

The effects of selection history on visual and auditory spatial attention

A Dissertation

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Abstract

Past research has demonstrated implicit experience-driven effects on spatial attention in vision and audition. In particular, what and where an observer has attended in the past affects future attentional selection. For instance, attention while searching for an item is biased towards locations which contained recent targets—an effect called inter-trial location priming—as well as towards locations which contain targets more often than other regions over a span of time—an effect called location probability learning. In this dissertation, I present three studies investigating selection history effects and how they differ from the better-understood goal-driven form of attention. The first two studies investigate the relationship between spatial selection history and top-down attention during visual search. Study 1 investigated how attending to spatial locations during a visual search task for letters affected a secondary memory task for scenes presented underneath the search array. Implicit location probability learning and goal-driven attention both affected search performance, but only goal-driven attention affected memory for scenes at attended locations. This suggests that implicitly learned probability learning has task-specific effects on attention, while goal-driven attention has task-general effects. Study 2 showed that, unlike goal-driven attention, implicit location probability learning causes shifts of visuospatial attention only after search stimuli appear, not in anticipation of stimulus onset. Study 3 investigated short-term and long-term auditory selection history effects, finding long-term location probability learning but a striking lack of short-term inter-trial location priming. Taken together, this dissertation provides evidence for differences in the implementation of goal-driven and implicitly

learned spatial attention that, while present in both vision and audition, manifest in modality-specific ways.

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1. Introduction

Spatial attention allows the brain to flexibly prioritize stimuli at relevant locations, altering sensory processing to accomplish behavioral goals. Research has long investigated the central roles of stimulus salience and top-down goals in guiding attention (e.g., Broadbent, 1954; Itti & Koch, 2001; Posner, 1980; Treisman & Gelade, 1980). Recent evidence for the influence of selection history on attention challenges the completeness of previous theories (Awh, Belopolsky, & Theeuwes, 2012). A growing body of evidence suggests that past attentional selection influences future attentional behavior, even in the absence of awareness. While the existence of these experience-driven attentional effects is well established (Jiang, 2018; Kristjánsson & Campana, 2010), more research is needed to fully characterize attentional learning and how it relates to other forms of attention.

One important step towards better understanding experience-driven attention involves studying multiple senses; most studies consider only the visual modality. There are a variety of benefits to researching in more than one modality. First, differences between sensory modalities (e.g., visual and auditory representation of spatial location) may influence how attention to a feature influences perceptual processing within a given modality (Shinn-Cunningham, 2008; Ward, 1994). Second, researching in multiple modalities can answer theoretical questions regarding the cognitive and neural processes that guide attention—for example, whether attention operates in supramodal (i.e., modality-independent) networks or separate networks for each modality (Spence, 2010; Spence & Driver, 1996). Finally, given the frequency with which we interact with multisensory objects, many practical applications of attention research necessitate

understanding attention in multiple modalities. Gherri and Eimer (2011) exemplified this strategy by investigating the interference of auditory semantic processing on visual perception, identifying potential mechanisms for the harmful influence of cell phone use on driving safety. Here, I adopt this multisensory approach by investigating experience-driven attention in both visual and auditory tasks.

In addition to an introductory literature review and a general discussion, the body of my dissertation presents three first-authored empirical studies published in peer-reviewed journals (Addleman & Jiang, 2019; Addleman, Schmidt, Remington, & Jiang, 2019; Addleman, Tao, Remington, & Jiang, 2018). These studies investigate three topics related to implicit attentional learning: (1) the spread of implicitly learned and explicit goal-driven visual attention to task-irrelevant visual stimuli; (2) whether implicit location probability leads to pre-stimulus baseline shifts of visuospatial attention; and (3) how implicit selection history affects auditory spatial attention. In the remainder of this introduction, I review relevant literature in visual and auditory tasks as background to these studies.

1.1 Visuospatial attention

This section provides an overview of behavioral, computational, and physiological research on visuospatial attention. I present work on top-down and bottom-up sources of attentional control, the priority map model that is widely accepted to account for how these sources are integrated to determine attentional guidance, and the oculomotor system's role in shifting attention. I also review research on short-term and longer-term visual selection history effects.

1.1.1 Top-down and bottom-up visuospatial attention

Attention research has long made a distinction between top-down and bottom-up spatial attention. Top-down attention typically involves conscious goals to attend to spatial locations. In contrast, bottom-up attention involves shifts of attention to locations with salient stimuli, such as sudden changes in stimulus luminance or regions with high contrast along some feature dimension. I briefly discuss these two sources of attention as well as how they combine to guide attention to spatial locations.

In everyday life, top-down attention often involves goals to find a specific item or type of items that result in guidance towards features of that item. People frequently use top-down attention to search for objects in particular locations: if you're looking for the ketchup bottle that you know you put somewhere in the door of your fridge, you'll probably look there first before looking in the vegetable drawer. In experimental paradigms, top-down spatial attention is often investigated using symbolic cueing of locations observers should attend. In a classic example, Posner (1980) presented an arrow in the center of a screen that correctly pointed to a visual target's location on 80% of trials. Whether participants were pressing a single button regardless of the target's location or identity, discriminating the target's identity, or discriminating the target's spatial location, they were faster to respond when the location was validly than invalidly cued. A great deal of work has investigated the contribution of factors including cue validity, cue-target onset asynchrony, and other methodological features to the effectiveness of endogenous spatial attention (for a review, see Carrasco, 2011).

While top-down attention supports goal-driven behavior, bottom-up attention allows for monitoring for environmental stimuli not relevant to a person's conscious

goals (Carretié, 2014). This is thought to serve both threat monitoring and awareness of potentially rewarding stimuli like food. In the lab, this is typically studied using briefly presented visual cues that attract attention to their locations (Jonides, 1981). These cues lead to transient shifts in attention lasting a few hundred milliseconds, which are often followed by shifts of attention away from the cued location termed inhibitions of return (Müller & Rabbitt, 1989; Posner & Cohen, 1984; for a more recent review of inhibition of return, see Klein & Ivanoff, 2005). These exogenous shifts are involuntary and usually insensitive to attempts to suppress attention to cued locations (for a review, see Carrasco, 2011).

Neuroimaging and electrophysiology have provided insight into the brain bases of top-down and bottom-up visuospatial attention. Primate multi-unit recording studies show that bottom-up spatial orienting largely originates from the lateral intraparietal area (LIP) within the dorsal stream (Bisley & Goldberg, 2006; Ipata, Gee, Bisley, & Goldberg, 2009). In contrast, top-down spatial orienting signals largely originate from the frontal eye fields (FEF) within frontal cortex (Kodaka, Mikami, & Kubota, 1997; Moore & Fallah, 2004). Despite this distinction, both bottom-up and top-down attentional guidance eventually involve both LIP and FEF (Buschman & Miller, 2007; Corbetta & Shulman, 2002). Furthermore, as discussed in Serences and colleagues (2005), FEF and LIP each have feedforward projections to the superior colliculus (Asanuma, Andersen, & Cowan, 1985; Stanton, Bruce, & Goldberg, 1993), an area involved in implementing both endogenous and exogenous shifts of spatial attention (Fecteau, Bell, & Munoz, 2004). Despite the suggestion that superior colliculus implements shifts of attention while FEF and LIP primarily involve selecting what and where to attend, all three encode maps of

the attentional priority of spatial locations, with the unique function of each yet to be fully understood (Bisley & Goldberg, 2010; Clark, Noudoost, Schafer, & Moore, 2014).

In the last two decades, priority map theories of selective attention have dominated our understanding of how attentional biases guide attention. These models explain attention through a set of spatial maps, each of which represents the physical salience of a specific feature value (e.g., the color red or a specific orientation) within the current visual field (Fecteau & Munoz, 2006; Itti & Koch, 2001). A single integrated priority map then computes an average of these maps, with each feature map weighted by the current goal-driven attentional priority of that feature. Spatial attention is allocated to the location with the highest activity on the integrated priority map. Priority maps can approximate neural computations of saliency and attentional priority and perform well at predicting first fixations on static natural images (Bisley & Goldberg, 2010; Mahdi, Qin, & Crosby, 2019; Zhao & Koch, 2011).¹

After the determination of attended locations via priority maps, shifts of visuospatial attention are implemented via the oculomotor system, either by inducing eye movements or via subthreshold activations of the oculomotor system that lead to covert shifts of attention (Rizzolatti, Riggio, Dascola, & Umiltá, 1987; Sheliga, Riggio, & Rizzolatti, 1994). Spatial attention can both speed responses and enhance perceptual representations for stimuli at the attended location, a finding that supports the view that

¹ Part of this section was published in *Trends in Cognitive Sciences* (2019). Full citation: **Addleman, D. A., & Jiang, Y. V.** (2019). Experience-driven auditory attention. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2019.08.002>. Part of the article is reproduced here.

attention affects perceptual representations in early sensory regions like V1 (Carrasco, Ling, & Read, 2004).

1.1.2 Visual attentional selection history

Visual attention is not only affected by top-down goals and bottom-up salience. A third source of attentional biases is one's experience, which can shape how visual features, objects, and locations are attended. Here, I review research on one type of visual experience-driven attention, effects of where one has attended on future attentional selection. I consider the operation of these selection history effects at both shorter and longer timescales. In this context, short-term biases typically fade within a handful of experimental trials or long gaps between testing, while long-term biases can persist across hours of a laboratory task or weeks-long test-retest delays.

Following a surprising discovery of inter-trial priming effects in a pop-out search task, a wealth of visual search studies have investigated short-term history effects in visual search (Maljkovic & Nakayama, 1994, 1996; for a comprehensive review, see Kristjánsson & Campana, 2010). Participants in Maljkovic and Nakayama's (1996) experiment performed a singleton color search task of diamond shapes and reported whether the left or right side of the target was truncated. In singleton search, targets are defined as being the only items possessing a feature value absent in all other stimuli (e.g., a white diamond among black ones or vice-versa), typically resulting in the target "popping out" from the distractors. Trials were differentiated by whether the location of the target was the same as in recent trials. Repetition of target location from up to eight preceding trials influenced reaction times on a subsequent trial; for example, trial n would have a faster reaction time on that trial if any of trials $n-1$ to $n-8$ contained targets in the

same location (versus a different location) as trial n 's target. These effects decreased rapidly as the number of trials from the current trial increased. The authors attributed repetition advantages to spatial attentional guidance by implicit, short-term memory representations of selected feature values. This result was quite surprising, as many theories of perceptual attention suggested that pop-out search relies on pre-attentive feature detection mechanisms, which would imply that attention is incapable of altering pop-out search performance. However, priming of pop-out has been replicated and extended in dozens of studies across many feature dimensions, task difficulties, and stimulus modalities (for a review, see Kristjánsson & Campana, 2010).

Following the original discovery of priming of pop-out, subsequent studies have generated a debate regarding the primary mechanism supporting inter-trial priming. One account argues that priming effects rely on short-term episodic memory retrieval. Evidence for this considers contingencies between repeating task-relevant features—e.g., size in a size-singleton search—and repeating task-irrelevant features—e.g., color in the same task (Huang, Holcombe, & Pashler, 2004). Results show an interaction between the repetition types, where repeating a task-irrelevant feature decreased reaction time if the task-relevant feature was repeated, while the same task-irrelevant repetition increased reaction times when the task-relevant feature changed. According to the authors, this result is incompatible with an account of attentional facilitation for independent features but is consistent with an account where implicit memory representations of recent targets influence search, such that only trials where targets match those of previous trials across many dimensions would facilitate search. While this view has been influential, evidence still exists supporting the original feature-based account. Kristjánsson, Ingvarsdóttir, and

Teitsdóttir (2008) found that task differences can elicit either object-based priming or feature-specific priming depending on the degree to which features are likely to be bound into holistic object representations. Thus, it is likely that both episodic memory for holistic targets and attentional biases to recent feature values contribute to inter-trial repetition priming.

Repeating target features is not the only way to induce inter-trial priming; repeating distractor features can have similar effects. Kristjánsson and Driver (2008) used a present-absent task in which targets were defined as the only unique items in displays of many items that could vary in color (black or white) and shape (circles or donuts). Importantly, on a given trial, distractors always consisted of only two of the four possible types, allowing distractor types to become unused on certain trials. By analyzing whether distractors became unused, targets, or repeated their roles as distractors, they could isolate the role of distractor features from that of targets. They found two effects of distractor repetition suppression—that is, the suppression of attentional shifts to features of recent distractors. First, repeating distractor identities in two consecutive target-present trials increased reaction times, regardless of whether the target identity repeated. Second, they found an effect similar to various instances of “negative priming” in non-search contexts (Tipper, 1985), in which a distractor identity becoming a target identity on a subsequent trial slows search compared to trials when items of the target identity were absent on the previous trial. These two effects each suggest that items were less likely to be selected if they were recently rejected as possible targets.

While distractor suppression effects clearly exist for a variety of features, there is evidence for a limited influence of location distractor suppression. Chao and Yeh (2005)

had participants search for a Chinese character defined by its color in a display with a single distractor character and speak the target's identity aloud. They contrasted their results from two blocked, within-subject conditions: in a few-locations condition, each item within the block occurred in one of four locations; in a many-locations condition, items repeated location within a block only on trials when targets were in the location of the preceding trial's distractor. They found that location negative priming only occurred in the few-locations condition. On the other hand, in the many-locations condition, the role reversal of a location (i.e., from distractor to target location) yielded faster reaction times than control trials within that block. One potential account provided for these results proposes a competitive role of positive priming, which occurs whenever a location is selected, and negative priming, which occurs when a distractor is rejected. When a given location often contains items (as in the few-locations condition), the positive priming effect rapidly saturates, and negative priming is evident in reaction times. However, in the many-locations condition, the initial positive priming effect of selecting the location for the first time in a block swamps the suppression effect of rejecting the location as a non-target.

Imaging studies have suggested that the main neural mechanism of priming involves the suppression of brain activity in attention-related regions that represent selected feature values, including the posterior prefrontal cortex (pPFC, or FEF in non-human primates; Bichot & Schall, 2002; Kristjánsson, Vuilleumier, Schwartz, MacAluso, & Driver, 2007) and intra-parietal sulcus (IPS; Geng et al., 2006). These regions are associated with spatial attention and have been shown to control overt and covert shifts of spatial attention in primates (Bisley & Goldberg, 2010; Buschman & Miller, 2007).

Importantly, Geng and colleagues found that IPS repetition suppression only occurred in trials requiring attentional selection of a target from among distractors, a result also present in their behavioral priming effects. They attribute location repetition suppression to mechanisms of general repetition-related BOLD-suppression, which may include neural fatigue, increased processing efficiency, and/or sharpening of tuning curves resulting in fewer neurons encoding a stimulus (Grill-Spector, Henson, & Martin, 2006). However, one group has pointed out that previous studies conflate target feature repetition benefits with distractor role reversal costs and that BOLD suppression in inter-trial priming may primarily index increased neural activity in role-reversal trials rather than decreased activity in target-repetition trials (Rorden, Kristjansson, Reville, & Saevarsson, 2011). More research may be needed to fully investigate the comparative effects of these two phenomena.

In addition to short-term priming, long-term location probabilities can also influence search behavior. Early work showed that altering target location probabilities speeded reaction times for high-probability relative to low-probability locations (Hoffmann & Kunde, 1999; Miller, 1988; Shaw & Shaw, 1977). While these studies did not evaluate whether participants were consciously guiding their attention to high-probability regions, subsequent studies have verified through post-test surveys that participants fail to report probability asymmetries and are unable to identify high-probability regions when choosing among options (e.g., Jiang et al., 2013). In a commonly-used paradigm, Jiang and colleagues had participants search an array of rotated letters for a T and report its orientation. In the first 576 trials of the experiment (the biased phase), one screen quadrant contained the target in half of trials, while in the

second 576 trials (the unbiased phase), target distribution was even across all quadrants. Within two hundred trials, participants developed faster reaction times to targets in the high probability location that persisted throughout the entire unbiased phase. While the results of the biased phase could be an effect of inter-trial priming (since trial-to-trial repetitions are more likely in a quadrant that often contains the target), inter-trial location repetition could not explain advantages in the unbiased phase because repetitions were equally prevalent in all quadrants.

Despite the persistence of LPL in unbiased phases with equally prevalent inter-trial repetition in all locations, one study argued that the acquisition of attentional learning in biased search phases relies on short-term inter-trial repetitions. Walthew and Gilchrist (2006) showed that location probability learning disappeared when restrictions were added to prevent recent trial repetitions across all quadrants, suggesting that mechanisms supporting LPL used short-term stimulus statistics to develop long-term biases. However, a similar study failed to replicate the lack of a LPL when preventing consecutive repetitions (Jones & Kaschak, 2012), and Druker and Anderson (2010) argue that Walthew and Gilchrist's method of eliminating immediate repetitions introduced statistical information unique to that condition, a change which may have swamped long-term LPL. In reviewing the conflicting evidence regarding the inter-trial priming account of LPL, Jiang (2018) suggests that "methodologies that do not depend on restricting location repetition are needed to resolve these inconsistencies" (p. 4).

1.1.3 Outstanding questions

While many studies have identified different sources of experience-driven spatial attention (e.g., inter-trial priming and location probability learning), we know little about

how attention is guided by selection history once attentional biases are acquired. The first two studies in this dissertation address this topic, investigating previously unknown aspects of the task-specificity and temporal dynamics of experience-driven attention. The goal of these studies is both to better characterize experience-driven guidance of attention and to identify contrasts between selection history effects and goal-driven attention.

These contrasts support theories of attentional habits suggesting that goal-driven and habitual attention differ both in their source and in how they are implemented.

1.2 Auditory spatial attention

To what extent can auditory spatial attention enhance processing of stimuli at an attended location? In vision, both endogenous, symbolic cues to an upcoming target location and exogenous cues appearing at upcoming target locations are known to facilitate processing at the attended location and impair processing at other locations relative to no-cue conditions (Jonides, 1981; Posner, 1980; Posner, Nissen, & Ogden, 1978). In audition, the story is more complex, especially because auditory location is computed in the brain using complex binaural and monaural cues rather than present in the earliest stage of sensory processing as is visual location in the retina (for one review of perceptual cues to auditory location, see Culling & Akeroyd, 2012). Auditory spatial orienting can be useful only when spatial location of stimuli is represented in regions that are both relevant for task performance and affected by attention, a condition which may not be met when a task can be completed rapidly or does not require spatial judgments. A long history of research on this topic has found mixed evidence regarding the effects of spatial orienting to auditory stimuli.

1.2.1 Top-down and bottom-up auditory spatial attention

In an early investigation of endogenous spatial auditory orienting, Posner (1978; see his figures 7.10 and 7.12) presented participants with central arrows that predicted likely target locations in an auditory reaction time paradigm. Participants responded to the onset of an auditory tone that appeared in one of two locations, either to the left or right of the observer. Visual cues were presented before targets only on some trials and predicted auditory target location with 80% accuracy, yielding three cue conditions: valid (when the cue pointed in the direction of the target); invalid (when the cue pointed in the opposite direction); and neutral (when no cue was presented). Whether in an experiment measuring simple detection of tone onset or discrimination of tone intensity, RTs were equivalent in all three cue conditions, suggesting that spatial attention in advance of the auditory targets did not effectively facilitate responses. An equivalent version of the paradigm using visual targets and identical cues showed a cueing effect in both simple reaction time and discrimination tasks, meaning the lack of an auditory effect could not be attributed to an insufficiently predictive cue. One interpretation forwarded by Posner is that, unlike in vision, detection of auditory tones may precede any spatial representation of these stimuli, in which case spatial attention would have no effect on stimulus processing. In this view, the results would change in tasks with longer RTs (which in this task were as low as 230ms for detection and 300ms for intensity discrimination), because representation of auditory location may occur more than 300ms after stimulus onset. An alternative view that Posner proposes, which I will later consider in depth, is that, regardless of exposure duration, stimulus location is only represented if people intentionally localize sounds.

A study using exogenous rather than endogenous cues found a similar null effect. Bachtel and Butter (1987) tested the effects of either auditory or visual peripheral cues on auditory or visual targets. They found that cues in either modality were effective in speeding responses to visual targets, but neither type of cue influenced reaction time to auditory targets, even at cue-target asynchronies ranging from 50 to 1000 milliseconds. The authors attributed the visual effect to covert orienting via the oculomotor system, which could presumably support shifts of visual but not auditory spatial attention. They concluded that covert shifts in spatial attention seldom if ever influence auditory processing.

The evidence reviewed so far suggests that spatial attention may play a minimal role in influencing early processing of auditory information, but subsequent research has suggested a more nuanced view. For example, in Rhodes (1987), simple auditory stimuli were presented at various locations in 22.5 degree increments along an invisible circle around the observer. Each location was given a semantic label (numbers in one version, names in another), and participants were instructed to verbally report the label corresponding to the target's location. In consecutive trials, targets were more likely to repeat in location than change to another specific location (29% of trials were repeats, with the remaining 71% distributed among eight other locations); this design and task instructions encouraged participants to maintain attention at the target's location following a trial until appearance of the subsequent target. If spatial attention facilitates processing of attended locations, locations far away from the previous trial's location would elicit longer reaction times than when target location was repeated. Results

confirmed this hypothesis, suggesting that in this paradigm, spatial attention did in fact speed stimulus processing at the attended region.

However, as discussed in subsequent research (Spence & Driver, 1994), Rhodes' (1987) paradigm confounds response priming, in which providing a response on trial $n-1$ speeds responding the same way on trial n , with the effects of spatial attention. To avoid this, it is preferable to use response variables independent of the cued feature. Paradigms doing this are commonly known as *orthogonal cueing tasks* (Koelewijn, Bronkhorst, & Theeuwes, 2010). Spence and Driver (1994) used orthogonal cueing to systematically investigate the role of exogenous and endogenous spatial attention on auditory discrimination tasks while avoiding response priming. In their paradigm, cues and targets each varied along the left-right dimension, while only targets varied in elevation. They altered the predictiveness of cues across experiments to induce exogenous or endogenous attentional orienting.

In their exogenous cueing experiments, horizontal location of the cues was uninformative of upcoming target location (Spence & Driver, 1994). In this case, any cueing effects would be exogenous, because no information was provided by the cue to influence endogenous attention. When participants judged the elevation of targets, validly cueing the horizontal location of a target speeded participants' reporting of target elevation. When participants instead judged the pitch of targets, the same cues to target location had no effect on performance. They concluded that exogenous auditory cues facilitate reaction time when tasks involve localization, but not when tasks involve nonspatial judgments.

A different pattern of results was found in endogenous cueing experiments (Spence & Driver, 1994). Just as before, tasks could involve either elevation or pitch discrimination, but endogenous auditory cues were predictive of the horizontal location of targets on that trial. Thus, in addition to the exogenous influence of the cues, participants could use the information about likely target location to endogenously guide spatial attention. To separate these effects, the targets were more likely to occur on the *opposite* side of the cue, meaning exogenous cuing would be working against endogenous guidance of attention. Faster responses to the side opposite the cue would be strong evidence for the influence of endogenous spatial attention. Surprisingly, results showed that endogenous cueing speeded not only location judgments but also pitch judgments. This differs from Posner's (1978) endogenous cueing paradigm, which showed no effect of endogenous spatial attention on intensity discrimination. Spence and Driver attribute this contrast to a difference in reaction times (600ms in their experiment vs. 300ms in Posner's), concurring with Posner that very fast responses may precede stimulus localization.

The behavioral results of Spence and Driver (1994) have been replicated and extended in many related studies, with one group providing the spatial relevance hypothesis as a parsimonious explanation of auditory spatial orienting (e.g., McDonald & Ward, 1999; Spence & Driver, 1996, 1997). In this view, spatial orienting only occurs when location is task-relevant. This is consistent with the exogenous cueing results of Spence and Driver (1994) in that localization tasks showed a cueing effect but pitch discrimination tasks did not. It also purportedly explains endogenous effects, as the information about target location provided by the cue makes target location relevant even

when participants perform nonspatial tasks. McDonald and Ward suggest that location-sensitive neural populations are only recruited for behavior when location is task-relevant. When location is irrelevant, selective enhancement of location-selective neurons would serve no task-related purpose, so it does not occur.

Based on the reviewed findings, the human auditory system clearly has some capacity for spatial orienting. On the other hand, the lack of an explicit spatial code at early levels of auditory analysis makes such orienting systems less consistently effective than in the visual modality. While early explanations of spatial cueing centered on whether localization has occurred at the time of orienting, the best current explanation of these differences is that auditory spatial orienting is only recruited when location-sensitive neurons are task-relevant. Because top-down goals in part define task-relevance, endogenously guided spatial attention should affect auditory processing in most contexts where spatial localization has occurred; however, exogenous spatial cues only become task-relevant, and therefore effective, during spatial judgments. Even at timescales when target location is explicitly represented in some regions before a response has been made, auditory spatial orienting likely never occurs if it is not behaviorally relevant.

1.2.2 Brain bases of auditory space and attention

Recent theories of auditory organization in the brain suggest close relations to well-known visual pathways. Auditory analogues of the visual dorsal and ventral streams exist and map onto similar neural substrates (Alain, Arnott, Hevenor, Graham, & Grady, 2001; Maeder et al., 2001). A rostral (and more ventral) stream has been shown to represent auditory object information, while again there is some debate over whether the caudal (more dorsal) auditory processing system represents *where* or *how* information.

The *where* argument suggests a role of the dorsal stream in representing spatial location of sounds and is in part based on evidence that spatially sensitive neural activity in the dorsal stream effectively predicts behavioral responses in spatial tasks (Kaas & Hackett, 1999; Recanzone, Guard, Phan, & Su, 2000). The *how* argument proposes that the main role of the dorsal stream is to track changes in auditory spectral content through time, a process intimately involved in comprehending complex sounds such as speech (Belin & Zatorre, 2000). This process is related to the concept of streaming frequently considered in behavioral studies (Best, Gallun, Ihlefeld, & Shinn-Cunningham, 2006). EEG recordings have confirmed that dorsal pathways represent spatial information as soon as 100ms post-stimulus onset (De Santis, Clarke, & Murray, 2007). Note that this is not evidence against a role of the dorsal pathway in auditory streaming; indeed, claims that spatial perception and attention play a major role in auditory streaming would suggest that the dorsal pathway could be involved in both streaming and localization (e.g., Shinn-Cunningham, 2008). Overall, there is strong evidence for spatial representations of auditory stimuli in dorsal auditory regions.

Furthermore, activity in the caudal auditory stream is sensitive to spatial orienting. One influential study showed that *what* and *where* auditory streams can be modulated by tasks involving speech comprehension and localization, respectively, suggesting a role of spatial attention in modulating representations of spatial location (Ahveninen et al., 2006). These experiments simultaneously recorded MEG/fMRI while participants attended to pairs of vowel sounds and performed a same-different judgment regarding, in alternating blocks, either the pattern of location or vowel identity of each set of two vowel pairs. This paradigm yielded an effect of feature-specific selective attention

on regions that encode that specific feature (e.g., location), but not regions that encode the other feature. While previous PET studies have failed to find such effects (e.g., Zatorre, Mondor, & Evans, 1999), Ahveninen and colleagues' combined use of MEG and fMRI provided a temporal resolution significantly exceeding prior studies, allowing them to investigate rapid adaptation effects not detectable by fMRI or PET alone. This paradigm provides evidence that attention can operate on relatively early location-sensitive regions, rather than only on later regions representing holistic auditory objects.

In addition to identifying auditory brain regions modulated by spatial attention, recent research has discovered probable neural mechanisms controlling auditory spatial orienting. Mayer, Harrington, Adair, and Lee (2006) used fMRI to identify such mechanisms. Participants were asked to report the location of targets that were preceded by lateralized auditory cues at either 100 or 800ms cue-target onset asynchronies (CTOAs). Cues predicted upcoming target locations with 75% validity. This paradigm combined the roles of exogenous and endogenous spatial orienting, as cues both occurred at the same spatial locations as targets and were predictive of target location. Results showed cue validity effects that diminished as a function of increasing CTOA, a result consistent with exogenous spatial cueing effects in behavioral location-judgment tasks (McDonald & Ward, 1999; Spence & Driver, 1994). The experimenters used brain activity in invalidly cued trials as an index of spatial reorienting from the cued location to the target location and found increased event-related activity in several regions: the portion of posterior prefrontal cortex (pPFC) thought to be the human analog of the frontal eye fields (FEF), left superior and middle temporal cortex, left inferior frontal gyrus, and right precuneus. These regions, especially those in fronto-temporal cortex,

have also been implicated in visual attentional control (Corbetta & Shulman, 2002). Similar results have implicated pPFC in auditory spatial orienting and provided evidence for the role of another visual-spatial attention region, the posterior parietal cortex, in auditory spatial orienting versus orienting to non-spatial auditory features (Shomstein & Yantis, 2006). A recent study using a similar simultaneous fMRI/MEG paradigm as Ahveninen and colleagues (2006) has provided additional support for the role of these regions in auditory spatial orienting (Lee et al., 2013). When taken together, there is strong evidence for existence of overlapping mechanisms controlling visual and auditory spatial attention.

A recent series of studies has sought to clarify the extent and nature of audio-visual attentional control overlap, particularly in frontal cortex. Michalka, Kong, Rosen, Shinn-Cunningham, and Somers (2015) conducted a series of fMRI experiments designed to test the attention-related recruitment of small subregions of lateral frontal cortex (LFC) typically associated with flexible task-related processing. This study first used interleaved blocks of auditory and visual spatial attention tasks to identify and define ROIs in LFC that preferentially recruit modality-specific spatial attention. In a later scanning session, participants performed change detection tasks that used either visual or auditory stimuli presented either at different spatial locations or in different temporal patterns. Using the previously defined ROIs, they first showed that regions associated with visual spatial attention in the earlier task were recruited in all tasks, and within each modality this activation was greater in spatial attention tasks than temporal attention tasks. Second, they showed that regions associated with auditory attention in the earlier task were activated in all tasks except for the visual spatial one, and furthermore

that these regions were comparably active in both auditory spatial and auditory temporal tasks. The authors interpret this complicated set of results by concluding that sub-regions of LFC do indeed direct spatial attention in modality-biased ways, but that tasks involving features more effectively represented in the other modality (i.e., spatial visual representations or temporal auditory representations) may flexibly recruit resources from the other modality. A subsequent study of these same regions had participants perform a two-back working memory task on alternating streams of faces or animal noises and replicated this pattern of results (Noyce, Cestero, Michalka, Shinn-Cunningham, & Somers, 2017).

The previously reviewed results suggest one of two main interpretations for the nature of overlap between visual and auditory spatial attention regions. One is the domain recruitment hypothesis advanced in these studies (Michalka et al., 2015; Noyce et al., 2017). In this view, the dominant organizing principle for LFC attentional control regions is sensory modality, but because the coding systems for audition and vision are strongly biased towards temporal and spatial information, respectively, these same regions more effectively support performance of tasks within that information domain. Furthermore, sensory tasks that require high-resolution information in a domain inappropriate to the task modality can recruit attentional control resources from regions associated with another modality (e.g., an auditory spatial task recruiting vision-biased LFC regions). For example, this may occur through subpopulations of vision-biased regions recruiting either sensory-independent or auditory-specific attentional resources. However, an alternative interpretation would be to consider feature (location vs. time) the dominant organizing principle for these regions, with a natural tendency to also organize by modality due to

the vastly different sensory resolutions of space and time across modalities. This concept is generally consistent with a controversial argument considering sensory modalities much less neurally distinct than is typically assumed (Shimojo & Shams, 2001).

Regardless of which principle is more relevant, modality or information domain, the spatial attentional resources of vision and audition appear dissociable but partially linked.

Finally, a different approach to studying neural substrates of auditory spatial orienting is the use of electrophysiology to identify relevant event-related potential (ERP) components. While there is little research on the ERP correlates of auditory spatial attention, one study has suggested the existence of such a component, the N2ac, involved with orienting to spatial locations within complex auditory environments (Gamble & Luck, 2011). The component emerges approximately 200ms following the onset of two sounds played from different locations, and its temporal profile is highly analogous to a well-studied ERP index of visual spatial attention, the N2pc (Eimer, 1996; Luck & Hillyard, 1994). However, the paradigm used could not separate effects of selective attention from later identification or response-related activity. Even so, the similarity of the N2ac to a known index of visual spatial attention, the N2pc, is consistent with evidence that spatial attention shares many characteristics across visual and auditory modalities.

1.2.3 Auditory attentional selection history

While the mechanisms of visual inter-trial priming are becoming increasingly well understood, few studies have investigated inter-trial priming in auditory tasks. Neuroimaging results show that longer-term stimulus repetition (i.e., repeating an item from minutes ago in an earlier block, rather than only seconds ago in an earlier trial)

leads to suppressed activation in auditory processing regions (Bergerbest, Ghahremani, & Gabrieli, 2004), but no imaging studies have investigated auditory inter-trial effects. In the behavioral literature, while an early auditory search task by Rhodes (1987) discussed previously ([Section 1.2.1](#)) found faster reaction times for repeated target locations, this paradigm increased the probability of repetitions above chance levels and told participants of this manipulation, conflating inter-trial priming effects with the endogenous guidance of attention. Furthermore, the task involved localizing targets, and previous results have shown that inter-trial priming effects occur primarily for non-response variables (e.g., location in a shape discrimination task with color as the response variable; Kristjánsson & Campana, 2010).

One study reported effects of inter-trial repetition in a pure tone discrimination task that are consistent with episodic memory retrieval accounts of priming (Dyson, 2010). Stimuli varied randomly in both location (above or below participants) and pitch (high or low), one of which was designated the relevant (i.e., target defining) feature on a trial-by-trial basis. Priming was absent in trials repeating only a single target feature, but large priming effects were found when both the irrelevant and relevant feature value repeated. Furthermore, when the relevant feature value changed, responses were actually faster if the irrelevant feature changed compared to if it stayed the same (though this effect was present in only two out of three experiments). This latter effect is the same one used to support episodic memory retrieval theories of visual inter-trial priming (Huang et al., 2004), and it clearly conflicts with purely feature-based accounts of auditory inter-trial priming. Even so, more research is needed to determine whether episodic retrieval alone supports auditory priming or if, as has been argued in the visual modality, feature-

based and holistic priming mechanisms each occur depending on task and stimulus characteristics (Kristjánsson et al., 2008).

Another study reported priming of pop-out in auditory search, this time with more consistent results between visual and auditory tasks. Participants engaged in a Rapid Serial Presentation (RSP) task in which participants searched a sequence of vowel sounds for a singleton (e.g., “UH”) among identical distractors (e.g., "EE"; Klein & Stolz, 2015). Participants reported whether targets were presented to the left or right ear. Results showed distractor priming but not target priming; participants were comparably fast when responding to targets with an identity the same as previous trials versus absent from previous trials, but were slower when target identity was identical to the previous trial’s distractors and faster when distractor identity repeated. No attempt was made in this study to dissociate the role of priming for pitch versus semantic identity of the items, so either or both could contribute to their results. In either case, their results are fairly consistent with visual search findings described above, where priming is best explained via effects of distractor rejection rather than target selection (Geng et al., 2006; Rorden et al., 2011).

Overall, studies of inter-trial priming might point to the presence of inter-trial priming of location in an auditory search task, but no study has yet reported such an experiment. What is known is that visual priming occurs in search tasks for repeated target and distractor locations (Kristjánsson & Driver, 2008) and auditory priming occurs in search tasks for non-spatial features (Klein & Stolz, 2015). Moreover, in a non-search pitch discrimination task, repeating locations speeded reaction times contingent on the repetition of pitch, but mechanisms for priming of search among distractors may be

different from priming of target selection (Geng et al., 2006; Klein & Stolz, 2015; Rorden et al., 2011). This is particularly likely in auditory tasks because auditory spatial orienting is only effective in certain contexts, whether because the localization of some items might not occur or because orienting to location is unnecessary to adequately perform some tasks (McDonald & Ward, 1999; Spence & Driver, 1994). Studies of inter-trial priming of auditory spatial search could provide insight into lingering questions related to inter-trial priming as well as auditory spatial orienting.

No studies have reported an investigation of auditory location probability learning. However, a variety of longer-term selection history effects have been found in auditory tasks. Wagener & Hoffman (2010) asked participants to classify tones based on pitch (high or low) in a variable foreperiod paradigm. Variable foreperiod paradigms present participants with “ready” cues that are followed by unpredictable cue-target onset asynchronies. In their paradigm, the length of the foreperiod predicted which target was likely to occur: two possible foreperiods (500 or 1500ms) each predicted a different target identity with 80% validity. Participants showed a small but reliable 15ms advantage for valid trials compared to invalid ones. Analyses of only unaware participants still showed an effect, albeit slightly smaller than for aware participants. The results of this study show that statistical learning can influence responding to pitch identity in an auditory task, though their use of pitch as a response variable conflates learned attention to a certain frequency with facilitation of a certain response.

In another study, Doan (2014) used contextual cueing to investigate implicit orienting of auditory temporal attention. In visual contextual cueing, certain configurations of distractors perfectly predict target location, allowing implicit memory

of these configurations to improve search on repeated trials even when repetitions are separated by many trials (Chun & Jiang, 1998). Auditory temporal contextual cueing was measured by having participants search for a spoken number among a sequence of letters and report its identity. Trials in which a repeated sequence of distractor identities predicted the target identity were responded to faster than trials with randomized distractor identities, despite participants reporting no awareness of repetitions during the task. While many differences exist in the mechanisms underlying contextual cueing and location probability learning (Jiang, 2018), Doan's results provide additional evidence for the role of implicit learning in the guidance of auditory attention.

To my knowledge, only one study has claimed to find evidence of long-term implicit factors guiding auditory spatial attention. Zimmermann, Moscovitch, and Alain (2017) used a three-phase design in which participants: (1) listened to environmental audio clips (e.g., a dog barking) that either contained laterally presented pure tones (memory trials) or did not (neutral trials) and made a left-right-absent judgment for the location of the pure tones; (2) performed an explicit recall task asking participants to re-listen to the environmental audio clips and indicate to which ear (if any) a tone was presented; and (3), following a one-hour break, performed another tone localization task using the same environmental stimuli, which this time all contained a pure tone (either in the same location for memory stimuli or a random location in neutral stimuli). The temporal and spatial position of tones within a given sound clip was held constant in the initial phase but temporal (but not spatial) position could vary randomly in the final phase, preventing the confounding of spatial and temporal attention effects. Results showed that reaction times were faster in the third phase for memory stimuli than neutral

ones, even for stimuli that participants failed to correctly recall in the second phase. The authors attribute these results to long-term memory associations between tones and environmental sounds speeding spatial attentional shifts to the locations of remembered tones.

While such memory associations may explain results from Zimmerman and colleagues (2017), their paradigm confounds potential spatial effects with response priming. Participants performed a tone localization task for stimuli in which target tones were always presented to the same ear for a given memory stimulus, meaning that the audio clip perfectly predicted the correct response, even in the final phase. Thus, participants could be learning associations between audio clips and motor responses rather than audio clips and attentional shifts. Moreover, neutral trials were the only trials in which response changed between the first phase and the final phase, suggesting a possible switch cost for these trials as well. In all, while implicit memory may influence auditory spatial attention, further research dissociating response dimension from implicit memory associations is needed before making such conclusions.

1.2.4 Outstanding questions

While several studies have identified selection history effects in audition, only one study has directly investigated auditory inter-trial location priming (Dyson, 2010), and no studies have investigated auditory location probability learning. The study that did report some evidence for auditory inter-trial location priming did so in a single-stimulus discrimination task, rather than a task requiring the selection of targets among distractors. Behavioral and fMRI evidence from visual priming suggests that the mechanisms of inter-trial priming differ when stimuli do versus do not compete for attentional selection

(Geng et al., 2006), perhaps because the attention-related repetition suppression that leads to priming effects occurs primarily when attentional selection among distractors is required. Therefore, in Study 3 of this dissertation, I investigated the mechanisms of inter-trial location priming resulting from attentional selection among distractors using a multi-talker auditory task. I also studied long-term location probability learning in the same paradigm. One unique feature of this study was the investigation of auditory spatial selection history effect in a multi-talker stimulus context. Distractor stimuli can make a critical difference in the function of auditory attention, particularly because the energetic masking they can introduce often make spatial cues of target identity more salient, perhaps rendering auditory spatial attention more critical than in single stimulus contexts (Eramudugolla, Mcanally, Martin, Irvine, & Mattingley, 2008). This study explores function of auditory spatial attention in multi-talker contexts and provides evidence for the existence of auditory spatial selection history effects.

1.3 Theoretical accounts of selection history effects

The findings I just reviewed show that, in addition to endogenous and exogenous guidance, an individual's attentional selection history can implicitly affect spatial selection. To provide context for the selection history effects discussed in this dissertation, this section discusses theories of how selection history influences attention. In an influential review of selection history, Awh, Belopolski, and Theeuwes (2012) outline how search tasks can be influenced by selection history in at least two ways. In *inter-trial priming*, people attend to stimuli differently based on whether their features are repeated from trial-to-trial. In *reward learning*, stimuli associated with either positive or negative outcomes are prioritized over other stimuli. The authors argue that these

phenomena constitute a third type of attention outside the top-down/bottom-up dichotomy.

Building on Awh and colleagues (2012), Todd and Manaligod (2018) provide a more comprehensive review of attentional learning research, distinguishing four categories of selection history that can implicitly influence attentional selection. First is statistical learning, in which attention becomes biased within an experimental search task to locations or features frequently diagnostic of targets. Second is semantic association, in which attentional selection of one object (e.g., a hammer) causes selection of semantically related objects (e.g., a nail); past experience with the relationship between objects can lead to implicit biases towards their co-occurrence. Third and fourth are the highly related categories of reward learning, in which attentional shifts that result in salient outcomes are reinforced, and affective salience, in which stimuli conditioned in or out of the lab to elicit emotional responses can involuntarily draw attention.

In addition to reviewing implicit attention research, Todd and Manaligod (2018) developed the *priority state space* (PSS) framework to explain how various sources of attentional control combine to guide attention. This is an important part of any theory of attention, because most spatial attention research accepts that a winner-take-all mechanism integrates goals and stimulus salience to determine a single region for spatial selection at a given time (Itti & Koch, 2001). In line with other models of exogenous attention (Bisley & Goldberg, 2010) and previous work on selection history (Awh et al., 2012), Todd and Manaligod suggest that implicit attentional guidance history influences attentional priority maps. These maps, each of which encodes the priority of sensory information for a feature value (e.g., red, vertical orientation, horizontal motion), are

integrated into a unitary priority map which in turn guides the subsequent attentional shift.² The PSS framework argues that the environment of the observer (e.g., ‘driving’ or ‘searching for keys’) constrains the possible states of the attentional system—that is, the environment determines the conceptual ‘space’ of states. Which of these many states is implemented is determined by the unitary priority map, which does not merely compute stimulus salience but is also influenced by top-down goals and implicit history. In this sense, the PSS framework operates much like contemporary models of bottom-up and top-down attention, adding additional priority maps that encode selection history as well as the concept of state spaces constrained by environmental contexts.

An alternative theoretical account of selection history, the *multi-level framework*, argues that some types of selection history influence attention in a manner different than explicit sources of attentional guidance (Jiang, 2018). Jiang proposes that attention can be conceptually divided into two components: a map-like component encoding salient locations for perception and an action-based component encoding motion vectors for executing behaviors like eye, head, or limb movements. Furthermore, whereas top-down and bottom-up attentional control may originate through representations of *where* the system should attend, selection history leads to habitual attentional behaviors – *how* the system should direct attention – and may not rely on explicit spatial representations of salient regions. Jiang compares various characteristics of habitual attention to those of

²How features are integrated to guide attention is a matter of great debate, for example between classic models like Feature Integration Theory, which argues that basic features like color are determined preattentively and are bound into object representations only through attentional selection, and newer models like Guided Search, which argues that top-down goals and preattentive, rudimentary object representations influence how features guide attention (A. M. Treisman & Gelade, 1980; Wolfe, 2012, 2014). The PSS is not theoretically committed to any one of these views.

dorsal action pathways in the visual system, suggesting that some forms of habitual attention may be implemented via a similar attentional action pathway rather than through spatial priority maps.

Jiang and colleagues have provided evidence for the multi-level framework in a variety of studies. These studies show that statistically learned spatial attention persists long after statistical biases that induced a behavior disappear (Jiang, Swallow, Rosenbaum, et al., 2013); transfers across contexts in which stimuli being attended differ but not to tasks requiring different behaviors (Jiang, Swallow, Won, Cistera, & Rosenbaum, 2015); is encoded within a viewer-centered reference frame (Jiang & Swallow, 2013; Twedell, Koutstaal, & Jiang, 2017); is not impaired under increased working memory load (Won & Jiang, 2015); and is mostly unimpaired due to aging (Twedell et al., 2017). These characteristics are both significant deviations from goal-driven attention as well as similar to habitual effects in perceptual and motor systems, and thus support the multi-level framework of attention.

Given the reviewed support for both the PSS framework and the multilevel framework, evaluating their competing claims will likely require more targeted studies. It is possible that, in certain contexts, implicitly guided attention acts through some sort of priority map, as Todd and Manaligod (2018) and others (Ferrante et al., 2018) have argued. However, especially in the case of long-term implicit effects guided by habit (e.g., statistical and reward learning), evidence suggests that some implicit attentional biases are implemented through action systems without the use of priority maps. Another possible, though less likely, explanation is that selection history operates through priority maps that are implemented on their own, separately from bottom-up and top-down maps.

1.4 Summary

This chapter summarized scientific research on visual and auditory spatial attention. I considered evidence for selection history effects in both modalities, concluding that such effects are better understood in the visual modality, and in both modalities more research is needed to understand how theories of spatial attention should incorporate the effects of experience.

The studies presented in this dissertation investigate a range of phenomena related to selection history effects in both visual and auditory tasks. In the first two studies, I compare the effects of an implicitly learned long-term selection history effect to that of conscious, goal-driven attention: in the first, with respect to the spread of spatial attention across tasks, and in the second, with respect to pre-stimulus, baseline shifts of attention in anticipation of task onset. In both cases I demonstrate important differences between implicitly learned attention and goal-driven attention, a finding which suggests the need to significantly alter models to incorporate the unique effects of selection history on spatial attention. In the final study, I investigate both short- and long-term selection history effects in the auditory modality, and in doing so provide evidence that selection history affects auditory attention. This dissertation addresses how selection history affects attentional guidance. It also shows key differences between selection history effects and goal-driven attention and considers how these findings may differ across modalities. In the final chapter, I synthesize these results with other recent studies of selection history to consider the mechanisms underlying location probability learning and to provide insight into the complicated relationship between visual and auditory attention.

2. Study 1: Explicit goal-driven attention, unlike implicitly learned attention, spreads to secondary tasks.

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Explicit goal-driven attention, unlike implicitly learned attention, spreads to secondary tasks

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Preface

To what degree does spatial attention for one task spread to all stimuli in the attended region, regardless of task-relevance? Most models imply that spatial attention acts through a unitary priority map in a task-general manner. We show that implicit learning,

unlike endogenous spatial cuing, can bias spatial attention within one task without biasing attention to a spatially overlapping secondary task. Participants completed a visual search task superimposed on a background containing scenes, which they were told to encode for a later memory task. Experiments 1 and 2 used explicit instructions to bias spatial attention to one region for visual search; Experiment 3 used location probability cuing to implicitly bias spatial attention. In location probability cuing, a target appeared in one region more than others despite participants not being told of this. In all experiments, search performance was better in the cued region than in uncued regions. However, scene memory was better in the cued region only following endogenous guidance, not after implicit biasing of attention. These data support a dual-system view of top-down attention that dissociates goal-driven and implicitly learned attention. Goal-driven attention is task-general, amplifying processing of a cued region across tasks, whereas implicit statistical learning is task-specific.

Keywords: spatial attention; goal-driven attention, incidental learning; probability cuing

Introduction

Influential models of selective attention explain covert shifts of attention in terms of a priority map, where attentional priority is determined by bottom-up stimulus salience, top-down goals, and in some cases selection history (Awh et al., 2012; Bisley & Goldberg, 2010; Jillian H. Fecteau & Munoz, 2006; Itti & Koch, 2001; Wolfe, 2012). While disagreement surrounds the relative contributions of these factors to attentional selection (A. C. Nobre & Kastner, 2014), most theories support the idea that a single

priority map determines attentional allocation. The majority of studies informing these theories draw their conclusions from single-task experiments (e.g., Folk, Remington, & Johnston, 1992; Hopfinger, Buonocore, & Mangun, 2000; Luck, Chelazzi, Hillyard, & Desimone, 1997; Theeuwes, 1994). In many real world contexts, though, humans must juggle multiple simultaneous tasks. When someone needs to attend to one region for a task and another, different region for other purposes, how would this affect spatial attention?

One possibility is that the attentional priority map is unitary across tasks. On this account, the spotlight of spatial attention for one task may inevitably spread³ to affect performance in all tasks (*task-general account*). This view is consistent with the idea that the cognitive system encourages coherence across the many tasks that it confronts (Cowan, 1988; Duncan, 1996), the observation of cross talks between concurrent tasks (Jiang & Swallow, 2014), and the cost of switching between tasks (Monsell, 2003). The task-general account also finds empirical support in studies on spatial attention; as reviewed next, attending to a spatial region in one task biases attention to that region in a concurrent task.

Participants in Awh, Jonides, and Reuter-Lorenz (1998) maintained in working memory either an object's spatial location or its identity. They simultaneously performed a secondary character identification task. Rehearsing the object's location in working memory facilitated the identification of a character in that location. The spread of spatial

³Note that we use “spread” as a general term to describe the processing of stimuli not relevant to the task for which spatial attention is allocated. Our study does not directly test whether the spread constitutes a slippage of spatial attention (e.g., owing to shared visual properties; Lachter, Forster, & Ruthruff [2004]) or a leakage of attention (e.g., owing to failure of executive control).

attention from the working memory task to the character identification task provides evidence that people do not maintain separate spatial attentional preferences for two simultaneous tasks. Analogous findings have been reported in research on multimodal allocation of attention. Spence and Driver (1996) asked participants to localize targets in two modalities. They provided a cue predictive only of upcoming auditory targets and examined responses when the target was visual instead. Even though the visual target was less likely to appear on the cued side, participants were faster detecting it when it appeared there. This finding supports the claim that spatial attention is task-general across different modalities. Similar results have been observed when the tasks involved visual and tactile modalities (Spence, Pavini, & Driver, 2000) and when participants performed two visual search tasks (Burnett, Close, D'Avossa, & Sapir, 2016). These results support the idea that goal-driven spatial attention acts through activation within a priority map common to all tasks.

A second possibility is that, at least in select circumstances, people are capable of maintaining independent attentional priority for concurrent tasks (*task-specific account*). One such circumstance is when one task involves spatial selection and a concurrent task does not. In Awh and colleagues (1998), for example, rehearsing an object's identity in working memory does not affect spatial attention in a secondary task. More broadly, a recent theory of attention dissociates two forms of top-down attentional control, suggesting that spatial attention may not be implemented in a unitary attentional priority map (Jiang, Swallow, & Capistrano, 2013). According to this view, "declarative" goal-driven attention operates much like priority map theories suggest, while incidental learning is a form of "procedural" attention that is habitual, rather than explicitly guided

(p. 9). In the first, an explicit cue, such as an arrow or verbal instructions indicating a likely target location in visual search, provides information about the most likely target location (Posner, 1980). In the second, task history (such as a target's high probability of occurrence in one region of space) facilitates search in that region even when participants are not explicitly aware of the target's location probability (Geng & Behrmann, 2005; Jiang, Swallow, Rosenbaum, et al., 2013). Evidence strongly suggests that location probability learning affects attentional guidance and differs from goal-driven attention (Jiang, Sha, & Remington, 2015; Jiang, Swallow, & Capistrano, 2013; Twedell, Koutstaal, & Jiang, 2016; Won & Jiang, 2015).

Even though goal-driven attention may act on a task-general priority map, habitual guidance of spatial attention may primarily affect performance for the relevant task. This is because incidentally learned attention is hypothesized to induce habitual search behavior (Jiang, Sha, et al., 2015), which is deployed only once stimuli have appeared and search has commenced (Jiang, Sigstad, & Swallow, 2013). In contrast, endogenous attention can be shifted in anticipation of the search task (Egeth & Yantis, 1997; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Luck et al., 1997). It is plausible, then, that implicitly learned attentional biases do not act through a representation common across concurrent tasks, as seems to be the case for endogenous cuing, but through biasing spatial attentional shifts within a specific task context. If true, this would provide evidence for the dual-system view and entail that unitary spatial map theories require revision to accommodate the unique effects of habitual learning on spatial attention.

To examine how endogenous and implicit spatial attentional biases affect the spread of attention between concurrent tasks, we conducted three dual-task experiments. On each trial, participants viewed an array of letters presented against a background of four natural scenes, one in each quadrant (Figure 2.1). The display was presented briefly to curtail saccadic eye movements. In the primary task, participants searched for the target (the letter T) and reported its orientation. In the secondary task, participants encoded the scenes for a later memory task. We introduced a spatial attentional bias in the search task either endogenously (through task instructions) or incidentally (through location probability learning). We then examined how spatial selection in the search task affected memory of the background scenes. Even though the memory task requires an equal allocation of attention to all scenes, any spread of spatial attention from the search task should result in superior memory for scenes presented in the cued quadrant relative to the other quadrants.

The combination of a visual search task and a scene memory task also enables us to test the interaction between attention and memory. Some theories of attention and memory suggest that shifting attention to a location should enhance memory at that location (Cowan et al., 2005). Because these theories do not distinguish endogenous attention from implicitly guided attention, they make predictions similar to those of the unitary priority map theory. In contrast, other studies on attention and memory suggest that attending to a location does not necessarily lead to better memory for that location. For example, although spatial attention is deployed to an object undergoing substitution masking (as indexed by the N2pc component), it is insufficient for the encoding of the object into working memory (Woodman & Luck, 2003). This latter finding suggests that

the link between attention and memory may be dependent on various factors. By testing two types of attentional guidance (explicit vs. implicit), this study may shed light on the relationship between spatial attention for one task and visual memory for another.

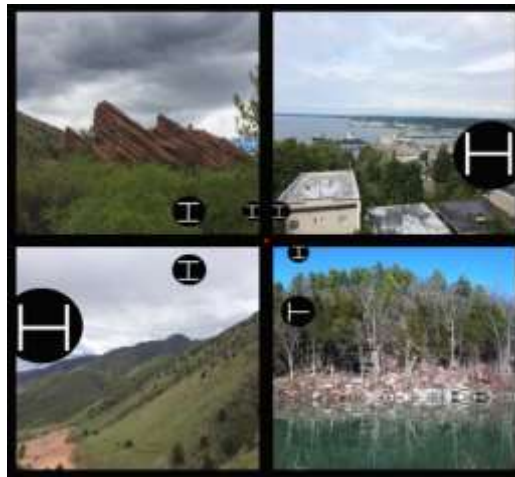


Figure 2.1. A sample search array. Participants were shown arrays like this for 216ms and were asked to report the orientation of the 'T'. Participants also needed to remember the background scenes for a memory test.

Experiment 1

Experiment 1 used an explicit, endogenous cuing paradigm to introduce an attentional bias toward one quadrant for the visual search task. The experiment was divided into 40 blocks of trials. At the beginning of each block participants were told that the target T was likely to appear in one specific quadrant, such as the upper left. They were asked to prioritize search in this quadrant. At the same time, we informed them that there would be a future memory test on all of the background scenes. The cued quadrant changed from block-to-block, preventing participants from acquiring consistent location probability learning. Spatial selection was therefore endogenously driven in the search

task. In the first 24 blocks, the letter T indeed appeared in the instructed quadrant more often than chance; it was there on 50% of the trials. In the last 16 blocks, the letter T appeared in random locations despite the instructions. Periodically, we probed memory for the background scenes to examine whether participants prioritized the encoding of scenes in the quadrant cued for visual search.

Method.

Participants. Participants in this study were students from the University of Minnesota. They were healthy adults naïve to the purpose of the study. All participants reported having normal or corrected-to-normal visual acuity and normal color vision. Participants signed an informed consent form prior to participation and were compensated with extra course credit or \$10/hour.

Sixteen participants completed this experiment. This sample size was predetermined to be the same as previous studies on location probability learning (e.g., Jiang & Swallow, 2014). The 16 participants included 13 females and 3 males with a mean age of 23 years.

Equipment. Participants were tested individually in a room with fluorescent overhead lighting. They sat an unconstrained distance, approximately 60cm, from a 19-inch CRT monitor (1024x768 resolution; 75 Hz). Experiments were run using Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com).

Stimuli. A red fixation dot subtending 0.15° was presented in the center of the display throughout the experiment. The search stimuli consisted of an array of eight white letters that ranged in size from 0.7° to 2.7° . Items farther from the fixation point were

larger, scaled according to the cortical magnification factor (Carrasco, Evert, Chang, & Katz, 1995). There were 32 possible item locations, evenly divided into four eccentricities (approximately 1.5°, 4°, 6.5°, and 12°). The eight letters included one letter T and seven letter Hs; each quadrant always contained 2 letters. Hs were created by combining a T with a second T rotated 180° to increase feature similarity to the target. The letter T had a random orientation of 0°, 90°, 180°, or 270°. The Hs could be upright or rotated 90°. The background of the search display contained four natural scenes, one in each quadrant (11.5°x11.5°). The distance between the center of a scene and fixation was 8.75°. Scenes were randomly drawn from a bank of 660 images taken from the Internet. To make sure the letters were visible against any part of the scene, the letters were inscribed in black circles (Figure 2.1).

Procedure. The experiment was divided into 40 blocks. Each block contained 12 dual-task trials in which participants searched for the T and encoded the scenes to memory, followed by 8 memory test trials. On each dual-task trial, participants initiated the task by clicking on the red fixation dot. The task required eye-hand coordination and ensured that fixation was centralized. The mouse click caused the search array and scenes to appear. The display disappeared after 216ms, leaving just the red fixation point. We used the brief presentation to limit eye movements. The participants' task was to report the orientation of the T (up, down, left or right) using the keyboard. A practice block of 16 trials was administered to familiarize participants with the task. The target's location was random during the practice block. We emphasized accuracy in performing the task. Participants were asked to also remember the scenes for an old/new recognition task. Participants were told to treat the T/H search task as the primary task, and remember the

scenes as best they could without sacrificing search accuracy. Upon response, an auditory tone provided accuracy feedback; following each block, participants were given their average block accuracy. To ensure that memory accuracy for the scenes was not at chance, we presented the same four scenes within a block of 12 dual-task trials. These scenes were randomly chosen from the database of 660 scenes with the constraint that scenes shown in earlier blocks would not appear again. Their spatial location was maintained across the 12 trials, ensuring that spatial selection biases induced by the search task would be consistently directed to the same scene.

Following the 12 dual-task trials, participants were shown 8 trials testing scene memory. These included the 4 scenes they had just seen and 4 new scenes they had not seen before. These scenes were presented one by one, in a random order, at the center of the display. Participants pressed ‘o’ or ‘n’ to indicate whether the scene was old or new, with accuracy feedback provided.

Design. We manipulated spatial attention for the visual search task through explicit instructions. At the beginning of each block, a yellow frame (13.5°x13.5°, border thickness 0.05°) surrounded one quadrant. A computer voice instructed participants to prioritize that region during the search task. The cued quadrant changed from block-to-block, preventing participants from acquiring consistent location probability learning. In the first 24 blocks (the ‘biased phase’) the instruction was informative – the target T appeared in the instructed quadrant 50% of the time, significantly above chance. It appeared in each of the other three quadrants 16.7% of the time. In the last 16 blocks (the ‘neutral phase’) the instruction was uninformative – the target T appeared in each quadrant 25% of the time. Participants were not informed of this change. This ‘neutral’

phase allows comparisons between the extinction of attentional bias in the memory advantage in different experiments; it is possible that data from biased phases would be similar, and yet different attentional cues would yield different extinction profiles during the neutral phase. We expect that participants would form a spatial bias toward the cued quadrant, and this bias should be stronger when the cue was informative (the biased phase) than when it was uninformative (the neutral phase).

Results.

Visual search. Because each block contained a total of just 12 trials in the dual-task phase, we binned every 4 blocks into an epoch. This yielded 6 epochs in which the target T's location was biased toward the cued quadrant ("biased" phase), and 4 epochs in which the target T's location was unbiased ("neutral" phase).

We first examined how successful participants were in establishing a spatial bias in the visual search task. Figure 2.2 shows search accuracy as a function of whether the target was in the cued quadrant for the two phases of the experiment.

Repeated-measures ANOVAs showed that participants were significantly more accurate when the target was in the instructed (cued) quadrant rather than in the other quadrants, both in the biased phase, $F(1, 15) = 43.43, p < .001, \eta_p^2 = .74$, and in the neutral phase, $F(1, 15) = 17.13, p < .001, \eta_p^2 = .53$. In neither phase did the cue effect interact with epoch, $F_s < 1$. The spatial bias was weaker in the neutral phase. This was confirmed in an analysis that contrasted all data from the biased phase with those from the neutral phase. A significant interaction between cue validity and phase was found, $F(1, 15) = 4.90, p < .05, \eta_p^2 = .25$.

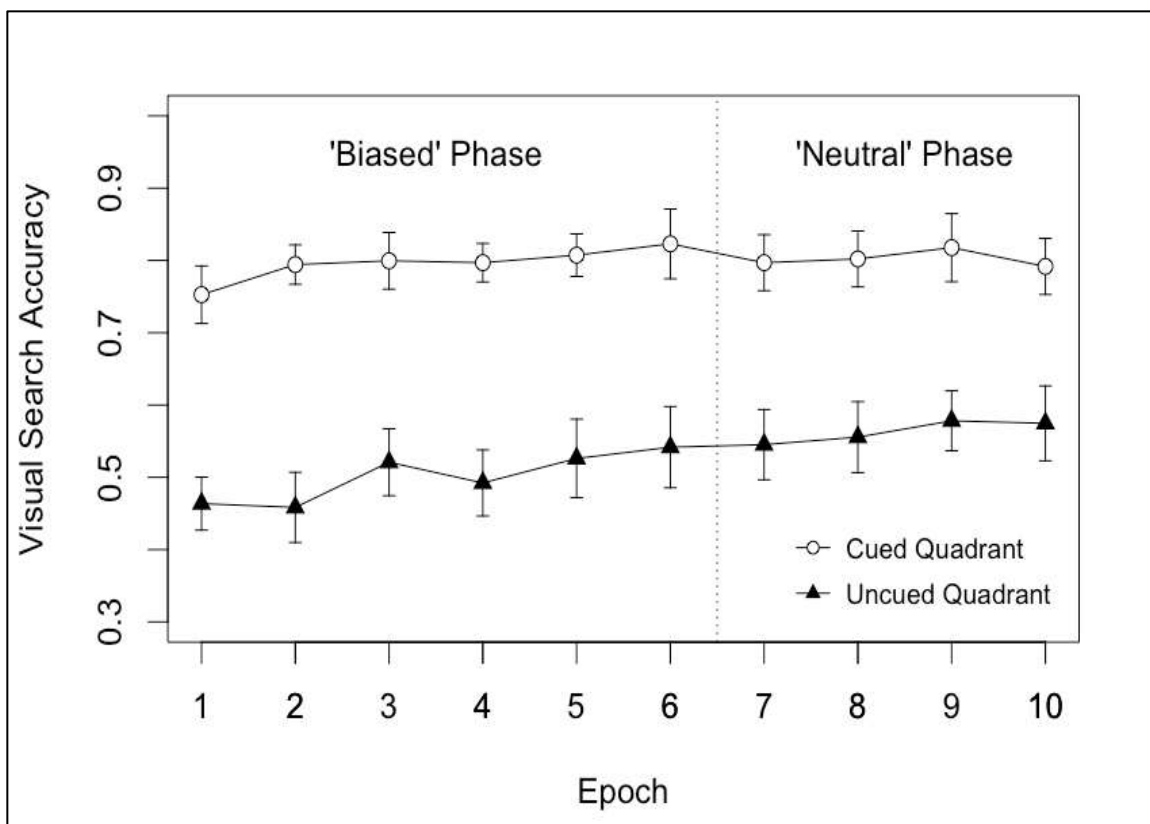


Figure 2.2. Results from the visual search task of Experiment 1. Participants were instructed (cued) to prioritize one quadrant. The target was frequently in the cued quadrant (which changed from block to block) during the biased phase, and was equally likely to be in all quadrants during the neutral phase. Error bars show +/- 1 standard error of the mean.

Scene memory. The 8 test trials of each block included 4 new scenes, providing an index of false alarm rates. It also included 4 old scenes, one in the cued quadrant and three in the uncued quadrants. This yielded just a single observation per block for the cued quadrant. To achieve sufficient statistical power, we combined data from all 24 blocks of the “biased” phase, and all 16 blocks of the “neutral” phase. Figure 2.3 shows

the memory hit rates, separately for scenes in the cued quadrant and those in the uncued quadrants.

First, we verified that, despite the difficulty of performing both tasks, participants' memory was above chance. The overall hit rate (correctly identifying an old scene) was significantly higher than the false alarm rate, $t(15) = 3.71, p < .002$. Next, we examined hit rates for scenes presented in the cued and uncued quadrants, separately for biased and neutral phases.

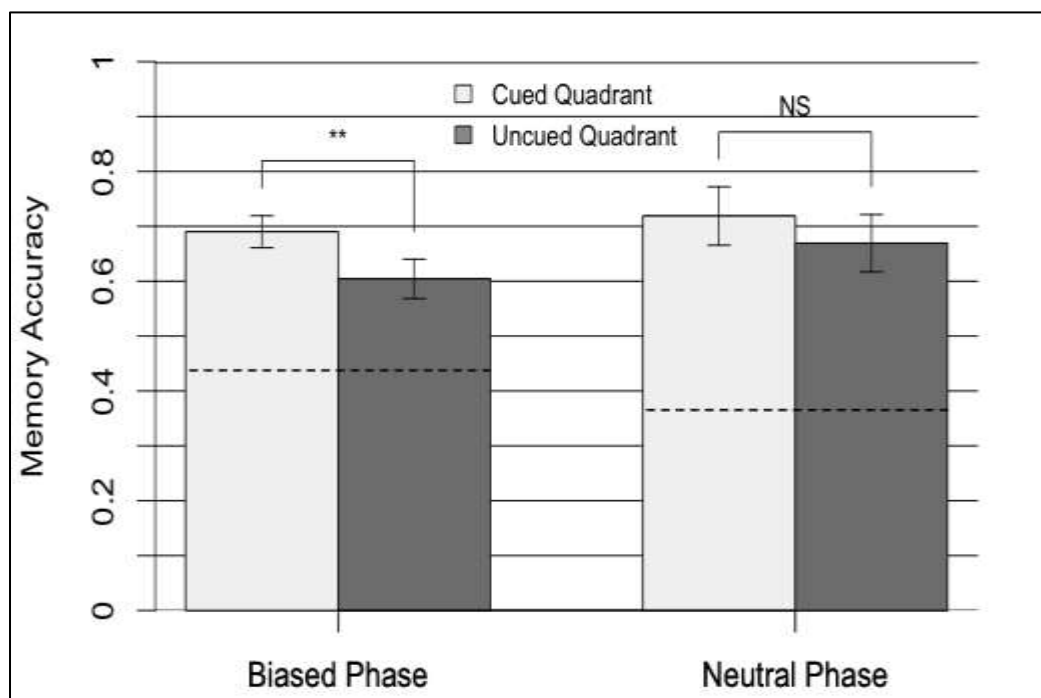


Figure 2.3. Recognition rates for scenes presented in Experiment 1. Horizontal dotted lines represent false alarm rate (classifying new scenes as old ones) for that phase. Error bars show +/-1 S.E. of the mean.

In the biased phase, scenes presented in the quadrant cued for visual search were identified more accurately than those in the other quadrants, $t(15) = 3.08, p < .008$. This

effect was not significant in the neutral phase, $t(15) = 1.20, p > .20$. An ANOVA combining data across both phases showed a significant main effect of the scene's quadrant, $F(1, 15) = 4.86, p < .05, \eta_p^2 = .25$. The interaction between scene quadrant and phase was not significant, $F(1, 15) = 1.12, p > .30$.

All scene memory analyses in all experiments were also analyzed using d' as a measure of sensitivity. In all cases, results were comparable when analyzing either hit rates as reported above or sensitivity. Note especially that, for within-phase analyses, d' differences come exclusively from differences in hit rates, as the false alarm rate is the same for all quadrants within a given phase.

Discussion.

In this experiment, endogenous spatial cuing yielded both a search advantage for the relevant task and a memory advantage for the secondary task. Given that all scenes were tested regardless of their encoding location, the memory task provided no incentive to preferentially attend to any region of space. The spatial bias in the memory task, therefore, provides strong evidence that spatial selection from the search task spread to the memory task. This finding is consistent with the idea that endogenous spatial attention is task-general and supports the idea that attention may operate in conjunction with working memory and long-term memory (Cowan et al., 2005). Specifically, attending to a location induces better memory for scenes from that location. Analogous effects were previously reported in cross-modal attention (Spence & Driver, 1996) and in spatial working memory (Awh & Jonides, 2001; Awh et al., 1998). Here, unlike in past studies, our results demonstrate spread of attention using a search task and a secondary background memory task. They support the conceptualization of goal-driven spatial

attention as an amodal and task-general mechanism that enhances processing in the attended location of stimuli from all tasks.

Experiment 1 also suggests that the spread across tasks was not complete. Spatial cuing appeared to have a larger effect on the relevant task—visual search—than on the secondary memory task. Search performance improved by 30% in the cued quadrant relative to the uncued quadrants, but memory recognition improved by less than 10%. In addition, in the neutral phase when the cue no longer validly predicted the target's location, participants continued to maintain a significant (albeit weaker) spatial bias toward the cued quadrant in search. Yet this was not sufficient to yield a strong cuing effect in the memory task. This is consistent with the findings of Burnett et al. (2016), in which a cue informative for only one of two simultaneous search tasks improved performance on both tasks, but did so to a greater degree in the relevant task. On balance, Experiment 1 shows that endogenous spatial attention can spread to secondary tasks.

Experiment 2

The first experiment shows that endogenously guided spatial attention can spread from the search task to the memory task. In Experiment 2, we used a different form of endogenous cuing for the search task. Rather than indicating a high-probability quadrant for a full block of trials, an arrow appearing before each trial indicated a likely target region for that trial. In addition, the arrow was presented briefly (100ms) and was followed immediately by the search display. This design extends our results to an additional form of endogenous cuing.

Method.

Participants. Thirty-two new participants completed Experiment 2, including 24 females and 8 males, with a mean age of 22 years.

Procedure. This experiment was similar to Experiment 1 except for the following changes. We removed the block-wise spatial cue, replacing it with a trial-specific central arrow cue. On each trial a white arrow (4.5° in length) was presented at the center of the display, pointing at one of the four quadrants. The arrow appeared immediately upon the participant clicking the fixation dot to initiate the trial, and after 100ms was replaced by the search array, which appeared for 216ms as before. In the first 24 blocks (the biased phase), the arrow was 50% predictive of the search target's quadrant (i.e., the target T appeared in the cued quadrant on 6 of the 12 trials). Counterbalancing ensured that for a given block of trials the arrow pointed equally often to each quadrant. These two constraints make it impossible to ensure that the target occurs equally often in each quadrant in each block; instead, the target's location was counterbalanced in every set of two blocks. In the next 16 blocks (the neutral phase), the arrow was not informative of the target's quadrant, as the target appeared in the cued quadrant only 25% of the time. For counterbalancing purposes, we increased the number of search trials per testing block to 16. As in Experiment 1, participants were given no indication that the utility of the cue for the search task would change; they were only told that the arrow was 50% predictive of target location.

Similar to Experiment 1, the same four natural scenes were presented within a block of trials. However, though the spatial cue changed directions from trial to trial, it was necessary to place the same scene in the cued quadrant on each trial. One scene was

assigned to be the “cued” scene and it always appeared in the quadrant to which the arrow pointed on a given trial. The position of the other three scenes was shuffled among the remaining quadrants.

Results.

Visual search. The central arrow cue successfully induced a spatial bias toward the cued quadrant (Figure 2.4). Accuracy was higher when the target appeared in the cued rather than the uncued quadrants. This effect was significant in the biased phase, $F(1, 31) = 42.17, p < .001, \eta_p^2 = .58$. It diminished, though remained significant, in the neutral phase, $F(1, 31) = 13.98, p < .001, \eta_p^2 = .31$. An ANOVA that directly compared data across the two phases showed a significant interaction between the target’s quadrant and phase, $F(1, 31) = 15.11, p < .001, \eta_p^2 = .33$. Thus endogenous spatial attention was induced in the biased phase and weakened in the neutral phase.

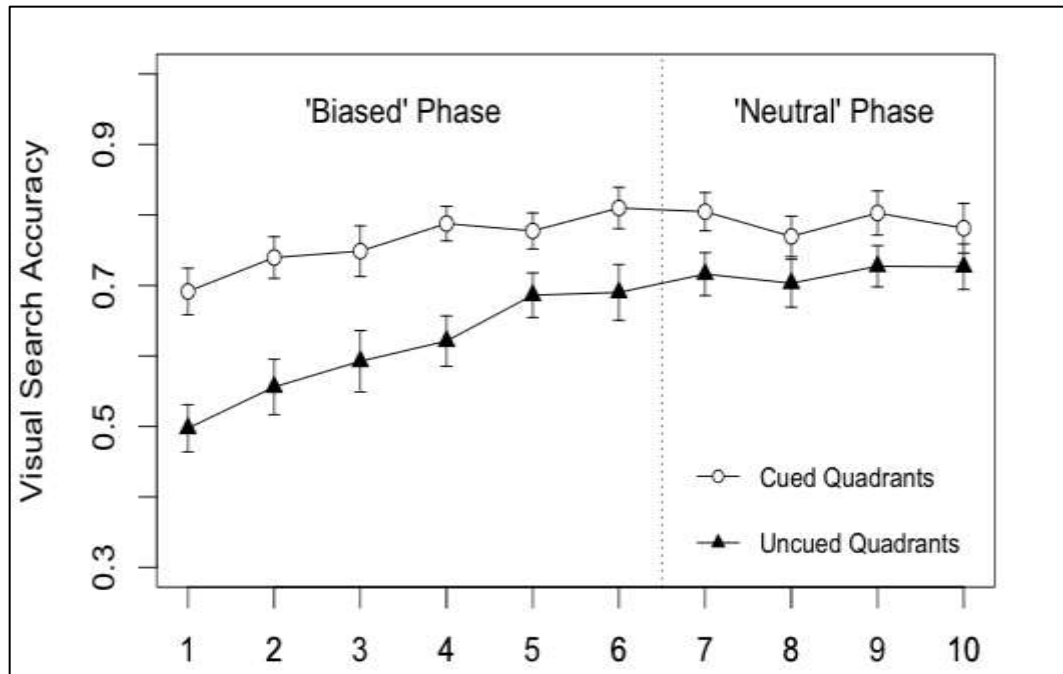


Figure 2.4. Visual search accuracy from Experiment 2. A central arrow instructed (cued) participants to prioritize one quadrant. The target was frequently in the cued quadrant (which changed from trial to trial) during the biased phase and was equally likely to be in each quadrant during the neutral phase. Error bars show +/- 1 S.E. of the mean.

Scene memory. The overall hit rate for old scenes was higher than the false alarm rate for new scenes, $t(31) = 6.47, p < .001$, suggesting that participants were able to perform both tasks at the same time (Figure 2.5). In the biased phase when spatial attention was directed to the cued quadrant, scenes presented in the cued quadrant were recognized better than scenes presented in the other quadrants, $t(31) = 2.97, p < .01$. As the spatial bias weakened in the neutral phase, the memory advantage for scenes in the cued quadrant became non-significant, $t(31) = 1.52, p > .10$. Similar to Experiment 1, the two-way ANOVA of phase and quadrant showed a significant main effect of quadrant,

$F(1, 31) = 10.37, p < .01$. The interaction between quadrant and phase did not reach significance, $F(1, 31) = 1.16, p > .20$.

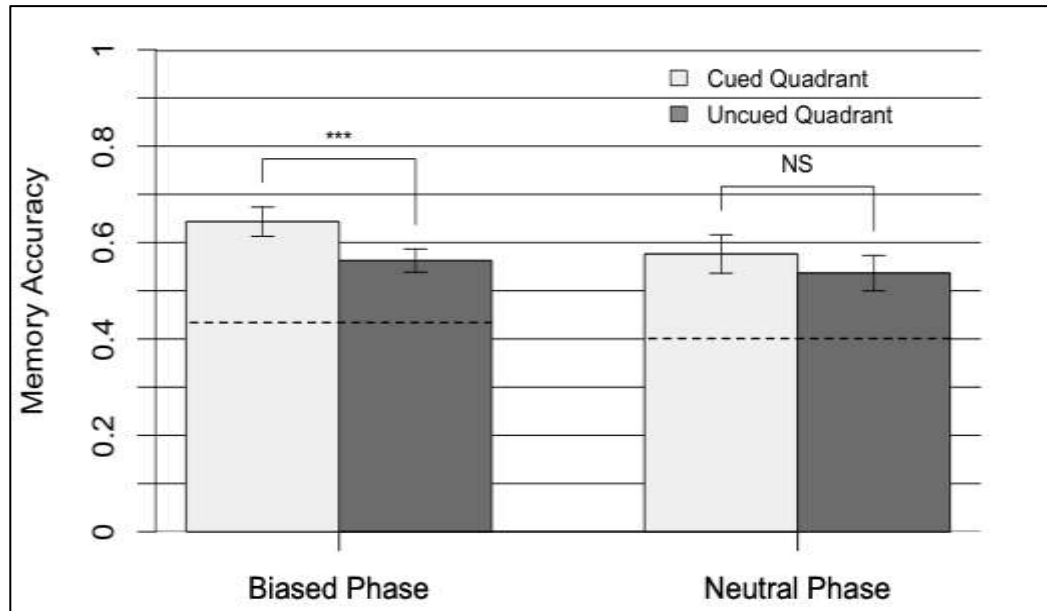


Figure 2.5. Scene memory from Experiment 2. Horizontal dotted lines represent false alarm rate (classifying new scenes as old ones) for that phase. Error bars show +/- 1 S.E. of the mean.

Discussion.

Experiment 2 replicated results from Experiment 1. Both experiments showed that endogenous spatial cuing in a visual search task yielded an advantage for scenes presented in the cued quadrant. As in Experiment 1, the spatial bias weakened in the neutral phase for visual search. The memory bias also weakened in the neutral phase. However, the existence of a significant memory effect during the biased phase is evidence that spread of attention between the two tasks occurred.

Experiment 3

Experiment 3 tests whether the spread of a spatial bias seen with endogenous cuing would also be observed with implicit location probability learning. In the location probability learning version of the search task, the target was presented more often in one quadrant of the screen. To promote implicit learning, subjects were not informed of the probability manipulation, and there was no demarcation between quadrants. Biasing a target's location in space makes it possible that some participants would become aware of the location asymmetry on their own, resulting in goal-driven attentional guidance to the location believed to contain the target most often. Since this would confound the effects of endogenous guidance of attention and location probability learning, self-report questions following the experiment gauged participants' awareness of the target location probabilities. Participants demonstrating awareness of the high-probability quadrant were excluded from the analyses.

Method.

Participants. To ensure a high enough number of participants unaware of the high-probability locations, we increased participant numbers for Experiment 3. 48 new participants, 33 females and 15 males, completed Experiment 3. Their mean age was 20.

Design and Procedure. This experiment was similar to Experiment 1 except for the following changes. First, participants were not instructed to prioritize any region of space, nor were they informed of the target's potential locations. Second, to introduce location probability learning, we manipulated the target's location probability in the first 24 blocks (the "biased" phase). During this phase, the target appeared in one quadrant 50% of the time, and in each of the other three quadrants 16.7% of the time. The high-

probability quadrant was randomly determined and counterbalanced across participants. Crucially, this quadrant was consistent during the entire biased phase, allowing participants to acquire location probability learning. In the next 16 blocks (the “neutral” phase), the target appeared in each quadrant 25% of the time.

For 16 of 48 participants, the neutral phase had 12 search trials per block as in Experiment 1. The other 32 participants in Experiment 3 had the same block structure as Experiment 2: 16 search trials in all blocks. The difference in trial number didn’t lead to significant differences in performance, so data were combined across all 48 participants.

Results.

To examine location probability learning separately from goal-driven attention, we divided participants into two groups: one group that was ‘aware’ of the target location probability structure and one group that was ‘unaware’. Two self-report questions determined the groups: the first asked if the search target occurred equally often in all locations, and the second informed participants that the target occurred in some regions more often than others and asked them to choose one quadrant as the higher-probability region. We considered participants aware, and therefore likely to have guided attention explicitly, only if they answered both questions correctly. Answering only the first correctly would suggest that participants did not have the correct awareness and may have answered “yes” due to demand characteristics; answering only the second correctly would suggest that participants were able to retroactively identify the high-probability quadrant, but were not using that knowledge actively prior to being told a high-probability region existed.

26 of the 48 participants answered at least one question incorrectly, and were thus considered unaware. The remaining 22 participants answered both questions correctly and were considered aware of the target probability structure. All analyses reported here consider only unaware participants who likely show implicit location probability learning rather than endogenous attentional guidance; results from aware participants are in the Appendix A, and bear strong resemblance to results of the endogenous cuing of Experiments 1 and 2.

Visual search. Replicating previous studies, the target's uneven location probability induced a strong spatial bias toward the high-probability quadrant. Unaware participants found the target more accurately when it appeared in the high-probability quadrant rather than the other quadrants (Figure 2.6). Search accuracy was higher in the high probability quadrant in the biased phase, $F(1, 25) = 30.28, p < .001, \eta_p^2 = .55$, and in the neutral phase, $F(1, 25) = 11.39, p < .01, \eta_p^2 = .31$. Comparing the biased and neutral phases for unaware participants showed a main effect of quadrant, $F(1, 25) = 23.57, p < .001, \eta_p^2 = .49$, and an interaction between quadrant and phase, $F(1, 25) = 7.64, p < .05, \eta_p^2 = .23$, suggesting that the accuracy advantage decreased in the neutral phase.

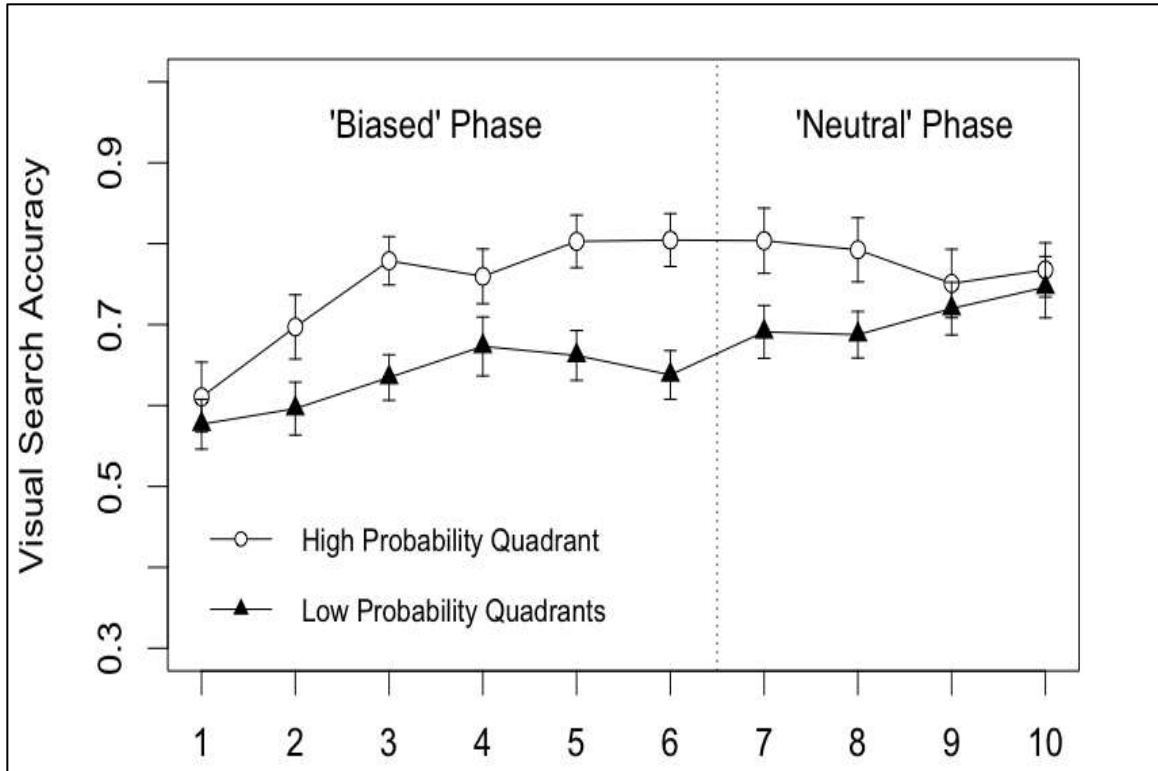


Figure 2.6. Visual search accuracy for unaware participants from Experiment 3. During the biased phase, the target occurred in a single high probability quadrant on 50% of trials (17% for each other quadrant). During the neutral phase, the target occurred equally often in each quadrant. Error bars show ± 1 S.E. of the mean.

Scene memory. Participants were able to recognize the scenes at above-chance levels. The overall hit rate for old scenes was higher than the false alarm rate for new scenes for unaware participants, $t(25) = 4.61, p < .001$. Implicit cuing participants showed a different pattern of memory results than those in the endogenous cuing experiments (Figure 2.7). In the biased phase, there was no accuracy difference for scenes based on quadrant, $t(25) = .45, p > .5$. In the neutral phase, accuracy was significantly greater in the low probability quadrants than the high-probability quadrant, $t(25) = 2.26, p$

< .05. Analyzing the two phases together yielded no significant main effect of quadrant, $F(1, 25) = 2.33, p > .1$. The phase by quadrant interaction was not significant, $F(1, 25) = 3.05, p = .09$.

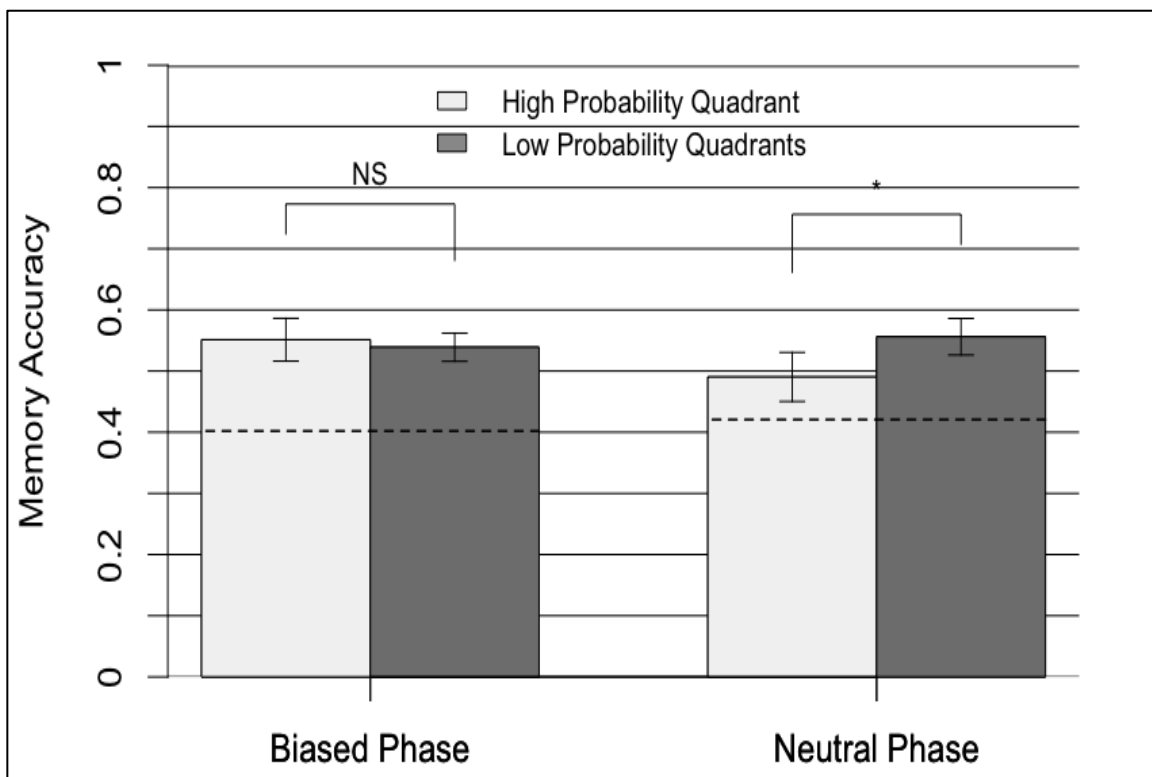


Figure 2.7. Scene memory for unaware participants in Experiment 3. Horizontal dotted lines represent false alarm rate (classifying new scenes as old ones) for that phase. Error bars show +/- 1 S.E. of the mean.

Discussion.

Participants in Experiment 3 developed a preference for the high-probability quadrant during visual search. This preference persisted into the neutral phase as in other research (Jiang, Swallow, Rosenbaum, et al., 2013). However, this selection bias did not

extend to scene memory for participants not reporting awareness of the high-probability target region. No memory advantage for the high-probability quadrant emerged in the biased phase, with accuracy regardless of quadrant being nearly identical (54% in the low-probability quadrants versus 55% in the high-probability quadrant). This is true even though the search advantage from arrow cuing (Experiment 2) is similar to that from location probability cuing (Experiment 3), $t(56) = 1.25$, $p > .20$. Results from Experiment 3 suggest that there is little to no spread of attention when location probability learning occurs implicitly. This supports the dual-system view of attention: location probability learning relies on different mechanisms than does endogenous guidance.

Combined Analyses

In three experiments, we found that goal-driven spatial attention for one task spread to a secondary task, while implicit location probability learning did not. To investigate this difference more directly, we ran additional analyses combining data from the endogenous cuing experiments (1 and 2) and comparing them to those of the unaware probability cuing group. We did not consider aware participants in these analyses, as the search advantage of aware participants would be affected both by implicit location probability learning (before participants became aware of the bias) and goal-driven attentional guidance (once they became aware).

First, we compared the strength of the memory advantage for scenes in the cued quadrant relative to uncued quadrants between experiments (Figure 2.8a). Using data from the scene memory task in the biased phase, we entered quadrant condition (visual search high- vs. low- probability) as a within-subject factor and type of cuing (endogenous cuing of Experiments 1 and 2 vs. implicit cuing of Experiment 3) as a

between-subject factor in an ANOVA. This analysis showed a significant interaction between quadrant condition and type of cuing, $F(1, 72) = 4.22, p < .05, \eta_p^2 = .06$. Specifically, the memory advantage for the cued quadrant was stronger in endogenous cuing experiments than in unaware probability cuing. The fact that endogenous cuing led to a greater attentional bias in the memory task than did implicit location probability learning supports the claim that goal-driven guidance and implicit guidance rely on different mechanisms.

Additionally, if the memory advantage for the high-probability quadrant is in fact an index of the spread of spatial attention from the search task, the strength of one participant's memory advantage should correlate with the strength of the corresponding search advantage. We examined this effect during the biased phase for the endogenous cuing experiment (Figure 2.8b) and for unaware participants in Experiment 3 (Figure 2.8c). For endogenous cuing participants, the correlation between biased phase search and memory advantage was significant, $r = .35, t(46) = 2.57, p < .02$. This correlation was apparent even when data from Experiments 1 and 2 were separately analyzed: $r = .45, t(14) = 1.92, p < 0.1$, in Experiment 1 and $r = .37, t(30) = 2.19, p < .05$, in Experiment 2. In contrast, no significant correlation was found between search advantage and memory advantage in the biased phase for unaware participants, $r = -0.02, t(24) = 0.11, p > .50$. This pattern of results provides additional evidence that the memory advantage in endogenous cuing experiments reflects the spread of attention between tasks, and that this spread does not occur with location probability learning.

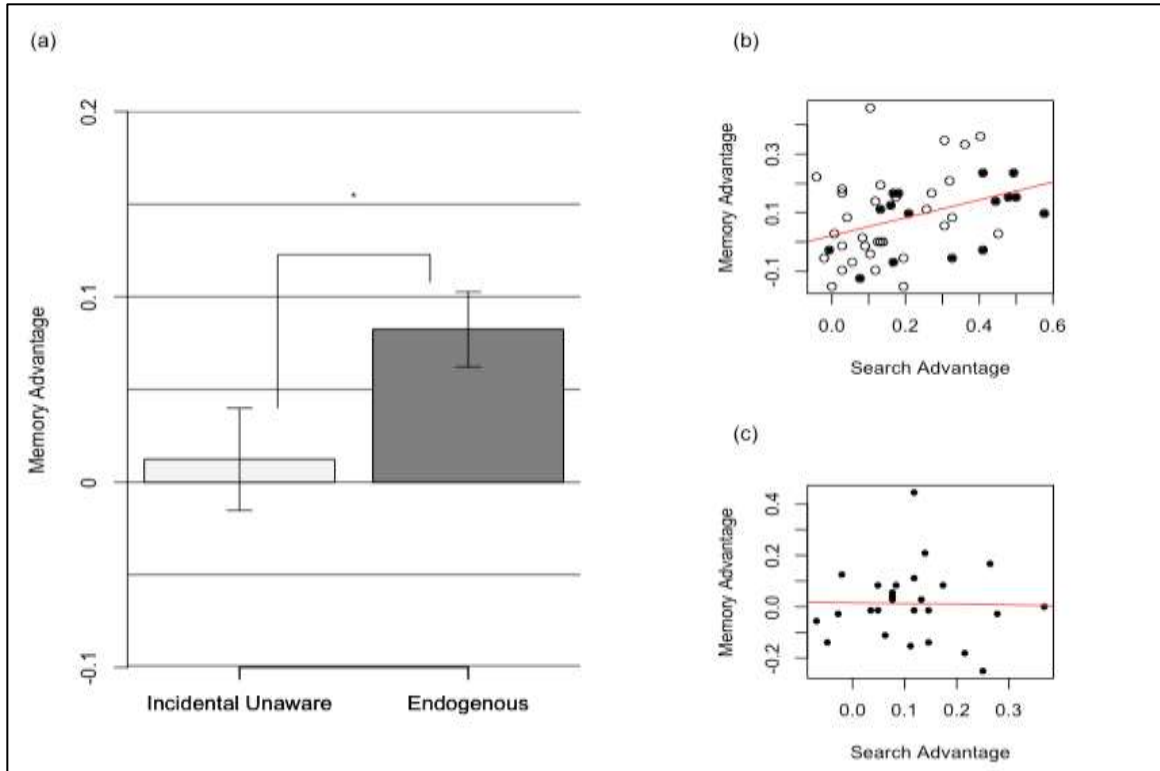


Figure 2.8. Results from comparisons between incidental unaware participants and endogenous cuing participants (Experiments 1 and 2). A. Memory advantages for high-probability quadrants during the biased phases of unaware participants in probability cuing experiments and endogenous cuing participants, as measured by the memory accuracy for the cued quadrant minus the average memory accuracy for the uncued quadrant. Error bars show ± 1 S.E. of the mean. B. Scatterplot of search advantage (search accuracy advantage for the high probability quadrant) and memory advantage (memory accuracy advantage for the high probability quadrant) for endogenous cuing participants during the biased phase (first 6 epochs). Filled dots are from Experiment 1, open dots from Experiment 2. Correlation line ($r = .35$) is also shown. C. Scatterplot of search advantage and memory advantage for 26 unaware probability cuing participants during the biased phase. Correlation line ($r = -.02$) is also shown.

General Discussion

These experiments revealed important differences between endogenous, goal-driven attention and implicitly learned attentional biases in the spread of spatial attention between concurrent visual search and scene encoding tasks. Goal-driven attention enhances processing in a region of space for both tasks, as indicated by the spread of attention to the memory task in Experiments 1 and 2 (and for aware participants in Experiment 3, Appendix A). On the other hand, probability cuing primarily affects selection in the relevant task: attentional biases to one region for visual search did not affect performance on the scene memory task. This suggests that these two forms of attention recruit different processes.

Could the spread of attention across tasks in the endogenous guidance experiments have occurred after the identification of the target, rather than when people respond to the spatial cue? On this account, spatial attention may dwell on the quadrant where the target is found, yielding a memory advantage. The results from our experiments, when considered together, do not support this view. First, since the display is presented briefly, by the time the search target is found the scenes are no longer present. Dwelling on the target quadrant is unlikely to provide any significant advantage for memory encoding. Second, and more critically, if dwelling contributes to a scene memory advantage, it should not be restricted to endogenous cuing. In the probability cuing experiment, the search target is more often found in the high-probability quadrant in the biased phase. Any dwelling should have facilitated memory for scenes presented in the high-probability quadrant. These results suggest that spreading of spatial selection occurs relatively early and is not a consequence of dwelling on the target's quadrant.

The present results show that contemporary theories of spatial attention inadequately explain habitual attentional biases. Unitary priority map theories (Bisley & Goldberg, 2010; Itti & Koch, 2001) suggest that any effects of spatial attention are determined by top-down and bottom-up factors through the influence of a priority map. Similarly, the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltà, 1987) proposes that all covert shifts of attention are subthreshold activations of the oculomotor system. Cowan's (1988) theory of memory and attention argues that shifting attention to a region should improve memory for that region. In each case, implicit guidance and goal-driven guidance should have the same effects on scene memory, contrary to our results.

Unlike most theories of attention, the dual-system view of spatial attention explains these findings well (Jiang, Swallow, and Capistrano, 2013). In this view, goal-driven attention is a form of declarative attention that guides spatial attention through an explicit cue prior to appearance of the search array. In contrast, incidentally acquired spatial preferences alter habitual search behavior, a procedural form of attention that occurs while performing the search task. Its generalization therefore depends not on *where* objects are, but on whether two tasks share the same procedure of moving attention. Consistent with this idea, previous studies have shown that changing viewer perspective interfered with habitually learned attentional biases but not explicit search (Jiang & Swallow, 2014; Jiang, Swallow, & Capistrano, 2013), and furthermore that probability cuing transfers between visual search tasks, even ones that use different stimuli (Jiang, Sha, et al., 2015).

Our results demonstrate the importance of incorporating habitual attention as an additional form of spatial attentional guidance. Some calls for incorporating explanations of habit into theoretical models of attentional guidance exist (Anderson, 2013; Awh et al., 2012; Wolfe & Horowitz, 2017), due to the growing evidence for the ability for environmental statistics and history of behavior to affect attentional guidance (Chun & Jiang, 1998; Geng & Behrmann, 2005; Jiang, Swallow, Rosenbaum, et al., 2013; Kunar, Flusberg, & Wolfe, 2008). For example, Awh and colleagues (2012) suggest that selection history is another way of affecting the priority map, adding a third category of influence alongside goal-driven controls and bottom-up salience. Our interpretation goes beyond some of these recent proposals. The present results demonstrate that habitual attention does not influence spatial attentional guidance with the same ultimate effect on attentional shifts; it guides attention in a way that has different effects once it rests on a region than does either goal-driven or salience-driven attention.

The difference between habitual and endogenous guidance of attention may involve the relationship of each to the process of segmenting the search array from overlapping visual information irrelevant to search. Such segmentation occurs preattentively, with search behavior restricted to the segmented search array for the duration of search (Wolfe et al., 2002). Because endogenous cuing engages spatial attention “off-line”, prior to stimulus onset, a task-general priority map is already deployed prior to the onset of the array (Egeth & Yantis, 1997; Kastner et al., 1999; Luck et al., 1997). This facilitates encoding of scenes in the cued quadrant, resulting in better memory for those scenes. Habitual attentional biases, on the other hand, act within the search process—that is, after the preattentive segmentation of scenes from background.

Targets in the high-probability locations are more accurately found because people have acquired a search habit to shift attention in that direction, but the spread of attention to scenes is limited because implicit learning shifts spatial attention among the already segmented search elements.

Existing empirical evidence for the difference between goal-driven and habitual attention is primarily based in research on target probability learning, including both location probability learning and feature probability learning. Such habitual guidance has been shown to differ from endogenous guidance in a variety of ways including temporal profile, decline in aging, and resilience to high working memory load (Jiang et al., 2015; Jiang, Sigstad, et al., 2013; Twedell et al., 2016; Won & Jiang, 2015). Further investigation into potential differences between habitual guidance of attention and other forms of guidance is needed to verify that they implement spatial attention differently, rather than merely recruit the same spatial attentional process through different causes.

Overall, our endogenous cuing results fit with the large literature on multitasking in demonstrating a limit in people's ability to exert parallel and independent attentional controls (Marti, Sigman, & Dehaene, 2012; Pashler, 1994). Although the data on endogenous cuing support the idea that humans have limited abilities in controlling spatial attention differently across two tasks, data from probability cuing suggest that not all forms of spatial attention are task-general. This finding is consistent with the broader literature on implicit learning. Adding secondary tasks typically interferes with explicit, but not implicit, learning (Hayes & Broadbent, 1988; Waldron & Ashby, 2001; Zeithamova & Maddox, 2006). More generally, incidentally learned attention is less likely to interfere with a secondary task, making management of various strategies

between tasks more realistic. This finding is both useful for informing theories of goal-driven and habitual attentional control and for developing applications of attention research in everyday settings.

Conclusion

The present study has demonstrated, in a novel paradigm, an important difference between spatial attention driven by top-down goals and incidentally acquired spatial preferences. Whereas top-down modulation improves both search performance and search-irrelevant memory for spatially proximate scenes, implicit learning improves only search performance. Based on this, we have argued for a dual-system theory of spatial attention that dissociates habitual attention from other forms of attention. Future research may elaborate on this theory by identifying specific cognitive and neural mechanisms uniquely supporting habitual spatial attention.

Introduction to Study 2

Study 1 demonstrated a dissociation between the effects of goal-driven and implicitly learned attention on a secondary memory task. This finding suggests that top-down and experience-driven attention differ not only in their sources of attentional biases, but also in how they are implemented—otherwise, effects on scene memory should have been comparable. One such implementational difference may relate to the time course of attentional shifts. The results of Study 1 are compatible with the idea that experience-driven attentional shifts occur after stimulus onset, once the search array has been segmented from the memory scenes (Wolfe et al., 2002), therefore preventing any effects of attention from affecting the memory task. However, Study 1 only provides

evidence that implementation of top-down and experience-driven attention differ, not that they differ specifically with respect to their time course. Study 2 directly investigated whether experience-driven attention leads to baseline shifts toward the attended location preceding the onset of task-relevant stimuli—a phenomenon known to occur during top-down attentional allocation (Kastner et al., 1999; Luck et al., 1997). If experience-driven and top-down attention differ in their recruitment of baseline attentional resources, this could potentially explain the difference in transfer to the secondary memory task in Study 1 (a possibility discussed in [Section 5.2.2](#)) and further elucidate the differences between experience-driven attention and goal-driven attention.

3. Study 2: Implicit location probability learning does not induce baseline shifts of visuospatial attention

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Implicit location probability learning does not induce baseline shifts of visuospatial attention

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Preface

We tested whether implicit learning causes shifts of spatial attention in advance of or in response to stimulus onset. Participants completed randomly interspersed trials of letter search, which involved reporting the orientation of a T among Ls, and scene search, which involved identifying which of four scenes was from a target category (e.g., forest). In Experiment 1, an initial phase more often contained target letters in one screen quadrant, while the target scenes appeared equally often in all quadrants. Participants

persistently prioritized letter targets in the more probable region, but the implicitly learned preference did not affect the unbiased scene task. In Experiment 2, the spatial probabilities of the scene and letter tasks reversed. Participants unaware of the probability manipulation acquired only a spatial bias to scene targets in the more probable region, with no effect on letter search. Instead of recruiting baseline shifts of spatial attention prior to stimulus onset, implicit learning of target probability yields task-dependent shifts of spatial attention following stimulus onset. Such shifts may involve attentional behaviors unique to certain task contexts.

Keywords: location probability learning, spatial attention, implicit attention, baseline shifts of attentional resources

Introduction

Many factors influence how people attend to the visual world. Task demands dictate certain goals, salient stimulus properties may capture attention, and how one has attended in the past influences selection in the future (Awh et al., 2012; Jiang, 2018). One “selection history” effect is location probability learning (LPL), in which people find stimuli more efficiently in frequently attended locations (Jiang, Swallow, & Rosenbaum, 2013; Shaw & Shaw, 1977). For instance, when a visual search task contains targets in one screen quadrant disproportionately often, people develop attentional biases to that quadrant. Unlike goal-driven attention, LPL is largely implicit and has long-lasting effects. Still, many differences between the two forms of guidance are not fully

understood. Here, we investigate whether LPL leads to “baseline” spatial shifts of attention—shifts occurring in anticipation of a trial, prior to any visual stimuli.

Goal-driven attention operates by shifting spatial attention in advance of stimulus presentation (for a review, see Beck & Kastner, 2014). Evidence for these baseline shifts of attention includes the observation that endogenous cues are more effective when participants have longer to deploy goal-driven attention in anticipation of target onset and increase activity in early visual areas prior to stimulus appearance. Because LPL recruits spatial attention, it may also enhance baseline activity at high-probability regions. However, rather than using baseline shifts, LPL may bias attention through a search habit encoded as motion vectors guiding attentional behavior (Jiang, 2018). Required motion vectors differ across tasks; those used in serial search, for instance, could differ substantially from those used in parallel search. Because the dynamics of shifting attention are specific to a given task, implicit LPL would only bias attention in tasks closely resembling the one used to establish the implicit bias. According to this account, LPL would affect attention *during*, not *before*, search. Investigating whether LPL yields baseline shifts could reveal important differences between goal-driven and implicitly learned attention.

Related research has investigated whether LPL affects attention narrowly—only in the trained task—or broadly—across any task involving spatial attention. Findings show that LPL is task-general only when two tasks involve similar search behaviors. For example, LPL acquired in letter search transfers to a similar search task for a small arrow superimposed on natural scenes (Salovich, Remington, & Jiang, 2017). Conversely, no transfer was observed from letter search to a letter foraging task that required selection of

any one of many target letters to receive a reward (Jiang, Swallow, et al., 2015), or from letter search to scene memory (Addleman et al., 2018). Unfortunately, these studies' two-phase designs, in which participants trained on one task and then completed a second task, prevent conclusions about whether LPL yields baseline shifts of attention; because participants knew the upcoming task, they could adjust their attentional set for each task.

The present study tests whether implicit LPL induces baseline shifts of spatial attention using two interleaved visual search tasks. One task involves finding a letter 'T' among 'H's. The other involves finding a particular scene category (e.g., forest) among other scenes. Critically, our study randomly intermixes the two tasks, departing from previous studies' blocked designs. Participants cannot predict an upcoming trial's task, so learned baseline shifts of spatial attention would influence performance on both tasks. If LPL instead yields only post-stimulus attentional shifts, the dissimilarity of search behaviors across tasks may prevent transfer. Such task-specificity would argue against baseline shifts in LPL.

Experiment 1

Experiment 1 manipulated the location probability of targets in a letter search task and probed pre-stimulus baseline shifts of attention with a scene search task. Most trials (two-thirds) involved letter search—participants searched among briefly presented letters for a target 'T' and reported its orientation. Unbeknownst to them, the target appeared disproportionately often in one screen quadrant, a manipulation shown to facilitate letter search in the high-probability quadrant (Jiang, Swallow, & Rosenbaum, 2013). Importantly, we unpredictably interspersed trials in which participants searched four scenes for one from a pre-specified category (e.g., forest). Target scenes occurred equally

often in each quadrant. If LPL acquired during letter search induces pre-stimulus baseline shifts of attention, then it should enhance scene search in the letter task's high-probability quadrant.

Method.

Participants. Analysis of previous research (Salovich et al., 2017) suggested that 80% power (at $\alpha=.05$) required testing 20 participants. Because some people may become aware of probability manipulations, we tested 32 participants to obtain data from at least 20 unaware participants.

Participants were college students naïve to the experimental purpose. They reported normal or corrected-to-normal visual acuity and normal color vision. All participants signed informed consent and were compensated with extra course credit. 13 females and 19 males with a mean age of 20 (range: 18-24) completed Experiment 1.

Equipment. Participants were tested individually with fluorescent overhead lighting. They sat at an unconstrained distance, approximately 60 cm, from a 19-in. CRT monitor (1,024 x 768 resolution; 75 Hz). Experiments were run using Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com).

Stimuli. Our paradigm was adapted from Addleman et al. (2018). Throughout the experiment, a red fixation dot subtending 0.15° visual angle remained in the display's center.

Letter search trials (Figure 3.1a) each presented eight white letters between 0.7° and 2.7° in size. Letters farther from fixation were larger, in proportion to the cortical magnification factor (Carrasco et al., 1995). Each letter could appear in any of 32 possible locations. Locations were divided evenly into four eccentricities (approximately

1.5°, 4°, 6.5°, and 12°), and each quadrant contained exactly two letters per trial. Each trial included one 'T' and seven 'H's. Each letter had a random orientation: either 0°, 90°, 180°, or 270°.

Scene search trials (Figure 3.1b) presented four natural scenes, one per quadrant (11.5° x 11.5°). The center of each scene was 8.75° from fixation. Each trial contained one scene from each of four categories: beach, mountain, forest, and field. Scenes were selected randomly (with counterbalanced frequency) from among 48 images within each category, taken from the SUN397 database (Xiao, Hays, Ehinger, Oliva, & Torralba, 2010).⁴ Following the scenes, an arrow (5° in length) appeared in each quadrant, each with a unique orientation selected randomly from 0° (pointing upward), 90°, 180°, and 270°.

⁴ Beach, mountain, and forest scenes were from categories labeled as such in the SUN database. Field images were images with few trees and no water or mountains from several SUN categories: cornfield, cultivated field, wild field, hill, pasture, valley, and vineyard.

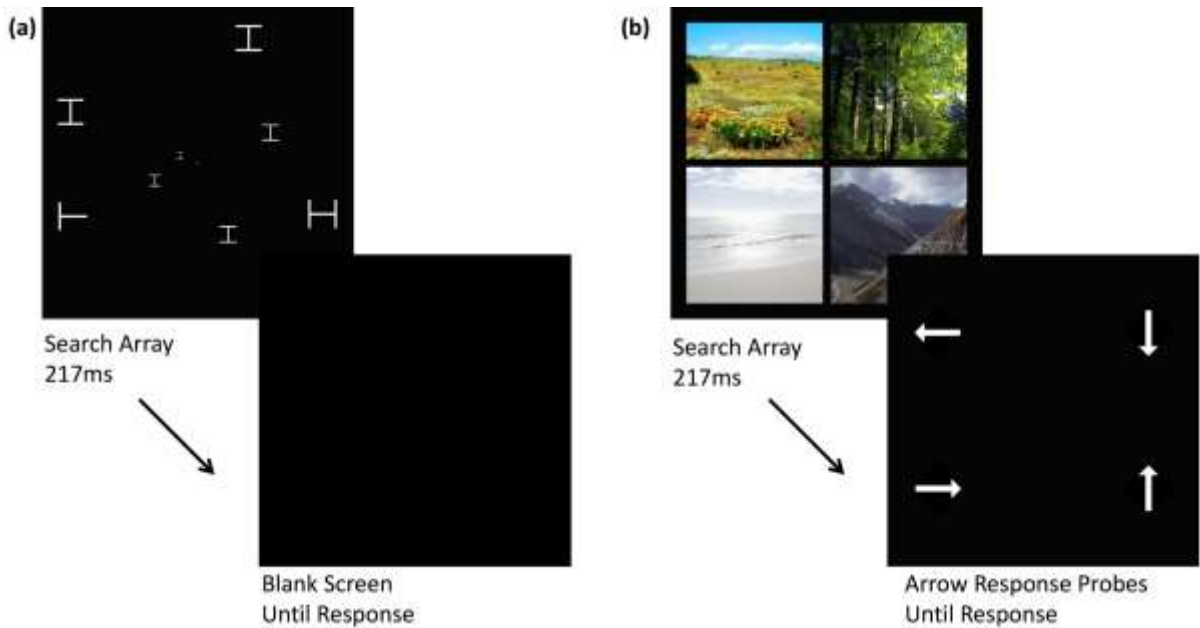


Figure 3.1. Example search arrays in the two tasks. (a) In letter search, participants searched for a target T and reported its orientation. (b) In scene search, participants searched for a scene of a target category. When the search array disappeared, it was replaced by a randomly arranged array of arrows. Participants reported the orientation of the arrow in the same screen location as target scene.

Procedure. Following two practice blocks without spatial biases, participants completed 720 trials divided into 20 blocks of 36 trials each. Each block contained 24 letter search and 12 scene search trials, randomly intermixed. For 16 participants we induced a spatial bias in letter search by creating a high-probability, “rich” quadrant that had 62.5% of targets, compared to 12.5% in each of the low-probability, “sparse” quadrants. To further reduce explicit awareness, the other 16 were trained with 50% of targets in the rich quadrant and 16.7% in each sparse quadrant. Data from these two groups were qualitatively similar and were combined. The first twelve blocks used this design to induce LPL. To assess the persistence of LPL, the final 8 blocks (the testing

phase) contained letter targets in each quadrant equally often. To probe pre-stimulus baseline shifts of attention, one-third of trials involved scene search. Scene targets occurred equally often in each quadrant throughout the experiment.

Participants began each trial by clicking the fixation dot, a task requiring hand-eye coordination to ensure central fixation. The search array then appeared for 216ms. On scene search trials, the array was then immediately replaced with four arrows, each pointing a different direction. The participants indicated the orientation of the target: the target T in letter search (an upright T, due to the direction of the long stem of the T, corresponded to a ‘down’ response), or the arrow in the same location as the target scene in scene search. Scene targets were those belonging to a fixed category for each participant, with target category counterbalanced across participants. The same buttons (W-A-S-D) were used in both tasks, corresponding respectively to “up”, “left”, “down”, and “right”. Upon response, a tone provided accuracy feedback; following each block, participants were given their proportion of correct responses in the block. Instructions emphasized both speed and accuracy.

Analysis. Performance was indexed by RT and accuracy. We excluded trials with outlier reaction times (more than 3 standard deviations above the mean task RT for that participant; between 1.5-2.6% of trials were excluded across all experiments) from all analyses, and trials with incorrect responses from RT analyses. To reduce noise, we binned every two blocks into an epoch, yielding 6 training and 4 testing epochs.

To avoid confounding effects of LPL and endogenous attention, we administered a post-experiment survey probing awareness of the experiment’s probability manipulations. The survey asked two questions: “did the target occur more often in some

places than others;” and “If you had to choose one quadrant you feel the target occurred most often, which would you choose?” Participants demonstrating awareness—those who thought the letter target’s location was biased and correctly identified the high-probability quadrant—were excluded from analyses. This yielded 23 unaware participants.

Results.

(1) Primary task: Letter search (Figure 3.2a-b). Participants acquired LPL in the letter search task during training. In training, an ANOVA on target quadrant (rich vs. sparse) and epoch (1-6) showed faster RTs in the rich quadrant, $F(1, 22) = 47.33, p < .001, \eta_p^2 = .68$; an effect of epoch, $F(5, 110) = 15.38, p < .001, \eta_p^2 = .41$, indicating that participants responded faster as training progressed; and no interaction, $F < 1$. Accuracy also showed main effects of target quadrant, $F(1, 22) = 19.23, p < .001, \eta_p^2 = .47$, and epoch, $F(5, 110) = 3.66, p = .004, \eta_p^2 = .14$, and no interaction, $F < 1$.

LPL persisted into testing; when letter targets occurred equally often in each location, RT remained faster in the previously high-probability quadrant, $F(1, 22) = 4.376, p = .048, \eta_p^2 = .17$. There was no effect of epoch, $F(3, 66) = 2.042, p = .117$, and no interaction, $F(3, 66) = 2.042, p = .117$. Accuracy data were similar: higher in the previously high-probability quadrant, $F(1, 22) = 8.063, p = .009, \eta_p^2 = .27$, with no effect of epoch, $F(3, 66) = 1.552, p = .209$, and no interaction, $F(3, 66) = 1.885, p = .141$.

(2) Probe task: Scene search (Figure 3.2c-d). We next examined whether LPL acquired from letter search induced baseline shifts of spatial attention. If so, scene search should benefit when targets appeared in the letter-rich quadrant. We found no evidence of this effect.

During training, an ANOVA of target quadrant and epoch for RT showed no effect of target quadrant, $F < 1$, a significant effect of epoch, $F(5, 110) = 7.294, p < .001$, $\eta_p^2 = .25$, and no interaction, $F(5, 110) = 1.029, p = .404$. Accuracy data were similar: no effect of target quadrant, $F < 1$, a significant effect of epoch, $F(5, 110) = 3.654, p = .004$, $\eta_p^2 = .14$, and no interaction, $F(5, 110) = 1.522, p = .189$.

Testing showed similar results. RT again showed no effect of target quadrant, $F(1, 22) = 2.512, p = .127$, an effect of epoch, $F(3, 66) = 4.235, p = .008, \eta_p^2 = .16$, and an interaction, $F(3, 66) = 4.893, p = .003, \eta_p^2 = .18$. The interaction was likely spurious, driven by a single data point in epoch 8 but not in other epochs, $ps < .05$. Accuracy showed no significant effects during testing, $ps > .05$.

(3) Cross-task comparison. We tested whether LPL was stronger during letter search than scene search. Training phase RT showed an interaction between task (letter vs. scene search) and quadrant (rich vs. sparse), $F(1, 22) = 6.148, p = .021, \eta_p^2 = .22$; during training, the rich-quadrant advantage was larger in letter search than scene search. The interaction was marginally significant in accuracy, $F(1, 22) = 3.172, p = .089$. During testing, the interaction was significant for RT, $F(1, 22) = 4.291, p = .050, \eta_p^2 = .16$, but not accuracy, $F < 1$.

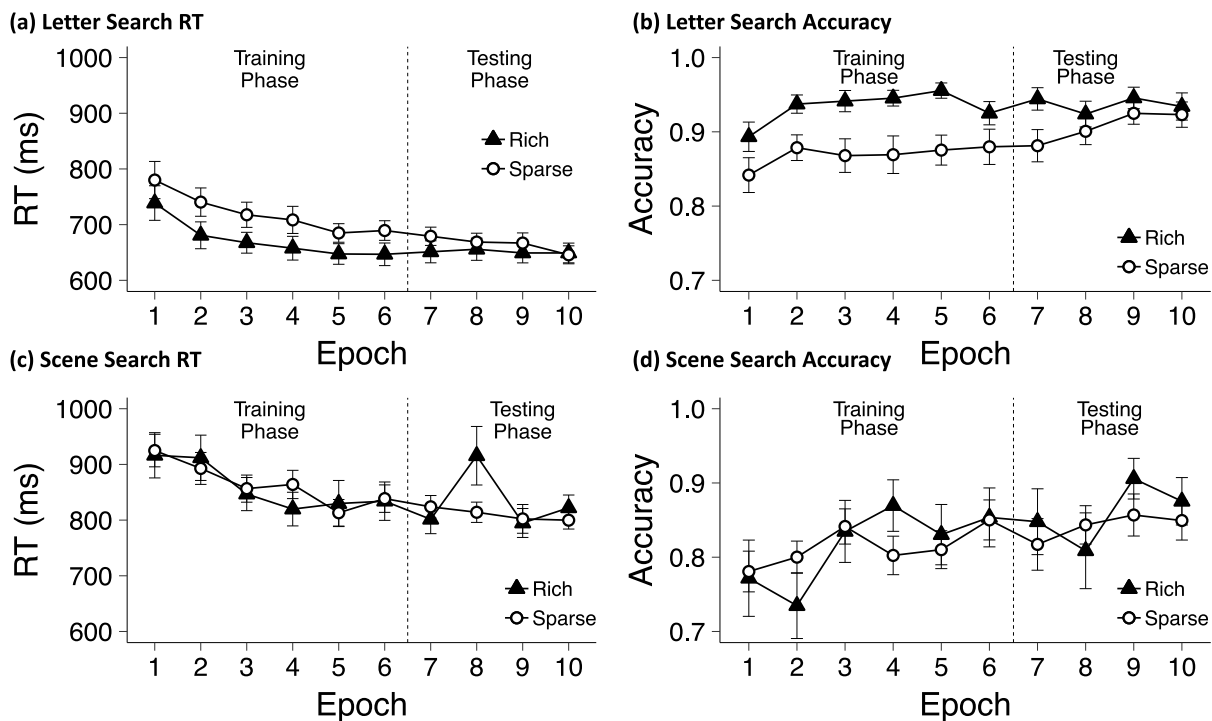


Figure 3.2. Results from unaware participants ($N=23$) in Experiment 1. Experiment 1 manipulated target location probability only in the letter task. (a) Letter task reaction time. (b) Letter task accuracy. (c) Scene task reaction time. (d) Scene task accuracy. Error bars show ± 1 standard error of the mean (S.E.M.).

Discussion.

Experiment 1 demonstrated a persistent attentional bias in the primary letter task. We found no evidence that this bias yielded pre-stimulus, baseline shifts of spatial attention; a randomly interspersed scene search task did not benefit from LPL. If spatial attention were already deployed at the high-probability quadrant before the task, participants should find targets in the high-probability quadrant more efficiently in both search tasks. Moreover, the higher frequency of letter trials than scene trials may have further incentivized the deployment of attention in anticipation of letter trials, but we

found no evidence of this effect. LPL benefitted only letter search, indicating that it results in an on-line search habit initiated after stimuli appear (Addleman et al., 2018; Jiang, 2018).

Because the probe task involved half as many trials as did the primary task, the lack of LPL in the probe task could reflect insufficient statistical power. If so, analyzing a random half of primary task trials should yield fewer significant results. Instead, target quadrant significantly influenced primary task RT in all four split-half ANOVAs (accuracy and RT in the training and testing phases). Experiment 2 showed a similar pattern. The lack of probe task effects likely indicates failure for LPL to transfer across tasks, not insufficient power.

Experiment 2

Experiment 2 manipulated the location probability of scene targets and probed baseline shifts of attention using letter search, conceptually replicating Experiment 1. It also examines the sensitivity of scene search to LPL. Because scene search relies more on global gist perception and less on serial scanning (Rousselet, Fabre-Thorpe, & Thorpe, 2002; Wolfe, Vo, Evans, & Greene, 2011), it may be insensitive to LPL. Acquisition of LPL in scene search would strengthen the conclusions of Experiment 1.

Method.

Experiment 2 was identical to Experiment 1, except it reverses the roles of the scene and letter tasks. Each block contained 24 scene search trials and 12 letter search trials. The scene task more frequently contained targets in one quadrant during training (62.5% for half of participants and 50% for the other half), with scene targets occurring equally often in each quadrant during testing. In both phases for letter search, targets

occurred in each quadrant at equal rates. 27 females, 4 males, and 1 non-binary participant with a mean age of 20 (range: 18-31) completed Experiment 2. Analyses report data from 22 unaware participants (10 participants were excluded based on responses about the primary scene task).

Results.

(1) Primary task: Scene search (Figure 3.3a-b). Participants acquired LPL in the scene task. During training, an ANOVA of target quadrant and epoch showed faster RT in the rich quadrant, $F(1, 21) = 9.542, p = .005, \eta_p^2 = .31$, a significant effect of epoch, $F(5, 105) = 10.28, p < .001, \eta_p^2 = .33$, and no interaction, $F(1, 105) = 1.218, p = .306$. Analyses of training accuracy as well as both accuracy and RT in testing showed no effects of quadrant, epoch, or their interaction, $ps > .1$. While we found significant LPL in training, it did not persist into testing.

(2) Probe task: letter search (Figure 3.3c-d). We found no evidence that LPL for scene search induced a baseline shift of attention reflected in letter search. In letter search, an ANOVA of target quadrant and epoch for RT during training showed no effect of quadrant, $F < 1$, a significant effect of epoch, $F(5, 105) = 14.71, p < .001, \eta_p^2 = .41$, and no interaction, $F(5, 105) = 1.031, p = .403$. Accuracy data showed a similar pattern: no significant effect of quadrant, $F < 1$, a significant effect of epoch, $F(5, 105) = 3.651, p = .004, \eta_p^2 = .15$, and no interaction, $F(5, 105) = 2.074, p = .074$. Testing phase analyses showed no effects of quadrant, epoch, or their interactions, $ps > .05$.

(3) Cross-task comparison. Comparing scene and letter RT during training showed a significant interaction between task and quadrant, $F(1, 22) = 6.102, p = .022, \eta_p^2 = .23$, with the rich-quadrant advantage significantly larger in scene search than letter

search. The task-quadrant interactions in terms of training phase accuracy, testing phase RT, and testing phase accuracy were insignificant, $ps > .25$.

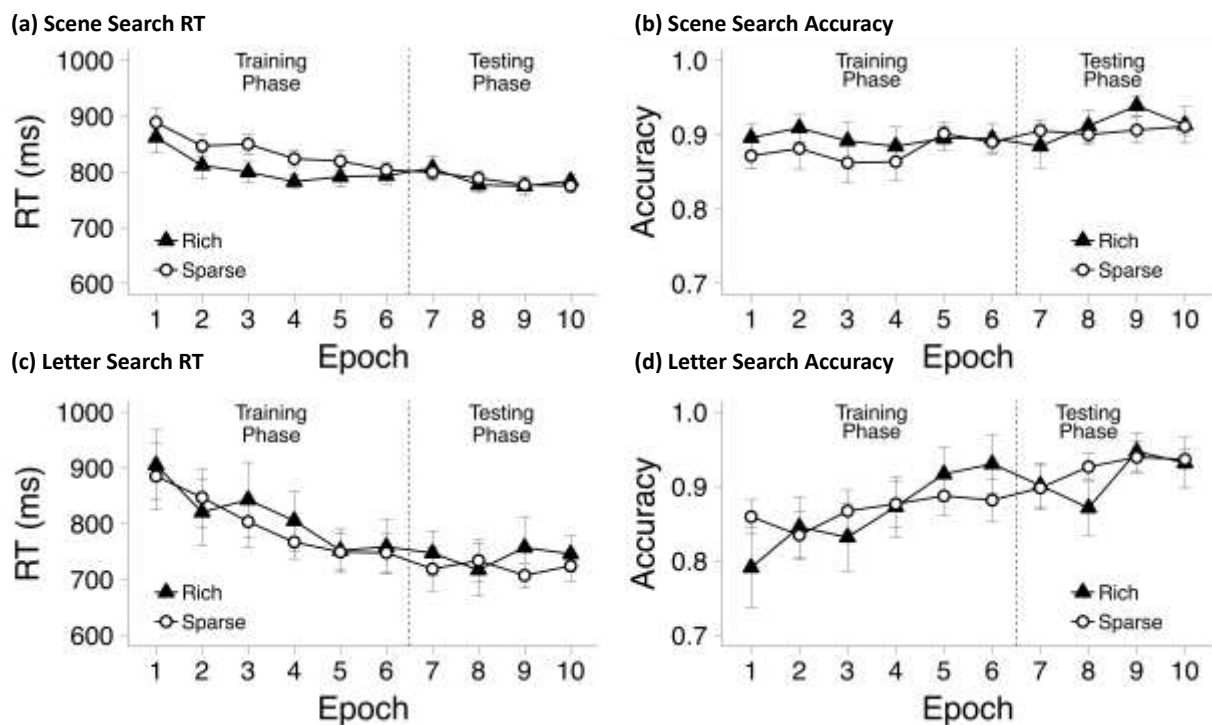


Figure 3.3. Results from unaware participants ($N=22$) in Experiment 2. Experiment 2 manipulated target location probability only in the scene task. Error bars show ± 1 standard error of the mean (S.E.M.).

Discussion.

Experiment 2 showed a failure for spatial attentional biases acquired during scene search to influence letter search. We also report LPL in the training phase of the scene task, showing that LPL can facilitate scene search. This finding informs discussions about how attention influences scene categorization. Some have argued that gist perception relies primarily on pre-attentive parallel processing (Rousselet et al., 2002). Other studies

show that, although parallel processing aids scene categorization more than it does many search tasks, selective attention does benefit scene processing (Gronau & Izoutcheev, 2017; Wolfe et al., 2011). Our results are consistent with the latter findings, as spatial attentional biases benefited scene search.

LPL acquired from scene search did not persist into testing. This is unique among LPL studies, which typically use letter search. The lack of persistence could indicate that the current study's effect is due to inter-trial location priming (Maljkovic & Nakayama, 1996), wherein attention is biased towards very recently attended locations. However, post-hoc RT analyses show evidence for LPL during training when only considering trials in which scene targets were in a different quadrant than the previous trial's target, $F(1, 21) = 8.828, p = .007, \eta_p^2 = .30$. Instead, the lack of persistence into testing may reflect the reduced role of serial attentional shifts in scene category search (Rousselet et al., 2002; Wolfe et al., 2011). In any case, evidence indicates that scene search is sensitive to LPL during training.

Experiment 2's findings on the letter search task are consistent with the lack of baseline shifts in Experiment 1. Baseline shifts would have influenced letter search. Instead, we find no facilitation of letter search in the high-probability quadrant.

General Discussion

The present study reports no transfer of implicitly learned attentional biases between letter search and scene category search tasks. Although LPL can be induced in both tasks, a learned, implicit attentional bias in one task failed to influence performance in the other task. Unlike previous studies, our tasks were unpredictably intermixed, preventing participants from predicting the upcoming task. Therefore, if participants had

deployed attention in anticipation of search, LPL would have influenced both tasks. The lack of such an effect is strong evidence that implicit LPL does not elicit baseline shifts of spatial attention. Instead, it suggests that probability cuing influences attention in response to, rather than in anticipation of, a specific task. This could be achieved by learning a vector of attentional movement that is only suitable for certain tasks. This differs from goal-driven attention, which enhances baseline visual processing at attended regions (Beck & Kastner, 2014). Baseline shifts may rely on conscious control to allocate attention, whereas implicitly learned attention may rely on the nature of attentional shifts in the active task. Consistent with this distinction, we found some evidence of cross-task transfer in participants who became aware of the target's location probability (see supplement available at <https://doi.org/10.31234/osf.io/dhmf4>).

Could LPL reflect response-level processes rather than attentional ones? Perhaps primary task targets outside the rich quadrant violate expectations, slowing response times. Alternatively, memory traces specific to the primary task could facilitate response preparation for biased quadrant targets (as has been argued for other search biases; Treisman, Vieira, & Hayes, 1992). However, response-level effects would primarily influence mean RT, while LPL can also significantly improve rich-quadrant accuracy (as in Experiment 1) and search efficiency (through reducing per-item processing time; Jiang et al., 2013). This suggests that LPL reflects attentional biases.

In our task, participants exhibited a spatial bias in a task containing biased targets and no spatial bias in a task with an unbiased target distribution. This reflects a remarkable ability to update attentional control based on learned task statistics. Such control is comparable to findings from the additional singleton paradigm, in which

location-dependent task statistics influence the degree to which color singletons capture attention (Crump, Milliken, Leboe-McGowan, Leboe-McGowan, & Gao, 2018). Our results provide evidence for similar, task-appropriate spatial shifts: when participants learn to prioritize one region for one task, presentation of a different task can prevent these shifts.

Our results are the first to demonstrate a failure for location probability learning to transfer between two visual search tasks. Despite the acquisition of a search habit in one task, learning did not affect a second interleaved task, suggesting that LPL leads to task-dependent, rather than baseline, shifts of attention. Our findings have implications for cognitive training. They suggest that training spatial attention in one task can significantly influence that task's performance, but transfer appears limited to similar tasks. This finding may inform effective attentional training methods for both healthy populations and people with neurological conditions or sensory loss, suggesting that training environments should closely mimic people's everyday problems.

Introduction to Study 3

Experience-driven spatial attention is typically studied using visual tasks. Studies 1 and 2 investigate the relationship between location probability learning—a specific type of experience-driven attention—and top-down attention, in order to refine theories of how different sources of visual attention relate to one another. There are reasons to think that experience-driven spatial attention may differ across modalities, however, and prior to the work in this dissertation, there have been no reported investigations of auditory location

probability learning. To address this, Study 3 reports experiments on both location probability learning and short-term inter-trial location priming in the auditory modality.

4. Study 3: The Influence of Selection History on Auditory Spatial Attention

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The influence of selection history on auditory spatial attention

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Preface

Evidence suggests that prior attentional selection guides visuospatial attention without conscious intent. Yet few studies have examined whether selection history influences auditory spatial attention. Using a novel auditory search task, we investigated two selection history effects: short-term inter-trial location priming and long-term location probability learning. Participants reported whether a spoken number, occurring simultaneously with three spoken letter distractors presented from different locations, was odd or even. We first showed that endogenous attention guided by informative arrows facilitates search in our paradigm. Next, inter-trial location priming was assessed by comparing reaction time when target location repeated across recent trials to when

target location changed. Unlike visual search, auditory search showed little evidence of inter-trial location priming. In a separate experiment, we investigated location probability learning by making targets disproportionately likely to appear in one location. Results showed location probability learning: participants were faster when targets occurred in the high-probability location than in the low-probability locations. To our knowledge, this is the first study of inter-trial location priming or long-term location probability learning in auditory search. The findings have implications for the role of spatial relevance in auditory attention and suggest that long-term attentional learning and short-term priming rely on separate mechanisms.

Keywords: Spatial attention; auditory search; selection history; inter-trial priming; location probability learning

Introduction

Spatial attention allows us to flexibly prioritize information at relevant locations. Decades of research have established the central roles of stimulus salience and top-down goals in guiding attention (Bédard, El Massioui, Pillon, & Nandrino, 1993; Itti & Koch, 2001; Mondor & Zatorre, 1995; Posner, 1980; Spence & Driver, 1994). In addition, a growing body of evidence suggests that past attentional selection influences future attentional deployment, even in the absence of awareness. While the existence of these “selection history” effects is well established in the visual modality (Jiang, 2018; Kristjánsson & Campana, 2010), relatively little is known about how they affect auditory attention. Here, using a novel auditory search task, we investigated two selection history

effects—short-term inter-trial location priming and long-term location probability learning. Our findings have implications for theories of attention and learning and advance our understanding of how people listen in noisy environments.

Selection history effects in visual search.

Inter-trial location priming refers to the facilitation of search when a target on a current trial occupies the same location as targets on recent trials (Maljkovic & Nakayama, 1996). In an early demonstration, Maljkovic and Nakayama asked participants to identify whether the left or right side of a target diamond, defined by being white among two black distractor diamonds or vice-versa, was truncated. Repetition of target location from up to eight preceding trials sped up reaction times (RT); for example, trial n would have a faster RT if any of trials $n-1$ to $n-8$ contained targets in the same rather than a different location as trial n 's target. The authors attributed this RT advantage to implicit, short-term memory representations of previous target locations guiding spatial attention more quickly to recent target locations. Though subsequent research has suggested that inter-trial priming may at times operate based on memory representations of bound objects and not of target locations (Huang et al., 2004; Kristjánsson et al., 2008), inter-trial location priming has been replicated and extended in dozens of visual search paradigms, including conjunction search tasks (for a review, see Kristjánsson & Campana, 2010).

In addition to short-term priming, long-term location probabilities can also influence visual search. Early work showed that altering target location probabilities sped up RT for high-probability relative to low-probability locations (Hoffmann & Kunde, 1999; Miller, 1988; Shaw & Shaw, 1977). Subsequent studies verified through post-test

surveys that the effect was largely implicit, as participants often did not spontaneously notice the probability manipulation and could not identify high-probability regions (Jiang, Swallow, Rosenbaum, et al., 2013). In a commonly-used paradigm, Jiang and colleagues had participants search an array of letters for a T and report its orientation. In an initial “biased” phase, one screen quadrant contained the target more often than the other quadrants, while in a subsequent “unbiased” phase, targets were distributed evenly across all quadrants. Participants rapidly acquired an RT advantage for targets in the high-probability quadrant that persisted throughout the unbiased phase. While the results of the biased phase could be an effect of inter-trial priming (since trial-to-trial repetitions are more likely in locations that often contain the target), inter-trial location repetition could not explain advantages in the unbiased phase because repetitions were equally prevalent in all quadrants. Instead, location probability learning (LPL) has been argued to operate based on a long-term habit to execute attentional shifts to the high-probability quadrant (Jiang, 2018).

As implicit effects, inter-trial repetition priming and location probability learning are neither purely endogenous (goal-driven) nor purely exogenous (stimulus-driven; Awh, Belopolsky, & Theeuwes, 2012). Like goal-driven attention, learning reflects an acquired state, modulated by previous attentional selection. Unlike goal-driven attention, selection history effects lack a deliberate component. In fact, target location need not be task-relevant to elicit visual selection history effects. The letter search task, for instance, defines targets by shape and requires responses to orientation; location is processed incidentally, as a byproduct of attending to the target (Jiang, Swallow, Rosenbaum, et al., 2013). Because central control is less engaged in these selection history effects, their

implementation may be more strongly constrained by effects unique to a sensory modality than is endogenous guidance of attention. This is particularly plausible for long-term LPL because its speculated mechanism is oculomotor learning (Jiang, 2018).

Short-term auditory selection history effects.

Repeating auditory stimulus location across trials has been shown to facilitate responses in several contexts. For instance, several studies have shown an effect in which repeated stimulus properties in a rapid sequence of stimuli speed target detection (e.g., Alain & Woods, 1993; Woods & Alain, 1993). Woods and Alain (1993) found that targets (defined by a conjunction of pitch and duration) in a dichotic listening task sharing location or pitch with a preceding distractor yielded faster RTs than those differing along either dimension. As is common for inter-trial priming of visual search (Huang et al., 2004), this effect was strongest when both location and pitch repeated. However, the mechanisms for these effects probably differ substantially from those underlying inter-trial priming during search: first, while priming in search tends to yield RT *costs* when distractors become targets, Woods and Alain's effect reduces RT when the most recent non-target shares features with the target; second, these effects operate at a more rapid time-scale (40-400ms) than inter-trial priming (usually several seconds); and third, the mechanisms of attending to one ear differ substantially from those used to attend to an external spatial location (Culling & Akeroyd, 2012).

Using a paradigm more similar to those of visual search tasks, Rhodes (1987) examined the effects of auditory spatial attention during one trial on performance in subsequent trials. Using a target localization task, Rhodes encouraged attention to preceding target locations across trials by making target location repetition highly

probable while also informing participants of this manipulation. Rhodes found faster RT for repeated target locations, providing the first demonstration of an auditory inter-trial location facilitation. However, this repetition effect is not equivalent to visual inter-trial location priming. First, the study incentivized participants to attend to trial $n-1$'s target location, conflating inter-trial priming with goal-driven guidance of attention. Second, whereas location was an incidental property in visual inter-trial priming, Rhodes' (1987) participants' task involved localizing targets, conflating location and response priming. Rhodes' finding thus provides little evidence for auditory inter-trial location priming.

Dyson (2010) examined effects of auditory feature and location repetitions by interleaving trials requiring either pure tone frequency discrimination (high vs. low) or spatial elevation discrimination (up vs. down). Priming was absent in trials repeating only a single target feature; in fact, repeating one but not the other property induced slower RT than altering both. On the other hand, priming was found when both feature values repeated. This finding was consistent with visual inter-trial priming effects, which suggest that priming may rely on episodic memory of the target stimulus as a whole (Huang et al., 2004). Unlike visual search tasks, however, Dyson's (2010) task lacked distractor stimuli that could compete for attentional selection. This difference is significant because inter-trial priming originates not simply from stimulus repetition, but also from the repetition of the selection status—target or distractor. Several studies suggest that rejection of distractors, rather than selection of targets, causes visual inter-trial location priming (Geng et al., 2006; Kristjánsson & Driver, 2008; Rorden et al., 2011). Because spatial orienting is effective in limited contexts in auditory tasks (reviewed below), changes in target context (single-stimulus or with distractors) could

influence the results. Therefore, although Dyson (2010) observed repetition effects in a single-stimulus paradigm, one cannot assume that a similar effect would be found in an auditory search paradigm that includes both targets and distractors.

Longer-term auditory selection history effects.

To our knowledge, location probability learning has not been investigated in the auditory modality. However, longer-term selection history effects have been found in a variety of auditory tasks. Doan (2014) asked participants to identify a spoken number among a sequence of spoken letters. Trials in which a repeated sequence of letters predicted the target number yielded faster responses than did trials with randomized letter identities, despite participants reporting no awareness of repetitions. In another study, Wagener and Hoffman (2010) asked participants to classify tones based on pitch. The tone was presented after a variable foreperiod - short or long. Unbeknownst to participants, the duration of the foreperiod predicted the target's pitch. Participants showed a small RT advantage when the foreperiod validly predicted the pitch, suggesting that they learned the association between foreperiod duration and target identity. Shen and Alain (Shen & Alain, 2012) reported a similar implicit attentional effect on auditory temporal attention. In their study, the attentional blink, in which detecting one target can impair accuracy at detecting a subsequent target, was reduced when second targets occurred at more probable times within a sequence of auditory stimuli. Rimelle, Jolsvai, and Sussman (2011) also showed that implicit temporal—but not spatial—expectation elicited attentional orienting: consistent inter-stimulus intervals in a tone sequence improved perceptual sensitivity and reaction time in a go/no-go task. A similar spatial manipulation, in which a tone's location changed in a partially regular pattern, had no

effect. They attribute this discrepancy partly to the elevated role of temporal processing in the auditory modality.

Finally, Zimmermann, Moscovitch, and Alain (2017) examined learning of implicit associations between auditory context and stimulus location. Different environmental audio clips (e.g., a dog barking) served as the context. Each context was consistently paired with a left or right lateralized pure tone or with no tone. Participants learned this association explicitly in an initial phase by reporting the laterality of the tone (or tone absence) in each context. A subsequent phase probed associative memory. To determine how this learning affected subsequent spatial orienting, an hour later participants listened to the same environmental clips, but this time, clips previously associated with no pure tone now contained a tone in a random (left or right) location, while the context clips' tones were presented from the same location as in the initial phase. Localization was faster for contexts learned with tones than those learned without them. This pattern was found even for contexts that participants did not successfully recall in a memory task. The finding suggests that implicit memory associations may bias spatial attention to the associated target location, a pattern reminiscent of the visual contextual cueing effect (Chun & Jiang, 1998). Unfortunately, both the learning and the testing tasks involved localization, meaning that each context was not only consistently associated with where the tone was, but also which response to make. Further research dissociating response learning from attentional learning is needed to clarify the role of long-term learning in guiding auditory spatial orienting.

Why selection history based on location may not affect auditory search.

The studies reviewed above suggest that both short-term repetition and long-term learning could facilitate auditory processing. However, these effects differed substantially from selection history effects found in visual search. The use of a single tone, for example, eliminated any need for attentional selection. What then, might be expected in an auditory search task? Several studies suggest that the findings could differ between visual and auditory tasks, owing to greater importance of spatial location in vision than audition.

Unlike the visual modality, in which location is a dominant organizational principle of neural coding even in the retina, in the auditory modality localization primarily depends on central structures comparing signals between the two ears via the inter-aural time difference and the inter-aural level difference. Furthermore, localization is less precise in audition than in vision—the threshold for differentiating two sound sources ranges from 1° to 10° depending on where the sound comes from, and zones of confusion between front and back and between points of different elevations are large (Middlebrooks & Green, 1991; Recanzone, Makhamra, & Guard, 1998). On the other hand, the auditory modality is suitable for processing temporally varying information, such as frequency, timbre, and other spectral information. These sensory constraints have consequences for attention. While almost all visual selection results in selecting an item's location, when selecting an auditory target among distracting sounds, spatial location has a more restricted role alongside spectrotemporal features (Shinn-Cunningham, 2008). The lack of spatial shifts of attention or even of target localization at all might prevent auditory location priming despite the presence of auditory priming for identity.

Spatial relevance as the determining factor of auditory spatial orienting.

Despite the reduced role of spatial orienting in auditory compared to visual perception, both goal-driven and stimulus-driven attention can influence auditory processing (Bédard et al., 1993; McDonald & Ward, 1999; Mondor & Zatorre, 1995; Spence & Driver, 1994). Even so, spatial orienting is less reliably beneficial for auditory stimuli than visual ones, particularly in the case of bottom-up attention. While endogenous, goal-driven spatial attention can speed target detection in both spatial and non-spatial tasks, exogenous attention typically does so only during localization tasks (for a review, see Spence & Santangelo, 2010). This may be because auditory spatial orienting seems to occur primarily when the target's location is task-relevant, either during a spatial task or when there is predictive information about target location (McDonald & Ward, 1999).

Though the spatial relevance hypothesis has successfully accounted for spatial cueing to pure tones, it is difficult to evaluate in more complex auditory contexts, such as in auditory search in multi-talker environments. In the latter situation, spatial attention may aid the isolation of a target stream from distractor streams over time, even though the target's location is, strictly speaking, task-irrelevant (Kidd, Arbogast, Mason, & Gallun, 2005; for a review, see Shinn-Cunningham, 2008). This may be because simultaneous speech sounds contain highly similar spectral profiles, rendering spectral cues inefficient in isolating the target talker. In these contexts, spatial orienting may be beneficial in detecting targets even when location is not task-relevant.

The studies noted above suggest that the role of spatial relevance in auditory spatial orienting is unclear, especially in complex listening environments. This makes it

difficult to predict whether selection history effects, such as inter-trial location priming and location probability learning, can influence auditory search. A target's location must be represented for either effect to occur, but it is unclear whether such representation typically exists when the target's location is neither the defining nor the reported property in auditory search. Investigations of these selection history effects are important for understanding interactions between attention and modality and can also provide insights into mechanisms of attention and learning.

Current study.

We report three experiments that determine the effects of selection history on auditory search. All experiments employ a novel auditory search task in which participants find a target among distractors in simultaneously presented speech. To validate the utility of this paradigm in attention research, Experiment 1 examined goal-driven guidance of attention via an explicit cue. Next, we probed inter-trial priming for spatial location in Experiment 2, and location probability learning in Experiment 3. In addition to being the first investigation of these two selection history effects in auditory search, this study provides insights into mechanisms of attention and learning.

General Methods

Participants.

General characteristics. Participants in this study were college students at the University of Minnesota. They were naive to the purpose of the experiments and reported having normal hearing and native English language skills. Each participant signed an informed consent form prior to participation.

Sample size and power analysis. Due to the lack of studies using similar paradigms from which to estimate effect size, we chose a sample size for Experiment 1—16—that was larger than those used in studies of goal-driven attention in visual search (e.g., Jiang, Swallow, & Rosenbaum, 2013). One goal of Experiment 1 was to estimate effect size when using an endogenous cue from which to determine sample size for Experiments 2 and 3. Based on the estimated effect size of Experiment 1, power analysis indicated a required sample size of 14 to achieve power of 0.8. Accordingly, and to match Experiment 1’s sample size, we tested 16 participants in each of Experiments 2, 3a, and 3b.

Gender and age. All participants were between 18 and 34 years of age. Experiment 1 included 13 females and 3 males with a mean age of 21 years; Experiment 2 included 13 females and 3 males with a mean age of 19 years; Experiment 3a included 9 females and 7 males with a mean age of 19 years; Experiment 3b included 13 females and 3 males with a mean age of 19 years.

Equipment.

Participants were tested individually in a sound attenuated, semi-anechoic chamber in the Multisensory Perception Laboratory at the University of Minnesota. Audiometric details of the room can be found at: <http://catss.umn.edu/msp>. Stimuli were presented via four Anthony Gallo Acoustics A’Diva Ti (Gallo Acoustics, San Antonio, TX) speakers powered by Crown Xli 800 amplifiers (HARMAN Professional Solutions, Northridge, CA); speakers were approximately 1.5m from participants. Visual instructions and trial feedback were presented via a 61cm LCD monitor (1920x1200 resolution; 60Hz) at a distance of approximately 1m from participants. Participants were

seated in a chair placed in the center of a 10ft x 13ft room (Figure 4.1, left). Experiments were conducted using MATLAB (www.mathworks.com) and Psychtoolbox (Brainard, 1997; Pelli, 1997).

Stimuli.

Raw recordings of human speech of English letters and numbers were taken from: <http://evolution.voxeo.com/tools>. In Experiments 1, 2, and 3a, numbers from 1-10 were targets, and letters were distractors. Letters W, X, Y, and Z were omitted due to a programming bug (this was the case for all participants and conditions). In Experiment 3b, distractors included all letters and the target set was reduced to 1, 2, 4, and 5.

Stimuli were preprocessed. First, clips were modified so that each clip's duration was 430ms, the median duration of the unedited clips. Speech began and ended at precisely the same time in all edited clips. This was done first by selecting only the speech portion of stimuli using a silence-eliminating algorithm, followed by a time-scale modification factor designed to alter tempo of stimuli without shifting pitch. In Experiment 3b, we made additional edits to the clips. Each clip was pitch-shifted to have a mean fundamental frequency (F0) equal to the median F0 of all clips (161Hz). In all experiments, each clip was then pitch shifted in Audacity® to create 4 pitch levels: -4, -2, 0, or +2 semitones higher than the original. The result was two masculine voices of lower pitch and two feminine voices of higher pitch. Each clip was then lengthened with silence to 1 second and stimulus root mean square (RMS) amplitude was equalized. Finally, because pilot data suggested that identifying a single stream among several of equal intensity yielded very low accuracies, targets (numbers) were presented at an RMS amplitude of 1.5 times that of each distractor.

Stimuli were presented using 4 speakers spaced equally in a semi-circle in front of the participants on the horizontal plane (Figure 4.1, right). Specifically, speakers were placed 90° counterclockwise of the direction the participant was facing, 30° counterclockwise, 30° clockwise, and 90° clockwise. These locations were chosen because pilot testing (as well as previous reports) found poor location discrimination in search tasks for stimuli behind versus in front of or above versus below participants (Rhodes, 1987). The speakers were placed along the walls of a rectangular 10'x13' room.

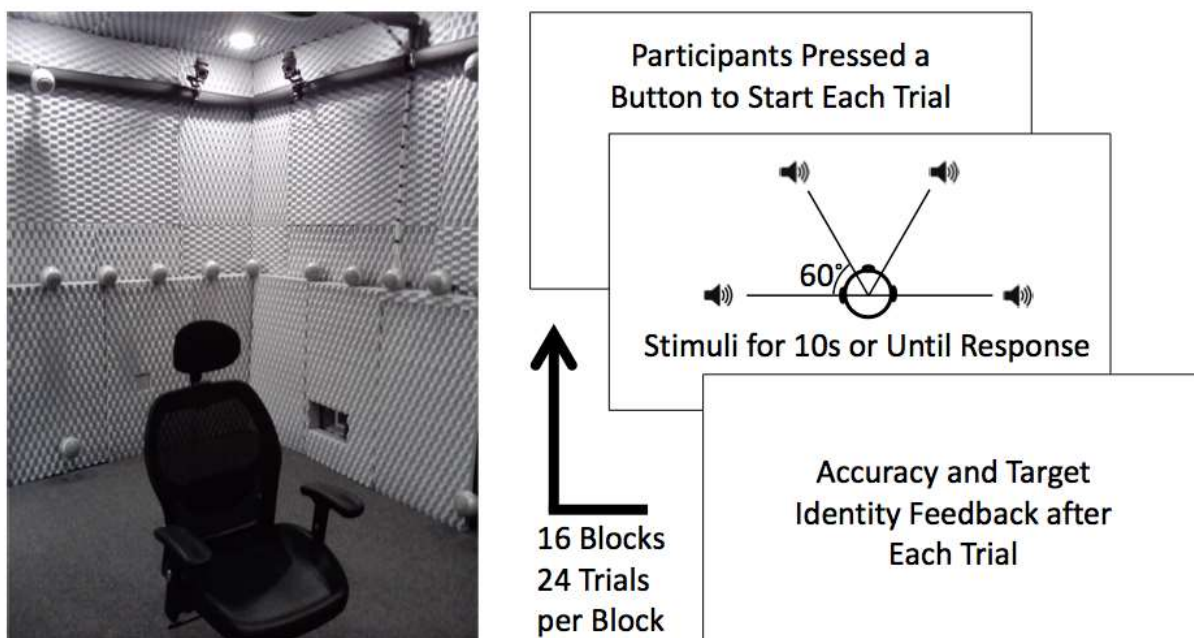


Figure 4.1. Experimental details. Left: a photograph of the experimental chamber. Participants sat in a chair in the center of the room and listened to sounds presented from speakers placed around them on the horizontal plane. Right: a schematic of the trial structure and design. Stimuli were presented from four locations on the horizontal plane. Speakers were placed at equal angular intervals (60°) from directly to the participant's left to directly to the participant's right.

Procedure.

Participants first completed a practice localization task to verify that, when required, they were able to identify the location of target stimuli. In this task, participants listened to a varying number (1-4) of simultaneous talkers from the 4 possible speakers. Each talker repeated a number or a letter (1s in duration) up to 10 times (10s). The task was to report the location of the single number spoken among the talkers by pressing a button as quickly and accurately as possible. Responses were permitted at any time during or after stimulus presentation and feedback about accuracy was displayed after each trial. The sound streams terminated upon response. Participants were instructed to keep their bodies and heads still and upright during the task and to attempt to maintain the same position in the chair throughout the experiment. There were 60 self-paced localization practice trials, separated into five 12-trial blocks. Blocks sequentially increased in difficulty. Block 1 contained just a single number presented from one of the four locations; block 2 contained a number and a distractor letter presented from different locations; Blocks 3-5 contained a number and 3 distractor letters, each from a different location. Target pitch was counterbalanced among the 4 pitch levels; distractors were given a randomly assigned pitch. Each talker presented on a given trial had a different pitch. Target and distractor identities were randomized on each trial; each stimulus had a different identity. Locations of the talkers were randomized provided that the target occurred equally often in each of the four locations within a block. As shown in the Appendix A, participants were able to localize the target at far-above-chance levels when asked to do so.

The main experiment was similar to the localization practice, with the following exceptions. First, participants now reported via the keypad whether the target number was odd or even. Second, there were sixteen 24-trial blocks, for a total of 384 trials. Third, all trials included one number (target) and three letters (distractors). The identity of the stimuli was randomized with the constraint that odd and even numbers occurred equally often in each block. Finally, following each trial, visual feedback informed participants of both their accuracy and the number being spoken for that trial. Target location probabilities were varied and are described separately for each experiment.

Analysis.

In all experiments, RTs greater than 10s were excluded from analysis (fewer than 1% of accurate trials).

Experiment 1

Experiment 1 examined the sensitivity of our auditory search task to endogenous spatial cueing. This served to contrast with findings from later experiments. Cues were provided visually in the form of arrows indicating which of the four speakers was likely to contain the target number. The arrow was predictive of the target's location at above-chance levels. Participants were informed of the arrow's predictability and encouraged to use this information to improve their task performance.

Previous studies using similar auditory endogenous cueing paradigms have shown a benefit at validly cued locations (Kidd et al., 2005; McDonald & Ward, 1999; Spence & Driver, 1994). However, the effectiveness of spatial cueing to sounds varies across experimental paradigms (McDonald & Ward, 1999). Experiment 1 aimed to verify that the auditory search paradigm used here was sensitive to spatial cueing, at least when

participants deliberately prioritized one location. If no endogenous cueing were found, it would be unlikely to find evidence for implicit effects of spatial selection history.

Method.

Procedure. Participants pressed a button to initiate each trial. 250ms later, a small white arrow (1° in length) was presented at the center of the display. This was followed 625ms later by the auditory stimuli. The arrow pointed in one of four directions: directly right (0°), front-right (45°), front-left (135°), and directly left (180°). These angles were chosen because the aspect ratio of the monitor (16:10) differed from the aspect ratio of the room (10:13). Participants found these arrow directions to unambiguously signal the speakers' locations. Target location was randomized provided that it occur equally often in each location in each block.

Design. Participants completed 16 blocks of trials (24 trials/block). To parallel the design of location probability learning (Won & Jiang, 2015; see also our Experiment 3), the arrow cue had a validity higher than chance in the first 12 blocks of trials. It predicted the current target's location on 50% of the trials (chance was 25%). 50% validity was used to match the informativeness of implicit probability cueing in Experiment 3. In the last four blocks, the arrow was uninformative; it indicated the target's location on 25% of the trials. Participants were told that the arrow would predict upcoming target location with 50% accuracy and encouraged to use this information to facilitate performance. They were not informed that the cue would change validity toward the end of the experiment.

Results.

In the experimental task, overall accuracy was 86% (Standard error: 1.1%).

Accuracy was not significantly different in validly versus invalidly cued trials when considering either trials in the informative cue phase (average accuracy advantage for valid cues = 1%, SE of the difference = 1%), $F(1, 15) = 1.058, p = .32$, or the uninformative cue phase, $F < 1$.

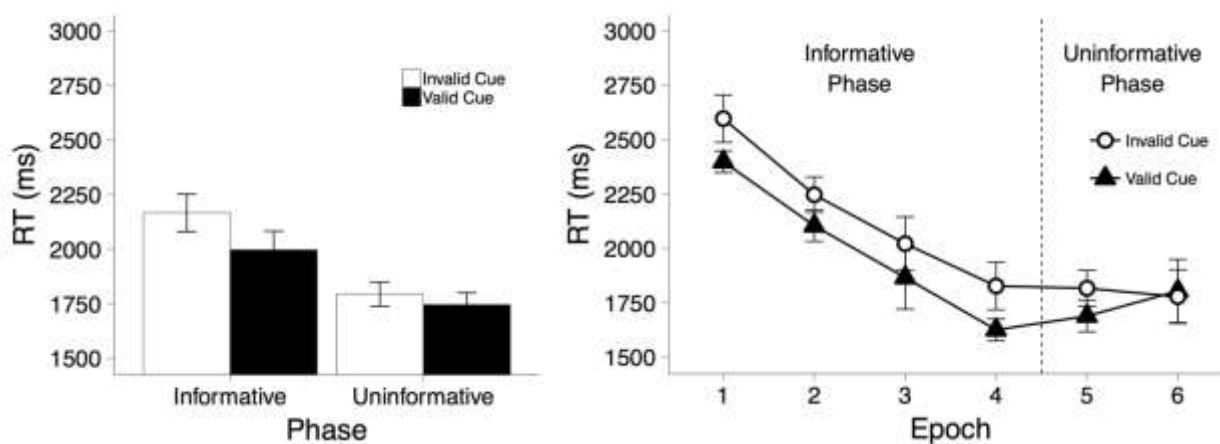


Figure 4.2. Results from Experiment 1 showing reaction time for accurate trials. Left: Trial average across informative blocks and uninformative blocks presented separately for valid cue trials and invalid cue trials. Right: RT across 6 epochs (Epochs 1-4: informative; Epochs 5-6: Uninformative). Error bars show +/- 1 S.E. of the difference.

We examined RT on correct trials, excluding outliers (Figure 4.2, left). An ANOVA of phase and cue validity found a significant main effect of cue validity. RT was faster on validly cued trials than invalidly cued trials (average RT difference = 82ms, SE of the difference = 50ms), $F(1, 15) = 7.48, p = .015, \eta^2 = .33$. The main effect of phase was also significant, as RT improved in the later phase versus the earlier one (average RT

difference = 299ms, SE of the difference = 66ms), $F(1, 15) = 24.76$, $p < .001$, $\eta^2 = .62$. The interaction between phase and condition was not significant, $F(1, 15) = 1.51$, $p = .238$.

A further analysis examined the time course of the cueing effect across blocks. To obtain a stable measure, data across 3 blocks in the informative phase and 2 blocks in the uninformative phase were combined to form 6 epochs (Figure 4.2, right). In the informative phase, an ANOVA using cue validity and epoch as factors found a main effect of validity (average RT advantage for the valid cues = 170ms, SE of the difference = 55ms), $F(1, 15) = 10.52$, $p = .005$, $\eta^2 = .41$, which did not interact with epoch, $F < 1$. In the uninformative phase, the main effect of cue validity was not significant (average RT advantage for the valid cues = 48ms, SE of the difference = 86ms), $F(1, 15) = 0.32$, $p = .579$, $\eta^2 = .02$. Though a residual cueing effect appeared in the first uninformative epoch, which then completely diminished, the interaction between unbiased epoch and cue validity was not significant, $F < 1$.

Discussion.

Experiment 1 used a novel auditory search task administered in a sound chamber. The search task differed from previous studies, which primarily evaluated effects of attention either on feature discrimination of simple stimuli (McDonald & Ward, 1999; Spence & Driver, 1994) or on high-level measures like speech comprehension in multi-talker scenarios (Kidd et al., 2005). Instead, we use a task with intermediate complexity, using more complex speech stimuli but a straightforward odd/even discrimination task. The paradigm used here helps bridge a gap between spatial cueing tasks on simple auditory stimuli and more complicated multi-talker speech comprehension. Results

showed that participants could use information about the target's likely location to aid search. They responded faster to targets presented at cued locations than those at uncued locations. The effect may be primarily goal-driven: cueing did not significantly speed RTs when the cue was uninformative of the target's location. Alternatively, the lack of an interaction of cue validity and phase may suggest that the effect was present in the unbiased phase but our design didn't have sufficient statistical power to detect the small effect. In either case, the results from the informative phase provide further evidence for the impact of covert, goal-driven spatial attention in auditory search.

Experiment 2

Having established an effect of spatial cueing in the current paradigm, Experiment 2 investigates the effect of inter-trial location repetition. While priming effects are well-known in visual search, only a few studies have investigated auditory location-based priming (e.g., Dyson, 2010), and none in a search task with both targets and distractors. To investigate this effect, we compared RTs for trials in which recent target locations repeated versus those in which they did not.

Method.

This experiment was similar to Experiment 1; shared aspects of the design are reported above in the General Methods. However, target location was randomized with the constraint that the target occurred equally often in each location in each block. There were no arrow cues, and participants were not given any instructions about target locations.

Results.

We first assessed the effect of location repetition from the immediately preceding trial. To this end, trials were separated into two categories: those in which target location was the same as targets on the immediately preceding trial and those in which location changed from the previous trial.

Overall accuracy in the task was 89% (SE = 1%). Accuracy was comparable for change trials and repeat trials (average accuracy advantage for repeat trials = 0.3%, SE of the difference = 0.9%), $t(15) = 0.32$, $p = .754$, $d = 0.08$. As before, we only considered reaction time for accurate trials. Following Kristjánsson (2006), we did not exclude trials based on the accuracy of preceding trials, only the current trial. On average, there were 75 repetition trials and 263 change trials per participant.

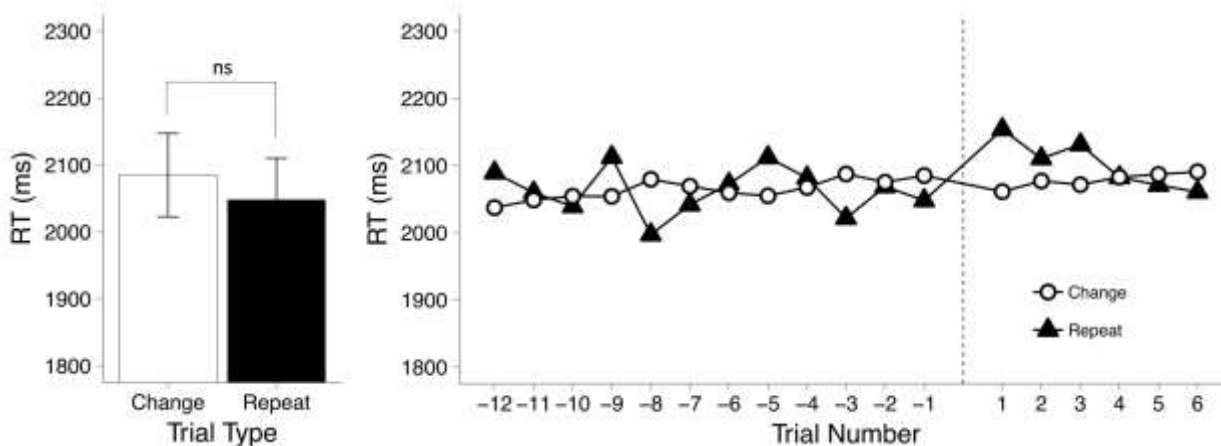


Figure 4.3. Results from Experiment 2 investigating effects of inter-trial repetition priming on reaction time for accurate trials. Left: A comparison of reaction time on trials in which target location repeated (i.e., was the same on trial n and trial $n-1$) and trials on which target location changed. Error bars show ± 1 SE of the difference. Right: Lines compare reaction time on trials in which target location repeated versus changed compared to another nearby trial. The x-axis represents the relative trial number being compared to the current trial, with negative numbers indicating past trials and positive numbers indicating future trials. Future trials should obviously have no effect on the reaction time on a current trial and are shown only to provide a rough index of measurement error to compare to any potential priming effects.

Location repetition from the previous trial did not significantly facilitate auditory search RT (average RT advantage for repeat trials = 37ms, SE of the difference = 62ms), $t(15) = 0.60$, $p = .56$, $d = 0.15$. Eight of the 16 participants had faster RT for repeat than change trials, whereas the other 8 did not. A bootstrapping procedure evaluated the reliability of within-subject repetition priming in those 8 who were faster on repeat trials - only 2 of them showed a reliable effect. A Bayes Factor using a standard prior was also

computed to determine evidence for the null hypothesis of no mean difference between repeat and change trials (Morey & Rouder, 2015). Values greater than one support the null hypothesis, while values less than one support the alternative hypothesis. The Bayes factor of 3.35 indicated moderate support for the null hypothesis.

Although inter-trial repetition priming is strongest from the immediately preceding trial, it has also been found in up to 8 previous trials (Maljkovic & Nakayama, 1996). To see if there was a consistent pattern of faster RTs when targets repeated location across nearby trials, we plotted RT on a given trial as a function of whether target location repeated compared to the 12 preceding trials (Figure 4.3, right). We also plotted RT for 6 future trials, which should obviously have no effect, but provide a rough index of measurement error. We found no evidence of inter-trial location priming, with high between-subject variability and no consistent pattern of faster RT for repeat than change trials.

Perhaps inter-trial priming effects only occur in our paradigm at less spatially precise scales, for instance when targets repeat on the same side of the participant. We analyzed whether RT was faster when targets repeated within hemifield, regardless of specific location; we found no evidence for a spatially diffuse repetition priming effect (mean RT advantage for hemifield repeat trials = 13ms; SE = 34ms), $t(15) = 0.38$, $p = .708$.

Discussion.

We found no evidence of inter-trial location priming in auditory search. The effect was inconsistent across participants. Bootstrapped confidence intervals for each participant showed that only 2 of the 16 participants displayed a priming effect from the

preceding trial. Furthermore, the Bayes Factor considering the relative likelihood of an absence versus a presence of repetition priming provided support for the lack of an effect. When looking at many preceding trials, there was also no evident pattern of faster responses when recent targets' locations repeated versus changed. These results are in stark contrast to inter-trial target location priming in visual search (Kristjánsson & Campana, 2010).

Experiment 2's finding also stands in contrast to a positive spatial cueing effect found in Experiment 1. Even though endogenously orienting to the target's location facilitates auditory search (Experiment 1), having recently found a target in one location does not facilitate auditory search of a target in the same location (Experiment 2). This contrast is consistent with the spatial relevance account of McDonald and Ward (1999), according to which spatial orienting occurs only when location is made task-relevant.

Experiment 2's results differ from Rhodes (1987), which showed a facilitation of auditory target localization when the current trial's target was in the same location as the previous trial's target. As noted earlier, Rhodes made the repeat trials disproportionately likely and encouraged participants to prioritize the previous target's location. Although Rhodes examined effects of location repetition, the effect was likely due to endogenous orienting to locations. Our study suggests that the sort of automatic target location priming commonly seen in visual tasks is less prevalent in auditory search.

It is also possible that the lack of exact repetition may have weakened repetition priming (Dyson, 2010; Huang et al., 2004). Owing to the use of many different alphanumeric stimuli, when a target repeated its location in Experiment 2 it was almost never the same number spoken in the same voice (i.e., pitch) as the preceding trial.

However, location inter-trial priming in visual search is a robust finding even when the target was a different shape or color (Maljkovic & Nakayama, 1996). Future studies should further examine whether auditory inter-trial location priming is more robust when a target repeats exactly.

Experiment 3

Using the same paradigm, in Experiment 3 we investigated a long-term selection history effect: location probability learning. In this experiment, the targets were made more likely to appear in one location during a portion of the task. Participants were not told about this manipulation. We examined whether the biased spatial distribution facilitated performance in the high-probability location, and if so, whether it persisted into an unbiased phase in which targets were equally likely to occur in each location.

The absence of short-term inter-trial priming in Experiment 2 need not suggest a lack of longer-term location probability effects. A key difference between long-term location probability and short-term repetition effects is that the former yields useful information about where the target may be. Consider Experiment 2's design where the target appears in random locations. A bias toward the preceding target's location would facilitate response when the target appears in that location again, but it may also slow down response when the target appears in other locations. Because the target's location is random, the preceding target's location is uninformative of where the target may be on the next trial. In contrast, when the target's location is made more probable in some locations than others, learning the target's location probability can validly predict where the target will be next. If the spatial relevance account extends from endogenous cueing

to implicit learning, then we may find location probability learning in the absence of repetition priming.

Method.

The experiment was separated into two phases: the first 12 blocks constituted the biased phase and the last four blocks constituted the unbiased phase. In the biased phase, either the front-left or the front-right location contained the target on 50% of trials, while each of the other three locations contained the target on 17% of trials. The high-probability “rich” location was counterbalanced across participants. In the unbiased phase, each location was equally likely to contain the target (25%).

The choice of the “rich” locations was constrained by pilot data, which showed worse performance for the two middle locations than the two lateral locations. This “eccentricity” effect means that when one location was used as the “rich” location, its performance could only be compared to one of the “sparse” locations - the one that matched the “rich” location in laterality. This is not a problem in Experiments 1 and 2 because all endogenous cueing and location repetition occurred equally often for each location, such that the proportion of trials in the more lateral and more central conditions was equivalent in all conditions. In Experiment 3, however, selecting only one rich location mandates comparisons solely to the laterality-matched location. We therefore restricted possible “rich” locations to the two middle locations. The slower RT for the harder locations has the advantage of allowing for greater performance differences if location probability learning were to occur.

Following the main experiment, a post-test probed awareness about the probability manipulation. The first question asked whether they believed that targets

occurred more often in some places than others. The second question informed participants that some locations did contain the target more often than others, and asked participants to choose the location from which they thought the target most often occurred. Participants were considered aware only if they answered both questions correctly, as in other studies (e.g., Addleman, Tao, Remington, & Jiang, 2018).

Data were collected in two versions that differed slightly in stimuli. Stimuli used in Experiment 3a were identical to those used in Experiments 1 and 2. In Experiment 3b, we reduced the set of potential targets to four numbers: 1, 2, 4, and 5. In addition, Experiment 3b audio clips all had the same fundamental frequency (see General Methods). These minor changes were made to reduce random noise associated with more diverse stimuli. Data from both versions are analyzed together, with experimental version included as a factor in the analyses.

Results.

Location probability learning. Similar to Experiment 1, the biased phase data were combined into four epochs (each epoch contained 3 blocks); the unbiased phase two epochs (each epoch contained 2 blocks). We compared RT on correct trials when the target was in the high-probability “rich” location and when it was in the laterality-matched “sparse” location. We also compared accuracy between the two locations (mean accuracy difference = 1.2%, SE of the difference = 0.8%); the pattern of results was comparable to those reported below for RT, but not significant in either phase ($p_s > .05$).

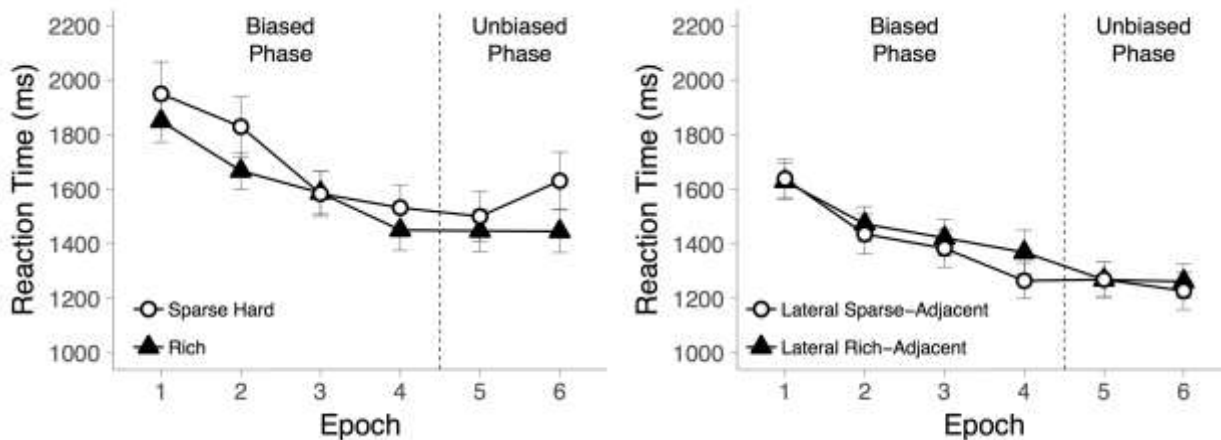


Figure 4.4. Results from Experiment 3 comparing reaction time as a function of epoch and condition. Left: Reaction time on trials in the high-probability location (“rich”) and its laterality-matched low-probability (“sparse”) location. Right: Reaction time on trials in the more lateral location in the same hemifield as the rich location (“lateral rich-adjacent”) and the opposite hemifield as the rich location (“lateral sparse-adjacent”). Error bars show +/- 1 standard error of the mean.

First, to examine the acquisition of location probability learning in the biased phase, we entered training epoch (1-4), target’s location (rich or sparse), and experimental version (3a and 3b) in an ANOVA (Figure 4.4, left). Results showed that participants found the target more quickly when it appeared in the rich rather than the sparse location (mean RT difference = 87ms; SE = 35ms), $F(1, 31) = 5.76, p = .02, \eta_p^2 = .15$ for the main effect of target location. The main effect of epoch during the training phase showed that performance improved as training progressed, $F(3, 93) = 16.02, p < .001, \eta_p^2 = .34$. Condition did not interact with the target’s location, $F < 1$. There was a marginal effect of experimental version (participants were faster in version 3b, which had 4 rather than 10 target identities; training mean RT for version 3a = 1814ms, SE = 99ms;

version 3b mean = 1550ms, SE = 92ms), $F(1, 30) = 3.83, p = .06, \eta_p^2 = .11$. Experimental version did not interact with either target location or epoch, $F_s < 1$, meaning that the magnitude of LPL and the practice effect over time were not significantly different across the two versions.

Next, we tested the persistence of the learned spatial bias in the unbiased phase, when the target's location was equiprobable. Here, too, we found a significant main effect of target location (mean RT advantage for the rich location = 122ms, SE = 56ms), $F(1, 31) = 4.48, p = .04, \eta_p^2 = .13$, an effect that did not significantly interact with epoch, $F(1, 31) = 2.096, p = .16$. RT was faster when the target appeared in the previously rich location than the previously sparse location. In testing, participants were significantly faster in version 3a than version 3b, (testing mean RT for version 3a = 1670ms, SE = 105ms; version 3b mean = 1344ms, SE = 99ms), $F(1, 30) = 5.08, p = .03, \eta_p^2 = .14$. Again, version did not interact with either target location or epoch, $F_s < 1$. An ANOVA of condition and phase showed no significant interaction between the two, $F < 1$, meaning that location probability learning did not significantly decline across phases.

The above analysis only considered the two middle locations—the “rich” location and its laterality-matched “sparse” location. To determine whether location probability learning was spatially diffuse, we also compared RT for the two more lateral sparse locations: the lateral location adjacent to (in the same hemifield as) the “rich” location, and the lateral location on the other side (Figure 4.4, right). The target appeared in those locations with low frequency (17% of trials in each location during the biased phase and 25% of trials in each location during the unbiased phase). These conditions did not differ

in either RT or accuracy in either the biased phase or the unbiased phase, $F_s < 1$, effects that did not interact with experimental version (all $p_s > .10$).

Inter-trial location repetition priming. Experiment 3 provided an additional opportunity to investigate inter-trial location repetition priming. To de-confound location probability manipulation from location repetition, we focused on trials in which the target appeared in the rich location. The high proportion of trials in this location allowed for a relatively large number of trials per condition. Repeat trials were defined in the same way as in Experiment 2; the only difference is that we now consider only data in which the current trial presented a target at the rich location.

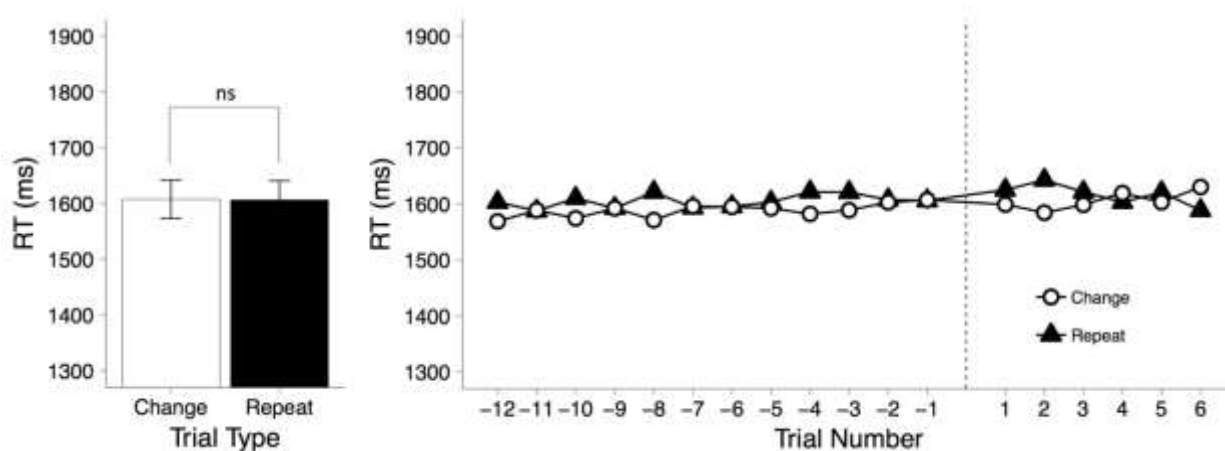


Figure 4.5. Results from Experiment 3 investigating effects of inter-trial repetition priming on reaction time for accurate trials. To avoid confounding inter-trial priming and location probability learning, only trials in which the current target was located in the rich location are included. Left: A comparison of reaction time on trials in which target location repeated (i.e., was the same on trial n and trial $n-1$) and trials on which target location changed. Error bars show ± 1 SE of the difference. Right: Lines compare reaction time on trials in which target location repeated versus changed compared to another nearby trial. The x-axis represents the relative trial number being compared to the current trial, with negative numbers indicating past trials and positive numbers indicating future trials. Future trials should obviously have no effect on the reaction time on a current trial and are shown only to provide a rough index of measurement error to compare to any potential priming effects.

Figure 4.5 (left) shows mean RT on repeat and change trials relative to the previous trial. Participants were not faster on repeat trials than change trials at the rich location (mean RT advantage for repeat trials = 1ms; SE = 34ms), $t(31) = 0.04$, $p = .97$, d

= 0.006. The Bayes Factor in favor of a lack of priming was 5.29, indicating moderate support for the null hypothesis.

Figure 4.5 (right) plots RT on a given trial as a function of whether target location repeated relative to the 12 preceding trials. As in Experiment 2, there is no evidence of inter-trial location priming in Experiment 3.

Explicit recognition. Of the 32 participants, only 6 answered both recognition questions correctly. To examine the association between explicit awareness and learning, we conducted an ANOVA comparing the effect of condition (rich vs laterality-matched sparse location) and awareness. This analysis showed no significant interaction $F(1, 30) = 2.097, p = .158$, meaning that learning was not significantly larger for participants who answered correctly to the self-report questions than those who didn't. Consistent with findings from visual search (Jiang, Sha, & Sisk, 2018), location probability learning in auditory search is largely implicit.

Discussion.

These results are the first to our knowledge to show an auditory search advantage based on location probability learning. Making a target more likely to occur in one location relative to other locations improved performance in that location. This effect persisted into an unbiased phase that contained the target equally often in each location. The effect appeared to be spatially specific and did not spread to nearby locations.

As in the visual modality, most of our participants could not identify the high-probability quadrant. It is possible that the post-experiment survey does not always accurately assess whether participants consciously attended to the high-probability quadrant during search. Asking the question after participants completed several blocks

with equiprobable target location probability could decrease the ability to report overall target location probability accurately. However, as is the case in visual search (Jiang et al., 2018), aware and unaware participants showed comparable effects of LPL. Truly endogenous guidance typically yields larger RT effects than implicit LPL (Jiang, Swallow, & Rosenbaum, 2013), suggesting that our effects are due to implicit learning.

Long-term probability learning observed in Experiment 3 could not be explained by short-term repetition priming. No effect of inter-trial location repetition was found. In addition, the long-term probability advantage persisted into the unbiased phase, during which repetitions were equally frequent in all locations. The pattern of data was consistent with past research using visual search (Jiang, Swallow, Rosenbaum, et al., 2013). The lack of inter-trial priming in these data, however, was unique to the auditory search task. These data also suggest that inter-trial priming is not a building block toward long-term location probability learning. Short-term and long-term effects of selection history likely reflect different mechanisms.

Could the lack of inter-trial priming in Experiments 2 and 3 be due to high localization difficulty in our paradigm? Localization practice data (reported in Appendix B) show only about 70% localization accuracy, much lower than in visual studies of priming or auditory studies without distractors. We believe that this does not explain our null results. If the lack of priming were due to poor representation of target location, we would expect no effect of any implicit attentional learning. On the contrary, we do find evidence for longer-term selection history effects in Experiment 3, suggesting that our results are not primarily contingent on localization difficulty. Even so, future research could investigate the role of localization difficulty on implicit attentional guidance.

General Discussion

This study designed a novel auditory search task that bridges a gap between spatial cuing using simple auditory stimuli and multi-talker speech comprehension. Results showed the presence of endogenous spatial cueing, the absence of short-term inter-trial location priming, and the presence of a long-term attentional bias to a frequently attended location. These results contribute to two separate literatures: attentional learning and auditory spatial attention.

The contrast between the absence of inter-trial priming and the presence of location probability learning informs a debate regarding the mechanisms underlying long-term attentional learning. Using visual search, one study has argued that mechanisms which acquire location probability learning rely on short-term inter-trial location priming (Walthev & Gilchrist, 2006). This claim was not consistently supported (Druker & Anderson, 2010; Jones & Kaschak, 2012). In fact, designs that prevent inter-trial repetitions while introducing high-probability locations necessitate new inter-trial regularities—specifically, target location on trial $n-1$ significantly predicts location switch on subsequent trials (Druker & Anderson, 2010). However, it has been difficult to evaluate whether short-term repetition priming may bootstrap long-term learning. Our auditory task is the first that fails to exhibit inter-trial priming while showing location probability learning. These results are incompatible with theories suggesting that long-term learning relies on the accumulation of short-term repetitions of spatial orienting. Furthermore, a recent study has also shown the opposite dissociation—the presence of short-term priming but no long-term learning (Sha, Remington, & Jiang, 2017). Together,

these studies suggest that short-term repetition priming and long-term statistical learning are dissociable mechanisms.

Visual location probability learning has been shown to operate at an early level of attentional selection, increasing search efficiency as measured by the set-size/RT slope and increasing the probability of first fixations to a high-probability quadrant (Jiang, Swallow, & Rosenbaum, 2013). Auditory LPL in the current paradigm also influenced RT. Interestingly, we did not observe a significant enhancement of accuracy, even though accuracy was not at ceiling. One reason for the lack of an effect on accuracy is that, as a binary value, accuracy may be a less sensitive dependent measure than RT. In addition, the ~90% accuracy achieved in Experiment 3 may be as high as participants could achieve even with attention. In fact, accuracy in Experiment 1 was only 86% and did not differ based on cue validity, even though participants could endogenously prioritize the target location. This suggests that aspects of the task (e.g., noise) constituted a “data limit” on performance (Norman & Bobrow, 1975). Thus, the lack of improved accuracy from LPL does not preclude the possibility that, like in visual LPL, auditory LPL operates at an early level of attentional selection.

Implications for theories of spatial attention and selection history.

Results from our study are consistent with either of two primary views of attentional selection history. One view considers selection history to be implemented in attentional priority maps shared across different forms of attentional guidance (Awh et al., 2012). By way of a weight assigned to each location, the map prescribes which locations should be prioritized in processing (Bisley & Goldberg, 2010). It is frequently depicted as a static Cartesian map, with hotspots highlighting high-priority locations.

Recently, research has shown that attentional priority is influenced by selection history (Awh et al., 2012; Ferrante et al., 2018; Todd & Manaligod, 2018). Via reinforcement learning, locations recently containing a target, or locations frequently containing a target over time, are given greater weight. Although much evidence for the priority map theory comes from visual search, the map need not be modality-specific. Indeed, cueing studies have found evidence that both endogenous and exogenous attentional guidance often have crossmodal effects (Spence & Driver, 1996, 1997). Therefore, the presence of auditory LPL is consistent with a view of implicit attention as acting through a priority map.

Our results are also consistent with another view of spatial attention, more complementary than contradictory to the priority map view, that conceptually divides attention into two components: the map-like component described above, which identifies salient locations for perception; and a procedural, action-based component encoding motion vectors for executing eye, head or limb movements (Jiang, 2018). Much like these movements, covert shifts of spatial attention are associated with a movement vector. Repeating a target's location, over either short or long time scales, induces repetition not only of a target's location but also of the way attention must shift to find it. This view has roots in Allport's and Rizzolatti's earlier work on attention for action (Allport, 1987; Rizzolatti et al., 1987). By linking attention to the underlying effector, the procedural view of attention might suggest that, in opposition to the presence of LPL in our Experiment 3, selection history would have different effects on visual and auditory attention. This is particularly true because auditory orienting lacks a directly analogous mechanism to overt eye movements in visual attention.

However, while the procedural view could accommodate differences in how selection history might influence attention across modalities due to cross-modal differences in overt orienting, it does not necessitate such differences. There are many neural similarities between visual and auditory spatial attention. For instance, an event-related potential (ERP) index of auditory spatial attention, the N2ac, may be an analogue to the well-known visuospatial N2pc component (Gamble & Luck, 2011; Gamble & Woldorff, 2014, 2015). Many imaging studies have also identified shared regions of spatial attentional control across visual and auditory modalities (e.g., Hill & Miller, 2009; Maeder et al., 2001), suggesting that auditory and visual spatial attentional control share overlapping supramodal mechanisms. Furthermore, oculomotor regions, such as the superior colliculus and portions of lateral frontal cortex, are active in auditory attention tasks (Michalka et al., 2015; Noyce et al., 2017; Winkowski & Knudsen, 2008), and some argue that a central role of auditory spatial processing is to subservise orienting behaviors (Arnott & Alain, 2011; Bédard et al., 1993). Despite the hypothesis that selection history effects reflect, in part, procedural learning, auditory selection history effects may occur through oculomotor mechanisms shared across modalities. The presence of attentional regions involved in both auditory and visual orienting behaviors suggests that a procedural account of attentional learning can adequately explain the presence of auditory LPL. Thus, our data do not favor one view over the other.

Implications for theories of auditory spatial attention.

Regardless of which specific mechanisms might support selection history in the auditory and visual modalities, the difference in spatial orienting between visual and auditory modalities is reflected in the present experiments. In the visual modality,

endogenous guidance, inter-trial location priming, and location probability learning all yield highly consistent facilitation of attended locations (Jiang, 2018; Kristjánsson & Campana, 2010; Spence, 2014). However, in the current study, these same methods of guiding auditory spatial attention yielded weaker and less consistent evidence of spatial orienting. We saw little effect of uninformative endogenous cues for auditory target location; such effects can, however, be found in the visual modality (Eimer, 1997; Won & Jiang, 2015). We also saw no evidence of inter-trial location priming. Further, the auditory location probability effect that we did find was numerically smaller (in terms of % RT reduction to a high-probability versus low-probability region) than many visual studies (Jiang, Swallow, Rosenbaum, et al., 2013). This may reflect differences in how attentional orienting occurs in the two modalities. For instance, shifts of visual attention to an item almost invariably require spatial selection of the item's location. However, it is possible that participants in our experiments did not localize targets on every trial, and even when they did, auditory target selection may not always necessitate spatial orienting. This could contribute to the relative weakness of attentional effects in our auditory paradigm versus previous visual ones.

Our results can be interpreted in relation to previous theories of auditory attention. They are consistent with the spatial relevance hypothesis, which argues that auditory spatial orienting occurs only when location is task-relevant (McDonald & Ward, 1999). In Experiment 1, spatial location is made task relevant through the introduction of an informative cue to spatial location. As McDonald and Ward have argued, informative endogenous spatial cues make location task-relevant even in tasks requiring non-spatial judgments. Furthermore, when endogenous cues became uninformative in the second

phase in Experiment 1, they did not significantly benefit performance. In Experiment 2, the target's location was completely random. The target's location on one trial yielded no information regarding where the target might appear on subsequent trials. The lack of a repetition priming effect may be attributed to the irrelevance of spatial location to the odd/even task. In Experiment 3, spatial location becomes relevant through location probability learning. This cue, though acquired implicitly, provided predictive information about where the target might be, rendering spatial location relevant. This sort of implicit relevance is broadly consistent with the claim that attentional control settings can be modified without conscious intent, as has been demonstrated in the contingent capture paradigm (e.g., Folk & Remington, 2008; Folk, Remington, & Johnston, 1992). Thus, as a whole, the experiments are consistent with the spatial relevance hypothesis.

However, because the hypothesized mechanism of LPL is reinforcement learning of attentional shifts, the spatial relevance hypothesis does not readily explain *how* location becomes relevant in Experiment 3. If LPL involves learning from patterns of past attentional behavior, acquisition of location probability learning necessitates that participants attend to target location prior to LPL's emergence. But the spatial relevance hypothesis explicitly argues that spatial orienting only occurs when location is task-relevant; otherwise, orienting occurs within non-spatial auditory feature maps (McDonald & Ward, 1999). Because spatial relevance could not be established in the current paradigm until the target's location probability is learned, this raises a cause-and-effect problem: did spatial relevance come before spatial orienting, or did spatial orienting come before establishing that location was relevant? This suggests either that the spatial relevance hypothesis is incomplete, or auditory LPL relies on mechanisms that don't

involve orienting until later in the task, after the target's location asymmetry is established. The successful acquisition of location probability learning could mean that spatial orienting is more obligatory than suggested by the spatial relevance hypothesis. Alternatively, perhaps auditory LPL can emerge via statistical learning of target location probabilities, even if this information is not used for spatial orienting until its relevance is established. More studies are needed to untangle the role of spatial relevance in auditory spatial orienting.

Conclusion

The present study develops a novel paradigm for studying spatial attention and auditory search, bridging a gap between spatial orienting to simple tones and more complex multi-talker speech segmentation. It is the first to report evidence for an implicit spatial attentional bias in auditory search. We show that endogenous guidance and spatial probability learning can each facilitate performance in a search task among spoken alphanumeric characters. Unlike visual search, the auditory search paradigm is insensitive to inter-trial location repetition priming. These results have implications for the relationship between short-term and long-term selection history effects; they also inform theories of auditory spatial attention. They have practical implications for how humans learn to understand speech and other complex sounds in noisy environments. This understanding can benefit people with sensory loss, as learned spatial attention could improve speech comprehension in people with hearing loss or spatial navigation in people with vision loss. It can also inform job training for people who must frequently cope with noisy environments, such as emergency personnel in disaster situations or workers needing to listen in loud industrial settings.

5. Grand Summary and General Discussion

5.1 Grand Summary

Study 1 showed that goal-driven spatial attention spread from a search task to affect memory for spatially coincident but search-irrelevant scenes, while implicit learned attention affected search but not scene memory. In Experiment 1, participants were given a cue that correctly predicted the target's quadrant in 50% of trials; the cue indicated the same location within each block of trials but varied from block to block. Results showed strong attentional facilitation to the cued quadrant in accuracy as well as higher memory for scenes presented in the cued than in uncued quadrants. Experiment 2 conceptually replicated Experiment 1 using a central arrow cue that again predicted target quadrant with 50% accuracy, but which varied in direction from a trial to trial basis. This reduced the magnitude of the search advantage for the cued quadrant to a level more comparable to that found in typical probability learning studies. Memory was again higher for scenes in the cued quadrant. Experiment 3 induced incidental location probability learning by placing targets more often in one quadrant than in other quadrants without informing participants of the target location probability asymmetry. While this led to accuracy advantages for the high-probability quadrant that were comparable in magnitude to those for the cued quadrant in Experiment 2, these participants showed no difference in memory performance across quadrants. These results suggest that location probability learning does not simply induce attentional shifts that are comparable to goal-driven shifts of attention; instead, goal-driven and experience-driven attention are implemented via different mechanisms.

Study 2 demonstrated that implicit location probability learning does not lead to shifts of attention in anticipation of a task (i.e., baseline shifts), instead resulting only in post-stimulus shifts of attention. Experiment 1 induced location probability learning during a T-among-L search task that was unpredictably interspersed with a scene category search task with unbiased target location probability. Participants learned to prioritize the target-rich quadrant during letter search but not during scene search. Experiment 2 reversed the roles of the two tasks, with probability learning induced in the scene task. Results mirrored those in Experiment 1, with some evidence of probability learning in the scene task but no transfer of this learning to the letter task. These results are inconsistent with baseline shifts of attention due to location probability learning; such shifts would be executed before participants could identify the upcoming task, therefore influencing both tasks.

Study 3 developed a multi-talker auditory target discrimination task for assessing the effectiveness of experience-driven auditory spatial attention. Experiment 1 demonstrated the effectiveness of the paradigm by showing that goal-driven attention induced by spatial cueing affected response times. Experiment 2 found a lack of inter-trial location repetition priming in this task, in contrast to past studies of both visual and auditory inter-trial priming. Experiment 3 made targets more likely to occur in one location and found evidence for auditory location probability learning. These results show that auditory spatial attention is sensitive to long-term probabilities of target location while being less sensitive to short-term inter-trial priming in the same paradigm. This further suggests that inter-trial priming is not a necessary precursor to location probability learning.

5.2 Implications

5.2.1 Location probability learning reflects attentional habits

Studies 1 and 2 showed differentiable effects of goals and experience on the implementation of spatial shifts of attention. These findings, when taken together with other recent studies (e.g., Jiang, Swallow, & Rosenbaum, 2013; Twedell et al., 2017; Won & Jiang, 2015), provide evidence for a habitual system of attention that cannot be explained within standard integrated priority map theories of spatial attention (see also Jiang, 2018). While goals and salience appear to operate through attentional priority maps, experience may operate both on priority maps and, at times, through forming search habits that affect how attention is shifted, rather than operating via an explicitly represented spatial map. This implies that priority map theories of experience-driven attention are incomplete. Many forms of experience-driven attention, including short-term inter-trial priming (Maljkovic & Nakayama, 1996), reward-based attention (Anderson, 2013), attention to stimuli semantically associated with one's attentional set (Malcolm, Rattinger, & Shomstein, 2016), and affectively conditioned attention (Todd et al., 2015), may operate via priority maps and not attentional habit. However, converging evidence from the location probability learning paradigm suggests that long-term search biases do operate via attentional habits, and these habits are not explainable via an integrated priority map. To accommodate these findings, attentional habit should be considered a subset of experience-driven attention that, although in many ways similar in its source to other forms of experience-driven attention, likely relies on significantly different mechanisms in its implementation

In this view, attention is a dual system, consisting of both a component explicitly representing spatial locations within priority maps and a habitual component encoding how attention is shifted. This habitual component may be encoded as search vectors of covert or overt attentional shifts (Jiang, 2018). This can explain why the transfer of attentional habits across tasks largely depends on the similarity of the required patterns of attentional shifts rather than the similarity of visual stimuli (e.g., in Study 2 and in Jiang, Swallow, et al., 2015).

5.2.2 Implicit and goal-driven attention have different temporal dynamics

Studies 1 and 2 also inform the timescale of attentional biases acquired via location probability learning. One explanation of the results of Study 1 is that experience may shift attention after stimulus onset, while goal-driven attention results in baseline shifts of attention prior to stimulus onset. This possibility was confirmed in Study 2, and other research has demonstrated that search for items interspersed among search-irrelevant visual “clutter” typically involves a pre-attentive segmentation process followed by search occurring primarily through a segmented mental representation of the search array (Wolfe et al., 2002). Taken together, this suggests that the lack of transfer of learned attention to the memory task during location probability learning may depend on the post-stimulus onset of learned attentional shifts. If these occur on an already segmented search array, they should affect memory for scenes only to the extent that the segmentation process failed to properly separate search items from the background, or the extent to which cognitive control failed. In contrast, baseline shifts of goal-driven attention initially affect both memory scenes and the search array until segmentation occurs, yielding higher memory for scenes in the high-probability quadrant.

This timescale account of Study 1 is consistent with the argument in [Section 5.2.1](#) that location probability learning results in attentional habits. At the same time, the timescale account may fully explain any differences in memory performance in probability learning and goal-driven attention. According to this explanation, the timescale of attentional shifts differs between location probability learning and goal-driven attention, and this combines with the timescale of the segmentation process to yield different memory performance depending on the source of attentional biases. Critically, if this explanation is true, attentional habits are not necessary to explain the task-specificity of location probability learning, as the initiation of attentional shifts only after stimulus onset would be expected regardless of whether location probability learning operates via attentional habits or via the standard attentional priority map.

Does this mean that, taken together, Studies 1 and 2 fail to provide evidence that location probability learning induces search habits? Perhaps not. Although Study 2 demonstrates a lack of baseline attentional shifts resulting from location probability learning, using this to fully explain the task-specificity of probability learning in Study 1 rests on many untested assumptions regarding the presence of successful segmentation of the search array from the background scenes. Segmentation may not occur in Study 1 in the same way it has been shown to occur in other studies. This is plausible given that the effects of segmentation may depend largely on the paradigm-specific factors. The similarity between relevant and irrelevant stimuli, the amount of time available for segmentation, and the specific stimuli within each task may all affect the success of the segmentation process.

This casts some doubt on how to interpret the implications of Study 1 on the existence of a habitual attention system. Furthermore, while the timescale account discussed above can fully explain the lack of a memory advantage during location probability learning, it is not evidence against probability learning involving attentional habits. It is possible that location probability may be implemented as an attentional habit rather than via attentional priority maps while at the same time operating at different timescales in a way that interacts with the segmentation process. Ultimately, when considered together with other studies demonstrating tensions between priority map theories and the effects of location probability learning (for a review, see Jiang, 2018), it remains likely that location probability learning does indeed involve habitual attention.

5.2.3 Visual and auditory spatial selection history affect attention differently

This dissertation provides some insight into how experience-driven attention might differ across the visual and auditory modalities.⁵ Based on a great deal of past work, we know that goal-driven and salience-driven attention are linked across the visual and auditory modalities, such that shifts in one modality affect processing in the other (Feng, Störmer, Martinez, McDonald, & Hillyard, 2017; Gray, Mohebbi, & Tan, 2009; Hillyard, Simpson, Woods, Van Voorhis, & Münte, 1984; Matusz & Eimer, 2011, 2013; Mehta, 2000; Mehta, Ulbert, & Schroeder, 2000; Shinn-Cunningham, 2008; Spence & Driver, 1996; Störmer, McDonald, & Hillyard, 2009; Störmer, 2019; Störmer, McDonald, & Hillyard, 2019). Even so, attention affects visual and auditory perception

⁵ This section was published in *Trends in Cognitive Sciences* (2019). Full citation: **Addleman, D. A., & Jiang, Y. V.** (2019). Experience-driven auditory attention. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2019.08.002>. Part of the article is reproduced here in slightly revised form.

differently. Visual attention can be directed more precisely to locations, whereas auditory attention can be directed more precisely to points in time (Rimmele et al., 2011; Spence, 2010; Woods, Diaz, Alain, Ogawa, & Rhodes, 2001). This pattern may result from differences in neural coding of perceptual features rather than from differences in mechanisms of visual and auditory attention themselves.

Differences between visual and auditory experience-driven attention parallel those of goal-driven and salience-driven attention. For example, the auditory location probability learning effect demonstrated in Study 3 was smaller than analogous effects shown in visual tasks (Addleman & Jiang, 2019). Other research shows that visual inter-trial location priming typically occurs even when non-spatial features (e.g., shape) change (Maljkovic & Nakayama, 1996), whereas visual non-spatial feature repetition often facilitates performance only when whole objects repeat (Ásgeirsson & Kristjánsson, 2011; Huang et al., 2004; Kristjánsson et al., 2008). Auditory location priming is less robust, often failing to occur when non-spatial features change across trials as it did in Study 3 of this dissertation (see also Dyson, 2010).

EEG research has further demonstrated modality differences in experience-driven spatial and temporal orienting. In two studies, one using visual stimuli (Doherty, Rao, Mesulam, & Nobre, 2005), the other auditory (Rimmele et al., 2011), participants completed a go/no-go task based on a feature of the final stimulus in a sequence of rapidly presented stimuli. Sequences preceding targets could appear in predictable or unpredictable locations and at predictable or unpredictable times. In the visual task, the P1 component was enhanced by spatial but not temporal predictability, whereas in the auditory task, early P1 and N1 components and the later N2 component were enhanced

by temporal but not spatial predictability. These differences suggest that spatial orienting plays a restricted role in auditory attention, whereas temporal orienting may be more central to auditory attention than visual attention.

These differences may arise from perceptual coding constraints or from modality-specific attentional mechanisms. Crossmodal linkages in goal-driven and salience-driven attention point to the former. However, another form of statistical learning, artificial grammar learning (Reber, 1967), has modality-specific effects and does not transfer across modalities (Conway & Christiansen, 2005, 2006; Li, Zhao, Shi, Lu, & Conway, 2018). Recent models attribute these findings to modality-general computational principles implemented separately in different networks operating in sensory areas of cortex (Frost, Armstrong, Siegelman, & Christiansen, 2015). Sensory-specific mechanisms with similarities across modalities may also support at least some forms of experience-driven attention. This view would predict that experience-driven attention, despite occurring in multiple modalities, should not result in the crossmodal effects of goal-driven and salience-driven attention.

5.3 Future Research

5.3.1 What mechanisms support attentional habits?

Studies 1 and 2 provide some evidence for the existence of attentional habits that do not operate via attentional priority maps. However, the strength of this evidence is not entirely clear (see [Section 5.2.2](#)), the nature of the cognitive mechanisms underlying attentional habits is only partially understood, and the neural substrates of those mechanisms are almost completely unknown. The most direct evidence may need to come from electrophysiology or neuroimaging work, which could be used to identify

what neural signatures are shared across habitual and non-habitual attention. For instance, the frontoparietal networks classically associated with both top-down and bottom-up attention may have a different or restricted role in habitual-driven attention. This would be consistent with evidence from other statistical learning paradigms showing that such learning involves structures lower in the cortical hierarchy than the frontoparietal network encoding priority maps (Frost et al., 2015).

Similarly, the presence of a classic signature of spatial attention, the N2pc event-related potential component, has never been reported in a location probability learning paradigm. An N2pc resulting from location probability learning would likely follow a different timescale than one resulting from endogenous shifts, reflecting a lack of a pre-stimulus baseline shift of attention. Furthermore, it is possible (though speculative) that the N2pc reflects only those types of attention resulting from the representational component of attention that relies on priority maps. In this case, probability learning may result in a low-magnitude or absent N2pc, which would be strong evidence for the dual-system view of attention involving both a representational, declarative component and a habitual, procedural component. This could be tested using a briefly presented visual search task where targets appear more often in one visual hemifield. If location probability learning affects the N2pc like goal-driven and salience-driven attention do, there should be a larger posterior negativity contralateral to the high-probability quadrant than ipsilateral to it at about 200ms following stimulus onset. The absence of an N2pc in the probability learning task would be a striking contrast to the effects of other attentional manipulations that speed reaction times to attended locations.

Another valuable area for future study would involve more thoroughly describing the attentional facilitation which results from location probability learning. While a great deal of work has established the presence of location probability learning in several different tasks (Addleman & Jiang, 2019; Addleman et al., 2019; Jiang, Swallow, Rosenbaum, et al., 2013), the preservation of such learning in various demographic groups (Jiang, Capistrano, Esler, & Swallow, 2013; Twedell et al., 2016), and the limits of transfer of learning across tasks (Jiang, Swallow, et al., 2015; Salovich et al., 2017), virtually no work has attempted to carefully measure the spatial extent of attentional biases due to location probability learning. Most paradigms train participants to prioritize a screen quadrant, with targets appearing more likely in that quadrant, but at random locations within that quadrant. This makes it difficult to assess the precise scope of spatial facilitation resulting from probability learning. If someone is trained to attend to one specific location, to what extent does habitual attention facilitate nearby locations? Investigating these questions could be used to understand the level of precision that habitual attention can achieve in directing attentional shifts and how this compares to top-down and bottom-up attention.

5.3.2 Does uncertainty prevent baseline shifts of attention?

Study 2 in this dissertation demonstrated that implicitly learned spatial attention does not transfer across tasks if the tasks are unpredictably intermixed. In two experiments, location probability learning influenced both a letter search task and a scene category search task when targets within a task were more likely to appear in one region. Learning did not influence the other task, in which targets were equally likely to occur in all locations. This shows that participants were shifting attention only in advance of

stimulus onset, as baseline shifts of attention before stimulus onset should have affected both tasks. This contrasts with many investigations of goal-driven attention showing that baseline levels of neural activity at attended regions is elevated. One reason for this distinction, defended above, is that attentional habits (but not top-down goals) affect search behaviors rather than abstract spatial priority, and these behaviors begin only once stimuli appear. However, another critical difference between Study 2 and other investigations of baseline shifts is that Study 2 unpredictably intermixed two search tasks rather than measuring the time course of attention in a single task. Could this difference, rather than the implicit nature of the attentional bias, have prevented baseline shifts of attention?

If uncertainty regarding where attention should be allocated determines whether baseline shifts occur, goal-driven attention should not yield baseline shifts of attention when people are instructed to attend to different locations in two unpredictably intermixed tasks.⁶ To test this, participants could complete an experiment similar to the ones in Study 2, except they are informed by experimenters that targets in, say, the letter task are more likely to appear in one region than other regions. If baseline shifts still occur in this paradigm, it would strengthen the argument that location probability learning fails to result in baseline shifts of attention. Alternative, if uncertainty regarding the upcoming task prevented baseline shifts in Study 2, baseline shifts should also fail to occur when participants know to attend to a location in one task but not whether they will complete that task on the next trial. This view could be strengthened by additional

⁶ Thanks to Viola Störmer for helpful discussions that led to this design.

experiments providing explicit instructions about the upcoming task as well as where to attend for that task. If the pattern of baseline shifts from goal-driven attention depended on whether participants knew what task they would complete on an upcoming trial, this would be strong evidence that task uncertainty prevents attention-related increases in baseline levels of neural activity.

5.3.3 What factors affect auditory spatial selection history effects?

Study 3 reported the absence of auditory inter-trial location priming. This is unlike visual studies, which show inter-trial location priming across a wide range of paradigms. This difference may reflect the fact that location plays a different role in vision and audition. In visual studies, inter-trial priming for non-spatial features like color often depends on repeating not just a target's color but also other aspects of a target (e.g., also its shape). This has been attributed to an episodic memory account of inter-trial priming, in which priming reflects activation of memory traces for specific trials, therefore only speeding search if targets repeat completely (Huang et al., 2004). Episodic memory does seem to underlie some visual priming effects, but activation of specific features independent of memory traces is found in some paradigms, especially for location priming (Ásgeirsson & Kristjánsson, 2011). This may reflect the important role of spatial processing in vision, such that location repetition recruits additional mechanisms that operate independently of the repetition of other features.

Because location is relatively less important in auditory processing, auditory inter-trial location priming may occur only via episodic memory traces. Study 3 involved trial-to-trial changes to semantic identity and pitch as well as location, making repetition of complete auditory objects rare. These nonspatial changes may have prevented inter-

trial location priming. This is consistent with a single-stimulus paradigm in which, when participants responded to targets varying in both location and pitch, location priming depended on repeating both features (Dyson, 2010). While other work suggests that mechanisms of priming differ when attention must select between multiple stimuli rather than respond to a single stimulus (Geng et al., 2006), an auditory search paradigm might show inter-trial location priming when both location and nonspatial features repeated together.

This suggests that a follow-up to Study 3 that reduces the variability of non-spatial features could identify inter-trial location priming when other features also repeated. I plan to test this in a multi-stimulus auditory paradigm using natural sounds rather than spoken letters and numbers. Participants will search for a sound from a target category (e.g., musical instrument) presented among three distractors taken from three other categories (e.g., animal noises). Similar stimuli were used in another auditory search paradigm to investigate the role of spatial separation on response times (Eramudugolla et al., 2008). Each trial will present participants with four stimuli, each from a different category and in a different spatial location, and across trials each category will contain only two exemplars (e.g., piano and saxophone). This design reduces the variability of stimuli across trials (there were 10 possible target numbers in Study 3, each with 4 possible pitches) while maintaining enough variability to prevent overlearning of features which distinguish specific targets from distractors. If repetition of both target identity and location leads to inter-trial priming, responses should be faster when both repeat than when both change. Additionally, many studies actually show slower responses when exactly one feature repeats (e.g., piano repeats but in a different

location) than when both change, perhaps because of uncertainty arising from partial conflict with recent memory traces (Ásgeirsson & Kristjánsson, 2011; Dyson, 2010; Huang et al., 2004). This pattern would provide evidence for a role of location repetition in auditory paradigms that is analogous to the role of non-spatial features in visual tasks.

5.3.4 How does experience-driven spatial attention operate across modalities?

This dissertation and other recent studies prompt questions about how experience-driven attention operates across modalities (Dyson, 2010; Rimmele et al., 2011). For example, do visuospatial attentional habits affect auditory as well as visual processing? If experience-driven attention partially relies on mechanisms shared between modalities, then experience in one modality may affect attentional biases across modalities.

Alternatively, experience-driven attention may rely on separate, modality-specific mechanisms, such that experience in one modality would have no effects on other modalities—even if comparable effects are found within each modality.

So far there is little empirical research on crossmodal experience-driven attention (though see Anderson, 2016; Kawahara, 2007). Because spatial information is processed differently in the visual and auditory modalities, it is possible that a change in search procedure involving one modality would not transfer to another. Testing crossmodal transfer of experience-driven attention could dissociate effects of experience on the spatial priority map from that on search procedure. Whereas spatial priority maps may partially overlap across modalities (or be separate but linked, Spence, 2010, 2014), the habitual component of attention may operate via relatively early, sensory-biased areas of the brain (Addleman & Jiang, 2019; Jiang, 2018; Jiang & Sisk, 2019). Studies

investigating crossmodal inter-trial priming and probability learning would provide fruitful answers to these questions.

Crossmodal selection history effects could be tested by intermixing trials of auditory and visual search. I plan to do this using a version of the auditory search task from Study 3, modified to reduce trial-to-trial stimulus variability and to allow for the combination of auditory trials with an appropriately analogous visual task. The same auditory search task for natural sounds described in [Section 5.3.3](#) could be paired with video clips representing the same objects. This paradigm reduces measurement noise by reducing the number of target and distractor stimuli while also increasing the discriminability of auditory targets from nontargets, hopefully to equate performance across the auditory and visual tasks. By investigating whether inter-trial priming and/or location probability learning effects are affected only by trials within a modality or if they cross modalities, this paradigm can identify whether experience-driven attention is modality-specific or is linked across modalities.

Transfer of experience-driven attention may not occur consistently across all visual and auditory tasks. Instead, task and stimulus features may determine the degree of transfer. For instance, the precision of a feature's representations may determine the weight of a trial's influence.⁷ Perhaps location probability learning is affected more by visual than auditory trials due to more precise estimates of stimulus location in the visual modality. This may differ from learning of non-spatial features such as a target's temporal position in a sequence of visual or auditory stimuli, as temporal attention is

⁷ Thanks to Viola Störmer for this suggestion.

more robust in auditory than visual tasks (Rimmele et al., 2011). It may also differ based on the level of abstraction required to complete a task. For instance, even if spatial and temporal learning are task-specific, learning of high-level stimulus features (e.g., semantic characteristics) may cross modalities due to the reliance of such representations on high-level, supramodal neural representations. This latter hypothesis could be tested directly in a paradigm comparing cross-modal transfer of low-level features like location and time to cross-modal transfer of semantic features like word or object identity.

Even if there are crossmodal effects of experience-driven attention, viable models should incorporate how these effects may be limited by differences between visual and auditory perception. Analogously, a lack of crossmodal effects does not provide conclusive proof against crossmodal attentional mechanisms, because differences in sensory representations across modalities induce modality-specific limitations on the effectiveness of attention. Converging evidence from behavioral and neural paradigms may be needed to untangle these possibilities.

5.4 Conclusion

This dissertation presented three studies investigating the effects of attentional selection history on visual and auditory spatial attention. Study 1 reported a dissociation between the spread of goal-driven and implicitly learned spatial attention to a secondary memory task, consistent with theories arguing that different mechanisms underlie guidance based on the two sources of attentional control. Study 2 reported a lack of transfer of location probability learning across two unpredictably intermixed visual search tasks, showing that, in this paradigm, location probability learning does not yield baseline shifts of attention. Study 3 reported the presence of auditory location probability

learning and the absence of auditory inter-trial location priming in a novel auditory task. These studies inform theories of the relationship between implicit selection history effects and other sources of attentional control as well as how these relationships may differ across sensory modalities.

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Appendix A: Results of Aware Participants in Location Probability Learning

Not all participants in [Study 1, Experiment 3](#) were oblivious to the manipulation in target location probability; 22 of 48 participants correctly identified that the target had a high-probability region and what that region was. Here we report results for these participants. The experimental design is identical to Experiment 3 described above; the only difference is in the participants' responses to self-report questions. Note that results reported here are highly similar to the results of endogenous cuing in Experiments 1 and 2.

Visual Search. A search advantage for the high probability quadrant developed for aware participants (Figure A.1). This was the case in the biased phase, $F(1, 21) = 46.01, p < .001, \eta_p^2 = .67$, and persisted in the neutral phase, $F(1, 21) = 21.01, p < .001, \eta_p^2 = .50$. A direct comparison between the biased and neutral phases revealed a significant main effect of the target's quadrant, $F(1, 21) = 38.44, p < .001, \eta_p^2 = .6467$, without a phase by quadrant interaction, $F = 1.44, p > .2$.

Scene Memory. Aware participants from Experiment 3 were able to perform the memory task at above-chance levels (Figure A.2). The overall hit rate for old scenes was higher than the false alarm rate for aware participants, $t(21) = 7.82, p < .001$. Furthermore, scene memory was significantly better for scenes presented in the high-probability quadrant than the low-probability quadrants. This was the case in the biased phase, $t(21) = 2.54, p < .02$, but not in the neutral phase, $t(21) = 0.64, p > .5$. Combining data across the two phases, we observed a significant effect of quadrant, $F(1, 21) = 4.71, p < .05, \eta_p^2 = .1832$, and no significant interaction between phase and quadrant, $F(1, 21) = 1.81, p > .1$.

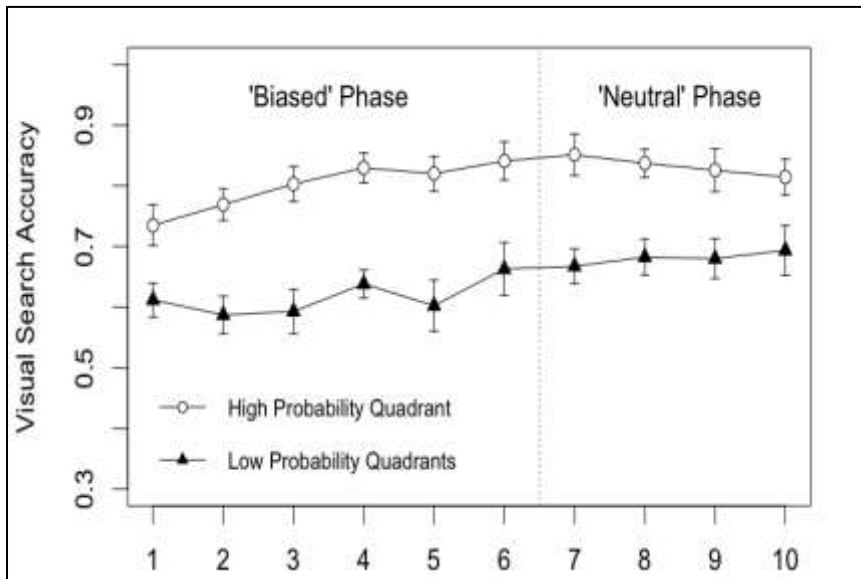


Figure A.1. Visual search accuracy for aware participants in Experiment 3. Error bars show +/- 1 S.E. of the mean.



Figure A.2. Scene memory for aware participants in Experiment 3. Horizontal dotted lines represent false alarm rate (classifying new scenes as old ones) for that phase. Error bars show +/- 1 S.E. of the mean.

Appendix B: Localization task

In all experiments, participants first completed a practice localization task (see [Section 4 General Methods](#)). Here, we report the results of the localization task from all experiments.

Performance (reaction time and accuracy) in the localization task is reported in Figure B.1. The localization task was identical in Experiments 1, 2, and 3a, and so were grouped together as the “target set size 10” condition (because there were 10 possible numbers serving as targets; total $N=48$). Experiment 3b used a smaller set size of possible targets (4 possible target numbers; $N=16$) and were analyzed separately.

When averaging across target set size conditions, distractors reduced localization performance in terms of both reaction time and accuracy. Participants were slower in the presence of one distractor than zero distractors (mean RT difference = 223ms; SE of the difference = 74ms), $t(63) = 3.01$, $p = .004$, Cohen’s $d = 0.38$; they were also less accurate (mean accuracy difference = 4%; SE = 1%), $t(63) = 4.56$, $p < .001$, $d = 0.57$. Similarly, participants were much slower, $t(63) = 8.53$, $p < .001$, $d = 1.07$, and less accurate, $t(63) = 14.91$, $p < .001$, $d = 1.86$, in the presence of three distractors than in the presence of one (mean RT difference = 710ms, SE = 83ms; mean accuracy difference = 23%, SE = 2%).

When zero or one distractors were presented, performance was comparable regardless of target set size (all $ps > .25$). However, when three distractors were present, participants were faster when only 4 numbers served as possible targets (mean RT = 1968ms, SE = 209ms) than when 10 numbers did (mean RT = 2448ms, SE = 163ms), $t(62) = 2.10$, $p = .040$, $d = 0.60$; they were also more accurate (4 numbers mean = 70%, SE = 3%; 10 numbers mean = 77%, SE = 2%), $t(62) = 2.40$, $p = .019$, $d = 0.69$.

The localization task demonstrates that people are highly capable of localizing targets in our paradigm with zero or one distractors present. When three distractors were presented simultaneously with the target, performance was still far above chance. These results may be of interest on their own to researchers interested in sound localization among noise. For our purposes, these results are important because they show relatively high localization accuracy even in the three-distractor condition used in the study. This suggests that participants are capable of identifying target location in this task; were this not the case, no location-based attention effects could be expected using this paradigm.

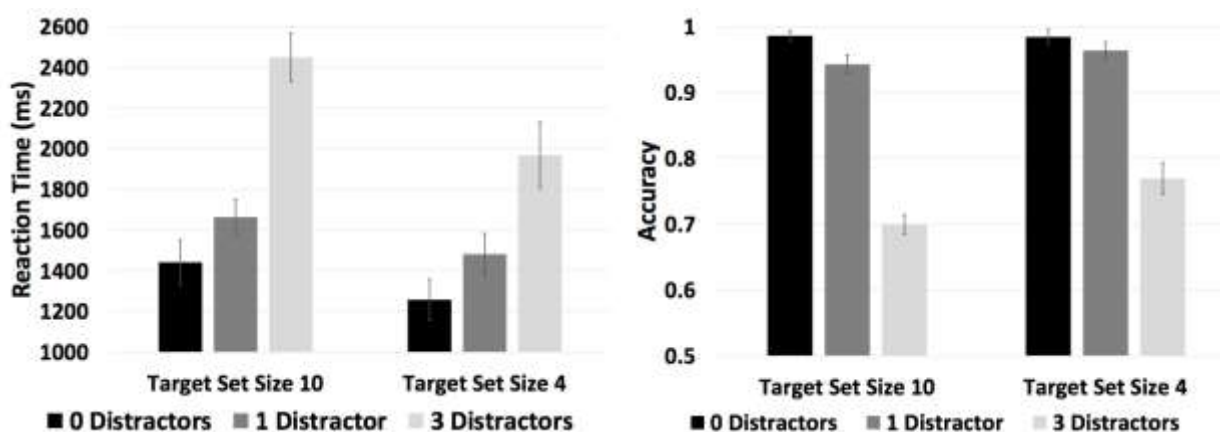


Figure B.1. Results from the localization task in all experiments. Left: Reaction time data (in ms) as a function of target set (Experiments 1, 2, and 3a are set 10; Experiment 3b is set 4) and number of distractors (0, 1, or 3). Right: Accuracy data presented across the same conditions as reaction time. Error bars show +/- 1 standard error of the mean.