant, $F(2, 92) = 1.72$, $p = .185$, $\eta_p^2 = .036$, neither was the main effect of experiment, $F(1, 46) = 1.29$, $p = .262$, $\eta_p^2 = .027$. LPL did not interact with experiment, $F(2, 92) = 1.47$ $p = .235$, $\eta_p^2 = .031$, or testing block, $F(2, 92) = 2.23$, $p = .113$, $\eta_p^2 = .046$, and there was no three-way interaction, $F(4, 184) = 0.49$, $p = .744$, $\eta_p^2 = .011$. Thus, the only persisting effect in both experiments was an attentional bias toward the previously T-rich quadrant. The need to overtly orient toward the C-shape, as was done in Experiment 1 but not in Experiment 2, did not have lasting effects on LPL.

Recognition

Even though the C-shape was presented several hundred times, the majority of the participants – 17 out of 24 – reported that they did not notice it. Of the 7 who reported noticing it, 4 found it distracting and the other 3 were not bothered. These 7 participants showed the same pattern of search behavior as the other participants (see the Appendix A). The general lack of subjective salience was consistent with the ineffectiveness of the C-shape in capturing attention.

In the awareness test of the T's spatial distribution, 11 participants said that they felt that it was more often in some locations than in others. In the forced-choice recognition test, 14 participants correctly identified the T-rich quadrant, a level that was significantly above chance, $\chi^2(1) = 14.22$, $p < .001$. A further analysis separating the 14 aware participants from the 10 unaware participants showed qualitatively similar results in search RT. Like aware participants, unaware participants developed an LPL toward the T-rich quadrant that persisted in the testing phase. Detailed analysis on recognition results can be found in the Appendix A.

Discussion

When the C-shape was task-irrelevant, it did not influence search RT in the training phase. Search was not faster when the target happened to be in the same quadrant as the C-shape.

The testing phase also did not uncover a persisting spatial bias either toward or away from the C-rich quadrant. Thus, the search advantage in the Experiment 1's C-rich quadrant can be attributed to endogenous orienting to the C-shape, rather than exogenous orienting to a singleton stimulus.

Why did we only observe an LPL for the target, but not an LPL for the singleton distractor? The finding may seem at odds with previous studies that reported LPL for salient distractors. For example, in Ferrante et al. (2018), participants searched for a target – a double arrow facing the same direction – among three distractors (double arrows facing opposite directions). On half of the trials, all items were red or green; on the other half of the trials, one distractor was in a different color (e.g., red) from the other items (e.g., green), making it visually salient (i.e., it is a color singleton). In one experiment, the target appeared disproportionately often in one of the four locations, and the color singleton appeared disproportionately often in another location. Participants demonstrated both types of learning: search was faster when the target appeared in the high target-probability location, but slower when it appeared in the high distractor-probability location, relative to the other two locations. Our study may seem inconsistent with Ferrante et al. (2018). However, the salient distractor in Ferrante et al. (2018) was part of the search array. Its color, though unique on a specific trial, could be the target's color on other trials. These features made the salient distractor not only partially task-relevant, but also confusable with the target. They increased the likelihood that participants would actively suppress the salient distractor in Ferrante et al. (2018). In contrast, the C-shape in the current study differed from the search items. This reduced its tendency to capture attention when it was task-irrelevant (as in Experiment 2). Even when it was task-relevant (as in Experiment 1), its distinction from the other search items made it unlikely that active suppression was needed. The use of a challenging T-among-L search task that exerted a high perceptual load may also have reduced attentional capture by the singleton stimulus (Forster & Lavie, 2008).

Having demonstrated that Experiment 1 reflected mainly endogenous orienting rather than exogenous orienting to the C-shape, in the next experiment we used eye tracking to both replicate Experiment 1's finding and characterize eye movements.

Experiment 3

Experiment 1 showed that the target's location probability learning was robust even when participants frequently saccaded away from where the target was most often placed. The online testing format, however, prevented us from obtaining eye movement data. The goal of Experiment 3 was to replicate these results in an in-person study with eye tracking. The eye data allowed us to verify that participants had made a saccade toward the C-shape. It also provided additional insights into the dynamics of search behavior, such as the frequency of first saccades toward each quadrant, saccade latency, and the direction of the second saccade.

Method

Participants. The 24 participants in Experiment 3 were from the same general population as those who did the earlier online experiments. There were 17 females and 7 males with a mean age of 20.5 years (*SD* = 3.6 years).

Equipment. Participants completed the experiment individually in a laboratory room with normal interior lighting. Viewing distance was kept at 90cm with the use of a chinrest. Stimuli were displayed on a 19-inch CRT monitor (spatial resolution: 1024 × 768 pixels; vertical refresh rate: 100 Hz). The experiment was programmed in MATLAB and Psychtoolbox (Kleiner, 2007). An EyeLink 1000 eye tracker (SR Research, Mississauga, ON, Cananda) tracked the left eye at a sampling rate of 1000 Hz. Eye position was calibrated using a 9-point calibration procedure before the experiment and verified with drift check before each trial.

Materials and Procedure. Other than being tested in-person with an eye tracker, participants in Experiment 3 went through the same procedure as those in Experiment 1. The stimuli and experimental design were identical as well. The only difference was the addition of an eye-position drift check before each trial. Specifically, to initiate each trial, participants first fixated at a central fixation point and pressed the spacebar. If the eye tracker verified their central fixation, the search display would appear on the screen. Re-calibration of eye position was conducted if needed.

Results

Behavioral results

The C-task. Participants responded to upward C-shapes 97.1% (*SE* = 0.5%) of the time, along with a false alarm rate of 1.1% (*SE* = 0.2%), for an overall accuracy of 98.8% (*SE* = 0.2%). The high accuracy in the C-task showed that participants had followed the instructions to orient toward the C-shape.

The T-task. Participants searched and responded to the T target on trials when the C-shape pointed downward. Search accuracy was uniformly high across all quadrants: T-rich (*M* = 99.1%, *SE* = 0.2%), C-rich (*M* = 98.8%, *SE* = 0.3%), and the sparse quadrants (*M* = 99.2%, *SE* = 0.1%), $F(2, 46) = 0.96$, $p = .392$, $\eta_p^2 = .040$. In the RT and eye data analysis, probe trials (i.e., with an upward C-shape) and incorrect search trials were removed. As is apparent from Figure 2.4, search RT results replicated those of Experiment 1.

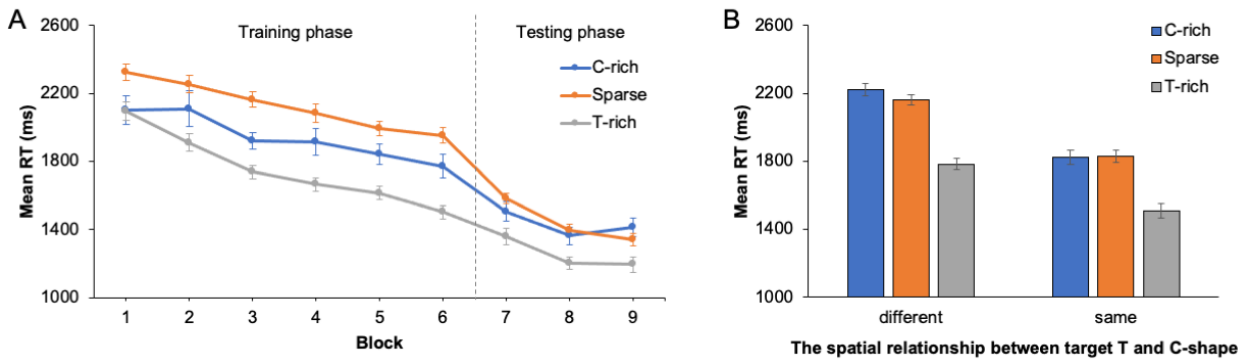

Figure 2.4 *Search RT from Experiment 3.(A) Search RT across blocks. The target T was presented more often in the T-rich quadrant in the training phase (Blocks 1-6) and was unbiased in the testing phase (Blocks 7-9). The C-shape appeared more frequently in the C-rich quadrant in the training phase and was removed in the testing phase. (B) Training phase RT as a function of whether the target T and the C-shape were located in the same quadrant, and where the target T was* [2]*. Error bars show ±1 within-subject SE of the mean.*

[2] The 6 bars shown in Panel B represented the mean RT of 6 types of trials. The number of trials falling into the 6 bars differed. In the 'same' location condition, the number of trials contributing to C-rich, Sparse, and T-rich conditions (assuming all trials received a correct response) was 18,

Training phase RT. An ANOVA on the target's location (T-rich, C-rich, or sparse) and training block (1-6) revealed a significant main effect of target location, $F(2, 46) = 29.74$, $p < .001$, $\eta_p^2 = .564$, a significant main effect of block, $F(5, 115) = 22.53$, $p < .001$, $\eta_p^2 = .495$, without an interaction between the two, $F(10, 230) = 1.06$, $p = .399$, $\eta_p^2 = .044$. Planned *t*-tests comparing the mean RT in the T-rich, C-rich, and sparse quadrants showed significant differences across all three conditions. Demonstrating LPL of the target's location probability, RT was faster in the T-rich quadrant than both the C-rich, $t(23) = 3.64$, $p = .001$, Cohen's $d = 0.743$, and the sparse quadrants, $t(23) = 8.66$, $p < .001$, Cohen's $d = 1.768$. Overt orienting toward the C-shape also affected search RT: RT was faster in C-rich quadrant than the sparse quadrants, $t(23) = 3.69$, $p = .001$, Cohen's $d = 0.754$. Thus, both LPL and endogenous orienting toward the C-shape affected search.

As in Experiment 1, we divided trials based on whether the target T appeared in the same quadrant as the C-shape, and where the T was located (T-rich, C-rich, or sparse). An ANOVA on these two factors (Figure 2.4B) again showed a significant main effect of T-C relationship, with faster RT when the letter T was in the same quadrant as the C-shape, $F(1, 23) = 110.72$, $p < .001$, $\eta_p^2 = .828$. The main effect of target location was significant, $F(2, 46) = 43.65$, $p < .001$, $\eta_p^2 = .655$, without an interaction, $F(2, 46) = 1.64$, $p = .206$, $\eta_p^2 = .066$. Thus, once participants had overtly oriented toward the C-shape, they tended to prioritize that region in the search for the letter T.

Testing phase RT. Results in the testing phase replicated those of Experiment 1. An ANOVA on target location (previously C-rich, T-rich, or sparse) and testing block (7-9) revealed significant main effects of target location, $F(2, 46) = 10.02$, $p < .001$, $\eta_p^2 = .303$, and block, $F(2, 46) = 19.71$, $p < .001$, $\eta_p^2 = .461$, without an interaction, $F(4, 92) = 0.99$, $p = .420$, $\eta_p^2 = .041$.

108, and 162, respectively. In the 'different' condition, the number of trials contributing to the C-rich, Sparse, and T-rich conditions was 42, 12, and 18, respectively. When all trials were considered, mean RT across conditions followed the same order as in Panel A (e.g., faster RT in the C-rich than the Sparse condition). However, differences in RT across conditions, in combination with an unequal number of trials, led to the 'same' and 'different' subsets of the data to have averages that did not always follow the same order.

Follow-up *t*-tests showed faster RT in the T-rich quadrant than both the C-rich, $t(23) = 3.29$, $p = .003$, Cohen's $d = 0.671$, and the sparse quadrants, $t(23) = 5.26$, $p < .001$, Cohen's $d = 1.073$. RT did not differ between the C-rich and the sparse quadrants, $t(23) = 0.25$, $p = .803$, Cohen's $d = 0.052$, Bayes Factor B_{01} (null vs. alternative) = 6.18 in favor of the null hypothesis. Thus, training induced a persisting LPL toward the T-rich quadrant, without evidence of a residual attentional bias toward the C-rich quadrant.

Eye movement results

The majority of the first saccadic eye movement – 86.5% (*SE* = 1.2%) – landed in the vicinity (i.e., same quadrant) of the C-shape, indicating that participants had prioritized the C-task and directed their eyes toward the C-shape. In the following analysis, we removed probe trials and trials with an incorrect search response. Of particular interest is how eye movements differed across visual quadrants in the visual search task.

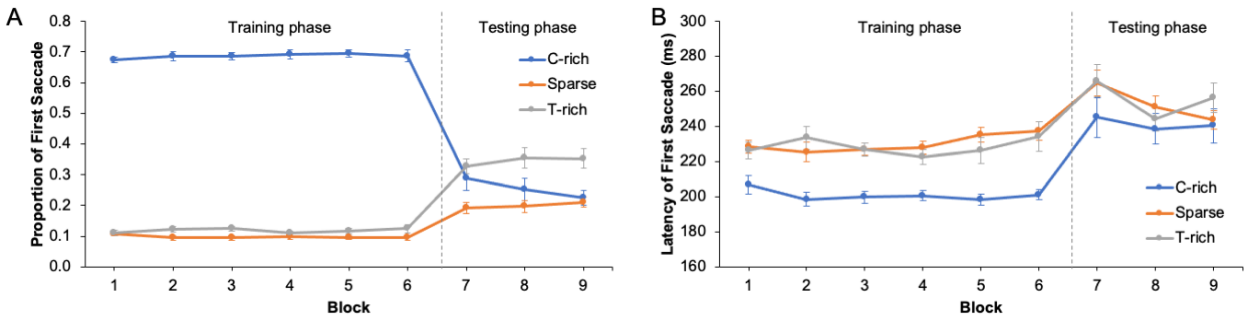

Figure 2.5 *First saccadic eye movements in Experiment 3. (A) Proportion of first saccadic eye movements landing in each quadrant. Note there were two sparse quadrants. The figure plots the average of the two. (B) Latency of the first saccadic eye movement on trials when it landed on the C-shape. Error bars show ±1 within-subject SE of the mean. The target T was presented more often in the T-rich quadrant in the training phase (Blocks 1-6) and was unbiased in the testing phase (Blocks 7-9). The C-shape appeared more frequently in the C-rich quadrant in the training phase and was removed in the testing phase.*

First saccades. Given that the C-shape was in the C-rich quadrant 70% of the time during training, it is not surprising that participants directed their first saccade toward that quadrant 68.6% (*SE* = 1.1%) of the time, showing good probability matching. The remaining trials showed a small preference for the T-rich quadrant (11.9%; *SE* = 0.7%), relative to either of the two sparse quadrants (9.8%; *SE* = 0.5%), $t(23) = 2.56$, $p = .017$, Cohen's $d = 0.523$. As seen in Figure 2.5A, these proportions were stable across all 6 training blocks. An ANOVA on first saccade quadrant and training block found just a main effect of quadrant, $F(2, 46) = 1220.36$, $p < .001$, $\eta_p^2 = .982$, no effect of block, $F(5, 115) = 1.50$, $p = .194$, $\eta_p^2 = .061$, and no interaction, $F(10, 230) = 0.63$, $p = .786$, $\eta_p^2 = .027$.

The preference for the C-rich quadrant in the training phase was additionally reflected in the latency of the first saccades. On trials when participants successfully directed their first saccades toward the C-shape, they did so more quickly if the C-shape was in the C-rich quadrant rather than in the other quadrants (Figure 2.5B). An ANOVA on quadrant and block (1-6) revealed a significant main effect of the saccade's quadrant, $F(2, 46) = 34.18$, $p < .001$, $\eta_p^2 = .598$, no effect of block, $F(5, 115) = 0.72$, $p = .610$, $\eta_p^2 = .030$, and no interaction, $F(10, 230) = 0.89$, $p = .546$, $\eta_p^2 = .037$.

Once the C-shape was removed in the testing phase, the first saccades no longer favored the C-rich quadrant. That quadrant received 25.5% (*SE* = 3.0%) of the first saccades, a level not different from chance, $t(23) = 0.16$, $p = .877$, Cohen's $d = 0.032$. Instead, there was a preference for the T-rich quadrant, which attracted 34.5% (*SE* = 2.6%) of the first saccades, a level that was significantly higher than chance, $t(23) = 3.63$, $p = .001$, Cohen's $d = 0.741$. Saccade latency in the testing phase showed no clear pattern, $F(2, 46) = 1.23$, $p = .301$, $\eta_p^2 = .051$, for the main effect of the saccade quadrant.

Consistent with the RT data, participants showed a strong oculomotor preference for the C-rich quadrant during training, but this effect did not persist in the testing phase. The only persisting oculomotor bias in the testing phase was toward the T-rich quadrant.

Second saccades. Because we instructed participants to direct their first saccades toward the C-shape in training, the first saccade direction reflected, for the most part, their ability to follow this instruction. It did not capture how participants would have spontaneously allocated

attention. The second saccadic eye movement provided insights into this question. Because the second saccade could be strongly influenced by where the first saccade landed on, in this analysis, we separated trials based on the landing location of the first saccade.

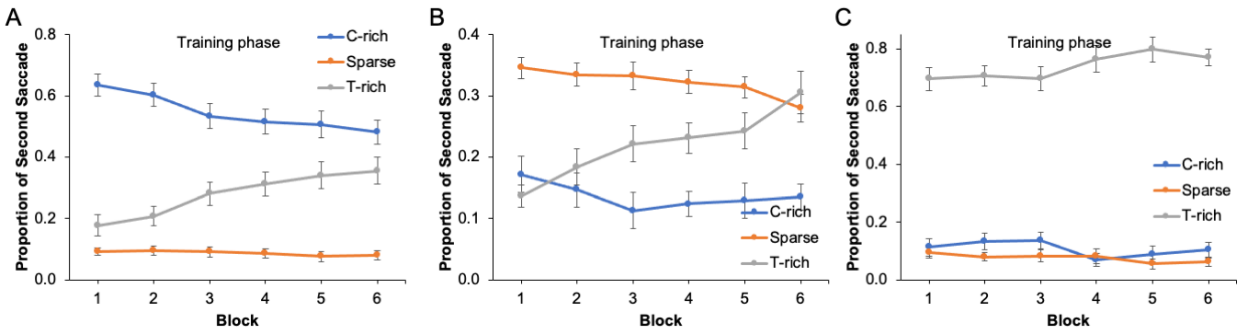

Figure 2.6 *Proportion of the second saccadic eye movement toward each quadrant in Experiment 3. The three panels separated trials based on where the first saccade was directed at: (A) the C-rich quadrant, (B) a sparse quadrant, and (C) the T-rich quadrant. Note that there were two sparse quadrants. The figures plot the average of the two. Error bars show ±1 within-subject SE of the mean.*

On the majority of the trials (68.6%), the first saccade landed on the C-rich quadrant. As shown in Figure 2.6A, on these trials, there was a strong tendency for the second saccade to remain in the C-rich quadrant. As training progressed, the tendency for the second saccade to stay in the C-rich quadrant waned while a tendency to direct the second saccade to the T-rich quadrant increased. An ANOVA on quadrant and training block revealed a significant main effect of quadrant, $F(2, 46) = 40.63$, $p < .001$, $\eta_p^2 = .639$. Although the main effect of block was not significant, $F(5, 115) = 0.83$, $p = .534$, $\eta_p^2 = .035$, there was a significant interaction between quadrant and block, $F(10, 230) = 10.92$, $p < .001$, $\eta_p^2 = .322$, reflecting a rising tendency to saccade toward the T-rich quadrant.

A similar pattern of results was found on trials when the first saccade landed on one of the two sparse quadrants (19.5% of the trials). On these trials, the second saccade tended to remain in the sparse quadrant. But over the course of training, this tendency weakened as the tendency to saccade toward the T-rich quadrant strengthened. An ANOVA on quadrant and

training block again revealed a significant main effect of quadrant, $F(2, 46) = 20.23$, $p < .001$, $\eta_p^2 = .491$, as well as a significant interaction between quadrant and block, $F(10, 230) = 3.19$, $p < .001$, $\eta_p^2 = .122$.

Finally, when the first saccade landed on the T-rich quadrant (11.9% of the trials), the second saccade tended to remain there. This pattern was maintained throughout training, yielding a main effect of quadrant, $F(2, 46) = 322.09$, $p < .001$, $\eta_p^2 = .933$, but no quadrant by block interaction, $F(10, 230) = 1.36$, $p = .202$, $\eta_p^2 = .056$.

Thus, on top of a preference for looking in the vicinity of the first saccade, participants also developed a tendency to direct the second saccade toward the T-rich quadrant as training progressed.

Recognition

In the recognition test, 7 of the 24 participants reported that the target T appeared more often in some locations than in others. In the forced-choice recognition test, 11 of the 24 participants correctly identified the T-rich quadrant, a level higher than chance, $\chi^2(1) = 5.56$, $p = .018$, but comparable to previous reports (Jiang et al., 2018). A further analysis comparing aware and unaware participants revealed no interaction between awareness status and other factors on search RT. Detailed analysis on the role of awareness can be found in the Appendix A.

Discussion

Experiment 3 replicated key findings from Experiment 1 while ensuring that participants had overtly oriented toward the C-shape. This initial saccade led to faster search RT when the target was in the C-rich relative to the sparse quadrants. However, it did not yield a persisting attentional bias toward the C-rich quadrant. It also did not prevent participants from acquiring LPL toward the target-rich quadrant.

The eye data in Experiment 3 ruled out the possibility that instead of being spatially incompatible, the first saccade toward the C-rich quadrant was integrated with the next saccade toward the T-rich quadrant. On this account, participants may have acquired a habit of sequentially saccading first to the C-rich quadrant and then to the T-rich quadrant. The eye

tracking data are inconsistent with this complex, "C-then-T," search habit. First, after directing the first saccade to the C-rich quadrant, participants did not habitually saccade to the T-rich quadrant. Instead, they had a strong tendency to keep the second saccade in the C-rich quadrant. The proportion of trials where eye movements followed the "C-rich, then T-rich" sequence was low – a mere 22.5% even at the end of training. Second, if participants had acquired the "C-then-T" oculomotor habit, then in the testing phase they should have retained the habit of directing their first saccade toward the C-rich quadrant. Our data did not show such persistence.

The robustness of LPL may, in part, be attributed to the sequential nature of the oculomotor and the search tasks. After all, the search task commenced only after the C-task had completed. Nonetheless, both RT and eye movements showed evidence of dependency between the two tasks. Search RT was faster when the target happened to be in the vicinity of the C-shape, suggesting that participants preferentially attended to that region. In addition, after participants fixated on the C-shape, they were highly likely to direct the next eye movement to an item near the C-shape (i.e., within the same quadrant). Both measures showed that the initial oculomotor response to the C-shape altered the starting state of visual search. Unlike standard LPL studies where participants initially fixated at the center and could start search from anywhere, in our study, there was a strong tendency for search to start from the C-rich quadrant. The sequential dependency between the two tasks suggests that the initial oculomotor response altered how participants subsequently conducted visual search. The preservation of LPL under this condition provides, to date, the strongest evidence that the search habit underlying LPL is a high-level mechanism abstracted from an oculomotor habit.

General Discussion

The strong connection between eye movements and attention has led researchers to ask whether eye movements are necessary for covert attentional selection. When this question was posed in the context of endogenous or exogenous attention, studies have uncovered partial independence of attention from eye movements. For example, people can preferentially attend to locations outside of the eyes' reach (Hanning et al., 2019; Hanning & Deubel, 2020; also see Craighero et al., 2004). Neuropsychological patients who suffer from paralysis to the eyes

nonetheless benefit from attentional cueing (Masson et al., 2020). These studies, however, have primarily focused on attention driven by task goals or perceptual salience. Using a location probability learning (LPL) paradigm, here we examined the relationship between goal-directed eye movements and a third driver of attention: experience-driven attention. Our results showed that LPL was preserved even when participants had to frequently saccade away from the target-rich locations.

In Experiment 1, participants were instructed to first look at a small C-shaped object presented frequently in one, C-rich quadrant. They then searched for a letter T that most often appeared in a different, T-rich quadrant. The goal-directed eye movement was spatially incompatible with the habit of searching in the T-rich quadrant. Nonetheless, participants acquired LPL, as reflected by faster search RT when the T appeared in the T-rich rather than the other quadrants. This effect persisted in an unbiased testing phase during which the T was equally likely to appear in all quadrants. In contrast, although participants exhibited faster RT in the C-rich quadrant during training, once the C-shape was removed in the testing phase, the attentional preference for the C-rich quadrant ceased. Thus, repeatedly finding a target, but not repeatedly looking in a specific direction, produced lasting attentional biases.

Experiment 2 tested whether the C-shape, which was a shape and color singleton, had influenced performance in a bottom-up manner. Participants were not asked to perform any task on the C-shape. Under this condition, search was unaffected by the location of the C-shape, or its biased spatial distribution. Unlike some previous studies (e.g., Ferrante et al., 2018), in Experiment 2, participants did not acquire a spatial bias away from the C-rich quadrant. This may be attributed to the lack of featural overlap between the C-shape and the search items, enabling participants to effectively filter out the C-shape. In the absence of potent attentional capture, we did not observe evidence for LPL of the singleton distractor. LPL for the search target, however, was robust. This finding suggests that spatial orienting toward the C-shape in Experiment 1 was endogenously driven rather than exogenously driven. It is important to note that the lack of LPL for the C-shape in Experiment 2 does not rule out the possibility that participants can acquire LPL for distractors. In fact, accumulating evidence supports the idea that LPL applies both to frequent target locations and to frequent distractor locations (Britton &

Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; B. Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019). Experiment 2 only indicates that the stimuli used in our study did not trigger LPL of the task-irrelevant singleton.

Using eye tracking, Experiment 3 replicated the findings of Experiment 1 and validated the assumption that participants preferentially moved their eyes toward the C-shape. First saccades landed in the vicinity of the C-shape on a vast majority of the trials. In addition, on trials when participants fixated on the C-shape, they did so with faster saccade latency if the C-shape was in the C-rich quadrant than elsewhere, demonstrating sensitivity to the C-shape's biased spatial distribution. Yet much like search RT, as soon as the C-shape was removed, first saccades no longer favored the C-rich quadrant. Instead, first saccades in the testing phase were disproportionately directed to the T-rich quadrant. Sensitivity to the T's spatial distribution additionally manifested in the second fixation in the training phase. After participants had fixated the C-shape, they tended to saccade to another location in the same quadrant, showing sequential dependency between two successive saccades. Nonetheless, as training progressed, the tendency to remain in the same quadrant weakened while a tendency to saccade toward the T-rich quadrant strengthened.

These results provide insights into several mechanisms associated with LPL. First, the findings help clarify the nature of search habit that is acquired through LPL. This habit has been conceptualized as an attentional vector that is preferentially directed toward the target-rich region. The degree to which this habit is linked to oculomotor control, however, was unclear. LPL often produces both faster search RT in the target's high-probability quadrant and an oculomotor habit of saccading toward that quadrant (Jiang, Won, et al., 2014). On the other hand, LPL can be acquired even when participants must maintain central fixation during the search task (Geng & Behrmann, 2005), suggesting that frequently moving one's eyes toward the high-probability region is unnecessary for learning. By requiring participants to frequently look in a direction away from the target-rich quadrant, the current study provides even stronger evidence that LPL is partially dissociated from an oculomotor habit. These findings suggest that LPL reflects a relatively high-level search habit, one that's not completely instantiated in eye movements.

Second, our study also showed that a habit of saccading to one location is insufficient for inducing a lasting attentional bias toward that region. In our Experiments 1 and 3, participants frequently looked in the direction of a C-rich quadrant. Yet once the C-task was removed, this tendency ceased: search RT was no longer faster in the previously C-rich quadrant than in the other quadrants, neither was there a persisting oculomotor habit of saccading toward the C-rich quadrant. The lack of a persisting oculomotor habit can be contrasted with the presence of LPL in the testing phase. This finding suggests that LPL results from successful target detection, rather than frequent overt orienting toward a certain location or direction. This finding is consistent with theoretical proposals from a different experimental paradigm – the attentional boost effect. In that paradigm, successfully detecting and responding to a target boosts memory for concurrently presented background images (J. Y. Lin et al., 2010; Swallow & Jiang, 2010, 2013). Seitz and Watanabe (2005) proposed that successful target detection triggers reinforcement learning of concurrently presented stimuli. Such reinforcement learning may also occur in visual search tasks, reinforcing the spatial attentional shifts that lead to successful target detection (Jiang, Swallow, et al., 2013).

Third, our study clarifies the relationship between goal-directed attention and LPL when these two sources of attention occur in close temporal proximity. In our design, participants must first endogenously orient toward the C-shape, followed immediately by the search task, with attention guided by previous experience of the target's location probability. We showed that LPL was preserved under this condition, even though the initial task goal produced endogenous orienting away from the target-rich region. As shown in the eye movement data, the C-task and the subsequent search showed sequential dependency. Following the initial saccade to the C-shape, participants were strongly likely to start search in the vicinity of the C-shape, meaning that their starting search location was frequently not where the target was. Nonetheless, LPL was observed in this condition, suggesting that it is, in part, independent of goal-driven attention. Our design does not inform us how LPL interacts with goal-driven attention when the two cues are concurrent rather than sequential. A previous study that cued participants to the target's likely location using a central arrow found the co-existence of both goal-driven attention and LPL

(Geng & Behrmann, 2005). Additional studies are needed to further elucidate the summation of goal-driven attention and LPL when both sources exist to affect visual search.

To summarize, by introducing biased spatial distributions to both an oculomotor target and the search target, this study helped elucidate the interaction between different drivers of spatial attention. Although the oculomotor target led to voluntary spatial attentional shift and sped up search in its vicinity, it did not yield a persisting spatial bias toward that region. In addition, frequently looking away from the target-rich region did not prevent participants from developing LPL. Our results showed that experience-guided attention is robust in the face of spatially incompatible oculomotor signal. These results are in line with the modular view of attention, suggesting that the search habit derived from LPL is, in part, a high-level process abstracted from eye movements. At an applied level, our finding raises the possibility that LPL may facilitate attentional allocation in patients with a vision impairment that restricts or impairs their eye movements.

3. Study 2: Looking away to see: The acquisition of a search habit away from the saccade direction

Visual search in daily activities often occurs with a sequence of eye movements that bring important objects to the fovea. Study 1 shows that frequently looking toward a region does not induce a habitual spatial bias of searching in that region. Instead, a habit of searching in a specific region emerges only as a result of frequently finding a target in that region. Importantly, frequently looking away from the target high-probability region did not prevent participants from acquiring location probability learning. Thus, location probability learning is robust in the face of a spatially incompatible saccade, suggesting that experience-guided attention is independent of goal-driven oculomotor control. These findings are in line with the modular theory of attention, which conceptualizes the search habit as a high-level process abstracted from eye movements (Posner & Dehaene, 1994).

Study 1 used a dual-task paradigm to combine an oculomotor task and visual search to introduce the misalignment between eye movements and experience-guided attention. However, one limitation was the sequential nature of the oculomotor and the visual search tasks. Participants always performed the saccade task first, then searched for the target letter. Though the saccade prior to the search was incompatible with the subsequent search habit, the saccade had already finished when participants searched for the target. The sequential nature of the two tasks may have allowed participants to acquire a separate search habit from the initial saccade direction.

To address the limitation noted above, Study 2 examined whether people can acquire a search habit toward a location that is incongruent with the current saccade direction. If experience-guided attention is independent of oculomotor control, then it may remain robust in participants with a simulated vision deficit that restricts the visible region to an area opposite from the current gaze.

Study 2 is currently under peer-review: Chen, C., & Lee, V. G. (under review). Looking away to see: The acquisition of a search habit away from the saccade direction. *Vision Research*. The article is reproduced here.

Looking away to see: The acquisition of a search habit away from the saccade direction

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Preface

Growing evidence has shown that attention can be habit-like, unconsciously and persistently directed toward locations that have frequently contained search targets in the past. The attentional preference typically arises when the eye gaze aligns with the attended location. Here we tested whether this spatial alignment is necessary for the acquisition of a search habit. To divert eye movements away from an attended location, we used gaze-contingent eye tracking, restricting the visible portion of the screen to an area opposite to the current gaze. Participants searched for a T target amidst a circular array of L distractors. Unbeknownst to them, the target appeared more frequently in one screen quadrant. Despite fixating on a location diametrically opposite to the visible, attended region, participants acquired probability cuing, producing quicker responses when the target appeared in the high-probability quadrant. They also showed a speed advantage in the diagonal quadrant. The attentional preference for the high-probability quadrant persisted during a testing phase in which the target's location was unbiased, but only when participants continued to search with the restricted view. These results indicate that a search habit can be acquired even when participants are required to look away from the high-probability locations. The finding suggests that the learned search habit is not solely a result of oculomotor learning.

Keywords: spatial attention, visual search, selection history effects, location probability learning, eye movements

Introduction

Although we can find an object without looking directly at it, visual selection often involves a series of eye movements that bring the desired object into the fovea (Kowler, 1995). The strong relationship between attention and eye movements has prompted vision scientists to ask whether eye movements are necessary for attention. The *premotor theory of attention* suggests that they are, proposing that eye movements and visual selection share the same neural mechanisms (Rizzolatti et al., 1987). Consistent with this view, brain imaging studies have demonstrated the involvement of the frontal eye fields, lateral intraparietal cortex, and other frontoparietal regions in both goal-driven attention and oculomotor control (Bisley & Mirpour, 2019; Corbetta et al., 1998; de Haan et al., 2008). Eye-tracking studies have indicated a preference for attending to the location of a saccade goal (Hoffman & Subramaniam, 1995). In addition, participants have difficulty covertly attending to a far peripheral location beyond the range of eye movements (Craighero et al., 2004; Smith et al., 2010, though see Smith et al., 2012; Hanning et al., 2019). Despite these strong connections, it is possible to covertly attend to a peripheral location while maintaining central fixation (Posner, 1980). Posner and Dehaene (1994) propose the *modular theory of attention*, according to which attention is a high-level cognitive function independent of the oculomotor circuit. Consistent with this view, patients with impaired oculomotor control still benefit from covert attentional orienting (Masson et al., 2020). Additionally, both humans and nonhuman primates are capable of voluntarily saccading away from a visual target that they covertly attend to, as demonstrated in antisaccade tasks (Hallett & Adams, 1980; Munoz & Everling, 2004). Single-unit recordings from nonhuman primates have revealed distinct populations of neurons in the frontal cortex associated with covert orienting and saccade production (Messinger et al., 2021; Thompson, 2005). Collectively, these studies suggest a close coupling as well as partial independence between attention and eye movements.

The aforementioned studies have focused on transient forms of attention, such as attention driven by perceptual salience or the observer's immediate goals. Increasing evidence has uncovered a third driver of attention – one's prior experience (Addleman & Jiang, 2019; Awh et al., 2012). For example, repeatedly finding a visual search target in a particular spatial region produces an attentional preference for that region, known as location probability learning

or “probability cuing” (Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Jiang et al., 2013; Wang & Theeuwes, 2018). The high-probability locations are not perceptually salient, nor do they engage goal-driven attention, as observers are often unaware of the target’s location probability. Theoretical accounts have connected probability cuing to the acquisition of a search habit, the dynamic tendency to shift attention towards the high-probability region (Addleman & Jiang, 2019; Jiang, 2018; Jiang & Sisk, 2019). Because other forms of habits are often motoric (Graybiel, 2008), it is possible that probability cuing involves the oculomotor circuit. In fact, probability cuing is accompanied by the development of an oculomotor preference. Participants not only locate the target more rapidly in the high-probability region but also are more likely to direct their initial saccadic eye movement at trial onset toward that region (Addleman et al., 2021; Addleman & Lee, 2022; Chen & Lee, 2022; Jiang et al., 2014). The concept of a learned dynamic search habit raises the possibility that probability cuing, as a form of experience-guided attention, reflects solely oculomotor learning.

However, several studies have found that probability cuing can emerge even in the absence of overt eye movements. For example, participants successfully acquired probability cuing even when instructed to refrain from making eye movements (Geng & Behrmann, 2005). Furthermore, some studies presented the visual search display for less than 200ms, a duration insufficient for saccadic eye movements. Nonetheless, participants acquired probability cuing (Addleman et al., 2018, 2019; Jiang & Swallow, 2013). These findings suggest that overt eye movements towards the high-probability location are unnecessary for the acquisition of a search habit. However, it is possible that participants may have programmed an eye movement towards the high-probability location, even though it was not executed. This oculomotor signal may be adequate to facilitate probability cuing. Without an incompatible oculomotor signal pointing towards a different location, it is impossible to exclude the possibility that the search habit relies on saccadic programming.

Three recent studies have tried to alter the conventional alignment between attention and eye movements, producing inconclusive results. Addleman et al. (2021) asked participants to find a letter T target among letter Ls, presented against a natural scene. Unbeknownst to the participants, the target letter appeared in a high-probability quadrant 50% of the time and in each

of the other three low-probability quadrants 16.7% of the time. To simulate central vision loss, Addleman et al. (2021) introduced an artificial central scotoma that blocked visual signals from the central 6.7º. This procedure prevented participants from seeing anything that they were fixating on, disrupting the correspondence between fixation and the attended location. Addleman et al. (2021) found that participants who became spontaneously aware of the target's biased spatial distribution acquired probability cuing, whereas those who remained unaware did not. Thus, preventing participants from using their central vision disrupted implicit location probability learning. However, this finding was not replicated in a subsequent study with a similar design (Addleman & Lee, 2022). This second study modified the search task by removing the background scene, thereby eliminating feedback to participants regarding their fixation location. In this modified design, both aware and unaware participants successfully acquired probability cuing. Hence, the habit of searching the high-probability region can be acquired under some circumstances even when direct fixation on the search target is not possible. However, because the artificial scotoma was positioned at the center of fixation, Addleman et al.'s task did not require participants to consistently shift their gaze away from the target. This means that eye movements and attention were not always spatially misaligned.

To divert eye movements away from the high-probability region, Chen and Lee (2022) conducted a dual-task experiment that combined an oculomotor task with a visual search task. Each trial of the search display contained a saccade target – a briefly presented black C-shaped object - and white search items (one target T and several distractor Ls). The participants' task was to immediately saccade towards the black C to determine the direction of its gap. Occasionally, the black C was oriented downward, prompting the participants to press the spacebar to end the trial. Most of the time, the black C was oriented upward, requiring participants to locate the target T and report its orientation. Importantly, Chen and Lee (2022) introduced two biased spatial distributions: the saccade target (the black C) was highly likely to be in a C-rich quadrant, while the search target (the white T) was highly likely to be in a different, T-rich quadrant. Thus, throughout several hundred trials, participants had to frequently direct their gaze toward the C-rich quadrant, a direction incompatible with covert attentional orienting towards the T-rich quadrant. Nonetheless, participants successfully acquired

probability cuing – search RT was faster when the target T appeared in the T-rich quadrant rather than in other quadrants. Furthermore, once the C-shape was removed and the target's spatial distribution became unbiased, the only remaining attentional bias was towards the T-rich quadrant. In other words, frequently looking towards the C-rich quadrant failed to produce a persisting search preference for that quadrant. Instead, a search habit emerged towards the T-rich quadrant, even though it was inconsistent with the frequent saccade direction.

Chen and Lee (2022) presented the most compelling evidence to date that people can acquire a covert search habit even when the attended location and eye gaze are misaligned. However, one limitation of the study was the sequential order of the saccade task and the search task. The saccade task was always conducted first, with the saccade target acting as a Go/No-Go signal for the subsequent visual search. Thus, although the saccade direction prior to the search conflicted with the subsequent search habit, the saccade task had already concluded by the time participants initiated the search for the target. The sequential nature of the two tasks may have allowed participants to acquire a distinct oculomotor habit from the initial saccade direction.

The studies reviewed raise an important question regarding whether people can acquire a search habit towards a location that contradicts the saccade direction. This question is important for understanding the nature of implicitly guided attention, specifically, whether probability cuing is solely attributed to oculomotor learning or whether it incorporates an abstract, higher-level component that is separate from eye movements. While previous studies have demonstrated partial independence between eye movements and attention (e.g., the ability to attend to both the saccade target and a non-saccade target location; Castet et al., 2006; Deubel, 2008; Moehler & Fiehler, 2014, 2015, 2018; Montagnini & Castet, 2007), these studies primarily focused on goal-driven attention rather than implicitly guided attention. Given the strong association between location probability learning and oculomotor habits, it is crucial to investigate whether implicitly guided attention, similar to goal-driven attention, exhibits partial independence from oculomotor control.

In natural viewing, we typically locate a target by looking directly at it. Researchers have successfully developed models, such as the Bayesian Ideal Observer model (Najemnik & Geisler, 2005) and the maximum a posteriori model (Najemnik & Geisler, 2008), that capture

gaze behavior in search tasks. Optimal eye movement strategies in these models include fixating on locations that currently have the highest posterior probability of containing the target or fixating on locations with the maximum information gain about target's location (e.g., fixating near the centroid of a cluster of locations with the highest probability of containing the target and avoiding previously fixated locations). While these models effectively capture gaze behavior in natural viewing, deviations from the ideal have been reported (Nowakowska et al., 2017). However, less is understood about gaze behavior when visible regions do not align spatially with gaze locations.

Eye-tracking technology has made it possible to restrict the visible regions of the visual field to locations opposite to the current fixation. This experimental setup resembles the antisaccade task commonly used to investigate cognitive control (Everling & Fischer, 1998; Hallett & Adams, 1980), where the visible region is limited to the opposite location from the current fixation. Unlike the explicit instructions given in the antisaccade task, which prompt participants to saccade towards the opposite side of the stimulus, our study did not inform participants of the relationship between the visible region and their fixation, so participants were not deliberately attending to a location away from their fixation. Nevertheless, successful searches required participants to divert their gaze away from the high-probability region while simultaneously maintaining their attention on it. This created conflicting signals for oculomotor control and spatial attention.

Figure 3.1A illustrates the experimental design used in the training phase of the study. Each search display consisted of eight items evenly spaced in a circular array indicated by placeholders. The task was to find the letter T and report its orientation. Unbeknownst to the participants, the T appeared in one, high-probability quadrant 50% of the time, and in each of the other low-probability quadrants 16.7% of the time. In addition, an eye tracker detected the current fixation location and restricted the visible area to only the 1-2 letters opposite to the fixation. For example, if a participant fixated on a circle in the lower-left quadrant, the letters in the upper right quadrant, diagonal from their fixation, became visible. As their fixation changed, the previously visible letters became hidden, while other letters, always diagonally opposite to the current fixation, became visible. This gaze-contingent setup produced "tunnel vision" where

the visible region was confined to a small circle of 6.7º, but importantly, this area was consistently positioned opposite to the current fixation.

Our experiment design introduced spatial incongruence between overt eye movements and covert attention. This design enables us to test whether the spatial alignment between the saccade direction and the attended (target) location is necessary for probability cuing. Consider the display illustrated in Figure 3.1A, where the upper right region serves as the high-probability quadrant. Finding the target in the upper right is associated with fixating on the lower left. As the training progresses, successful target detection becomes increasingly linked to two factors: (1) attending to the target in the upper right and (2) fixating on the lower left. If the acquisition of a search habit for a particular region solely depends on moving one's eyes towards that region, it would be difficult, if not impossible, for participants to develop a spatial bias toward the high-probability target region. In contrast, if probability cuing has an abstract, higher-level component, participants may still develop an attentional preference for the upper right, even though successful target detection necessitates moving their eyes to the lower left.

In addition to investigating the necessary conditions for acquiring a search habit, our study also explored the persistence of the learned habit after removing the biased spatial distribution. During the testing phase, the target had an equal probability of appearing in all locations. Because habits tend to persist beyond the initial reinforcement period (Graybiel, 2008), a search habit towards a region may persist in the unbiased testing phase. However, habits are often context-specific (Wood & Rünger, 2016), meaning that a change in the task or context could lead to their elimination. Thus, we divided participants into two groups for the unbiased testing phase. One group continued to search with the restricted view, maintaining the same task context (Figure 3.1B). The other group searched with an unrestricted view, meaning that all items were visible at all times (Figure 3.1C). We examined whether the learned search habit persisted when the task context was preserved and when it changed.

Our novel paradigm has implications for eye movement training. The antisaccade-like setup raises the question of how the eyes adapt to this unusual task demand. The visual system and visuomotor coordination are remarkably adaptive, as demonstrated by various artificial tasks like prism adaptation (Redding et al., 2005; Rossetti et al., 1998), simulated low acuity (Bochsler

et al., 2012), and augmented reality (Bao & Engel, 2019). Eye movements, too, can be trained, as seen in cases where patients with macular-degeneration learn to control their eye positions during reading (Seiple et al., 2005) or patients with hemianopia learn to systematically scan the visual field (Mannan et al., 2010). In our study, the biased spatial distribution of the search target means that saccading toward the diagonal quadrant is optimal for finding the target. The tendency to saccade in that direction may be reinforced, resulting in an increased tendency to saccade toward the diagonal quadrant. By measuring the direction of the first saccadic eye movements after trial onset and analyzing other aspects of oculomotor behavior, our study provides an opportunity to examine eye movement training.

Our study findings may provide insights into the development of a preferred retinal locus (PRL) in individuals with macular degeneration. In macular degeneration (MD), the loss of central vision occurs due to cell loss in the macular region of the retina that includes the fovea. Many patients with MD develop PRLs in a region of peripheral vision. However, the idiosyncratic nature of PRLs has remained a puzzle. The specific locations of PRLs are variable across patients: PRLs do not typically correspond to the areas of the retina with the highest acuity or the part of the visual field of most functional significance (e.g., lower visual field). Additionally, PRLs may not always be optimal for important tasks like visual search, reading, and navigation. When central vision is artificially eliminated in normally sighted people using a gaze-contingent paradigm, participants also develop an idiosyncratic PRL after explicit training (Kwon et al., 2013). The location of the PRL has some correspondence with individual differences in regions of high attentional acuity, though this correspondence is not perfect (Barraza-Bernal et al., 2017). To date, no studies have examined how attention training interacted with the development of the PRLs. By separating gaze location from visible regions, the current study contributes to an understanding of attention training, potentially shedding light on the mechanisms underlying the development of PRLs in patients with macular degeneration.

Methods

Participants

A prespecified sample size of 48 was used in the experiment. The sample size was determined based on Cohen's *f* of 0.48 in Experiment 2 (training with scotoma) of Addleman and Lee (2022). G*Power analysis (Faul et al., 2007) showed that a minimum of 17 participants was needed to reach a power of .95, with an alpha-level of .05 in a two-tailed test.

Forty-eight participants were tested in the experiment to counterbalance the testing conditions and quadrant assignments across participants. All participants were students from the University of Minnesota who volunteered their time for extra course credit or monetary compensation. They were naive to the purpose of the study and were fluent in English and had normal or correct-to-normal vision. The study received Institutional Review Board approval from the University of Minnesota and all participants provided written informed consent. The participants included 29 females and 19 males, with a mean age of 19.8 years (*SD* = 3.3 years).

Equipment

Participants completed the experiment individually in a room with normal interior lighting. They maintained a viewing distance of 90 cm using a chinrest. The visual stimuli were presented on a 19-inch CRT monitor with a spatial resolution of 1024 × 768 pixels and a vertical refresh rate of 100 Hz. The experiment was coded with MATLAB and Psychtoolbox (Kleiner, 2007). Monocular eye tracking of the left eye was performed using an EyeLink 1000 eye tracker (SR Research, Mississauga, ON, Canada) at a sampling rate of 1000 Hz. Eye position was calibrated using a 9-point calibration procedure before the experiment and verified with an eye-position drift check before each trial. The eye tracker automatically detected saccades, defined as eye movements with an instantaneous velocity exceeding 30º/s, acceleration surpassing 8000º/s^2, and motion larger than 0.1º.

The eye tracker enabled gaze-contingent eye-tracking in real time, limiting the visual display based on the current fixation position. The precision of real-time adjustment was validated in Addleman et al. (2021), who asked participants to identify the gap direction (up, down, left, or right) of a small C-shape presented in the periphery. When participants had

unrestricted vision and could freely look at the gap, they achieved 91% accuracy. However, when an artificial central scotoma was imposed using gaze-contingent eye tracking, performance declined to 26%, indicating chance-level accuracy. Thus, the eye tracker was highly accurate in detecting the gaze location for gaze-contingent visual presentation. Our study used the same equipment and technical setup as described by Addleman et al. (2021).

Stimuli

Figure 3.1 depicts the visual search display. Each display consisted of eight letters: one T and seven Ls (0.9° × 0.9°), evenly spaced in a circular array (4.5° in radius) against a gray background. Circular placeholders (1.8° × 1.8°) were constantly visible. The target T was randomly rotated to the left or the right with equal frequency. The orientation of the Ls was chosen randomly from four possible orientations (0°, 90°, 180°, or 270°). The experiment employed gaze-contingent eye tracking to restrict the visible portion of the letters to a circular region with a diameter of 6.7°, entered on the location opposite (180°) from the current gaze position. Specifically, upon detecting the current gaze position (sampled at 1000 Hz), we rotated that location 180º about the center of the screen and drew a visible region, a circle 6.7º in diameter, around it. To update the location of the visible region, we used MATLAB codes to extract eye gaze location every screen refresh (100 Hz). The visible region was re-drawn if the current eye position differed by 8 pixels or more (in either the x- or y- direction) from the eye position 10ms ago. There were no remnants of visible stimuli at the previous location.

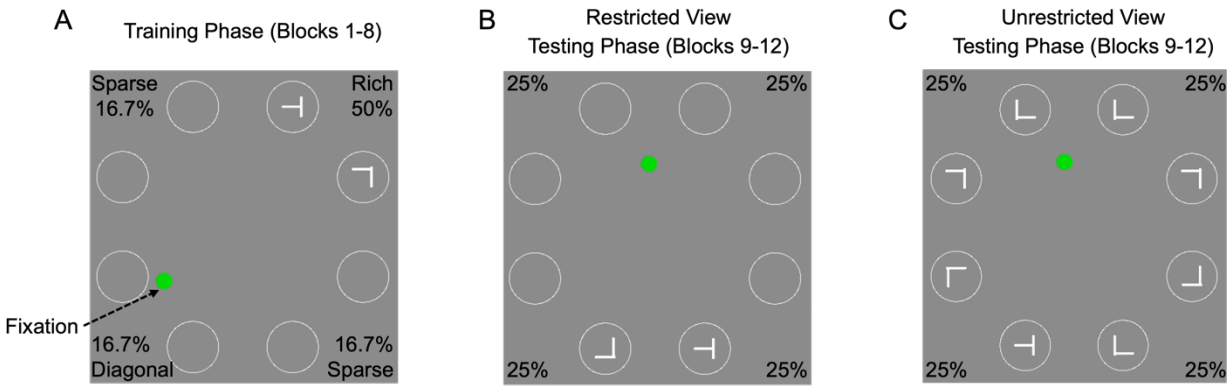

Figure 3.1 *A schematic of stimuli and design. (A) During training (Blocks 1-8), participants performed a T-among-Ls search task to report the orientation of the target T. The target T appeared more frequently (50% of the trials) in the high-probability, "rich" quadrant. The low-probability quadrant in the opposite direction of the rich quadrant was the "diagonal" quadrant, and the other two low-probability quadrants were the "sparse" quadrants. Using gaze-contingent eye tracking, we restricted the visible area to a diagonal location opposite to the current gaze position. (B) During testing (Blocks 9-12), the target's location was unbiased across all regions. Half of the participants continued to search with the restricted view. (C) The other half of the participants searched with an unrestricted view in the testing phase. The fixation location (green dot) and the numbers indicating the target's location probability are for illustrative purposes only.*

Procedure and design

Participants began by completing 24 practice trials with unrestricted viewing. To initiate a trial, participants fixated on a small white circle in the center and pressed the spacebar. After the eye tracker confirmed central fixation, an array of white letters was presented until participants responded. Their task was to find the letter T and indicate its orientation by pressing the left or right arrow key as quickly and accurately as possible. Correct responses were followed by three ascending tones for 200ms, while incorrect responses were followed by a low buzz for 2s. Participants then completed 16 additional practice trials with restricted viewing, during which they could only see letters in the opposite direction from their current gaze position. The circle placeholders were constantly visible to mark out where the letters might be. The target was equally likely to appear in any location during practice. After practice, participants were asked a multiple-choice question regarding their task, and all participants correctly indicated what their task was.

The experiment encompassed 12 blocks, each containing 24 trials. The first eight blocks constituted the training phase (Figure 3.1A), during which the target T appeared in a high-probability "rich" quadrant 50% of the time and each of the other three low-probability quadrants 16.7% of the time. The specific high-probability "rich" quadrant was consistent for each

participant throughout the training phase but was counterbalanced across participants [3]. The search was conducted with the restricted view using gaze-contingent eye tracking. The final four blocks comprised the unbiased testing phase, during which the target T appeared in each quadrant 25% of the time. Half of the participants continued to search with the restricted view in the testing phase (Figure 3.1B), whereas the other half searched with an unrestricted view in that items were visible at all times regardless of where the participant's fixation was (Figure 3.1C). Participants were not informed about the target's location probability, the transition from the training to testing phase, or the relationship between their gaze location and the visible region.

At the end of the experiment, participants were presented with recognition questions to assess their awareness regarding the target's location and the visible region. First, participants were asked whether the target T appeared more frequently in some regions than others. Regardless of their responses, we informed participants that the target was indeed more often in one quadrant and asked them to identify the high-probability quadrant. Second, participants were asked to report where the visible area was in relation to their gaze position. Participants made a forced-choice response among four options: the visible area was (a) opposite (180°) to where I was looking at; (b) random relative to where I was looking at; (c) in the same direction as where I was looking at, and (d) shifted by 90° relative to where I was looking at. Finally, participants were asked to provide a written response to the question: "what strategies, if any, did you use to help you find the target when the artificial blind spot was on?"

Results

Training phase

Behavioral results

Participants were equally accurate when the target was in the high-probability, "rich" quadrant (M = 98.3%, SE = 0.3%), the low-probability, "diagonal" quadrant (M = 98.4%, SE =

[3] The current study did not find a visual field effect. Search RT and the size of probability cuing were comparable for participants whose rich quadrant was in the upper left, upper right, lower left, or lower right quadrant. This was consistent with Jiang et al. (2018). Detailed analysis of the visual field effect can be found on the Open Science Framework (https://osf.io/cek82/).

0.3%), and the other two low-probability, "sparse" quadrants (M = 98.0%, SE = 0.3%), $F(2, 94) = 0.87$, $p = .424$, $\eta_p^2 = .018$. In the RT analysis, we excluded incorrect trials and trials with an RT outside of the 3 *SD* of an individual's mean RT. Figure 3.2A shows the mean RT across the 8 training blocks.

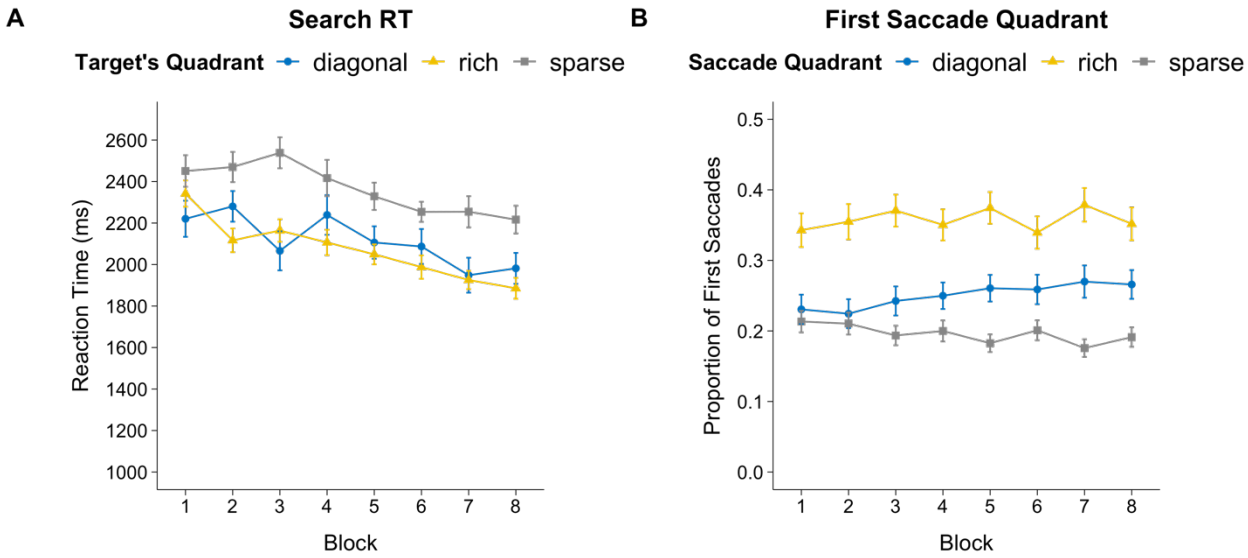

Figure 3.2 *Search RT and proportion of the first saccade directions in the training phase. (A) Search RT. (B) The proportion of first saccadic eye movements landing in each quadrant. Note there were two sparse quadrants. The figures plot the average of the two. Error bars show ±1 within-subject S.E. of the mean.*

We conducted an ANOVA on training phase RT using the target's quadrant (rich, diagonal, or sparse) and training block (1-8) as within-subject factors. We also incorporated participant group – those who went on to the testing phase with a restricted view or with an unrestricted view – as a between-subject factor. The two groups underwent identical training, so this factor was not expected to affect the training results. The ANOVA showed significant main effects of target quadrant, $F(2, 92) = 29.07$, $p < .001$, $\eta_p^2 = .387$, and block, $F(7, 322) = 6.94$, $p < .001$, $\eta_p^2 = .131$, without an interaction between the two, $F(14, 644) = 1.17$, $p = .292$, $\eta_p^2 = .025$. There was no main effect of participant group, $F(1, 46) = 2.86$, $p = .097$, $\eta_p^2 = .059$, nor

did participant group interact with target quadrant, $F(2, 92) = 2.73$, $p = .070$, $\eta_p^2 = .056$, block, $F(7, 322) = 1.11$, $p = .357$, $\eta_p^2 = .024$, or produce a three-way interaction, $F(14, 644) = 0.72$, $p = .751$, $\eta_p^2 = .015$. We pooled data across all participants in the follow-up analyses.

To examine how search RT differed across quadrants, we conducted three planned *t*-tests, using $p = .0167$ as the critical alpha adjusted for multiple comparisons. RT was faster when the target was in the rich quadrant relative to the sparse quadrants, $t(47) = 7.53$, $p < .001$, Cohen's $d = 1.087$, demonstrating probability cuing toward the high-probability quadrant. RT was also faster in the diagonal quadrant relative to the sparse quadrants, $t(47) = 5.48$, $p < .001$, Cohen's $d = 0.791$, a unique finding likely attributable to the "antisaccade" restricted viewing. RT did not differ significantly between the rich quadrant and the diagonal quadrant, $t(47) = 1.05$, $p = .301$, Cohen's $d = 0.151$. Bayesian analysis for null results revealed a Bayes Factor B_{01} (null vs. alternative; Bayesian prior: uniform distribution) of 5.20, providing evidence supporting the null hypothesis (Dienes, 2014; Morey & Rouder, 2011). Thus, participants acquired a search advantage in both the high-probability quadrant and the low-probability quadrant diagonal to it.

First Saccade

We next examined eye movements in the training phase, focusing on the direction of the first saccadic eye movements at trial onset. This analysis excluded incorrect trials. The first fixation that landed outside of the vicinity of central fixation (1.8º × 1.8º) but within the search area (13.5º × 13.5º) was used to calculate the direction of the first saccadic eye movement.

The latency of the first saccades was fast, 257.5ms, an order of magnitude faster than the search RT. This suggests that the first saccades were made prior to having visual analysis. Since the first saccade was initiated rapidly, it is a relatively pure measure of attention learning. Within the Bayesian framework (Bayes, 1958; Vilares & Kording, 2011), these first saccades reflect the prior learned knowledge that guides eye movements, justifying their use as the primary index of probability cuing.

If successfully finding the target in the rich quadrant had reinforced the oculomotor behavior of looking toward the diagonal quadrant, we would expect participants to acquire a tendency to direct their first saccades toward the diagonal quadrant. Figure 3.2B plots the

proportion of first saccadic eye movements in the direction of the rich quadrant, the diagonal quadrant, and the sparse quadrants. The chance level was 25%. Paradoxically, even though saccading toward the rich quadrant would have been counterproductive for finding the target, participants were strongly likely to direct their first saccades toward the rich quadrant, with a smaller though significant preference for the diagonal quadrant. We conducted an ANOVA using the direction of the first saccade quadrant (rich, diagonal, sparse1, or sparse2) and training block (1-8) as within-subject factors and participant group (i.e., those who went on to the testing phase with a restricted or unrestricted view) as a between-subject factor [4]. We found a significant main effect of saccade quadrant, $F(3, 138) = 19.14$, $p < .001$, $\eta_p^2 = .294$, which did not interact with block, $F(21, 966) = 1.23$, $p = .217$, $\eta_p^2 = .026$, participant group, $F(3, 138) = 0.22$, $p = .881$, $\eta_p^2 = .005$, or produce a three-way interaction, $F(21, 966) = 1.31$, $p = .157$, $\eta_p^2 = .028$.

Planned contrasts (critical alpha = .0167) showed that the first saccades were more likely directed toward the rich quadrant compared to both the sparse quadrants, $t(47) = 6.73$, $p < .001$, Cohen's $d = 0.972$, and the diagonal quadrant, $t(47) = 3.81$, $p < .001$, Cohen's $d = 0.549$. In addition, the first saccades occurred more frequently toward the diagonal quadrant than the sparse quadrants, $t(47) = 2.70$, $p = .010$, Cohen's $d = 0.390$. The preference for the diagonal quadrant, relative to the sparse quadrants, was more pronounced in later training blocks compared to earlier ones ($t(47) = 0.56$, $p = .578$, Cohen's $d = 0.081$ in Block 1; $t(47) = 2.79$, $p = .008$, Cohen's $d = 0.403$ in Block 8). Thus, participants acquired a tendency to saccade toward the diagonal quadrant relative to the other sparse quadrants, as expected from reinforcement learning. Nonetheless, they had an even stronger tendency to saccade toward the rich quadrant.

Testing phase

The persistence of the learned spatial preference depended on the nature of the task in the unbiased testing phase. As seen in Figure 3.3, participants who conducted the search with a restricted view were faster at finding the target in the rich and the diagonal quadrants relative to

[4] Note that because the proportions added up to 100%, this analysis would not produce main effects of block or participant groups.

the sparse quadrants, but participants who searched with an unrestricted view showed no RT difference across conditions.

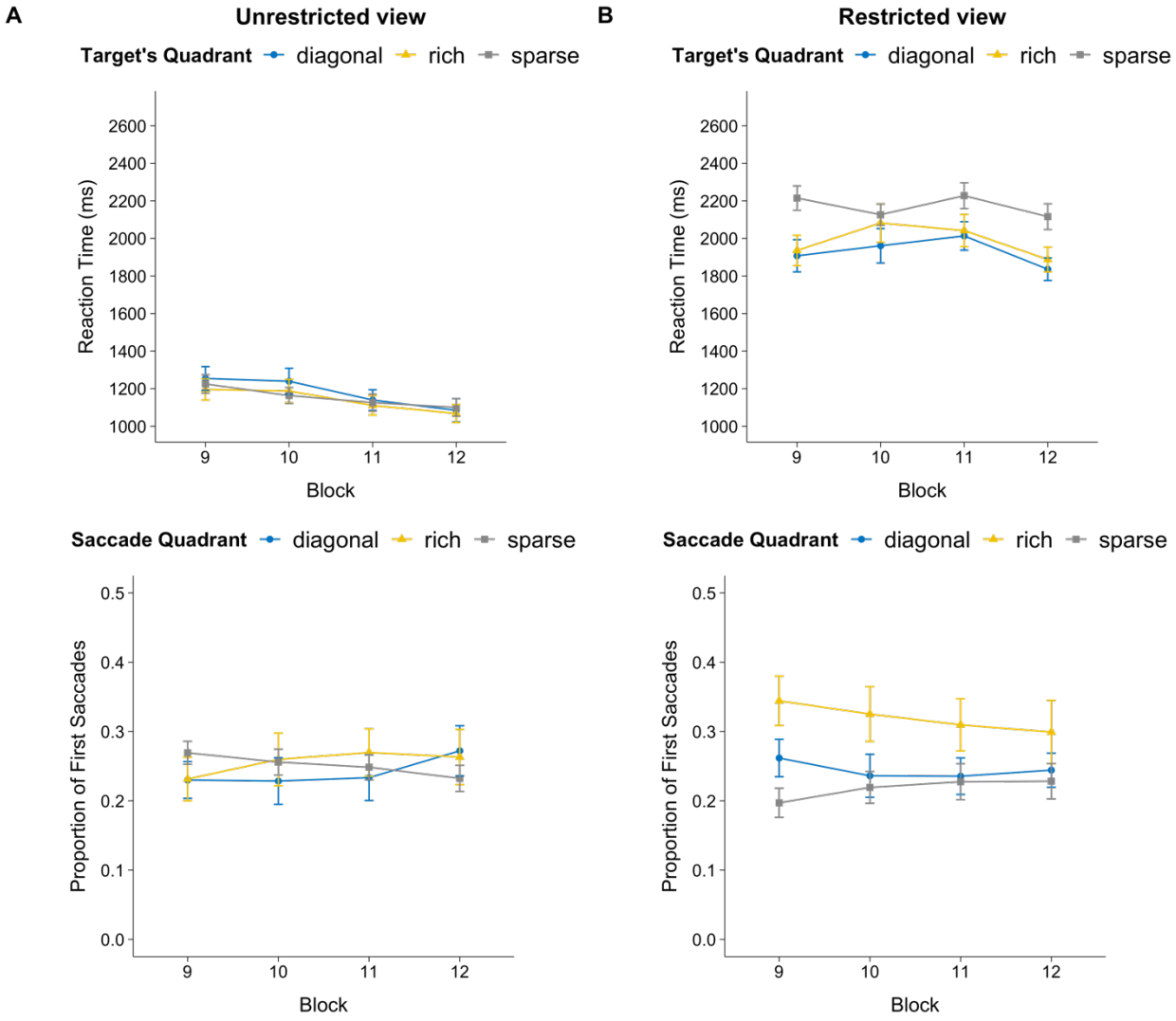

Figure 3.3 *Search RT and direction of the first saccades in the testing phase, separately for participants who searched with an unrestricted* view *(A) and with the restricted view (B). The proportion of first saccadic eye movements landing in the two sparse quadrants was averaged. Error bars show ±1 within-subject S.E. of the mean.*

Behavioral results

In search RT, an ANOVA using participant group (restricted or unrestricted view) as a between-subject factor, and target quadrant (rich, diagonal, or sparse) and testing block (9-12) as within-subject factors revealed significant main effects of participant group, $F(1, 46) = 137.75$, $p < .001$, $\eta_p^2 = .750$, target quadrant, $F(2, 92) = 4.55$, $p = .013$, $\eta_p^2 = .090$, and testing block, $F(3, 138) = 3.89$, $p = .011$, $\eta_p^2 = .078$. Participant group interacted significantly with target quadrant, $F(2, 92) = 5.85$, $p = .004$, $\eta_p^2 = .113$. The other interactions were not significant: between block and target quadrant, $F(6, 276) = 0.75$, $p = .611$, $\eta_p^2 = .016$, block and participant group, $F(3, 138) = 1.84$, $p = .143$, $\eta_p^2 = .038$, and the three-way interaction, $F(6, 276) = 0.31$, $p = .934$, $\eta_p^2 = .007$.

Follow-up tests separately examined the two groups. In the group that searched with an unrestricted view (Figure 3.3A), an ANOVA on target quadrant and testing block showed a significant main effect of testing block, with faster RT in later than earlier testing blocks, $F(3, 69) = 7.80$, $p < .001$, $\eta_p^2 = .253$. The main effect of target quadrant was not significant, $F(2, 46) = 0.35$, $p = .709$, $\eta_p^2 = .015$, nor did it interact with testing block, $F(6, 138) = 0.42$, $p = .862$, $\eta_p^2 = .018$. That is, the learned spatial preference did not transfer to search with an unrestricted view. In contrast, the group that searched with the restricted view showed persisting search advantages in the rich quadrant and the diagonal quadrants (Figure 3.3B). An ANOVA on target quadrant and testing block showed a significant main effect of target quadrants, $F(2, 46) = 7.96$, $p = .001$, $\eta_p^2 = .257$, but no main effect of block, $F(3, 69) = 1.72$, $p = .171$, $\eta_p^2 = .069$. or interaction between quadrant and block, $F(6, 138) = 0.55$, $p = .771$, $\eta_p^2 = .023$. Planned contrasts revealed faster RT in the (previously) rich quadrant than the sparse quadrants, $t(23) = 2.91$, $p = .008$, Cohen's $d = 0.594$, and faster RT in the diagonal quadrant than the sparse quadrants, $t(23) = 5.01$, $p < .001$, Cohen's $d = 1.022$. The rich and the diagonal quadrants did not differ significantly, $t(23) = 0.76$, $p = .453$, Cohen's $d = 0.156$, Bayes factor B_{01} (null vs. alternative) = 4.83 in favor of the null hypothesis. Thus, probability cuing in search RT persisted in participants who continued to search with the restricted view, but not in those who searched with an unrestricted view.

First Saccade

Given the divergent behavioral patterns in the two participant groups with restricted or unrestricted viewing, we separately analyzed first saccades in the two groups. For participants in the unrestricted viewing group, an ANOVA on first saccade direction (rich, diagonal, sparse1, or sparse2) and testing block (9-12) revealed no main effect of saccade quadrant, $F(3, 69) = 0.03$, $p = .992$, $\eta_p^2 = .001$, or interaction with block, $F(9, 207) = 0.72$, $p = .688$, $\eta_p^2 = .030$.

Participants in the restricted viewing group directed a numerically greater proportion of saccades toward the previously rich quadrant (Figure 3.3B). This effect, however, did not reach statistical significance, $F(3, 69) = 2.10$, $p = .108$, $\eta_p^2 = .084$ for the main effect of saccade quadrant and $F(9, 207) = 0.83$, $p = .586$, $\eta_p^2 = .035$ for the interaction between saccade quadrant and testing block. The oculomotor preference for the rich quadrant appeared to have weakened when the target's spatial distribution became even.

Unique patterns of oculomotor behavior

To gain insights into participants' eye movements during the search task, we compared eye movements patterns when participants searched with the restricted view and later with the unrestricted-view. We identified several differences that could help explain why the transfer of probability cuing was limited between the two viewing conditions.

First, fixation precision declined in restricted viewing relative to unrestricted viewing. Figure 3.4 shows the heatmap of fixation location during the testing phase, separately for participants in the unrestricted viewing (Figure 3.4A) and restricted viewing (Figure 3.4B) conditions. In this figure, we aligned the previously rich quadrant to the upper right quadrant for all participants; the heatmap was generated based on the duration of fixations. When all the letters were visible and participants could see wherever they were fixating, they spent considerable time fixating on each of the 8 letter locations. In contrast, when the visible regions were limited to the location opposite the current fixation, the heatmap displayed several concentrated areas: participants frequently fixated on the letters as well as the spaces between adjacent letters. The decrease in spatial precision may reflect a delay in visually-guided saccades: when fixating on the 1 o'clock position, for example, participants may have caught a glimpse of

the 7 o'clock stimulus. However, when they attempted to look directly at that stimulus, it became invisible, resulting in memory-guided saccades instead of visually guided ones. Fixating on the spaces between letters may also have increased the likelihood of two letters (rather than one) falling within the visible area.

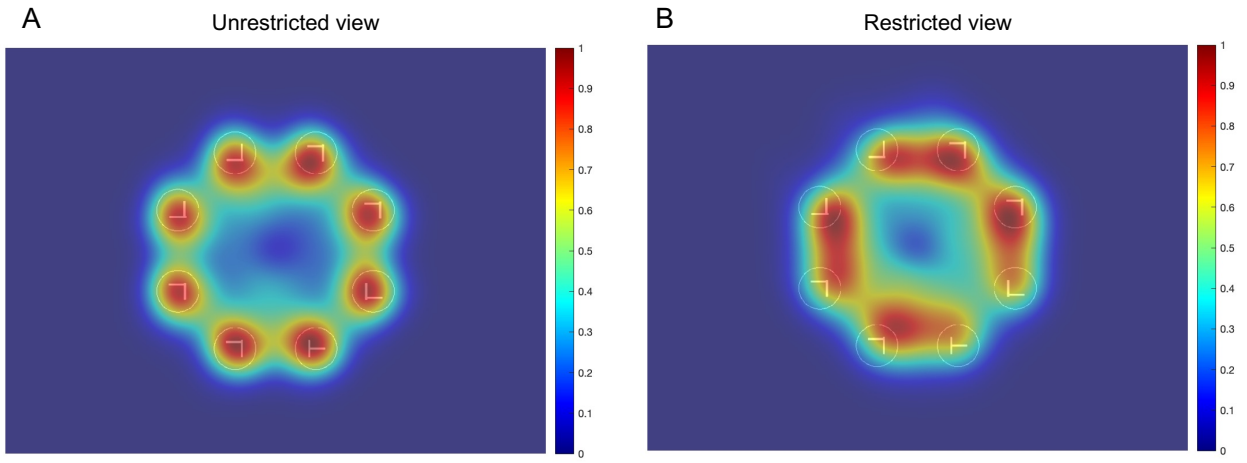

Figure 3.4 *Heatmaps showing fixation duration on the display in the testing phase, for participants with an unrestricted view (A) or restricted view (B). The previously rich quadrant was aligned to the upper right region for all participants. Duration was normalized to fit in the range of 0-1.*

Second, the amplitude and velocity of saccades differed between restricted and unrestricted viewing. Figure 3.5 shows the saccade amplitude (Figure 3.5A) and mean velocity (Figure 3.5B). The blue curves were from participants trained and tested with the restricted viewing; the yellow curves were from participants trained with the restricted viewing but tested with unrestricted viewing. A noticeable drop in saccade amplitude from restricted viewing (approximately 6º) to unrestricted viewing (approximately 3º) was accompanied by a sharp decrease in mean saccade velocity (from around 150º/s to 100º/s). An independent-samples *t-test* on the testing phase data revealed a significant effect of participant group, $t(46) = 18.43$, $p < .001$, Cohen's $d = 5.32$ in saccade amplitude and $t(46) = 13.07$, $p < .001$, Cohen's $d = 3.77$ in velocity.

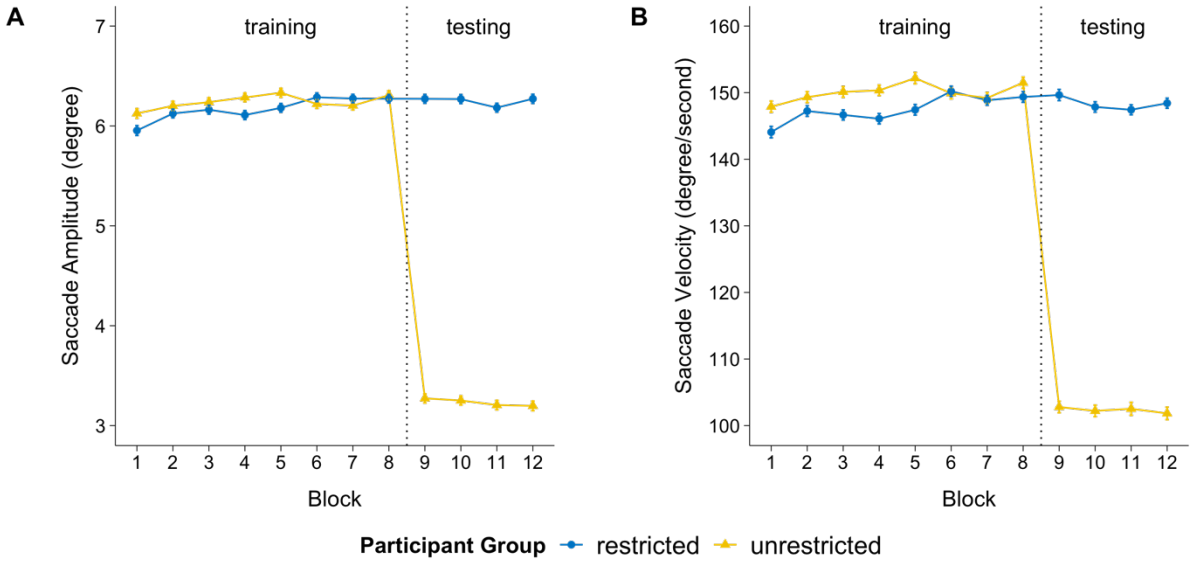

Figure 3.5 *Saccade amplitude (A) and mean velocity (B), separately for participants who had restricted viewing throughout the experiment, and those who were trained with restricted viewing but tested with unrestricted viewing. Error bars show ±1 within-subject S.E. of the mean.*

What might account for the high-amplitude, high-velocity eye movements in the antisaccade-like task with restricted viewing? In a third analysis, we examined the sequential dependency of the first two saccades at trial onset. Following the first saccade to quadrant X, the second saccade could stay in quadrant X ("same"), move to one of two adjacent quadrants ("adjacent"), or to the opposite quadrant ("opposite"). Figure 3.6 shows the proportion of trials in which these three types of second saccades occurred, separately for the training phase and the two viewing conditions of the testing phase.

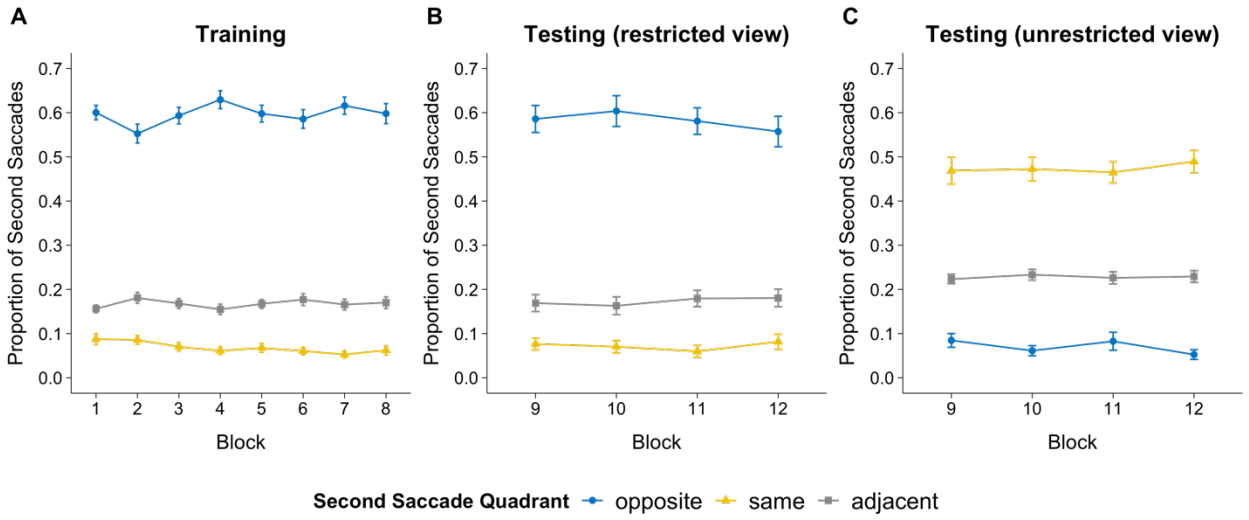

Figure 3.6 *Sequential dependency of the first two saccades at trial onset. The Y-axis shows the direction of the second saccade – it could be in the same quadrant as the first saccade, or it could move to an adjacent quadrant or the opposite quadrant 180° away. (A) Training phase. (B) Testing phase with restricted viewing. (C) Testing phase with unrestricted viewing. Data from the two adjacent quadrants were averaged. Error bars show ±1 within-subject S.E. of the mean.*

In the training phase when participants searched with the restricted view, they preferentially directed the second saccade toward a quadrant opposite from where their first fixation was (59.7%); they were less likely to stay in the first saccade quadrant (6.8%) or saccade toward one of the two adjacent quadrants (16.7%). These proportions were significantly different from one another ($F(2, 94) = 540.07$, $p < .001$, $\eta_p^2 = .920$ in an ANOVA contrasting the same, opposite, and the average of the two adjacent quadrants). The preference for looking in the opposite direction persisted during the testing phase among participants with restricted viewing (58.2% opposite, 7.2% same, and 17.3% toward either of the two adjacent). But the pattern changed in participants with unrestricted viewing during the testing phase, where the second saccade was predominantly directed towards the vicinity of the first fixation (47.4% same quadrant, 22.8% toward either one of the adjacent quadrants, and 7.0% toward the opposite quadrant). In the testing phase, an ANOVA on participant group and second saccade direction (same, opposite, adjacent1, adjacent2) in the testing phase revealed a significant main effect of

saccade direction, $F(3, 138) = 13.96$, $p < .001$, $\eta_p^2 = .233$, and a significant interaction between saccade direction and group, $F(3, 138) = 129.91$, $p < .001$, $\eta_p^2 = .738$. The opposite look was therefore unique to the restricted viewing condition. It likely resulted from the experimental procedure: fixating on a quadrant brought to view visual stimuli in the opposite quadrant, driving the next eye movement toward it.

The above analysis on sequential dependency combined data from all trials, regardless of where the first saccade landed. Table 3.1 separated the training phase data according to the location of the first saccade: in the rich quadrant, the diagonal quadrant, or the sparse quadrants. In all cases, the second saccade was preferentially directed to a quadrant opposite from the first. This strength of this preference, however, was modulated by where the first saccade was, $F(9, 423) = 12.90$, $p < .001$, $\eta_p^2 = .216$ for the interaction between the first saccade quadrant (rich, diagonal, sparse1, sparse2) and second saccade quadrant (same, opposite, adjacent1, adjacent2). The strongest tendency for "opposite look" was shown in trials where the first saccade was toward the diagonal quadrant, in which case an opposite look brought to view the rich quadrant. The weakest preference was when the first saccade was toward a sparse quadrant, in which case an opposite look brought to view another sparse quadrant. Thus, while the restricted viewing condition introduced a pattern of sequential dependence – the "opposite look", the strength of this effect was modulated by the target's location probability.

Table 3.1 *Sequential dependency of the first two saccades at trial onset in the training phase. The data shows the proportion of second saccade direction relative to the first saccade, separately for trials in which the first saccade was directed to the rich, diagonal, or a sparse quadrant. Data were averaged for the two adjacent looks. The parenthesis shows within-subject S.E. of the mean.*

First saccade landed in	Second saccade relative to the first saccade quadrant		
	Same	Adjacent	Opposite
Rich	7.5% (0.6%)	17.3% (0.7%)	57.8% (1.4%)
Diagonal	5.8% (0.8%)	11.5% (0.7%)	71.2% (1.4%)

Sparse	6.0% (0.5%)	21.9% (0.6%)	50.2% (1.2%)

Explicit Awareness of the target's location probability

We used a forced-choice task of the target-rich quadrant to probe participants' awareness of the target's location probability. This task did not have the sensitivity to reveal nuanced aspects of explicit awareness (Vadillo et al., 2020). Nonetheless, recognition data are informative and may facilitate comparisons across studies. Nineteen of the 48 participants correctly identified the rich quadrant, which was significantly above chance, $\chi^2(1) = 5.44$, $p = .020$. This level was comparable to previous reports on probability cuing using unrestricted viewing (Jiang et al., 2018) or a simulated central scotoma (Addleman & Lee, 2022).

To examine how awareness related to search performance in the training phase, we separated "aware" ($N = 19$) and "unaware" ($N = 29$) participants based on whether they correctly identified the rich quadrant. An ANOVA on awareness group, target quadrant, and training block revealed significant main effects of target quadrant, $F(2, 92) = 29.10$, $p < .001$, $\eta_p^2 = .387$, and training block, $F(7, 322) = 6.07$, $p < .001$, $\eta_p^2 = .117$, without a significant interaction, $F(14, 644) = 0.96$, $p = .497$, $\eta_p^2 = .020$. The main effect of awareness group was not significant, $F(1, 46) = 0.01$, $p = .922$, $\eta_p^2 < .001$, nor did awareness interact with target quadrant, $F(2, 92) = 2.09$, $p = .130$, $\eta_p^2 = .043$, or with block, $F(7, 322) = 0.31$, $p = .951$, $\eta_p^2 = .007$, or produce a three-way interaction, $F(14, 644) = 0.70$, $p = .780$, $\eta_p^2 = .015$. Thus, awareness group did not significantly modulate probability cuing.

We next restricted the analysis to just the 29 participants in the unaware group. An ANOVA on the target quadrant and training block revealed significant main effects of target quadrant, showing probability cuing, $F(2, 56) = 15.62$, $p < .001$, $\eta_p^2 = .358$, and training block, $F(7, 196) = 4.91$, $p < .001$, $\eta_p^2 = .149$, without an interaction, $F(14, 392) = 1.44$, $p = .130$, $\eta_p^2 = .049$. Thus, probability cuing occurred even in participants who were mistaken about where the rich quadrant was.

We then examined whether the awareness group affected the direction of first saccades in the training phase. An ANOVA on the saccade quadrant (rich, diagonal, sparse1, or sparse2), training block (1-8), and awareness (aware or unaware) found only a significant main effect of

saccade quadrant, $F(3, 138) = 20.92$, $p < .001$, $\eta_p^2 = .313$. Awareness group did not interact with saccade quadrant, $F(3, 138) = 1.47$, $p = .225$, $\eta_p^2 = .031$, or produce a three-way interaction, $F(21, 966) = 0.77$, $p = .757$, $\eta_p^2 = .016$. Saccade quadrant did not interact with the training block, $F(21, 966) = 1.20$, $p = .240$, $\eta_p^2 = .025$. Similar to search RT, awareness did not significantly modulate the direction of the first saccade.

Results from the testing phase were qualitatively similar to the training phase: the awareness group did not modulate search behavior. The sample size was reduced, however, owing to the lack of transfer in the unrestricted viewing group. Detailed results from the testing phase can be found on the Open Science Framework (https://osf.io/cek82/).

Explicit awareness about the relationship between fixation and visible region

In a 4-alternative-forced-choice on the spatial relationship between current fixation and the visible region, 12 of the 48 participants correctly stated that the visible region was diagonal to the current fixation. This did not differ from chance, $\chi^2(1) < .001$, $p = 1.000$. We analyzed search RT and first saccades for the correct and incorrect responders. This analysis, reported on the Open Science Framework (https://osf.io/cek82/), found no evidence of qualitative differences between these two groups of participants in their search RT or first saccades.

Appendix B Table B.1 details the self-reported strategies participants used in the experiment. Few participants reported fixating on a location opposite from their intended target area. Most adopted idiosyncratic strategies that ranged from systematic scanning (e.g., left to right) to random search. The lack of spontaneous awareness about the relationship between gaze and the visible region may seem surprising. However, this finding aligns with previous studies that have highlighted people's limited awareness of their gaze location (Clarke et al., 2017; Theeuwes et al., 1998; Võ et al., 2016).

Discussion

This study examined the acquisition of a visual search habit towards locations that frequently contained a target in the past. Using a novel gaze-contingent eye-tracking paradigm, we limited the visible region to a location opposite from where participants were fixating. This

antisaccade-like task required participants to direct their gaze towards one location while covertly attending to the opposite location. If the acquisition of a search habit relies on the alignment between gaze direction and the attended location, participants would have had difficulty in acquiring probability cuing for the high-probability region. Our results showed, to the contrary, that probability cuing was preserved, providing strong evidence that location probability learning is not solely dependent on oculomotor learning. These results expand the scope of the modular theory of attention by suggesting that implicitly guided attention can be partially separated from eye movements.

The successful acquisition of LPL toward the rich quadrant indicates that participants likely attended covertly to the location opposite to the saccade direction. This is consistent with previous studies on the relationship between attention and saccade direction (Castet et al., 2006; Deubel, 2008; Moehler & Fiehler, 2014, 2015, 2018; Montagnini & Castet, 2007). What sets our study apart is that it presents the most compelling evidence to date that implicit learning leads to attention learning, rather than solely oculomotor learning. Specifically, if learning were confined to the oculomotor system, the preference would be limited to the saccade direction. However, the fact that participants demonstrated LPL toward a location opposite to the saccade direction indicates the presence of an abstract, high-level component in LPL. Although the current study did not directly measure attention at the saccade goal and the opposite location, the presence of LPL toward the rich quadrant, coupled with an oculomotor preference for both the diagonal and the rich quadrants, indirectly suggests that both locations receive greater attention compared to the sparse locations. This finding may be further strengthened in a future study that directly measures attention at both the saccade goal and the opposite location.

Another noteworthy finding in our study is the emergence of a spatial bias towards the location opposite from the high-probability region, the “diagonal” quadrant. The diagonal preference is not commonly observed in visual search studies, except where attention is cued using a transient cue (Rolfs et al., 2004; Tse et al., 2002, 2004). When participants search the display with an unrestricted view, probability cuing follows a spatial gradient: the farther a location is from the high-probability region, the slower the search. As the diagonal quadrant is 1.4 times more distant from the high-probability quadrant compared to the adjacent quadrants, it

typically yields the slowest search RT (Jiang et al., 2018). Thus, the diagonal preference observed in the current study is attributable to the specific nature of the antisaccade-like task.

Because the visible region was diagonal to the fixation location, the faster search RT in the diagonal location could result from participants' tendency to saccade toward the rich quadrant, as doing so would bring the diagonal items into view. Interestingly, the RT advantage in the diagonal quadrant was just as significant as that in the rich quadrant, largely due to participants' strong preference for fixating on the rich quadrant first. Nonetheless, eye tracking showed that participants also developed a tendency to saccade towards the diagonal quadrant. The first saccadic eye movements landed in the diagonal quadrant more often than in the sparse quadrants. The probability manipulation, in conjunction with the antisaccade-like task, had successfully trained participants to alter their eye movements. Thus, in addition to the spatial preference for the rich quadrant, participants also showed an oculomotor preference for the diagonal quadrant. The oculomotor learning occurred even though most participants did not have explicit knowledge about where the target most often appeared, or where the visible region was in relation to their fixation. The successful training of eye movements aligns with findings from other paradigms involving eye movement training in healthy adults (Fooken et al., 2018), children with an autism spectrum disorder (Lee et al., 2020), and patients with age-related macular degeneration (Seiple et al., 2005) or hemianopia (Mannan et al., 2010).

Saccading toward the diagonal quadrant was "rational" – doing so would bring the rich quadrant into view, maximizing the chances of finding the target. Surprisingly, however, participants were highly likely to fixate directly on the rich quadrant. This finding is reminiscent of the observation that individuals who recently experienced central vision loss tend to reflexively fixate on the targets, only developing a habit of relying on their preferred retinal locus after an extended period of time (Crossland et al., 2005, 2011; Verghese et al., 2021). It suggests that reinforcement learning of the oculomotor system played a relatively weak role compared to attentional learning towards the rich quadrant. The first saccades were strongly biased toward the rich quadrant, even though looking at the rich quadrant would render the visual stimuli there invisible. Unlike visual search in natural viewing conditions, gaze behavior in the antisaccade task does not fit with predictions of the Bayesian Ideal Observer model (Geisler, 2011; Najemnik

& Geisler, 2005, 2008). The irrational fixation on the rich quadrant suggests that instead of preferentially attending to where the eyes move to, participants tend to move their eyes to the current focus of attention. This is consistent with previous findings on pre-saccadic shifts to attended locations (Harrison et al., 2012; Zhao et al., 2012).

The antisaccade-like setup of our study induced a distinct pattern of eye movements. Participants made high-velocity and high-amplitude saccades that were not seen when they searched with an unrestricted view. An analysis of the sequential dependency of successive saccades showed that after saccading to one quadrant, participants were highly likely to saccade towards the opposite quadrant positioned 180º away from their current fixation. Though unique, this pattern of opposite saccades is a reasonable strategy since fixating on a quadrant brings visual information from the opposite quadrant into view. However, this pattern of "opposite look" does not explain why participants preferentially direct their first saccade to the rich quadrant. Furthermore, the proportion of "opposite look" varied depending on the location of the first fixation. "Opposite looks" occurred more frequently when the first fixation was in the diagonal quadrant compared to the rich or sparse quadrants. Thus, both the direction of the first saccade and the strength of "opposite look" in the second saccade were influenced by the target's location probability, demonstrating an attentional preference for the rich quadrant. This preference may reflect the fact that the target was frequently found there.

Reinforcement learning, introduced by the target's uneven spatial distribution, could affect not only simple oculomotor behaviors like the direction of first saccades but also more complex ones involving a sequence of successive saccades. For example, participants could increase both their first saccades toward the diagonal quadrant and their second saccades toward the diagonal quadrant by looking first toward the rich quadrant and then making an opposite look. This strategy – "rich first, then diagonal" – is arguably less direct compared to directly saccading to the diagonal quadrant first, but reinforcement learning is known to produce inefficient or superstitious behavior (Jin et al., 2022; Skinner, 1948). However, reinforcement of the complex "rich first, then diagonal" behavior should not be stronger than reinforcement of the more direct "diagonal first" behavior. Yet the data showed many more "rich first" than "diagonal

first" trials, suggesting that reinforcement learning of complex oculomotor patterns is unlikely to explain the observed probability cuing.

Our study has shown that it is possible to train a search habit using an antisaccade-like paradigm that disrupts the alignment between saccade direction and the target location. However, this does not imply that participants have acquired two distinct habits as a result of location probability learning – an oculomotor habit towards the diagonal quadrant and an attentional habit towards the rich quadrant. On the contrary, participants were strongly likely to saccade in the same direction as the attentional habit – toward the rich quadrant. Thus, while the attentional habit towards the rich quadrant can be acquired in an antisaccade-like setup, learning does not result in spatially separate oculomotor and attentional habits. We did, however, observe a gradual increase in the tendency to saccade towards the diagonal quadrant. It is possible that extensive training of days or months may further reinforce the oculomotor habit towards the diagonal quadrant. Future studies with longer training sessions are needed to test whether participants can eventually acquire spatially distinct attentional and oculomotor habits.

Three recent studies have used an antisaccade paradigm to change oculomotor behavior, yielding different results for feature-based and location-based training tasks. Kim and Anderson (2019) trained participants in an anti-saccade task, during which participants must look away from a stimulus that could be in either of two colors; one of the colors appeared more frequently than the other. In a subsequent prosaccade task that included the high-frequency color and a neutral new color, participants tended to saccade away from the previously high-frequency color. Similarly, Kim and Anderson (2021) trained participants in an antisaccade task in response to a target in one of two colors; one color was associated with electrical shocks (CS+) whereas the other was not (CS-). Despite the absence of punishment for the CS- color during training, participants displayed a tendency to saccade away from the CS- color when it appeared alongside neutral colors. These findings showed that participants could learn to saccade away from attended colors in an antisaccade training task.

Results changed in a spatial attention task. In Gillen and Heath (2014), participants made an antisaccade away from a target that appeared in different locations. When the target more often appeared in the proximal location, the antisaccade showed an undershooting tendency, in

the direction of the target. Conversely, when the target appeared more frequently in the distal location, the antisaccade showed an overshooting tendency, also in the direction of the target. Thus, in antisaccade tasks involving different spatial probability of targets, saccades were drawn towards the probable target locations. This finding aligned with our results but differed from feature search tasks (Kim & Anderson, 2019, 2021). Thus, while it is possible to successfully induce antisaccade training based on a feature, it is much harder to achieve this based on location. This may be because spatial learning necessitates attending to the target location, resulting in attention learning towards it that counters the oculomotor learning away from it.

Although probability cuing was preserved when the attended region was incongruent with the saccade direction, the two factors are spatially aligned in normal viewing conditions. The alignment may result in a stronger search habit that combines both covert attentional preference and overt eye movements. Yet it is unclear how much stronger probability cuing could have been if these two factors had aligned. In the antisaccade-like setup of the current study, the relative RT gain in the rich quadrant compared to the sparse quadrants was approximately 8.5% when testing with restricted viewing, which was weaker compared to the RT gain observed under intact vision (15% in Chen & Lee, 2022; 10-25% in Jiang et al., 2013). However, the unrestricted viewing studies tended to have larger set sizes (e.g.,12-16 instead of 8). In an unpublished study using the same 8-letter search task but with a prosaccade-like setup where the visible area aligned with the fixation location, we observed a learning effect of approximately 15.6% during training, suggesting that spatial congruency may affect the size of learning. However, RT in the prosaccade-like setup was much faster than in the antisaccade-like task. Future studies are needed to determine how oculomotor learning interacts with covert attentional learning. What our study has shown is that spatial alignment is unnecessary for probability cuing. A strong spatial preference for the high-probability quadrant can be acquired even when attending to that region requires looking away.

Probability cuing in our study was durable, persisting in an unbiased testing phase. The persistence was only evident in participants who continued searching with the restricted view. Eliminating the restricted view also removed any spatial preferences. Searching with the unrestricted view took much less time and required fewer fixations. These two types of search

induced distinct eye movements, as reflected in the spatial precision of the fixations, saccade amplitude and velocity, and the nature of successive saccades. The persisting effect in the restricted viewing group was reminiscent of other long-term effects of statistical learning. For example, Leber and Egeth (2006) found when given sufficient training with one of two attentional sets (i.e., the single detection mode or feature search mode), observers persisted in the learned attentional set during testing. Notably, the training effect was still evident one week after training, indicating that the attentional set was primarily guided by long-term learning (Leber et al., 2009).

Unrestricted viewing likely changed the nature of the task, yielding no transfer. This finding is consistent with several previous studies, in which probability cuing only transferred when the nature of the search task was preserved (Jiang et al., 2013; Sha et al., 2018). However, the lack of transfer from search with a restricted view to search with unrestricted viewing differed from Addleman et al. (2021) and Addleman and Lee (2022). In those studies, training with a restricted view produced probability cuing that transferred to search with an unrestricted view. Several factors may have contributed to the discrepancy in the results. First, Addleman et al. used more complex displays consisting of 16 letters randomly placed on the screen. The artificial scotoma in Addleman et al.'s study only obscured the central 6.7º of the visual field, allowing participants to see most of the items even under restricted viewing. Consequently, the displays were similar between the restricted-view and unrestricted-view in Addleman et al. (2021). In contrast, the antisaccade-like restricted-view used in the current study blocked out most of the search items. At any given time, participants could only see a maximum of 2 letters, and sometimes none at all, depending on their fixation location. As a result, the search displays differed completely between the tasks with restricted and unrestricted views, explaining the lack of transfer. Second, Addleman et al.'s central scotoma allowed participants to acquire a spatial preference toward just the high-probability region. In our study, participants acquired two spatial preferences, one toward the high-probability region and the other toward the diagonal region. Maintaining two spatial preferences may be more challenging for participants when the search task undergoes such drastic changes.

Conclusion

This study applied gaze-contingent eye tracking to a visual search task to induce a mismatch between gaze direction and attended locations. Although participants could only see the target by looking away, they successfully acquired location probability learning towards the target's high-probability region. Furthermore, they also developed an oculomotor preference for fixating on both the high-probability region and the diagonally opposite region. Thus, probability cuing can be acquired even when the attended region does not align with the direction of eye movements, supporting the notion that habitual attention and eye movements can exhibit relative independence.

4. Study 3: Contribution of peripheral vision to attention learning

Frequently finding a target in one region produces a habit of searching there. The search habit typically emerges when eye gaze and attention are spatially aligned. When limiting visible stimuli to a location diagonally opposite from the eye gaze, Study 2 showed that a search habit toward the high-probability location was still preserved. These findings add to the existing evidence supporting the modular theory of attention, demonstrating that experience-guided attention is a high-level process partially separable from eye movements.

Study 2 showed that participants acquired an attentional preference for locations that frequently contained a target, even when the visible area was restricted to a peripheral region. This finding suggests that observers can acquire location probability learning (LPL) without central vision. But can observers also acquire LPL without peripheral vision? To date, no studies have tested the role of peripheral vision in the acquisition of implicit selection history effects. Study 3 examined how peripheral vision affected LPL using gaze-contingent eye tracking that removed peripheral vision. I tested three possible hypotheses. First, if the absence of peripheral vision reduces cues available for coding the target's location, then LPL may be impaired when participants search with central vision alone. Alternatively, participants may rely on the remaining spatial cues, such as the target's location relative to themselves, to acquire LPL. A third possibility is that in the absence of peripheral vision, explicit awareness of the target's spatial distribution may modulate whether participants can acquire LPL.

Study 3 is currently under peer-review: Chen, C., & Lee, V. G. (under review). Contribution of peripheral vision to attention learning. *Attention, Perception, & Psychophysics*. The article is reproduced here.

Contribution of peripheral vision to attention learning

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Preface

Attention is tuned towards locations that frequently contain a visual search target (location probability learning: LPL). Peripheral vision, covering a larger field than the fovea, often receives information about the target. Yet what is the role of peripheral vision in attention learning? Using gaze-contingent eye tracking, we examined the impact of simulated peripheral vision loss on location probability learning. Participants searched for a target T among distractor Ls. Unbeknownst to them, the T appeared disproportionately often in one quadrant. Participants searched with either intact vision or "tunnel vision," restricting the visible search items to the central 6.7º of the current gaze. When trained with tunnel vision, participants in Experiment 1 acquired LPL, but only if they became explicitly aware of the target's location probability. The unaware participants were not faster finding the target in high-probability than low-probability locations. When trained with intact vision, participants in Experiment 2 successfully acquired LPL, regardless of whether they were aware of the target's location probability. Thus, whereas explicit learning may proceed with central vision alone, implicit LPL is strengthened by peripheral vision. Consistent with Guided Search (J. M. Wolfe, 2021), peripheral vision supports a nonselective pathway to guide visual search.

Keywords: visual attention, visual search, selection history effects, location probability learning, peripheral vision loss

Introduction

Visual activities like finding a friend or reading street signs often require us to look at a succession of objects until we locate the sought-after one, the "target." Fixating on the faces or

words brings them to the fovea, the part of the retina with the highest visual acuity. The non-fixated stimuli fall in the visual periphery, providing crude information about the spatial layout, gist, and global visual statistics of the environment (J. M. Wolfe et al., 2011). The daily experience supports the essential function of central vision, the loss of which is devastating to reading, face recognition, and navigation (Bullimore et al., 1991; Cloutier & DeLucia, 2022; Legge et al., 1985). But what is the role of peripheral vision in cognition? By one account, peripheral vision may deliver just an illusory sense of "seeing everything," even though changes in the visual periphery are rarely noticed (O'Regan et al., 1999). Other theories have ascribed greater significance to peripheral vision. In Guided Search 6.0 (J. M. Wolfe, 2021), peripheral vision contributes to a "nonselective" pathway of attention, guiding visual search by providing information about scene gist and other global image statistics. But how important is peripheral vision, especially in visual search tasks accomplished by fixating on individual objects?

Two lines of research have shown that search tasks involving central fixation may benefit from information delivered through peripheral vision. In Evans et al. (2013), radiologists were asked to determine whether a mammography contained cancerous tumors, a task typically achieved with central vision. To limit the opportunities for central fixation, Evans et al. presented the mammography for just 250 ms in some conditions, comparing it with longer durations of 2s where multiple fixations were possible. Longer presentation time yielded better performance, demonstrating the importance of central vision. But even at the shortest duration of 250 ms, expert radiologists performed at above-chance levels, even though they had no time to fixate on the tumor and could not identify its location (see also Evans et al., 2016). Evans et al. proposed that the global image statistics contained information about tumor status, supporting the importance of peripheral vision.

Using letters as stimuli, a second line of research shows that peripheral vision is important for learning spatial configurations. In Geringswald and Pollmann (2015), participants searched for a letter T among letter Ls. Unbeknownst to them, some search displays occurred multiple times in the experiment, interspersed with unrepeated displays. When searching with intact vision, participants typically became faster at finding the target in repeated than unrepeated displays, showing contextual cueing (Chun & Jiang, 1998; Sisk et al., 2019). To examine the role

of peripheral vision, Geringswald and Pollmann (2015) used gaze-contingent eye tracking to create "tunnel vision," where participants saw stimuli within the central 7º of the current eye position. Under this condition, participants did not acquire contextual cueing; neither did contextual cueing reemerge in a later testing phase viewed with intact vision. Zang et al. (2015) replicated the lack of contextual cueing in the tunnel vision phase, though they uncovered evidence of contextual cueing after the tunnel was removed. These findings showed that information about the larger visual context, some of which fall outside of the central fovea, may be important for spatial context learning.

The studies reviewed above suggest that peripheral vision contributes to the processing of global image statistics and spatial contexts. Yet not all forms of visual statistical learning are global or contextual. This raises questions about whether central vision alone is sometimes adequate in attention learning. One well-characterized form of attention learning – location probability learning (LPL) – relies on spatial probability learned over time (Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Jiang, Swallow, et al., 2013; B. Wang & Theeuwes, 2018a). In a typical LPL task, participants search for a T target among L distractors. Unbeknownst to them, across multiple trials, the T appears disproportionately often in one, high-probability visual quadrant. Although often not noticing the target's uneven location probability, participants are faster at finding the target in the high-probability relative to the low-probability quadrants (Jiang et al., 2018; Jiang, Swallow, et al., 2013; Jiang, Won, et al., 2014). Unlike contextual cueing which depends on learning the spatial relationship between the search target and the surrounding distractors, LPL reflects learning of a target's location probability over time. This raises questions about whether central vision alone is adequate for learning.

To date, most studies on LPL have allowed participants to search with both central and peripheral vision. An exception was Addleman et al. (2021), which compelled participants to search with peripheral vision using an artificial central scotoma. In that study, participants searched for a T target among L distractors presented against a natural scene background. Using gaze-contingent eye-tracking, Addleman et al. eliminated the central 6.7º of the visual input around the current fixation position. The study contained two phases: a training phase in which the target appeared disproportionately often in a high-probability quadrant, and a testing phase in

which the target's location was random. The two phases also differed in whether participants searched with intact vision or with a central scotoma. When trained with intact vision, participants acquired LPL, an effect that persisted in the testing phase. This finding was independent of explicit awareness about the target's location probability. That is, regardless of whether participants correctly identified the high-probability quadrant, they learned to search that quadrant faster and continued to do so when central vision was blocked. The results changed when trained with a central scotoma. Under this condition, only participants who demonstrated explicit awareness showed LPL; those who lacked awareness, reflected by an inability to identify the high-probability quadrant, showed no LPL. Addleman et al. (2021) concluded that while explicit learning survived central vision loss, implicit learning depended on having intact vision.

A subsequent study with a modified search task, however, weakened the link between central vision loss and implicit learning. Addleman and Lee (2022) repeated the earlier study but removed the natural scene from the background. Due to their high memorability, natural scenes often alter the nature of attentional learning. For example, contextual cueing in scene-based tasks involves explicit and global learning (Brockmole et al., 2006; Brockmole & Henderson, 2006), in contrast to the more implicit and local learning shown in contextual cueing of letter arrays (Brady & Chun, 2007; Chun & Jiang, 2003). When the scene background was removed in Addleman and Lee (2022), central vision loss no longer interfered with implicit LPL. Regardless of whether participants were trained with intact vision or central scotoma, they acquired LPL, a finding that held for both the aware and unaware participants. Thus, it was possible to acquire implicit LPL with peripheral vision alone.

To date, no studies have tested whether central vision alone is sufficient for LPL. That is, does LPL depend on peripheral vision? LPL involves probability learning of spatial locations. It relies on participants' ability to consistently represent the target's location across trials. When searching with intact vision, participants may code the target's location relative to themselves, landmarks such as the edge of the monitor, or the other search items. Eliminating peripheral vision reduces cues available for coding the target's location, particularly information about where the target is in relation to the other search items. The loss of spatial cues makes it possible that peripheral vision loss may interfere with LPL. Alternatively, the surviving spatial cues, such

as the target's location relative to the viewer or screen landmarks, may continue to support LPL. A third possibility is that explicit awareness may modulate how participants use the various spatial cues. Participants who can reliably identify the target's high-probability quadrant are likely to have stable access to the target's location. For them, LPL may survive peripheral vision loss. In contrast, participants who are unable to identify the high-probability quadrant may have less reliable coding of the target's location. For them, peripheral vision loss is likely to disrupt LPL.

We conducted two experiments to examine the role of peripheral vision loss in LPL, with an added focus on the modulatory role of explicit awareness. While explicit awareness sometimes increases the magnitude of LPL (Vadillo et al., 2020; but not Jiang et al., 2018), how it alters the characteristics of LPL has attracted less research. This study may reveal one effect of awareness – whether attentional learning survives peripheral vision loss. Modeled after Addleman and colleagues' studies on central vision loss, the following experiments trained participants with an uneven target location probability and tested them with an even location probability. In addition, training and testing differed in whether vision was intact or restricted. In Experiment 1, participants were trained with tunnel vision and tested with intact vision. This was reversed in Experiment 2. Together, these experiments contribute to an understanding of how peripheral vision affects attention learning. They may shed light on the visual function of patients with peripheral vision loss and clarify the role of peripheral vision in activities like driving and reading.

Experiment 1

Using gaze-contingent eye-tracking, Experiment 1 introduced simulated peripheral vision loss in the training phase of an LPL study (Figure 4.1A). The search display contained 8 items equally spaced in a circular configuration. The target – a letter T – appeared in a high-probability quadrant 50% of the time, and in each of the other three low-probability quadrants 16.7% of the time. To produce "tunnel vision," an eye tracker detected the current fixation position and restricted the visible search items within the central 6.7º. After 8 blocks of training with an uneven target location probability, we tested participants in a testing phase during which the

target's location was random. In addition, participants searched with intact vision. Thus, whereas the training phase examined the acquisition of LPL with restricted viewing, the testing phase assessed the persistence of LPL with unrestricted viewing. This design paralleled that of Addleman and colleagues (Addleman et al., 2021; Addleman & Lee, 2022), except that we limited peripheral vision rather than central vision. A recognition test at the conclusion of the experiment evaluated the degree to which participants were aware of the uneven target distribution.

If peripheral vision is important for LPL, as in contextual cueing and gist-guided search, then searching with tunnel vision may impair the acquisition of LPL. Alternatively, if central vision is sufficient for the coding of the target's location probability, then LPL may survive the loss of peripheral vision. A third possibility is that awareness of the target's location probability mediates the impact of peripheral vision loss on LPL.

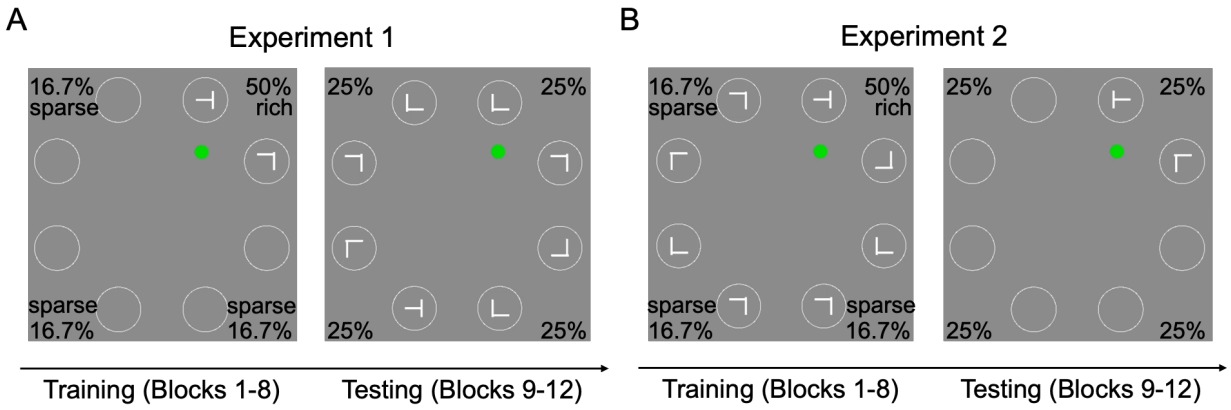

Figure 4.1 *A schematic illustration of the search display and experimental design. (A) Experiment 1. (Left) Training phase (first 8 blocks of trials). The target appeared in a high-probability "rich" quadrant 50% of the time and in each of the three low-probability "sparse" quadrants 16.7% of the time. An eye-tracker restricted the visible search items to 6.7° around the location of the current gaze. (Right). Testing phase (last 4 blocks of trials). The target appeared with equal probability in all quadrants. In addition, all search items were visible. (B) Experiment 2. Experiment 2 was the same as Experiment 1, except that participants were trained with intact*

vision and tested with tunnel vision. The green dot (current fixation location) and the black text (quadrant design) are for illustrative purposes only.

Method

Participants

Sample size. We prespecified 24 as the targeted sample size. This number was based on Cohen's *f* of 0.48 for LPL in Addleman and Lee (2022, Experiment 2). G*Power analysis (Faul et al., 2007) showed that at least 17 participants were needed to reach a power of .95 in a two-tailed test at an alpha-level of .05. We set the target sample to 24 to accommodate the need to counterbalance quadrant assignments.

Participant characteristics. Participants in this study were healthy adults from the University of Minnesota. They were 18-45 years of age, naïve to the purpose of the study, fluent in English, and had normal or corrected-to-normal vision. All participants provided written informed consent before the experiment and were compensated for their time. The University of Minnesota Institutional Review Board approved the study protocol. The 24 participants in Experiment 1 included 15 females and 9 males with a mean age of 19.8 years (*S.D.* = 1.7 years).

Equipment

Participants were tested individually in a quiet room with normal interior lighting. A chinrest kept the viewing distance fixed at 90 cm. Visual stimuli were displayed on a 19-inch CRT monitor (spatial resolution: 1024 × 768 pixels; vertical refresh rate: 100 Hz). The experiment was programmed with MATLAB and Psychtoolbox (Kleiner, 2007). An EyeLink 1000 eye tracker (SR Research, Mississauga, ON, Canada) tracked the left eye at a sampling rate of 1000 Hz. Eye position was calibrated using a 9-point calibration procedure before the experiment and verified with a drift check before each trial.

The eye tracker detected the current gaze location and restricted the search items to a circle centered on the central 6.7º of gaze. Addleman et al. (2021) verified the precision of gaze-contingent eye tracking using a gap detection task. Participants reported the gap direction of a small C presented in the periphery. Accuracy was 91% when participants could move their eyes

to look directly at the gap, but dropped to 26% (chance was 25%) when viewed using peripheral vision in a gaze-contingent paradigm; this demonstrated the effectiveness of the gaze-contingent method. This study used the same equipment and setup as those of Addleman et al. (2021).

Stimuli

Each search display contained eight white letters (0.9º × 0.9º) presented against a gray background. There was one T, rotated 90º to the left or right, and 7 Ls, each rotated randomly by 0º, 90º, 180º, or 270º. The letters appeared inside circular placeholders (1.8º × 1.8º) that were visible at all times; the placeholders were equally spaced on a virtual circle with a 4.5º radius. We included the placeholders to minimize the futile search in empty locations, a pattern of behavior that our pilot participants demonstrated when restricted viewing prevented them from knowing where the search items might be.

In the training phase, we restricted the visible search items to a circle 6.7º in diameter centered on the current fixation location. Specifically, once the eye tracker detected the current gaze position (sampled at 1000 Hz), we used MATLAB to extract the gaze position and define a visible region around it. The visible region was updated if the current fixation was 8 pixels (or more) away, in either x- or y- axis, from the previous fixation 10 ms ago. The circle placeholders were visible at all times.

Procedure and Design

Participants completed practice, training, testing, and recognition, in that order.

(1) Practice. The experiment began with 24 trials of practice conducted with intact vision. To initiate a trial, participants fixated on a small central fixation point and pressed the spacebar. Upon the eye tracker's successful verification of central fixation, the search letters along with the placeholders were presented. Participants were asked to find the letter T and respond as accurately and as quickly as possible, pressing the left arrow for a left-facing T and the right arrow for a right-facing T. The search display was erased upon the response, followed by sound feedback (i.e., three rising tones totaling 200ms after a correct response, or a low buzz and a blank timeout for 2s after an incorrect response). Next, participants completed 16 trials of

practice using “tunnel vision.” These trials were the same as the earlier ones, except that the search items were limited to the central 6.7º of current fixation. Following practice, participants answered a multiple-choice question about what their task was. All participants correctly answered this question.

(2) Training. The training phase consisted of 8 blocks of 24 trials each. Similar to the last part of practice, training was conducted with restricted viewing, eliminating search items outside of the central 6.7º of the current fixation position. Unbeknownst to the participants, the target T appeared in a high-probability, “rich”, quadrant on half of the trials, and in each of the other three low-probability, “sparse”, quadrants on 16.7% of the trials. The assignment of the rich quadrant was counterbalanced across participants but remained the same for a given participant. Participants were not informed of the target’s location probability or that it might change. They also received no information about the relationship between their current gaze position and the visible region.

(3) Testing. Blocks 9-12, each with 24 trials, constituted the testing phase. The target’s location probability was random during this phase: 25% of the time in each quadrant. Participants searched with intact vision, which allowed them to see all search items regardless of their fixation position.

(4) Recognition. At the completion of the search task, participants answered a few questions that gauged their explicit awareness of the target’s location probability and gaze restriction. First, “was the target T equally likely to appear anywhere on the display?” Next, regardless of their answer, participants were then told that the target was more often located in one screen quadrant. They were asked to choose the high-probability quadrant with a key press. Third, we asked participants to report where they thought the visible region was in relation to their gaze position. The four choices were “(a) opposite (180º) to where I was looking; (b) random relative to where I was looking; (c) in the same direction as where I was looking; and (d) shifted by 90º relative to where I was looking. Finally, we asked participants to type out a response to the following question: “What strategies, if any, did you use to help you find the target when the artificial blind spot was on?”

Results

Behavioral Results

Accuracy was high and did not differ between the rich (M = 99.0%, SE = 0.2%) and sparse (M = 98.8%, SE = 0.2%) quadrants, $t(23) = 0.78$, $p = .446$, Cohen's $d = 0.158$. In the RT analysis, we excluded incorrect trials and trials with an RT outside of the 3 *SD* of an individual's mean RT. Figure 4.2 shows the mean RT across blocks.

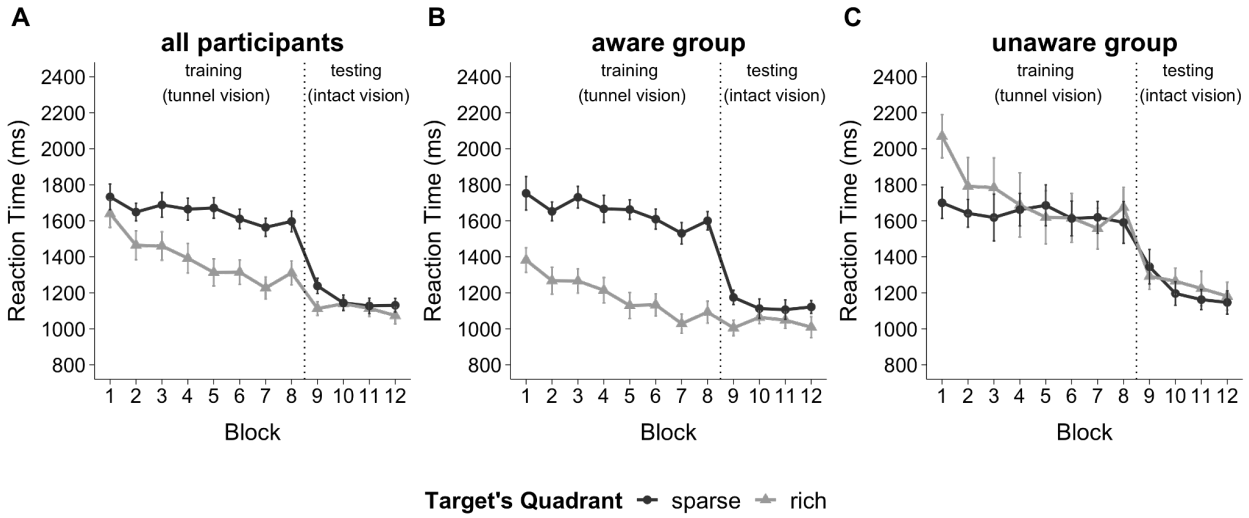

Figure 4.2 *Search RT in Experiment 1. The training blocks with an uneven target probability were conducted under tunnel vision whereas the testing blocks with an even target probability were conducted under intact vision. (A) Data from all participants. (B) Data from participants who correctly identified the rich quadrant ("aware"). (C) Data from participants who failed to identify the rich quadrant ("unaware"). Error bars show ±1 within-subject S.E. of the mean.*

Training phase with tunnel vision

All participants. We first examined RT data from all participants. In the training phase, an ANOVA using target quadrant and training block as within-subject factors revealed a significant main effect of target quadrant, showing LPL, $F(1, 23) = 5.65$, $p = .026$, $\eta_p^2 = .197$. RT was faster in later blocks than earlier ones, producing a significant main effect of the training block, $F(7, 161) = 11.88$, $p < .001$, $\eta_p^2 = .341$. The two factors interacted, $F(7, 161) = 2.33$, p

= .027, η_p^2 = .092, driven by an increase in LPL in later blocks than earlier ones. Thus, participants acquired LPL with tunnel vision.

Awareness groups. Fifteen of the 24 participants correctly identified the rich quadrant, a level substantially higher than expected by chance, $\chi^2(1) = 18.00$, $p < .001$. The level of awareness was higher than previous reports (e.g., 47% in Jiang et al., 2018's analysis of 400 participants). This could be attributed to the use of simpler displays (8 possible locations vs. Jiang et al. 's 100 possible locations) or searching with tunnel vision. Following Addleman et al. (2021), we divided participants into "aware" and "unaware" groups based on whether they correctly identified the rich quadrant.

As is apparent in Figure 4.2, only the aware participants showed clear evidence of LPL. An ANOVA using awareness group as a between-subject factor and target quadrant and block as within-subject factors showed significant main effects of training block, $F(7, 154) = 10.90$, $p < .001$, $\eta_p^2 = .331$, with faster RT in later than earlier blocks, and group, $F(1, 22) = 9.75$, $p = .005$, $\eta_p^2 = .307$, with faster RT in the aware than the unaware group. The main effect of target quadrant did not reach significance, $F(1, 22) = 3.69$, $p = .068$, $\eta_p^2 = .144$, but target quadrant interacted with awareness group $F(1, 22) = 7.70$, $p = .011$, $\eta_p^2 = .259$, and with block, $F(7, 154) = 2.76$, $p = .010$, $\eta_p^2 = .111$. The awareness group did not interact with block, $F(7, 154) = 0.51$, $p = .826$, $\eta_p^2 = .023$. The three-way interaction was not significant, $F(7, 154) = 0.76$, $p = .620$, $\eta_p^2 = .033$.

The interaction between the awareness group and target quadrant indicated that awareness modulated LPL. In a follow-up test, we separately analyzed the two awareness groups. For the aware participants, an ANOVA on target quadrant and training block revealed significant main effects of target quadrant, showing LPL, $F(1, 14) = 25.42$, $p < .001$, $\eta_p^2 = .645$, and block, $F(7, 98) = 8.25$, $p < .001$, $\eta_p^2 = .371$, without an interaction, $F(7, 98) = 0.66$, $p = .710$, $\eta_p^2 = .045$. For the unaware participants, the main effect of the target quadrant was not significant, $F(1, 8) = 0.17$, $p = .693$, $\eta_p^2 = .021$. The main effect of block was significant, $F(7, 56) = 4.00$, $p = .001$, $\eta_p^2 = .333$, as was the interaction between quadrant and block, $F(7, 56) = 2.35$, $p = .035$, $\eta_p^2 = .227$. Thus, whereas the aware participants showed the typical LPL effect, the unaware group never became faster in the rich than the sparse quadrants, lacking clear

evidence of LPL. However, they did overcome an idiosyncratic preference for the sparse quadrants exhibited early in training.

To rule out possible confounds of the visual field on awareness, we examined whether the aware and unaware participants differed in where their rich quadrant was. The rich quadrant was balanced in both the aware participants (4 in the upper right quadrant, 4 in the upper left quadrant, 4 in the lower left quadrant, and 3 in the lower right quadrant) and the unaware participants (2 in the upper right, 2 in the upper left, 2 in the lower left, and 3 in the lower right quadrant). Therefore, quadrant assignment did not contribute to the grouping of aware and unaware participants. In addition, self-reported strategies revealed no apparent differences between aware and unaware participants, most of whom reported searching around the circle or scanning from top-to-bottom or left-to-right. Detailed reports of the self-reported strategies can be found on the Open Science Framework (https://osf.io/zc4vu/).

Testing phase with intact vision

When tested with intact vision in blocks 9-12, participants did not show a persisting spatial preference for the previously rich quadrant (Figure 4.2). We conducted an ANOVA using the awareness group as a between-subject factor and target quadrant (previously rich or sparse) and testing block as within-subject factors. This analysis did not find a significant main effect of target quadrant, $F(1, 22) = 0.72$, $p = .406$, $\eta_p^2 = .032$, or any interactions between quadrant and other factors: quadrant × awareness: $F(1, 22) = 2.34$, $p = .140$, $\eta_p^2 = .096$; quadrant × block: $F(3, 66) = 1.42$, $p = .246$, $\eta_p^2 = .061$; three-way interaction: $F(3, 66) = 0.03$, $p = .994$, $\eta_p^2 = .001$. The only significant effects were the main effects of block, $F(3, 66) = 3.29$, $p = .026$, $\eta_p^2 = .130$, with faster RT in later than earlier testing blocks, and awareness group, $F(1, 22) = 4.56$, $p = .044$, $\eta_p^2 = .172$, with faster RT in the aware than the unaware group; these two factors did not interact, $F(3, 66) = 1.84$, $p = .148$, $\eta_p^2 = .077$. Thus, although participants (especially the aware group) acquired LPL when trained with tunnel vision, they did not maintain the spatial preference when tested with intact vision.

Eye movements

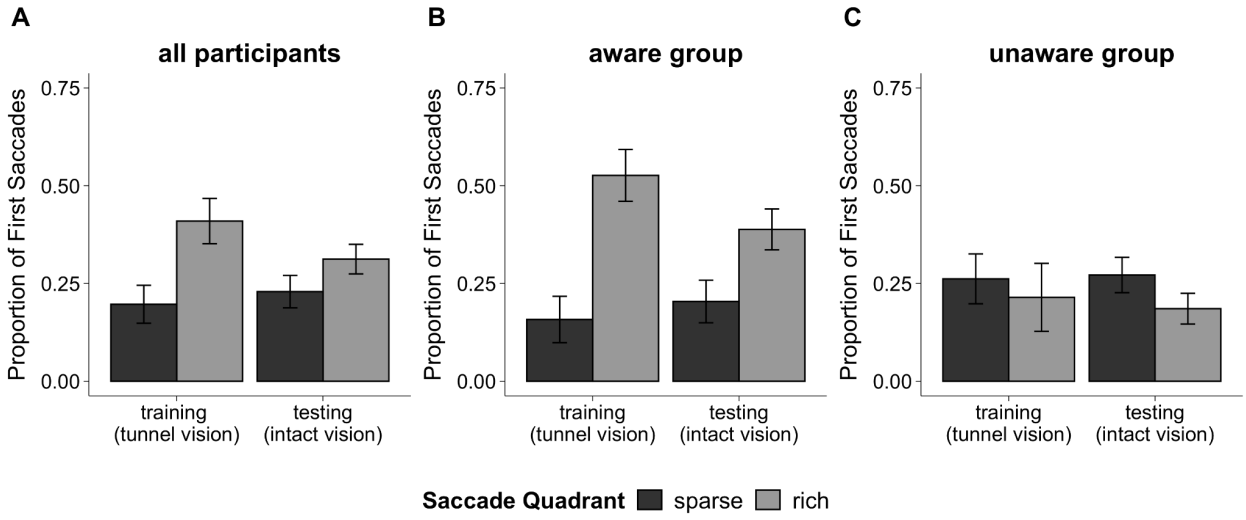

Figure 4.3 *Proportion of first saccadic eye movements toward the rich and sparse quadrants in Experiment 1. (A) All participants. (B) The aware participants. (C) The unaware participants. Note there were three sparse quadrants; the proportion of first saccades toward the three sparse quadrants was averaged. Error bars show ±1 within-subject S.E. of the mean.*

Given its rapidity, the first saccadic eye movement after trial onset is an excellent measure of the learned attentional preference (Addleman et al., 2021; Chen & Lee, under review; Jiang, Won, et al., 2014). Following these previous studies, we measured the proportion of trials in which the first saccade landed in either the rich quadrant or one of the sparse quadrants (Figure 4.3). This analysis excluded trials with an incorrect response.

In the training phase with the tunnel vision, participants preferentially directed first saccades toward the rich quadrant (*mean* = 40.9%, *S.E.* = 6.9%), which was significantly higher than the proportion to any of the sparse quadrants (*mean* = 19.7%, *S.E.* = 2.3%), $t(23) = 2.32$, $p = .030$, Cohen's $d = 0.472$. As in search RT, awareness about the target's location probability modulated the saccade pattern. An ANOVA using awareness group as a between-subject factor and first saccade direction (rich vs. sparse) revealed significant a main effect of group, $F(1, 22) = 5.81$, $p = .025$, $\eta_p^2 = .209$. The main effect of first saccade direction did not reach significance,

$F(1, 22) = 3.47$, $p = .076$, $\eta_p^2 = .136$, but it significantly interacted with awareness group, $F(1, 22) = 5.81$, $p = .025$, $\eta_p^2 = .209$. For the aware participants, first saccades were preferentially directed toward the rich quadrant, $t(14) = 3.40$, $p = .004$, Cohen's $d = .878$. In contrast, the unaware participants did not exhibit a significant saccade preference for the rich quadrant, $t(8) = 0.36$, $p = .725$, Cohen's $d = .121$.

Evidence for the saccade preference toward the rich quadrant was equivocal in the testing phase with intact vision. Numerically, the aware participants appeared to have retained their tendency to direct the first saccades toward the previously rich quadrant (rich: *mean* = 38.8%, *S.E.* = 6.9%; sparse: *mean* = 20.4%, *S.E.* = 2.3%), $t(14) = 2.01$, $p = .064$, Cohen's $d = 0.519$. This pattern reversed in the unaware participants, though the saccade bias away from the previously rich quadrant was insignificant in this group (rich: *mean* = 18.6%, *S.E.* = 5.2%; sparse: *mean* = 27.1%, *S.E.* = 1.7%), $t(8) = 1.24$, $p = .251$, Cohen's $d = 0.412$. Despite the apparent differences between the awareness groups, we did not find a significant interaction between awareness and saccade quadrant in an ANOVA using saccade quadrant and awareness as factors. The ANOVA showed no main effect of saccade quadrant, $F(1, 22) = 0.57$, $p = .460$, $\eta_p^2 = .025$, or main effect of awareness, $F(1, 22) = 4.27$, $p = .051$, $\eta_p^2 = .163$, nor did saccade quadrant interact with awareness, $F(1, 22) = 4.27$, $p = .051$, $\eta_p^2 = .163$. The equivocal saccade results, together with search RT, did not provide clear evidence for the persistence of LPL in the testing phase.

Discussion

In a location probability learning (LPL) task, participants trained with "tunnel vision" successfully acquired a spatial preference for the high-probability target locations. The extent of learning, however, was modulated by explicit awareness of the target's spatial distribution. Participants who correctly identified the rich quadrant showed unequivocal evidence of learning. Those who mistook another quadrant for the rich quadrant, on the other hand, never became faster at finding the target in the actual rich quadrant. Instead, they showed an idiosyncratic RT advantage in the sparse quadrants early in training. Thus, when participants could only see the search items within the central visual field, LPL reflected largely explicit learning.

A second finding from Experiment 1 was the weakening of LPL in the testing phase when participants searched with intact vision. For the aware participants, the RT advantage in the previously rich quadrant was statistically insignificant, a substantial reduction relative to the effect in the training phase. The unaware participants showed no LPL in the testing phase. The lack of clear persistence was in contrast to previous LPL studies that had used a "training-testing" two-phase design. When the search was conducted with unrestricted viewing in both phases, LPL reliably persisted in the even testing phase (Addleman & Lee, 2022; Jiang, Swallow, et al., 2013; Jiang, Won, et al., 2014). Restricting the visual field to include only peripheral vision, as was done in Addleman and Lee (2022), yielded an LPL in the training phase. This effect persisted in the testing phase with unrestricted viewing. Thus, transfer from tunnel vision to intact vision appeared to be more limited than transfer from peripheral vision to intact vision.

Experiment 2

Experiment 2 trained participants with intact vision and tested them with tunnel vision. Compared to Experiment 1, this design reversed the viewing conditions assigned to the training and testing phases, allowing us to address two questions. First, does awareness determine the acquisition of LPL when trained with intact vision? Several previous studies have shown that although awareness may increase LPL, the effect remained robust in participants who failed the recognition test (Addleman & Lee, 2022; Jiang et al., 2018; Vadillo et al., 2020). These previous studies were conducted with intact vision, suggesting that implicit learning is a component of LPL. However, Experiment 1 showed that awareness was key to LPL in the simplified, 8-location design. Here, using the same 8-location search array but under unrestricted viewing, we tested whether LPL could be found in participants lacking explicit awareness. If intact vision allows participants to acquire implicit learning, then we may expect that LPL to occur in both aware and unaware participants in Experiment 2.

By including a testing phase with tunnel vision, Experiment 2 addressed a second question – task transfer between intact-vision and tunnel-vision search. Training with intact vision may induce a more robust form of LPL that transfers to tunnel-vision search.

Alternatively, differences in the nature of search between intact- and tunnel- vision may prevent LPL from transferring between the two types of viewing.

Method

Participants

The 24 new participants in Experiment 2 included 16 females and 8 males with a mean age of 20.2 years (*S.D.* = 4.4 years).

Stimuli, procedure, and design

The experiment was the same as Experiment 1, except that participants searched with intact vision in the spatially-biased training phase and tunnel vision in the spatially-unbiased testing phase (Figure 4.1B).

Results

Behavioral Results

Search accuracy was slightly higher in the rich quadrant (M = 99.4%, SE = 0.2%) than the sparse quadrants (M = 99.0%, SE = 0.2%), $t(23) = 2.31$, $p = .030$, Cohen's $d = 0.471$. We excluded incorrect trials and trials with an RT outside of the 3 *S.D.* of an individual's mean RT. Figure 4.4 shows the mean RT across blocks.

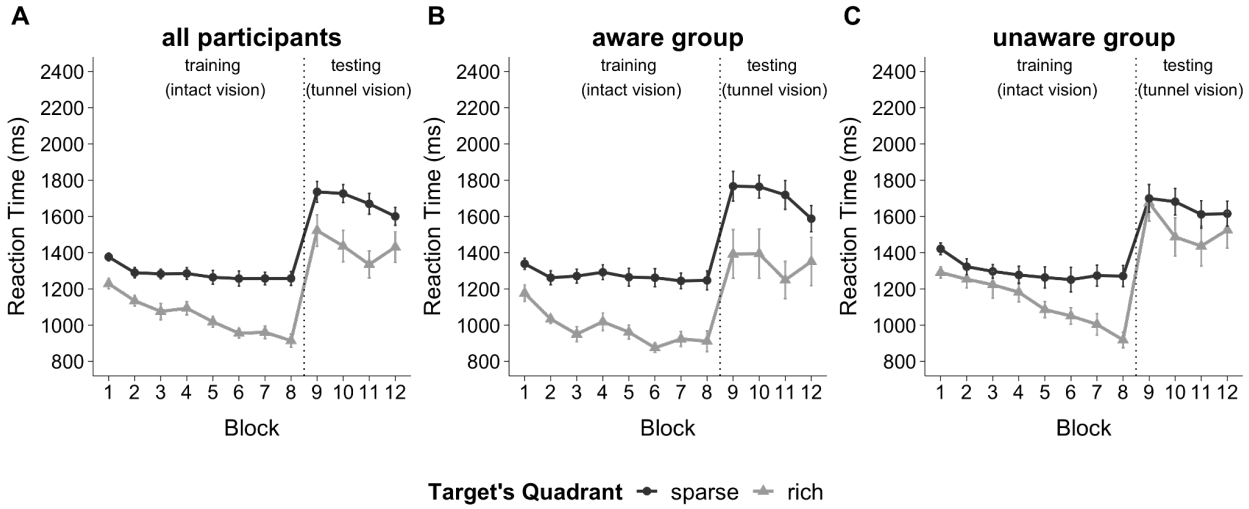

Figure 4.4 *Search RT in Experiment 2. The training blocks with an uneven target probability were conducted under intact vision whereas the testing blocks with an even target probability were conducted under tunnel vision. (A) Data from all participants. (B) Data from participants who correctly identified the rich quadrant ("aware"). (C) Data from participants who failed to identify the rich quadrant ("unaware"). Error bars show ±1 within-subject S.E. of the mean.*

Training phase with intact vision

All participants. We first examined data from all participants. In the training phase, an ANOVA on target quadrant and training block revealed a significant main effect of target quadrant, showing LPL, $F(1, 23) = 37.51$, $p < .001$, $\eta_p^2 = .620$. RT declined with increasing training, leading to a significant main effect of block, $F(7, 161) = 15.55$, $p < .001$, $\eta_p^2 = .403$. The two factors interacted, $F(7, 161) = 4.07$, $p < .001$, $\eta_p^2 = .150$, reflecting an increase in LPL in later blocks than earlier ones. As expected, when searching with unrestricted viewing, participants acquired LPL.

Awareness groups. Thirteen of the 24 participants correctly identified the rich quadrant, a level higher than expected by chance, $\chi^2(1) = 10.89$, $p < .001$. We divided participants into "aware" ($N = 13$) and "unaware" ($N = 11$) groups based on whether they correctly identified the rich quadrant (Figure 4.4).

When trained under intact vision, both aware and unaware participants evidenced LPL. An ANOVA using awareness group as a between-subject factor, and target quadrant and training block as within-subject factors showed significant main effects of target quadrant, $F(1, 22) = 38.13$, $p < .001$, $\eta_p^2 = .634$, revealing LPL. The main effect of training block was significant, $F(7, 154) = 16.30$, $p < .001$, $\eta_p^2 = .426$, with faster RT in later than earlier blocks. Target quadrant interacted with block, with an increasing LPL as training progressed, $F(7, 154) = 4.31$, $p < .001$, $\eta_p^2 = .164$. Importantly, unlike Experiment 1, awareness group did not mediate the results. The main effect of awareness group was not significant, $F(1, 22) = 0.77$, $p = .390$, $\eta_p^2 = .034$, nor did awareness interact with target quadrant, $F(1, 22) = 2.58$, $p = .123$, $\eta_p^2 = .105$, or with block, $F(7, 154) = 1.55$, $p = .155$, $\eta_p^2 = .066$, or produce a three-way interaction, $F(7, 154) = 1.60$, $p = .141$, $\eta_p^2 = .068$. Thus, awareness of the target's location probability was not necessary for acquiring LPL under unrestricted viewing conditions.

Testing phase with tunnel vision

When tested with tunnel vision in the testing phase, participants continued to show the spatial preference for the previously rich quadrant (Figure 4.4). An ANOVA using awareness group as a between-subject factor, and target quadrant (previously rich or sparse) and testing block as within-subject factors revealed a significant main effect of target quadrant, $F(1, 22) = 5.08$, $p = .035$, $\eta_p^2 = .187$, showing a persisting LPL. The main effect of block was significant, $F(3, 66) = 5.13$, $p = .003$, $\eta_p^2 = .189$, which did not interact with target quadrant, $F(3, 66) = 1.22$, $p = .309$, $\eta_p^2 = .053$. Awareness did not significantly affect results. The main effect awareness was not significant, $F(1, 22) = 0.41$, $p = .527$, $\eta_p^2 = .018$, nor did awareness interact with target quadrant, $F(1, 22) = 1.27$, $p = .273$, $\eta_p^2 = .054$, block, $F(3, 66) = 0.89$, $p = .451$, $\eta_p^2 = .039$, or produce a three-way interaction, $F(3, 66) = 0.53$, $p = .664$, $\eta_p^2 = .023$. Thus, aware and unaware participants produced qualitatively similar results – a persisting LPL in the testing phase.

Eye movements

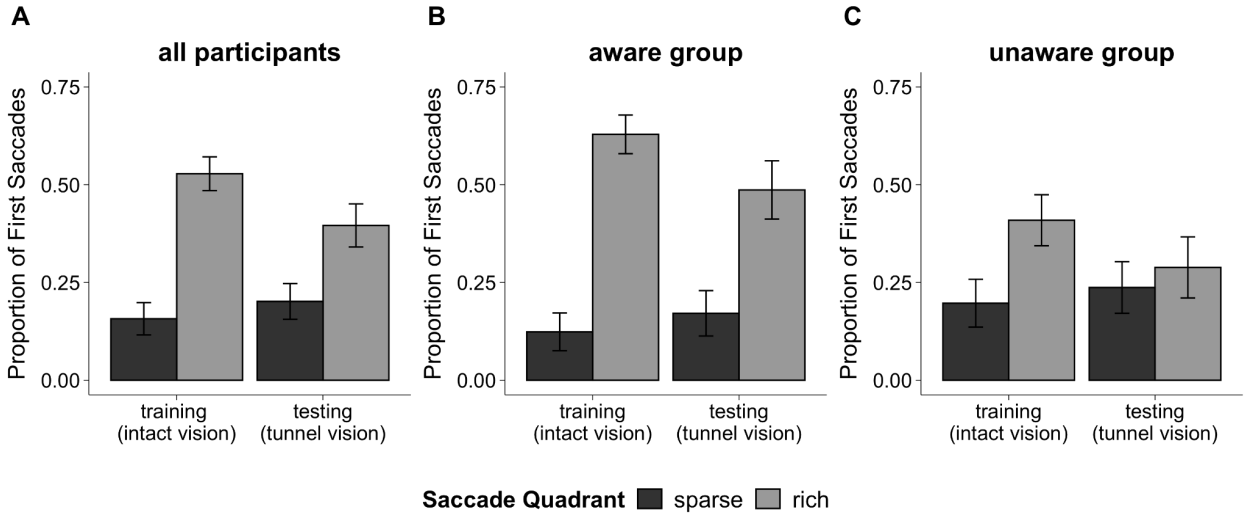

Figure 4.5 *Proportion of first saccadic eye movements toward the rich and sparse quadrants in Experiment 2. (A) All participants. (B) The aware participants. (C) The unaware participants. Note there were three sparse quadrants; the proportion of first saccades toward the three sparse quadrants was averaged. Error bars show ±1 within-subject S.E. of the mean.*

We examined the proportion of trials in which the first saccade landed in either the rich quadrant or one of the sparse quadrants (Figure 4.5). In the training phase with intact vision, participants preferentially directed first saccades toward the rich quadrant (*mean* = 52.8%, *S.E.* = 5.4%), which was significantly higher than the proportion to any of the sparse quadrants (*mean* = 15.7%, *S.E.* = 1.8%), $t(23) = 5.17$, $p < .001$, Cohen's $d = 1.056$. The tendency to saccade towards the rich quadrant was greater in aware than unaware participants. An ANOVA using awareness group as a between-subject factor and first saccade direction (rich vs. sparse) revealed significant main effects of first saccade direction, $F(1, 22) = 28.98$, $p < .001$, $\eta_p^2 = .568$, and awareness group, $F(1, 22) = 4.83$, $p = .039$, $\eta_p^2 = .180$. First saccade direction significantly interacted with awareness group, $F(1, 22) = 4.83$, $p = .039$, $\eta_p^2 = .180$. Both aware and unaware participants preferred to direct their first saccade toward the rich quadrant, though the effect was stronger in the former. For the aware participants, first saccades were preferentially directed toward the rich quadrant, $t(12) = 6.16$, $p < .001$, Cohen's $d = 1.708$. The unaware participants showed a weaker effect, $t(10) = 1.97$, $p = .077$, Cohen's $d = .593$.

The testing phase showed a persisting but weakened saccade bias toward the rich quadrant. An ANOVA using saccade quadrant and awareness as factors showed a significant main effect of saccade quadrant, $F(1, 22) = 4.76$, $p = .040$, $\eta_p^2 = .178$. The main effect of awareness group was not significant, $F(1, 22) = 2.47$, $p = .130$, $\eta_p^2 = .101$. The two factors did not interact, $F(1, 22) = 2.47$, $p = .130$, $\eta_p^2 = .101$.

Discussion

When trained with intact vision, participants in Experiment 2 acquired LPL. This effect was qualitatively similar between aware and unaware participants, suggesting that intact vision supported implicit learning of the target's location probability. This finding differed from that of Experiment 1, where LPL in tunnel vision search was largely restricted to participants with explicit awareness about the target's location probability.

A second difference between the two experiments was the degree to which LPL persisted in a spatially unbiased testing phase. When trained with tunnel vision and tested with intact vision (Experiment 1), participants did not continue to prioritize the previously rich quadrant. In contrast, when trained with intact vision and tested with tunnel vision (Experiment 2), LPL persisted. Training with intact vision may have produced a more robust form of LPL that supports task transfer.

General Discussion

Central vision has higher resolution, acuity, and contrast sensitivity than peripheral vision. Extensive vision research has focused on characterizing the function of central vision (Anstis, 1974; Bedell et al., 2009; Qiu & Leat, 2009; Virsu & Rovamo, 1979; Y. Z. Wang et al., 2002). Yet the vast majority of visual information falls in the visual periphery, raising questions about the role peripheral vision plays in supporting high-level functions like attention. Using gaze-contingent eye tracking, here we showed that attentional learning became more limited when peripheral vision was restricted. Our findings are consistent with the proposal that a nonselective pathway, supported by peripheral vision, contributes to visual search (J. M. Wolfe, 2021).

In two experiments, we tested location probability learning (LPL) – the acquisition of an attentional preference for locations that contained a target disproportionately often. The experiments used a "training-testing" two-phase design, in which the target's location probability was biased in the training phase and unbiased in the testing phase. Using gaze-contingent eye tracking, we restricted visible search items to the central 6.7º in one phase of the experiment. The "tunnel vision" mode limited the contribution of peripheral vision. When restricted viewing occurred in the training phase (Experiment 1), participants acquired LPL – faster RT when the target was in the high-probability "rich" quadrant than the low-probability "sparse" quadrants. This effect, however, was modulated by the participants' explicit awareness of the target's spatial distribution. Participants who correctly identified the rich quadrant exhibited a typical LPL, accompanied by an increased tendency to direct the first saccadic eye movement toward the rich quadrant. Participants who failed to identify the rich quadrant, on the other hand, were not faster in the rich than the sparse quadrants, nor did they preferentially saccade toward the rich quadrant. Instead, they appeared to disfavor the rich quadrant early in training. This was not because LPL always depended on explicit awareness. In Experiment 2, participants searched with unrestricted viewing in the training phase. Both the aware and unaware participants successfully acquired LPL, supporting the idea that under intact vision conditions, LPL reflects, in part, implicit learning (Jiang, 2018; Jiang et al., 2018). Together, these experiments suggest that peripheral vision is important for acquiring implicit location probability learning.

The lack of LPL in the unaware participants of Experiment 1 differed from the intact learning of unaware participants under simulated central vision loss. In Addleman and Lee (2022), participants who searched with only their peripheral vision successfully acquired LPL, an effect demonstrated by both aware and unaware participants. Thus, whereas implicit LPL survives central vision loss, it is more fragile in conditions of peripheral vision loss.

Our findings are consistent with previous studies on ensemble perception (Whitney & Yamanashi Leib, 2018) and contextual cueing (Sisk et al., 2019). Ensemble perception refers to the representation of summary visual statistics from a spatial array or a temporal sequence (Florey et al., 2017; Gorea et al., 2014), such as information about the average object size (Albrecht & Scholl, 2010; Chong & Treisman, 2003), the centroid of multiple objects (Lew &

Vul, 2015), or the average facial expression or identity (Haberman et al., 2009; Haberman & Whitney, 2010; Yamanashi Leib et al., 2014). Notably, foveal information is not critical for ensemble perception. For example, participants were highly accurate in determining the average facial expression of faces when their central vision was occluded (B. A. Wolfe et al., 2015). Studies on contextual cueing have likewise underscored the importance of peripheral vision. As noted earlier, tunnel-vision search disrupted spatial context learning (Geringswald & Pollmann, 2015; Zang et al., 2015). In contrast, simulated central vision loss did not prevent participants from acquiring contextual cueing (Geringswald & Pollmann, 2015; also see Geringswald et al., 2012).

Peripheral vision may contribute to visual search in several ways. First, it allows observers to rapidly extract global image characteristics, such as the gist of a scene, mean size or centroid of objects, and other image statistics that are predictive of targets. Second, peripheral vision facilitates spatial context learning, which by definition, requires participants to form associations among objects that fall in the visual periphery. Third, by providing a glimpse of the entire visual display, peripheral vision facilitates the spatial representation of individual search items, allowing the items to be coded not just relative to the observer or the screen, but also to the other items. These factors may explain why attentional learning, such as contextual cueing and location probability learning, becomes less robust when peripheral vision is limited.

Besides illustrating the role of peripheral vision in attentional learning, our study has implications for understanding LPL. When searching with an unrestricted view, participants typically exhibit implicit learning – the faster search time in the high-probability locations is not contingent on having an explicit awareness of where those locations are (Druker & Anderson, 2010; Geng & Behrmann, 2002; Jiang, 2018; Jiang et al., 2018; Jiang, Swallow, et al., 2013). Other studies, however, have shown that explicit awareness contributes to LPL. For example, participants with greater awareness about the target-rich locations sometimes show a larger LPL (Vadillo et al., 2020). In addition, informing participants about the probability manipulation ahead of time increases the observed LPL (Jiang, Swallow, et al., 2014). These findings show that the uneven target spatial distribution can yield both implicit and explicit learning – the dual-system for learning. The current study further supports the dual-system view. It additionally

shows that the two systems may have different characteristics. Explicit learning is preserved in tunnel vision, but it does not support transfer of the learning to intact-vision search. Implicit learning may require peripheral vision; once acquired, the effect may persist in tunnel-vision search. Future research is needed to determine what other differences exist for explicit and implicit LPL.

Our study reopens the question of how LPL persists and transfers across different task settings. Several previous studies have shown that LPL transfers when the nature of the search task is preserved, but not when different search procedures are used. For example, LPL acquired in a T-among-L search task transferred to a 2-among-5 search task, and vice versa (Chen & Lee, under review; Jiang et al., 2015). In contrast, LPL acquired in a T-among-L search task did not transfer to a treasure-hunt decision task (Jiang et al., 2015). Likewise, LPL acquired in a camouflaged T-detection task did not transfer to a well-segmented letter search task (Chen & Lee, under review; Sha et al., 2018). These findings have supported the idea that LPL reflects a procedure-like search habit. That is, tasks that share similar search procedures, such as self-terminating serial search, would show task transfer in LPL. To the degree that intact vision and tunnel vision yield different search procedures, the procedural account explains why LPL failed to transfer from tunnel vision to intact vision (Experiment 1). But without additional assumptions, this account does not explain why LPL transferred from intact vision to tunnel vision (Experiment 2). A full account of such data may need to consider the nature of LPL – explicit or implicit learning. For explicit learning, participants' top-down knowledge and assumptions about the tasks would influence whether LPL transfers across tasks. For implicit learning, task transfer may conform to the procedural account.

LPL illustrates the complexity of understanding transfer effects in attention learning. The larger literature on brain training is ripe with contradictory findings and interpretations (Simons et al., 2016). Future studies need to consider multiple factors, including the explicit vs. implicit nature of learning, the serial or parallel mode of the search, and the availability of central vs. peripheral vision.

Our study raises the possibility that mechanisms governing visual search with unrestricted viewing may not operate the same way as when participants search with a restricted

view. Search with unrestricted viewing is strongly visually guided – the spatial layout, visual features, and scene gist provide rich sources of information about where to deploy attention. In contrast, tunnel vision search limits available visual information about the display, making the task more strategic. In Chun et al. (2011)'s terminology, unrestricted viewing may rely primarily on external attention, whereas tunnel vision exerts greater demands on internal attention. The existing literature contains excellent models for visual search with external attention (Desimone & Duncan, 1995; Treisman, 1996; J. M. Wolfe, 2021). In contrast, relatively little is known about how people search with internal attention, a topic for future research.

Conclusion

This study applied gaze-contingent eye tracking to a location probability learning paradigm to simulate peripheral vision loss. When trained in a restricted view that limited search items to the central vision, participants acquired an attentional preference toward the target's high-probability region. This effect, however, was evident only in those who became explicitly aware of the target's location probability. The unaware participants did not produce faster search RT in the high-probability relative to the low-probability regions. In contrast, when trained with intact vision, both aware and unaware participants successfully acquired location probability learning. Thus, whereas explicit learning may proceed with central vision alone, peripheral vision is important for implicit location probability learning. The findings are in line with the proposal of a nonselective pathway, supported by peripheral vision, that conveys summary statistical information to guide visual search (J. M. Wolfe, 2021).

5. Summary and general discussion

5.1 Summary of the findings

At any given moment, the visual environment is teeming with abundant information that exceeds our limited processing capacity. With multiple stimuli competing for selection, attention is required for prioritizing the most relevant information. One primary goal of attention research is to uncover which information is selected and how it is selected (Chun et al., 2011). In the visual domain, the central fovea of the retina, which has the highest acuity, is directed toward target objects through a sequence of eye movements. Thus, on the one hand, we tend to find a target by looking directly at it, resulting in a tight coupling between eye movements and spatial attention. Preparing for saccades enhances attentional orienting, and conversely, attending to a location facilitates saccade preparation toward that location. Both processes activate largely overlapping regions in the brain. On the other hand, orienting attention and saccadic movements appear to be governed by two separate populations of neurons in the brain. Previous studies on the relationship between attention and eye movements have predominantly focused on goal-driven or stimulus-driven attention. However, emerging evidence demonstrates that previous experience serves as a third driver of attention, alongside task goals and physical salience. This experience-guided attention often occurs implicitly and does not change the sensory salience of stimuli, setting it apart from goal-driven and stimulus-driven attention. These distinctions raise the possibility that experience-guided attention may interact with eye movements in unique ways, influencing not only where to attend in space but also how to shift attention between locations.

The first two studies in this dissertation examined the robustness of location probability learning under conditions with unnaturally directed eye movements. When a target frequently appears in one location, it leads us to consistently gaze toward its direction. Previous experience affects both covert attention and overt eye movements, raising the possibility that oculomotor learning may underpin experience-guided attention. An oculomotor habit that is spatially incompatible with selection history may interfere with experience-guided attention. However, the findings in Study 1 did not support this hypothesis. Instead, Study 1 demonstrated that frequently saccading away from a search target did not prevent location probability learning. Yet, the

sequential nature of the saccade and search tasks did not provide clear-cut evidence for the independence between oculomotor movements and location probability learning. To determine whether location probability learning persists when eye movements are forced away from the attended location, Study 2 applied eye tracking to restrict the visible regions of the visual field to a location opposite from where one was fixating. Does location probability learning reflect oculomotor learning or a high-level cognitive process? If LPL is solely oculomotor learning, it would be impossible to establish an attentional habit in an antisaccade-like training procedure. The results in Study 2, contrarily, showed that people can acquire an attentional habit even when they must move their eyes away from the target to see. Together, these two studies are in line with the modular theory of attention, suggesting that experience-guided attention is a high-level process partially separable from oculomotor circuits.

The independence of attention learning and oculomotor movements led to the second focus of this dissertation: what role does peripheral vision play in guiding spatial attention? To address these questions, Study 3 used gaze-contingent eye tracking to simulate peripheral vision loss in a location probability learning task. Participants were only able to see items in the central region of their current gaze position. When trained with the restricted tunnel-vision view, Study 3 found that participants who became aware of the target's biased location probability acquired an attentional preference for the target's high-probability region, but those who lacked explicit awareness did not. In contrast, when trained with intact vision, both aware and unaware participants developed attentional preferences for the high-probability region. These findings enhance our understanding of the role peripheral vision plays in attention learning. Whereas explicit learning may occur when individuals are constrained to exclusively rely on central vision, implicit attention learning is mainly facilitated by peripheral vision. Thus, the spatial information gleamed through peripheral vision may facilitate implicit experience-guided attention via a nonselective pathway that conveys summary statistical information.

In summary, this dissertation addressed three key questions related to experience-guided attention. First, attentional preference for high-probability locations does not depend on repeated oculomotor movements toward those locations. In fact, location probability learning persisted even when participants frequently saccaded away from the target's high-probability locations.

Conversely, repeatedly saccading toward one location did not induce a lasting attentional bias toward that region. Second, the spatial alignment between eye gaze and attended location is unnecessary for acquiring location probability learning. Participants still acquired location probability learning even when they consistently looked away to find the target. Third, while explicit learning may occur when individuals are constrained to rely exclusively on central vision, implicit location probability learning is strengthened by peripheral vision. Hence, experience-guided attention is a high-level process that is partially independent of oculomotor systems and is implicitly supported by peripheral vision.

5.2 Theoretical implications

5.2.1 Experience-guided attention partially separates from oculomotor movements

Although much of our visual experience results from moving our eyes to explore the visual world, both goal-driven and stimulus-driven attention are, in part, abstracted from oculomotor movements. Single-unit recording studies provide the most compelling evidence supporting this idea, demonstrating that covert attention and overt eye movements activate separate populations of neurons in the brain (Messinger et al., 2021; Thompson, 2005). However, in addition to task goals and stimulus salience, attention is also guided by previous experience (Addleman & Jiang, 2019; Awh et al., 2012; Jiang, 2018; Theeuwes, 2019). People acquire an attentional preference for locations that frequently contained a search target in the past, resulting in both faster response and more frequent eye movements toward those locations. One missing piece in attention research is whether experience-guided attention and eye movements can be separable. This dissertation shows that location probability learning is partially independent of oculomotor movements.

Location probability learning (LPL) is abstracted from oculomotor movements, as evidenced in various ways. First, participants can acquire LPL while maintaining central fixation, indicating that repeatedly shifting one's eyes toward the high-probability region is not necessary for LPL (Addleman et al., 2018; Geng & Behrmann, 2005; Jiang & Swallow, 2013). Second, Study 1 found that frequently directing eye movements toward a certain location was insufficient for LPL. Similarly, in an easy feature search task, where participants were asked to

find a color-defined singleton T among L distractors, they did not acquire LPL (Jiang et al., 2015). Third, Study 1 showed that repeatedly directing one's eyes away from the high-probability location did not impede LPL toward the high-probability region. The magnitude of learning observed in Study 1 (15% of RT savings) was comparable to that reported in previous studies (10-25% of RT savings in Jiang, Swallow, et al., 2013). Lastly, even under the extreme situation where the attended region never aligned with the saccade direction, Study 2 demonstrated that LPL was still preserved. Taken together, the persisting LPL is tied to the attended target rather than oculomotor programming. While the location probability biases both attention and oculomotor movements, oculomotor movement is neither necessary nor sufficient for LPL, nor does it interfere with LPL, supporting the modular theory of attention.

What about other forms of experience-guided attention, such as contextual cuing and reward-driven attention? In contextual cuing, participants not only search faster for repeated displays relative to novel ones, but they also make fewer fixations and follow more direct scanpaths in repeated displays (Brockmole & Henderson, 2006; Peterson & Kramer, 2001; Tseng & Li, 2004). For instance, the proportion of trials where the first saccades landed directly on the target was higher in repeated displays than in novel displays (Peterson & Kramer, 2001). These findings may imply a link between contextual cuing and eye movements. However, contextual cuing was still observed when the search display was too brief for eye movements to occur (Chun & Jiang, 1998; Makovski & Jiang, 2011), or when participants were instructed not to make any eye movements, and successful adherence to this instruction was confirmed by an eye tracker (Makovski & Jiang, 2011). Therefore, akin to location probability learning, oculomotor movements are unnecessary for contextual cuing.

When it comes to reward-driven attention, previous studies have found that stimuli previously associated with high rewards triggered more oculomotor capture than those associated with low rewards (Failing et al., 2015; Failing & Theeuwes, 2018; Hickey & van Zoest, 2012). However, oculomotor training alone is not sufficient for reward-driven attention. McCoy and Theeuwes (2018) investigated whether the reward-driven attentional bias can be transferred from overt eye movements to covert attention. Participants were trained to saccade toward locations that were either associated with or without rewards. Over time, participants became faster at

saccading to the rewarded location compared to the non-reward locations. However, during testing, participants did not search faster at the highly rewarded location. These results suggest that reward-based oculomotor training does not alter the covert deployment of attention. In other words, oculomotor training is insufficient for acquiring reward-driven attention.

Taken together, experience-guided attention is partially independent of oculomotor movements, much like goal-driven and stimulus-driven attention, supporting the modular theory of attention. This relative independence from eye movements has been observed in various forms of experience-guided attention, encompassing not only location probability learning, but also contextual cuing and reward-driven attention.

5.2.2 Peripheral vision facilitates implicit experience-guided attention

Although human eyes are often compared to cameras, our visual field is not uniform. The fovea, which has the highest photoreceptor density, corresponds to approximately 50% of the visual cortex (Curcio et al., 1990; Tootell et al., 1982). This retinal anatomy leads visual processing to vary with eccentricity. The central fovea has higher visual acuity and contrast sensitivity than peripheral vision (Anstis, 1974; Robson & Graham, 1981), while peripheral vision exhibits faster processing speed and enhanced perceptual grouping (Banks & White, 1984; Carrasco et al., 2003). The differences between central and peripheral vision are not only reflected in visual perception but also in the allocation of attention. Both feature and conjunction search become less efficient as eccentricity increases (Carrasco et al., 1995, 2006; J. M. Wolfe, 1998). These results are partially due to the cortical magnification of central vision, meaning that a larger cortical area is dedicated to processing visual stimuli presented in the fovea than in the periphery (Daniel & Whitteridge, 1961; Virsu & Rovamo, 1979). Magnifying stimuli by the cortical magnification factor flattens out the eccentricity effects in visual search (Carrasco & Frieder, 1997; Motter, 2009, but see Y. Bao et al., 2013; J. M. Wolfe et al., 1998). Nevertheless, central and peripheral vision differ in visual search and influence how spatial attention is allocated.

Then, how do central and peripheral vision affect experience-guided attention? Studies 2 and 3 inform the distinction between central and peripheral vision in location probability

learning. Study 2 used gaze-contingent eye tracking to restrict visible areas to a location opposite to where participants were gazing. In this setup, search items were presented in the periphery at approximately 7° eccentricity. Even with only peripheral vision, participants persistently biased attention toward the high-probability locations during restricted-view search. This attentional preference was not affected by awareness of the target's spatial distribution, suggesting that peripheral vision supports both implicit and explicit location probability learning. However, when searching with central vision alone, Study 3 demonstrated that only participants with explicit awareness of the target's spatial distribution acquired location probability learning. These findings are consistent with Addleman and Lee (2022), who showed that location probability learning can be acquired even when searching with simulated central vision loss. Thus, while explicit attention learning occurs with central vision alone, implicit learning appears to rely on peripheral vision.

Similar to location probability learning, contextual cuing, another form of implicit experience-guided attention, likely depends on peripheral vision. As previously noted, contextual cuing is characterized by faster search in repeated configurations compared to novel ones. Contextual cuing was eliminated when participants conducted visual search with a central scotoma (i.e., searching with peripheral vision alone in either healthy participants with simulated central scotoma or patients with age-related macular degeneration; Geringswald et al., 2012; Geringswald, Herbik, et al., 2013). However, contextual cuingimmediately emerged once the central scotoma was removed during testing (Geringswald & Pollmann, 2015). In contrast, when searching with peripheral scotoma (i.e., searching with central vision alone) during training, contextual cuing was not observed, and its reemergence was not ensured after the tunnel was removed during testing (Geringswald & Pollmann, 2015; Zang et al., 2015). Moreover, these studies did not find a correlation between explicit awareness of repeated displays and the magnitude of contextual cuing (Geringswald, Baumgartner, et al., 2013; Geringswald, Herbik, et al., 2013; Geringswald & Pollmann, 2015; Zang et al., 2015, but not in Geringswald et al., 2012). Therefore, contextual cuing appears to rely on peripheral vision, regardless of participants' explicit awareness of configuration repetition.

These findings on implicit experience-guided attention are in line with the proposal in Guided Search 6.0 (J. M. Wolfe, 2021) that, in addition to the selective "bottleneck," a nonselective pathway supported by peripheral vision guides visual search, enabling participants to rapidly extract statistical information. This idea originates from another line of research on ensemble perception: observers can estimate the mean and distribution of various basic visual features, such as size, orientation, or motion direction, as well as complex attributes like face identity and emotion (for reviews, see Whitney & Yamanashi Leib, 2018; J. M. Wolfe et al., 2011). According to this view, summary statistical information obtained through a nonselective pathway can influence attention allocation and eye movements. In other words, people may sense the target's location before actually finding it. This can explain why participants were likely to direct their first saccades toward the high-probability region in location probability learning tasks (Addleman & Lee, 2022; Jiang, Won, et al., 2014), and more frequently landed first saccades directly on the target in the repeated displays during contextual cuing tasks (Peterson & Kramer, 2001). When peripheral vision is eliminated, without a nonselective pathway, participants no longer acquire an attention bias or first saccadic preference in implicit experience-guided attention.

5.2.3 Selection history implicitly alters procedural attention

As mentioned in the Introduction, there are two main views on how previous experiences affect attention (Figure 1.1): the integrated attentional priority map (Awh et al., 2012; Chelazzi et al., 2014; Theeuwes et al., 2022), and the habitual attention view (Jiang, 2018; Jiang & Sisk, 2019). The integrated attention priority map is derived from the attentional priority map view: locations with the highest weight on a mental map are prioritized to guide attention and plan saccades, regardless of whether the weights originate from a task goal or stimulus salience (Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Itti & Koch, 2001; J. M. Wolfe, 1994). Attention is guided to the peak on the priority map in a winner-take-all fashion and may be updated rapidly. However, there is no consensus on the updating rate: the attention priority map may update around the time of each saccade (Bisley & Goldberg, 2010) (primates typically make

about three to four saccades per second), or in the 3-8 Hz theta-band (Fiebelkorn & Kastner, 2019), or approximately 20 times per second depending on task difficulty (J. M. Wolfe, 2021).

Recently, researchers integrated previous experience into a theoretical framework and proposed the integrated priority map view (Awh et al., 2012). In this view, frequently placing a target in one location or associating higher rewards with that location increases the priority weights assigned to that location on the priority map. One influential behavioral study supporting this view was conducted by Chelazzi et al. (2014) on reward-driven attention. In a training phase, participants identified targets (letters or digits) among distractors, with the target's locations associated with various probabilities of obtaining a high reward. During testing, participants were instructed to discriminate the color of the target (an upper triangle) among distractors. The researchers found that locations associated with higher rewards during training were prioritized during testing. Although this result is taken as evidence for the integrated priority map, it can be simply explained by task transfer, irrespective of stimulus type. Furthermore, the integrated priority map view fails to explain the unique characteristics of location probability learning that distinguish it from goal-driven attention, such as insensitivity to outcome devaluation, viewer-centered reference frame, low reliance on working memory resources, preservation in older adults and Parkinson's patients, and, most importantly, implicit guidance (for a review, see Jiang, 2018).

The unresolved questions have led researchers to propose a complementary account: the habitual attention view (Jiang, 2018; Jiang & Sisk, 2019). In general, a habit refers to a structured, ordered sequence of actions that are triggered by a particular stimulus or context; once triggered, the sequence can reach completion without constant conscious control (Graybiel, 2008). Similar to motor habits, location probability learning implicitly guides attention and is insensitive to outcome devaluation, which distinguishes it from goal-driven attention (Jiang, Swallow, et al., 2013). Rather than simply shifting attention to the peaks on the priority maps over time, the habitual attention view proposes an additional action-like "procedural component" in attention. The procedural component specifies how to shift attention, with locations specified as vectors of movements. According to this view, location probability learning reflects a change

in the procedural action-like component of attentional shifts, rather than a change on a priority map.

Studies 2 and 3 provide evidence that location probability learning does not lead to a generic, task-independent change in spatial priority. Study 2 showed that the attentional preference for the high-probability quadrant was eliminated when participants switched from a restricted view to an intact view. Eye data in Study 2 revealed distinct oculomotor patterns during search with a restricted view, such as sharply decreased saccade amplitude and velocity. In contrast, Study 3 found that the spatial preference was durable, persisting from an intact view to a tunnel-vision restricted view. Eye data in Study 3 showed high similarities in saccade amplitude and velocity between the intact view and the tunnel-vision restricted view. Together, Studies 2 and 3 suggest that location probability learning is likely to be enforced in the action-like search procedure. This is consistent with previous findings by Sha et al. (2018), which showed that location probability learning was acquired in the T-among-L search task but failed to persist when people searched for a T against a cloud-like noise background. Eye-tracking showed that the camouflaged-T detection task involved fewer saccades but longer fixations than the T-among-L discrimination task. That is, location probability learning does not persist to tasks involving different search procedures, even when participants search for the same target (i.e., letter T) in the same search space. Thus, implicit experience-guided attention may be implemented in the search procedure, in line with the habitual attention view.

Figure 5.1 depicts the multiple stages involved in visual selection. Here I incorporate the role of explicit awareness into the current attention framework, focusing on how previous experience affects spatial attention. The first layer encompasses two primary streams of attentional sources: implicit sources, such as selection history (e.g., target's location probability) and cue-target association, and explicit sources, such as reward history, task goals, and stimulus salience. The second layer illustrates how attentional preferences derived from different sources may guide attention through distinct processes. Experiences gained from explicit learning (e.g., reward history) may guide attention via the attention priority map, whereas implicit learning (e.g., target's location probability, cue-target association) may drive attention through the procedural component of attention. As a relatively high-level cognitive process, attention

subsequently influences motor planning and control within motor systems (e.g., oculomotor, head, or limb movements), to optimize response to the search target. The studies presented in this dissertation suggest that it is less probable for implicit sources, e.g., location probability learning, to directly affect motor systems. In essence, when searching for a target, potential processes may involve the following: the summary statistical information extracted by the nonselective pathway in peripheral vision may trigger procedural attention, enabling attention to be implicitly guided by selection history and cue-target association. Concurrently, other information (e.g., current goals, stimulus salience, and reward history) is represented on the priority map to explicitly guide attention. When observers become explicitly aware of the target's location probability (in location probability learning tasks) or cue-target association (in contextual cuing tasks), attentional guidance may transition from procedural attention to the attention priority map, beginning to interact with other explicit sources, such as task goals.

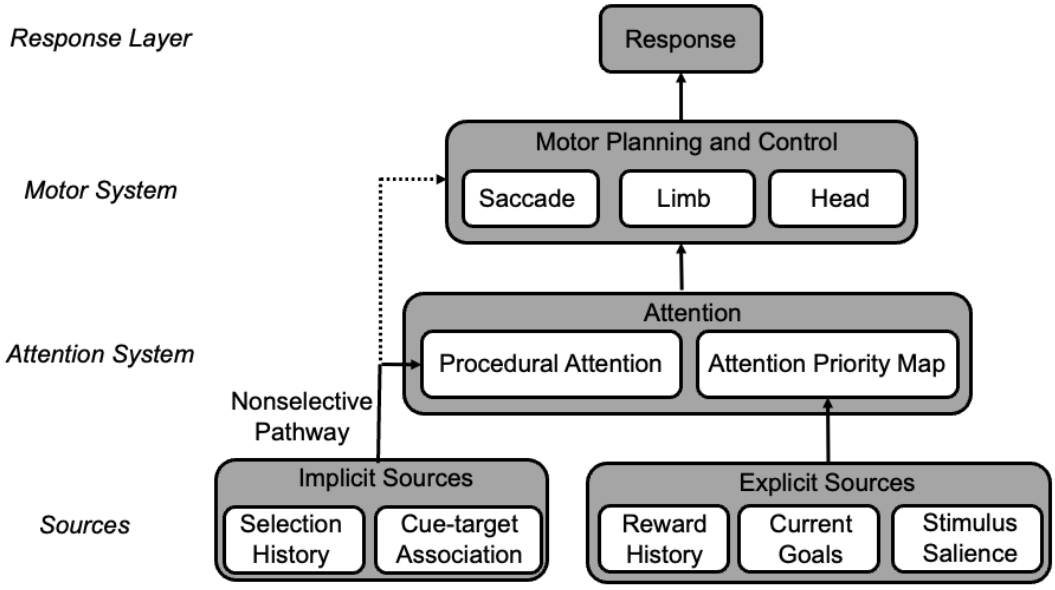

Figure 5.1 *A possible schematic representation of how previous experiences guide attention to find targets optimally in visual selection. Selection history, e.g., target's location probability, may implicitly affect procedural attention, while experiences gained through explicit learning, e.g., reward history, may proceed through the attentional priority map along with current goals and stimulus salience.*

5.3 Future directions

5.3.1 The neural bases of experience-guided attention

One important, yet unresolved question is the neural basis of experience-guided attention. Attention has been categorized into different anatomical systems for decades, with three main systems: the alerting network, the orienting network, and the executive control network (Petersen & Posner, 2012; Posner & Petersen, 1990). In this dissertation, I specifically focus on selective attention oriented toward the external sensory input, particularly visual information. Extensive evidence from the task-state fMRI and resting-state functional connectivity has shown that two brain networks underlie attention orienting (Corbetta & Shulman, 2002; Power et al., 2011). The dorsal network is involved in goal-driven attention, including the frontal eye fields and the intraparietal sulcus/superior parietal lobe, while the ventral network contributes to stimulus-driven attention, including the temporoparietal junction and the ventral frontal cortex (Corbetta & Shulman, 2002). Previous experience is considered the third driver of attention independent of task goals and physical salience. Therefore, an intuitive question is what neural basis underlies experience-guided attention, such as location probability learning. This question can be divided into two parts: (1) which brain regions are associated with location probability learning, and (2) whether brain activity increases or decreases in location probability learning.

Currently, there is limited research investigating the neural basis of location probability learning. As location probability learning in visual search is a form of statistical learning in visual attention, it may involve both the visual attention and statistical learning systems in the brain. Visual attention is known to enhance neural responses of neurons in the visual cortex that encode the attended location or feature (Kastner et al., 1999; Reynolds & Chelazzi, 2004). Statistical learning has been found to attenuate neural responses in visual cortex to predictable stimuli, based on the predictive coding framework (Alink et al., 2010; Ouden et al., 2010; Richter et al., 2018; Richter & de Lange, 2019). These two systems appear to be in opposition to each other. To investigate this apparent contradiction, Kok et al. (2012) had participants perform an orientation identification task on a grating that appeared on the left or right of fixation. Participants were presented with location prediction cues and spatial attention cues

independently. The location prediction cue (i.e., left or right), presented before each block, indicated that the grating would appear on one specific side 75% of the time. The spatial attention cue (i.e., a sideways triangle), presented at the beginning of each trial, indicated which hemifield was task-relevant, and participants only responded if the grating appeared in the indicated hemifield. Kok et al. (2012) found that when stimuli occurred in predicted locations compared with unpredicted locations, stimuli on the unattended side induced a reduced activation in primary visual cortex, while stimuli on the attended side evoked a larger activation in early visual areas. These results showed that prediction attenuated sensory signals when the stimulus was task-irrelevant (in the absence of attention), but enhanced the sensory signals when it is task-relevant. Though Kok et al.'s prediction cues were defined by instruction, reflecting explicit goal-driven attention, and largely separate from the probability cue in location probability learning, these findings offer insights into the potential brain activities that may underlie location probability learning.

There is currently no direct evidence on the neural basis of the target's location probability learning, but studies on distractor's location probability learning provide some insight. Won et al. (2020) combined fMRI with a distractor's location probability learning task, where a salient distractor frequently appeared at one location relative to the other locations. They found that search became less interfered by distractors appearing at high-probability than low-probability locations, and their fMRI results showed reduced activations in the visual cortex when distractors occurred in high-probability locations. Zhang et al. (2022) replicated this finding, showing that BOLD signals in the early visual cortex decreased for distractors at high-probability versus low-probability locations. More recently, Ferrante et al. (2023) used magnetoencephalography (MEG) and found reduced neuronal excitability in the early visual cortex for the location more likely to contain distractors. Therefore, recent brain imaging studies using the distractor's location probability learning paradigm consistently showed reduced neural activities in the early visual cortex at the distractor's high-frequency than low-frequency locations. These results are consistent with Kok et al.'s finding that prediction attenuates sensory signals when the stimulus is task-irrelevant. However, it should be noted that target's location probability learning may not share the same mechanisms as distractor's location probability

(Failing et al., 2019; Ferrante et al., 2018; Zhang et al., 2022; Zhou et al., 2023). As the target is task-relevant in visual search, the target's location probability learning may enhance neural activities in the early visual cortex.

Another important question is which brain regions drive neural activity changes in the early visual cortex. Won et al. (2020) found that bilateral intraparietal sulcus showed more activation in trials with a low-frequency singleton compared to trials with a non-singleton counterpart, but did not show differences between a high-frequency singleton and a non-singleton counterpart. Similarly, Zhang et al. (2022) found that superior parietal lobule was more activated when the color-defined singleton distractor appeared in the low-probability location than in the high-probability location. These two studies suggest that, compared to the high-probability distractor, the low-probability singleton distractor evoked more attentional signals in frontoparietal areas. However, the processing of target and singleton distractor largely differs. When removing the singleton distractor in visual search, frontoparietal areas may no longer modulate target's location probability learning. Instead, the striatum is a more plausible brain region that may be involved in target's location probability learning. In a study by Goldfarb et al. (2016), participants performed a visual search task (searching for T among Ls) guided by probabilistic stimulus-response associations. Unbeknownst to the participants, the target appeared in one quadrant 80% of the time with a fixed button-press response (e.g., target T was always oriented to the right, requiring a right-arrow key press). Using fMRI, Goldfarb et al. (2016) found that neural responses in the striatum predicted attention facilitation from stimulus-response associations. While they called it the stimulus-response associations, this cue is analogous to the location probability, except that location probability learning studies generally randomize the button-press responses. Furthermore, location probability learning may rely on the same regions activated in other visual statistical learning tasks. Besides the striatum, previous studies on visual statistical learning found neural activations in object-selective lateral occipital complex and the medial temporal lobe, including the hippocampus (Alink et al., 2010; Ouden et al., 2010; Richter et al., 2018; Turk-Browne et al., 2009, 2010).

In summary, there is currently no direct evidence on the neural basis of the target's location probability learning. It is possible that the target's location probability learning in the

visual domain may enhance neural activity in the early visual cortex, and further increase neural activities in the striatum and medial temporal lobe. Future research can focus on whether there are modality-specific and domain-general brain systems underlying experience-guided attention.

5.3.2 Experience-guided attention across motor systems

Previous research suggests that location probability learning is a relatively high-level habit-like attention, which is not entirely dependent on oculomotor or hand movements. However, this has not been directly tested. The three studies presented in the dissertation rely on eye and hand movements to find the target and respond. If location probability learning relies on mechanisms shared across motor systems, then probability learning acquired in one motor system should affect preferences in other motor systems. So far, there has been little research on location probability learning across motor systems.

To investigate location probability learning across motor systems, future studies can train participants with an eye-contingent search task that restricts the visible region to an area adjacent to the current gaze, and then test participants with a mouse-contingent search task. In the visual search task, participants can identify a target letter T among distractor Ls and report its orientation. In the training phase, the target would appear more often in one high-probability quadrant, and in the testing phase, the target's distribution would be unbiased to test the persistence of the location probability learning. If the learning acquired through eye-contingent search persists in the testing phase with mouse-contingent search, it would suggest a shared mechanism across motor systems.

Another possible study is to test whether location probability learning trained with fixation maintained in the center (covert attention) persists during searching with free saccades (overt attention), or conversely, whether the learned preference based on searching with overt attention can persist in searching with covert attention. In the training phase, people can be required to maintain fixation in the center while searching for the target T among distractor Ls, with the target appearing more frequently in one visual quadrant. In the testing phase, when the target is evenly distributed in all quadrants, participants can freely move their eyes to search for

the target. This potential study can help us understand whether similar motor planning is needed for the persistence of location probability learning.

5.3.3 Experience-guided attention in realistic scenes

People may not solely rely on their peripheral vision to develop implicit attention when searching under meaningful, realistic scenes. In the past, Sisk et al. (2021) demonstrated location probability learning in 3D virtual search environments. However, participants in this study searched for a letter T on the ground among distractor Ls in a virtual space without complex landmarks or cues. It is important to examine how people search under more natural scenes as backgrounds. In line with this idea, Addleman et al. (2021) had participants complete a T-among-L search against a natural scene background in a location probability learning task. The results showed that implicit location probability learning depended on intact vision, though explicit learning persisted despite central vision loss. Thus, naturalistic scenes may alter the deployment of experience-guided attention and its reliance on peripheral vision.

Similarly, in contextual cuing, previous studies used gaze-contingent eye tracking in a visual search task (e.g., search for the yellow mug against an interior scene background) and found different results. Pollmann, Geringswald, et al. (2020) examined contextual cuing in realistic scenes with simulated central or peripheral vision loss and observed contextual cuing in both scotoma conditions. In a subsequent study, Pollmann, Rosenblum, et al. (2020) showed preserved contextual cuing in realistic scenes in patients with age-related macular degeneration. It is important to note that, unlike the typical contextual cuing paradigm, Pollmann et al.'s studies using nature scenes always found that participants successfully recalled the repeated target locations in the repeated displays. It remains unclear whether the change in experience-guided attention in natural scenes is due to a shift from implicit to explicit learning.

Future research can investigate multiple forms of experience-guided attention under naturalistic scenes with simulated central and peripheral scotoma, and test patients with tunnel vision or age-related macular degeneration.

5.3.4 Interaction between long-term search habit and experience-guided attention

Increasing evidence demonstrates that prior experiences induce long-lasting changes in attention. Reading, as a prolonged experience in daily life, leads people to search from specific directions (e.g., from top to bottom in English) and may influence visual selection. Previous studies have shown that the habit of reading from top to bottom affects some attention tasks (Clarke et al., 2022; Quirk et al., 2018; Rinaldi et al., 2014), but does not consistently influence visual search (Carrasco et al., 2001). Across the many studies conducted in our lab, there are conflicting findings regarding how the visual field affects location probability learning. In a large dataset with 400 participants tested about a decade ago in in-person studies, there was no visual field effect on either search RT or location probability learning (Jiang et al., 2018). However, when testing on an online platform recently, there was an upper field advantage in search, likely driven by a top-to-bottom scanning habit (Chen & Lee, under review). Participants were faster at finding the target in the upper than the lower visual field. This contaminated LPL, yielding a larger LPL when the rich quadrant was in the upper rather than the lower visual field. It remains to be seen why visual field effects differed between the earlier in-person and recent online studies. In other words, it is unclear whether long-term reading habits interact with location probability learning in lab experiments.

Habits are known as automatic, fixed action sequences under specific contexts (Graybiel, 2008; Jiang & Sisk, 2019). Using a broader definition of "context," it can be task context, testing devices, or even the surrounding environment. If so, the most likely answer to the above question is that when testing online on participants' own devices, the same context triggers the search habit of browsing a web page from top-to-bottom. This long-term search habit, favoring the upper visual field, can be carried over to the visual search task. In addition, the transfer from the long-term search habit to location probability learning may suggest that the transfer in location probability learning is independent of task difficulty, stimulus similarity, or learned statistical information. Future studies can examine how context affects the interaction between long-term search habits and location probability learning. It is also unknown whether the top-to-bottom search habit influences other forms of experience-guided attention, such as contextual cuing.

Future studies can also test contextual cuing online and examine whether long-term search habits interact with contextual cuing.

5.4 Conclusion

To summarize, this dissertation presents three empirical studies investigating the relationship between experience-guided attention and the oculomotor system. Study 1 revealed that location probability guided attention is independent of goal-driven oculomotor control. Frequently looking at a location does not necessarily induce location probability learning. Study 2 demonstrated that participants can acquire a search habit even when they have to repeatedly look away from (rather than toward) the target, indicating that the spatial alignment of attention and gaze direction is unnecessary for location probability learning. Study 3 found that implicit location probability learning is strengthened by peripheral vision, whereas explicit learning can proceed when individuals must exclusively rely on central vision. Overall, these studies suggest that experience-guided attention is a high-level process abstracted from oculomotor movements, thereby enriching our theoretical understanding of the relationship between experience-guided attention and the oculomotor system.

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Appendix A. Recognition results in Study 1

Experiment 1

The 8 participants who correctly identified the T-rich quadrant were placed in the "aware" group, whereas the remaining 16 participants were in the "unaware" group. To examine how awareness affected search RT, we conducted an ANOVA using awareness as a between-subject factor, and target location (T-rich, C-rich, or sparse) and experimental block as within-subject factors. In the training phase (the first 6 blocks), we found a significant main effect of target location, revealing LPL, $F(2, 44) = 14.75$, $p < .001$, $\eta_p^2 = .401$, a significant main effect of block, with faster RT in later blocks, $F(5, 110) = 19.45$, $p < .001$, $\eta_p^2 = .469$, and a significant main effect of awareness, with faster RT in unaware than aware participants, $F(1, 22) = 5.54$, $p = .028$, $\eta_p^2 = .201$. Critically, however, awareness did not interact with the target's location, $F(2, 44) = 0.19$, $p = .829$, $\eta_p^2 = .008$, nor did it produce a three-way interaction, $F(10, 220) = 1.18$, $p = .308$, $\eta_p^2 = .051$.

Likewise, in the testing phase, we found a main effect of target location, showing a persisting LPL in the T-rich quadrant, $F(2, 44) = 6.48$, $p = .003$, $\eta_p^2 = .228$. But there was no main effect of testing block, $F(2, 44) = 0.26$, $p = .774$, $\eta_p^2 = .012$, or awareness, $F(1, 22) = 1.46$, $p = .239$, $\eta_p^2 = .062$. Awareness did not interact with target location, $F(2, 44) = 0.57$, $p = .569$, $\eta_p^2 = .025$, or produce a three-way interaction, $F(4, 88) = 0.03$, $p = .998$, $\eta_p^2 = .001$. Thus, LPL of the T-rich quadrant was comparable between the aware and unaware participants in both phases of the experiment. Readers interested in results from just the aware or just the unaware participants can find additional statistical analysis on the Open Science Framework, https://osf.io/9vdpw/.

Experiment 2

The aware group included the 14 participants who correctly identified the T-rich quadrants; the unaware group included the other 10 participants. In the training phase, an ANOVA on awareness, target location, and block showed main effects of target location, revealing LPL, $F(2, 44) = 40.89$, $p < .001$, $\eta_p^2 = .650$, and training block, $F(5, 110) = 14.42$, $p < .001$, $\eta_p^2 = .396$. The main effect of awareness was not significant, $F(1, 22) = 3.31$, $p = .082$,

η_p^2 = .131, neither did awareness interact with target location, $F(2, 44) = 2.35$, $p = .107$, η_p^2 = .097, or induce a three-way interaction, $F(10, 220) = 1.05$, $p = .406$, $\eta_p^2 = .045$.

Similarly, in testing phase, we found main effects of target location, $F(2, 44) = 3.52$, p = .038, η_p^2 = .138, and testing block, $F(2, 44) = 3.77$, $p = .031$, $\eta_p^2 = .146$. But there was no main effect of awareness, $F(1, 22) = 1.73$, $p = .202$, $\eta_p^2 = .073$, or interaction between awareness and LPL effect, $F(2, 44) = 2.15$, $p = .128$, $\eta_p^2 = .089$, or a three-way interaction, $F(4, 88) = 1.52$, p = .203, η_p^2 = .065. Thus, we did not find evidence that awareness modulated LPL. Additional results from just the aware or just the unaware participants can be found on the Open Science Framework, https://osf.io/9vdpw/.

Participants in Experiment 2 were also asked whether they had noticed the task-irrelevant C-shape. Seven of the 24 answered in the affirmatory. To test whether these participants evidenced attentional capture, we conducted an additional analysis on the search RT of these 7 participants. This analysis was qualitatively similar to the results from the full sample, revealing an LPL toward the T-rich quadrant in both phases, and no difference in RT between the C-rich and sparse quadrants. Detailed statistical results can be found can be found on the Open Science Framework, https://osf.io/9vdpw/.

Experiment 3

In Experiment 3, the aware group included 11 participants and the unaware group included 13 participants. We performed an ANOVA using awareness as a between-subject factor, target location (T-rich, C-rich, sparse) and training block (1-6) as within-subject factors. The training phase revealed main effects of target location, showing LPL, $F(2, 44) = 31.47$, p < .001, η_p^2 = .589, and block, $F(5, 110) = 25.08$, $p < .001$, $\eta_p^2 = .533$. But there was no main effect of awareness, $F(1, 22) = 1.96$, $p = .176$, $\eta_p^2 = .082$, nor did awareness interact with target location, $F(2, 44) = 1.71$, $p = .192$, $\eta_p^2 = .072$, or produce a three-way interaction, $F(10, 220)$ = 1.10, $p = .364$, $\eta_p^2 = .048$.

Similarly, in the testing phase, we found significant main effects of target location, $F(2$, 44) = 10.49, $p < .001$, $\eta_p^2 = .323$ and block, $F(2, 44) = 19.25$, $p < .001$, $\eta_p^2 = .467$. But there was no main effect of awareness, $F(1, 22) = 1.89$, $p = .183$, $\eta_p^2 = .079$, or interaction between

awareness and target location, $F(2, 44) = 1.12$, $p = .336$, $\eta_p^2 = .048$, or a three-way interaction, $F(4, 88) = 0.88$, $p = .479$, $\eta_p^2 = .038$. Thus, similar to Experiments 1 and 2, awareness did not significantly modulate LPL. Additional results from just the aware or just the unaware participants can be found on the Open Science Framework, https://osf.io/9vdpw/.

Appendix B. Self-reported Strategies in Study 2

At the completion of the experiment, participants were asked where the visible region was relative to their fixation location during restricted viewing, and what strategies they might have used. Out of the 48 participants, 12 correctly indicated that the visible region was 180º opposite from where they were looking; 7 said it was in the same location, 11 said it was 90º rotated, and 18 said it was random. The following table listed participants' self-reported strategies.

Table B.1 *Strategies participants reported to search with the restricted view, separated by whether they indicated that the visible region was 180º away, 90º away, in the same location, or at a random location relative to the visible area. Also noted was whether the individual underwent restricted (superscript 1)or unrestricted viewing (superscript 2) in the testing phase.*

Recognition	Self-Reported Strategy
Opposite[1]	I would try and move my eyes directly across from the circle I wanted, and I would shift my eyes in a circle
Opposite[1]	I start by looking to the right side then left before I look up and down. I found that my field of vision was better and larger whenever I look up and down, rather than side by side. Therefore, I start by doing what I'm bad at first.
Opposite[1]	Looking up and down and left and right
Opposite[1]	Look at the opposite circles and use my peripheral (vision)
Opposite[1]	I was looking in the 180º circle that pop up first, then looking for a horizontal space
Opposite[1]	Looking in the direction opposite to where I wanted to view

Opposite[1]	I looked at the same spot to start unless it had been in the same spot for 2-3 times in a row
Opposite[1]	I moved my eyes around first from left to right and if I couldn't see the T, then I moved/looked up and down. I did this all very quickly.
Opposite[1]	I tried to look opposite to where I saw the T in order to reveal the blind spot.
Opposite[2]	I tried to look directly in the middle of the screen and think of the letter T, and sometimes if I kept my eyes in the middle at first, I could find it faster, rather than looking around initially.
Opposite[2]	I tried to circle my eyes across the screen.
Opposite[2]	No (strategies)
Same[1]	I would let my eyes take a lap around and then focus in for when they would show the T.
Same[1]	I would either follow the visible spot until I saw the T, or I would try and look at the entire screen at once to find the target.
Same[1]	I just kept moving my eyes until I caught sight of it somewhere.
Same[1]	I didn't focus on one spot, rather the whole screen.
Same[1]	I looked for where the vertical and horizonal line crossed in the middle of each other
Same[2]	I would look in the middle of the screen and let the peripheral parts of my eyes look for the T. I would also try and track the shapes as they popped up to see if I could locate the T.
Same[2]	To look where the letters were initially visible and try to eliminate the spots where I was sure the target was not located so I could look in the most likely next spots.
90º [1]	I don't really have any strategies, but I generally just did a lot of process of elimination automatically
90º [1]	I didn't use much of a strategy, I mainly looked around the circle until I saw the letter or moved to the opposite side of what I could see.
90º [1]	Made my eyes look in a circle to find it when it first pops up

90º [1]	I would start in a similar spot on the bottom, then follow the flashes to find where the T was.
90º [1]	I looked up at the upper corners first
90º [2]	I would look in the bottom half first. If I did not see the target, I would only focus on the upper half.
90º [2]	Doing something called a sector scan, I focus my vision on the center for a few seconds and then go from closest to farthest target.
90º [2]	First, I would pick a random spot look at in the circle right after I pressed the space bar. Then I would scan 90 or 180 degrees around the circle, I looked for the shape that appeared to have equal distance of white on either end of the tail
90º [2]	I just did my best to react as quickly as the blind spots were disappearing
90º [2]	Sometimes I centered my vision on the center of the screen. Other times, I looked in the area where the T was last to start off. I tried to avoid doing the same thing each time.
90º [2]	Moving my eyes towards random areas and staying there for a second to see if the T was there and shifting to another area if it was not.
Random[1]	I swiped my eyes over the whole circle and just paid attention because I usually would see the T and my brain (would) realize I saw the T a few seconds later.
Random[1]	I would see if the T was in the first four circles flashed at me, and if I discerned that it wasn't, then I would look to the empty circles to be ready for when the T appeared there. I think I naturally would look at the last circle that held the T as well sometimes.
Random[1]	To daydream and it helped not worrying about the time nor rushing.
Random[1]	I don't think I used any specific strategies. When I thought I saw the T I would stare at the spot to make sure it was the T until it was fully shown.
Random[1]	Stay focused. I usually look in the middle first
Random[2]	I tried to look at the top two and bottom two circles before looking at the side one's.

Random^2	There were 8 spots, I separated each side into 4 spots to limit where I had to look. If the T wasn't on the side I was looking at, I could limit it down to four spots.
Random^2	I thought it would pop up in similar areas, so I looked back at that stop the T was before.
Random^2	I tried not to directly look at any one spot.
Random^2	I would follow the blind spot around and kind of wait for the T to appear, but most of the time the T would appear fast enough to where it would almost be reflexive.
Random^2	I started to look for defining chunks of the T that wouldn't be present on the other symbols. And when I noticed one circle had a symbol that wasn't T I would disregard it and try not to pay it any attention.
Random^2	Thinking of the letter T and only thinking of that to keep my focus to be looking for T.
Random^2	No strategies
Random^2	I just tried to follow the figures that popped up and tried to look focus more on the ones that looked more similar to the sideways T, I also sometimes stared at one spot and waited for the T to appear again in order to confirm that it was actually there; I did this whenever I was doubting whether or not I actually saw it.
Random^2	I had my eyes focus on the center to get a view of all symbols. And when I noticed the T I would click on the left or right key
Random^2	I began trying to keep my eyes focused on the center of the screen and using my peripheral vision to find the T. Also, I looked for patterns with where the "tail" was located within the circles.
Random^2	One thing I tried was focusing at the top and then letting my eyes just catch it if I saw it.