The neglected contribution of memory encoding in spatial cueing:

A new theory of costs and benefits

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Abstract

Spatial cueing is thought to indicate the resource limits of visual attention, since invalidly cued items are reported more slowly and less accurately than validly cued items. However, limited resource accounts cannot explain certain findings, such as dividing attention without costs, or attentional benefits without invalidity costs. The current study presents a new account of exogenous cueing, namely the memory encoding cost (MEC) theory, which integrates attention and memory encoding to explain costs and benefits evoked by a spatial cue. Unlike conventional theories that focus on the role of attention in yielding spatial cueing effects, the MEC theory argues that some cueing effects are caused by a combination of attentional facilitation evoked by the cue, but also the cost of encoding the cue into memory. The crucial implication of this theory is that limitations in attentional deployment may not necessarily be the cause of invalidity costs. MEC generates a number of predictions that we test here, providing five convergent lines of evidence that cue encoding plays a key role in producing cueing effects. Furthermore, the MEC suggests a common mechanism underlying cueing costs and the attentional blink, and we simulate the core empirical findings of the current study with an existing attentional blink model. The model was able to simulate these effects primarily through manipulation of a single parameter that corresponds to memory encoding. The MEC theory thus simplifies our theoretical understanding

of attentional effects by linking the attentional blink and some varieties of spatial cueing costs to a common mechanism.

Keywords: spatial cueing, visual attention, attentional blink, working memory, costs and benefits

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Introduction

At any moment in time, we are bombarded with an overwhelming amount of information but we nonetheless experience an apparently effortless understanding of our visual environment most of the time. Visuospatial attention plays a key role in this ability by allowing us to prioritize some relevant information over distracting and competing information. One method by which attention achieves this prioritization is by orienting attention to a spatial region of the visual field, thus improving the speed and efficacy of information processing presented at the attended location (Posner 1980). However, the putative downside of this benefit is that stimuli in unattended regions would suffer the opposite effect (i.e., slower reaction times and poorer accuracy) compared to cases in which attention was not specifically focused at one location.

Such cueing effects (benefits and costs) have supported a large family of attentional theories in which spatial attention is a limited resource that, when concentrated at one location, necessitates the withdrawal of attention from other locations (Carrasco, 2011). In other words, according to these theories, both benefits and costs are driven by attentional reorienting triggered by the presence of a cue. While these theories provide a natural explanation for many of the

cueing effects, there is a growing number of findings that suggest attentional effects can be elicited simultaneously at multiple locations (e.g., Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; Grubert & Eimer, 2015) or even in large regions of the visual field (White, Lunau, & Carrasco, 2014, Experiment 4) without necessarily producing considerable costs. Another new development is a recent observation that subjects form partial memories of the cues within a typical visual cueing paradigm, even when they do not expect to report it (Chen & Wyble, 2015a). These findings have prompted us to consider another potential, and heretofore neglected contribution to cueing effects, which is that encoding¹ the cue into memory may affect subsequent target processing in addition to the attentional effects it may elicit. We posit that cue-encoding provides an alternative explanation to many cueing effects, relative to conventional theories that rely on assumptions of limited attentional resources. Furthermore, this theory has the additional advantage of providing a unified explanation for both the attentional blink, which is a predominantly temporal attentional effect (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992), and visual cueing effects in the spatial domain. The current studies are designed to clarify the mechanisms underlying cueing effects by proposing and demonstrating an alternative, but not necessarily mutually exclusive, theory, which particularly focuses on the role of

¹ Here we define encoding specifically as consolidation of information into an explicit memory representation.

processing/encoding of the cue in producing cueing effects.

In almost every experiment that studies spatial attention a cue indicates which spatial area to attend. This cue is typically comprised of one or more objects that are presented in advance of the target. The visual system must process that cue to some degree, since it does have an effect on perception, but very little is known about how that cue is processed and what effect that processing might have on the ability to report a subsequent target. For example, it is not well known if subjects remember the presence of the cue, the cue's location, or its shape, color etc, since those questions are rarely asked. Indeed if subjects were asked to report the cue, it would essentially become another kind of target that would certainly be encoded into memory. Such encoding of the cue would produce a severe impairment in processing a subsequent target, according to the well-known effect of Attentional Blink (Dux & Marois, 2009; Martens & Wyble, 2010).

Furthermore, what if the cue is automatically encoded, at least partially, into memory even though subjects never have to report it explicitly (Chen & Wyble, 2015a)? Given such encoding, any observed cueing effects should reflect a combination of attention and memory encoding effects. As mentioned before, none of the previous attentional cueing theories consider the contribution of memory encoding when explaining cueing effects.

Moreover, the likelihood of encoding the cue into memory might change over the course of an experiment, being initially large, and eventually reducing as subjects learn how to use cue without remembering it. If this were true, cueing effects should vary across trials within an experiment. Such effects would be crucial for explaining variability between experiments that vary in number of trials.

These aforementioned possibilities constitute core assumptions for our new theory, which will be systematically tested in the current study. Before introducing the new theory, we begin with a review of core findings in visual spatial attention research and the attentional blink, which we will demonstrate is essentially related to spatial cueing effects.

Two types of covert spatial attention: endogenous and exogenous

It is widely agreed that there are two kinds of covert spatial attentional systems: endogenous and exogenous (Carrasco, 2011; James, 1890). The former is an active system that is voluntarily controlled by observers, while the latter is a reflexive system that is automatically drawn towards visual transients. In terms of temporal characteristics, endogenous attention is also known as “sustained” attention, since it can be sustained in one location as needed. By contrast, exogenous attention is sometimes called “transient” attention because it is triggered almost immediately by the abrupt onset of stimuli and dissipates within about 200 ms (e.g.,

Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Wyble, Bowman, & Potter, 2009). Note that some researchers recently argued that this top-down versus bottom-up dichotomy is inadequate and a third component of attentional control, i.e., selection history, is needed (Awh, Belopolsky, Theeuwes, 2012).

Spatial cueing effects

The majority of studies concerning how covert spatial attention is allocated across the visual field were based on a particularly popular and useful paradigm--spatial-cueing (Chica, Martín-Arévalo, Botta, & Lupiáñez, 2014, for a tutorial review). In such experiments, participants are required to detect or identify a target stimulus that is sometimes preceded by a cue. Different types of cue were adopted in measurements of different kinds of attentional orienting. For example, central symbolic cues (e.g., an arrow at the center of the display pointing to a particular location) are used to direct endogenous attention, while peripheral cues (e.g., a colored bar appearing at a peripheral location of the display) are employed to orient exogenous attention to the possible location of the impending target. The trials are denoted as *Valid* when the cue correctly indicates the location of the upcoming target, and *Invalid* when the cue indicates a location where the target does not appear. Thus, this paradigm manipulates attentional allocation before the onset of the target, with attention being directed toward the target location

in valid trials and away from the target location in invalid trials. The validity manipulation thus enables assessment of how spatial attention can influence behavioral performance in response to the target. Typically, participants' response to a target is faster and more accurate in the valid condition than in the invalid condition, which indicates the role of attention in processing visual information. Note that the classic form of the validity effect in exogenous cueing paradigms occurs across large distances and does not have an obvious spatial gradient, such that invalid target processing is impaired even when the target and cue are presented substantially far apart (Eriksen & Yeh, 1985; Folk, Remington, & Johnston, 1992; Muller, & Rabbitt, 1989; Posner, 1980). There are other, more complex aspects of attentional control, such as evidence for suppressive surrounds, in which a salient stimulus evokes impaired processing in its spatial vicinity out to a distance of several visual degrees (Mounts, 2000a; 2000b) and expectancy effects with a spatial gradient (Downing 1988). Another finding shows that suppression of processing can be selectively elicited at the location of task-irrelevant distractors presented alongside a target (Cepeda, Cave, Bichot, & Kim, 1998). These effects may represent additional mechanisms of attentional control that occur when stimulus cueing displays contain multiple items and will be addressed in the discussion.

Many spatial cueing studies also included a neutral or control condition in which there was either no cue at all (*No-cue neutral*) or the cue(s) did not carry any information about the

location of the upcoming target (e.g., *Central-cue neutral*: a cue appearing near the fixation; *Full-cue neutral*: multiple cues appearing at all possible target locations). Usually, target report performance for the neutral trials lies somewhere in between the performance in the valid and invalid conditions. Consequently, two comparisons can be made against the neutral condition, which would divide the cueing effect into ‘Benefit’ and ‘Cost’. The benefit refers to the difference in target performance between valid and neutral conditions, while the cost corresponds to the difference between invalid and neutral conditions.

The benefit-cost analysis provides a straightforward way for us to understand how spatial attention operates. In the past 30 years, despite the fact that a large body of research has extensively investigated these cuing effects (i.e., benefit and cost) in an attempt to elucidate the nature of attentional selection, the mechanism underlying these effects remains largely controversial, as can be seen from a variety of models/theories described below. To address this challenge, we will then describe a new theory of attentional cueing effects that has the potential to clarify inconsistencies in the literature, along with five convergent lines of empirical support.

The Attentional Blink

Another relevant topic is the attentional blink (AB), a phenomenon in which two explicitly designated targets are presented in sequence, and the second target is difficult to report

when it occurs within about 200-500 ms of temporal lag following the first (Chun & Potter, 1995; Raymond, Shapiro, & Arnell 1992). Like invalidity effects in spatial cueing, the reduction in report of the affected item is not spatially localized, which means that a second target can be blinked even if it occurs in a different location than the first (Shih, 2000; Wyble & Swan, 2015). There are a variety of theories regarding the AB, many of which indicate that the processing or encoding of the first target plays a key role in reducing report of the second target (Dux & Marois, 2009; Martens & Wyble, 2010). Findings of the AB and many of the accompanying theories support the possibility that encoding a visual cue into memory would affect processing of a following target. Later in the paper, we will return to a consideration of the AB, and one theory in particular (Wyble, Bowman, & Nieuwenstein, 2009) as we evaluate the similarity between the AB and visual cueing phenomena.

Previous theories regarding the mechanisms underlying spatial cueing effects

Attentional allocation model. One of the most popular interpretations of cuing effects derives from capacity models of attention, such as Spotlight (Posner, 1980; Posner & Petersen, 1990), Zoom lens (Eriksen & James, 1986; Eriksen & Yeh, 1985), and Gradient-filter models (Cheal, Lyon, & Gottlob, 1994). These models suggest that attentional resources are limited, and can be allocated only to one region of the visual field at any one time. Any stimuli appearing

within this attended region are preferentially processed relative to stimuli presented at other regions. Therefore, the spatial cueing effects arise from the differential allocation of attentional resources as a result of the cue(s). In the valid condition, as a result of a cue, attention is deployed to the target location in advance, which enhances the processing of the subsequent target. By contrast, in the invalid condition, allocation of attention to the cued location is necessarily accompanied by a withdrawal of attention from all uncued locations, and thus target processing suffers at any uncued location on invalid trials. In the neutral condition, without a cue, attention might be pre-allocated to one of the target locations, at random producing a mixture of benefits and costs on different individual trials, which average to produce an overall value somewhere between performance on valid and invalid trials. This theory could also allow resources to be distributed across the visual field in the no-cue condition, producing a similar result when averaged across trials. Thus, the comparison of valid and invalid to neutral trials reveals a cost and a benefit effect respectively. In the case of a neutral cue at the center of the display, the cue provides temporal information about the target, but no spatial information which should the amount of attention at the cue locations undifferentiated. In other words, according to this attentional deployment hypothesis, benefits and costs reflect a tradeoff that is driven by a common mechanism.

Noise exclusion/uncertainty reduction model. An alternative model of cueing effects focuses on attention's role in excluding the noise or distractor signals that might be confused with the target signal in decision processes (e.g., Shiu & Pashler, 1994; 1995; but see Luck, Hillyard, & Mouloua, 1996). According to this noise exclusion hypothesis, any distracting stimulus (e.g., distractors, masks) that is confusable with the target creates noise within the visual system. Precuing a location allows the attenuation of such noise from stimuli in uncued locations, thereby leading to spatial cueing effects. In this model, the benefit of a valid cue arises because processing of a target at an attended region is less influenced by noise from the unattended regions. The cost effect occurs because the target signal is attenuated when it appears at an unattended location, as if it were itself noise.

Another similar hypothesis, namely, spatial uncertainty reduction, interprets spatial cueing effects as a result of temporarily reducing the number of location(s) to be monitored, which thereby minimize the noise sources (e.g., Davis, Kramer, & Graham, 1983; Nachmias, 2002). Therefore, in this perspective, both the noise exclusion and spatial uncertainty reduction models explain cueing effects by focusing on how a cue can facilitate target performance by excluding noise or distractor signals that might be confusable with the target without assuming the existence of limited capacity attention. In these models the cost and benefit result from the use of a single attentional mechanism.

Perceptual template model (PTM). Lu and Doshier (2008) proposed a theoretical framework attempting to integrate previous findings about spatial cueing effects with their own model, termed the perceptual template model. According to this model, there are three mechanisms (signal enhancement, external noise exclusion, and internal noise exclusion) that might contribute to spatial cueing effects, with each of them operating in different contexts. In a low external noise display, the signal enhancement is the dominant contributing factor, which means attention affects target performance by strengthening a signal of interest. By contrast, in a high external noise display (e.g., blurring), external noise exclusion plays a key role in how attention influences target performance. The third possible mechanism, internal noise reduction, operates across all levels of external noise. This model could explain costs and benefits as arriving from any combination of these mechanisms across different paradigms.

Attentional gating model. Unlike the aforementioned models of spatial attention that were mainly based on the studies with spatial-cueing paradigm, the attentional gating model (Reeves & Sperling, 1986; Sperling & Weichselgartner, 1995) derived from experiments adopting the rapid serial visual presentation (RSVP) attention shift paradigm. As a consequence, the attentional gating model focuses on the temporal characteristics of attention. On the basis of this model, attentional allocation does not operate through shifting from one location to another continuously in the visual field, but through opening and closing an attentional gate at one

location and then at another. These dynamics are independent of the spatial distance traversed during the transition. Like the spotlight model, this model also suggests that attention cannot operate in parallel.

Despite an extensive investigation of cueing effects, the mechanism(s) underlying these effects are still vigorously debated, as can be seen from the variety of theories mentioned above. We speculate that this might be due to the fact that previous studies focused exclusively on how attention triggered by the cue affects target processing or noise exclusion, but without considering the possibility that the cue is itself encoded into memory and that might influence target processing as well. A recent study demonstrates that participants will automatically encode some information related to a cue (e.g., location) into memory during the typical spatial-cueing paradigm, even though they were asked to ignore the cue (Chen & Wyble, 2015a). According to AB theories (Bowman & Wyble, 2007; Dux & Marois, 2009), this encoding of the cue into memory would produce a substantial impairment on the processing of subsequent target stimulus, if we regard the cue as T1 and subsequent target stimulus as T2 in an analogy to the AB. Therefore, the theories/models mentioned above provide an incomplete story with respect to the mechanism(s) underlying spatial cueing effects because none of them, to the best of our knowledge, considers the contribution of memory encoding of the cue in explanations of cueing effects.

A new alternative theory of spatial cueing: Memory encoding cost

In order to better understand the causes of spatial cueing effects, we propose an alternative theory that integrates attention and memory encoding effects in an explanation of the costs and benefits evoked by a spatial cue. We term this theory *memory encoding cost* (MEC). According to this new theory, spatial cueing effects were mainly driven by a combination of two distinct mechanisms: *attentional facilitation* and *memory encoding induced cost*. The former results from attentional boost triggered by the presence of an abrupt cue (or multiple cues). Specifically, in the absence of, or prior to a cue, attention (i.e., sustained attention) is initially distributed as a gradient across some regions of visual field that are expected to be task relevant (e.g., the possible target locations and fixation). Then onset of a cue (or cues) causes additional attentional enhancement (i.e., transient attention) at the cued location(s). This is similar to the gradient model of attention by Cheal et al., (1994), with a key difference being that our theory does not assume limits in the deployment of attention as the key factor in causing invalidity effects. Instead, according to the strongest version of MEC model, attention can be deployed to multiple locations/regions simultaneously and produce facilitation in information processing at each of these attended locations without necessarily resulting in concomitant attention deficits at uncued locations. At the level of neural mechanisms, we consider attention as an enhancement of processing at specific locations in one or more spatiotopic maps and there is no need to posit that

the number of enhanced regions is limited. In this theoretical framework, limitations in processing are present at subsequent stages, for example at the point in which information is being consolidated into working memory, or speeded responses are being executed. Thus, the role of attention is not to select which specific pieces of information are processed, but rather to enhance certain pieces of information in order to provide an advantage in subsequent, central stages of processing. This idea represents a subtle but important distinction from a theory that attention is itself limited, and similar ideas are implied in earlier models of attentional filtering (e.g., Cave, 1999; Desimone, 1998; Reynolds & Heeger, 2009). One of the advantages of this variety of model over limited attention accounts is that it has no difficulty in interpreting the aforementioned findings of divided attention without cost, as long as stimuli are sufficiently spaced. Such unlimited-attention models are also consistent with the new findings of a dissociation of costs and benefits that are demonstrated in some of the experiments described below. Note that this assumption about the unlimited-capacity attention might not hold in all cases, such as when the stimuli are spatially proximal, a case that evokes attentional interference (Mounts 2000a).

The other more crucial component of the MEC model is the assumption that some information about the cue itself is often encoded into memory, which impairs the ability to attend or encode the target into memory. We showed in earlier work (Chen & Wyble, 2015a) and also

in some of the experiments below that participants can often report information about the cue in a surprise test, despite the fact that they are told explicitly to ignore the cue. According to most theories of the AB (Dux & Marois, 2009; Martens & Wyble, 2010) such memory encoding would yield a non-spatiotopic cost that can significantly impair the processing of upcoming information (e.g., subsequent target) during that encoding stage. Consequently, we suggest that the observed cost effect of an invalid cue might be partially or entirely driven by memory encoding of the cue in the invalid condition as compared to a no-cue neutral condition.² The choice of a baseline or control condition in visual cueing is controversial, and many studies opt for a neutral cue that is centrally presented. However, Schubert & Eimas (1977) suggest in their paper on lexical cueing that it is not always appropriate to use a neutral stimulus as a control condition, since that stimulus can impose a cost on subsequent processing. We return to this issue in section 4 of the paper.

In the MEC framework, valid targets would be affected by encoding the cue into memory, producing a cost but the cost would often be masked by the beneficial effect of

² As described before, there are three different types of neutral condition: No-cue neutral, Central-cue neutral, and Full-cue neutral. According to MEC, the Central condition should produce a cost, since that cue is also encoded, while the effect of a Full-cue condition would depend on the parameters of the display. Thus, the current studies focused on the No-cue neutral condition but the Central-cue condition will be studied as well. The Full-cue condition will be addressed in future work.

attentional enhancement. In fact one of the strengths of the MEC model is its ability to explain tradeoffs between costs and benefits that are difficult to explain using conventional theories.

As many prior studies suggested distinct mechanisms for different kinds of attention (e.g., sustained/endogenous vs. transient/exogenous attention, e.g., Berger, Henik, & Rafal, 2005), it should be noted that the mechanisms of spatial cueing effects proposed here are based on transient/exogenous attention as opposed to slower, sustained/endogenous attention (Jonides, 1981). This is because the key characteristic of transient attention, for our purpose, is that it occurs about 100-200 ms of the cue onset (e.g., Bay & Wyble, 2014; Nakayama & Mackeben, 1989; Wyble, Bowman, & Potter, 2009), which matches the time window during which encoding-induced cost is predicted to occur. Effects that happen at longer time scales, such as centrally cued forms of orienting and inhibition of return (Klein, 2000; Posner & Cohen, 1984) are considered outside of the scope of the MEC model.

Key assumptions of the MEC model

To summarize, the MEC model can be described in terms of five specific assumptions that occur for exogenous cueing experiments with widely spaced stimuli:

- (1): Memory encoding, rather than attention, is the bottleneck in controlling the amount of information acquisition at each moment, and thus it is not necessary to assume spatial attention as having a highly restrictive capacity limit.
- (2): Cues cause a transient, spatiotopic³ enhancement of processing at each cued location.
- (3): Memory encoding of cues yields a non-spatiotopic cost that reduces the probability of encoding the upcoming stimuli (e.g., the subsequent target) within an interval of several hundred milliseconds.
- (4): The observed cost of an invalid cue is partially or entirely caused by memory encoding of the cue into working memory, which shares a common mechanism as AB.
- (5): The observed benefit of a valid cue is caused by the net effect of two separate processes: attentional facilitation triggered by the abrupt cue at the cued location and a non-spatiotopic cost resulting from memory encoding of the cue.

The advantages of this new theoretical framework are several. First, we will outline a series of novel predictions that this theory makes, which we test empirically. These findings indicate the crucial role of memory encoding in determining cueing effects and how they can

³ We use the term spatiotopic here, although it is likely that part of this attentional effect occurs in retinotopic coordinates. We are not aware of data that are sufficient to resolve this question.

change across experimental conditions and within an experiment across trials. Collectively these new findings are difficult to explain with previous theories of cueing effects. Next, because of its emphasis on memory encoding, the model generalizes to the AB domain as well. This generality has the advantage of providing a single explanatory framework with a scope that includes both spatial cueing and the AB. Thus, in terms of explanatory power, the MEC is efficient relative to theories that are only able to explain data from cueing studies. Finally, the MEC theory clarifies confusing findings when costs or benefits of spatial cueing cannot be observed.

The remainder of this paper is organized as follows. First, we will describe five specific predictions of the MEC model and systematically evaluate them with a series of experiments. Then, we will simulate these new empirical findings with a computational model that had developed based on AB studies (Bowman & Wyble, 2007; Bowman, Wyble, Chennu, & Craston, 2008; Wyble, Bowman, & Nieuwenstein, 2009). After that, we will try to interpret the current new empirical findings as well as some previous seemingly unexplainable results by adopting the MEC model. Finally, we will discuss the implications of these novel findings and the new model in understanding the nature of attentional selection.

New predictions deriving from MEC model

Prediction 1: *Spatial cueing effects change with the requirement of cue encoding*

The first prediction derived from the MEC model is that spatial cueing effects should change with the cost induced by encoding the cue into memory, which is positively related to the requirement of reporting the cue.

Prediction 2: *Spatial cueing effects change systematically with experience*

Our previous work (Chen, Swan, & Wyble, 2016) and some pilot studies demonstrated a progressive worsening of memory for the features and even the location of a visual cue as subjects have experienced more trials. This indicates that participants might automatically encode some aspects of cue (e.g., location) at the beginning of an experiment but then learn to filter out such unnecessary encoding with repeated trials. We also assume that attentional facilitation evoked by a cue is not dependent on its memory encoding, and thus attention will be evoked by a cue even though it is not encoded into memory. Thus the second prediction is as follows: If cue encoding drops out as an experiment progresses, then the cost effect should decrease across blocks of an experiment as well, while the benefit effect remains constant or perhaps even increases across blocks.

Prediction 3: *There is a relationship between spatial cueing effects and the ability to report cue information in a surprise test (e.g., cue location)*

Given that the variation of spatial cueing effects across blocks is due to the changes in cue encoding as suggested in Prediction 2, then we should find a concomitant relationship between spatial cueing effects and the ability to report cue information in a surprise-test experiment. For example, the drop of the cost effect across blocks as observed in Prediction 2 should be accompanied by a decline of the ability to report cue location.

Prediction 4: *Generalization to reaction time and central-cue conditions.*

According to the MEC, the use of a central-cue should produce an effect that resembles a fully invalid cue, since subjects would encode even a central cue into memory. Also, the block effects in Prediction 2 should generalize to reaction time measures, such that reaction time costs decrease across trials while benefits remain constant or increase.

Prediction 5: *Extension of Attentional blink theories to cueing through encoding parameters*

If these cueing effects share a common mechanism with the AB, with the analogy that the cue acts as a T1, then it should be possible to simulate these data using an existing computational model of the AB, in which we vary the T1-encoding parameter.

In the following five sections, we evaluate each of these predictions in turn. The code and stimuli for running all of the experiments in the paper, as well as the data and the simulation

code are available through an Open Science Framework repository at this URL:

https://osf.io/ckqrj/?view_only=0d1e9b6f412d47109e933201b61de78c

Section 1: How are spatial cueing effects affected by memory encoding of a cue?

In the first section, we tested Prediction 1 by investigating how spatial cueing effects (benefit and cost) could be influenced by changing the requirement of memory encoding of the cue within the task. The requirement of cue encoding was manipulated by asking participants to report some aspects of the cue (e.g., location or color; Experiment 1), by masking the cue (Experiments 2a and 2b), and by adopting an invisible cue (Experiment 3). Furthermore, if spatial cueing and the AB share an underlying cause, then it should be possible to observe lag-1 sparing in a typical cueing paradigm, which we test in Experiment 4.

Experiment 1

Here we tested whether memory encoding of the cue alters the pattern of spatial cueing effects. Specifically, we manipulated the amount of information encoded about the cue across three groups of participants by asking them to report the cue's location, to report the cue's color, or not to report any information of the cue. MEC theory predicts that requiring participants to

report the color of a cue would produce a larger cost effect as compared to requiring them to report its location, since previous research showed that cue location, but not color is moderately well encoded in a typical cueing experiment (Chen & Wyble 2015a). For the same reason, requiring participants to report cue location would not produce considerable additional cost as compared to not reporting the cue at all. In addition, we systematically manipulated the stimulus onset asynchrony(SOA) between the cue and the target so as to investigate the time course of the cost and benefit.

Method

Sample size. Based on previous work (Chen & Wyble, 2015a) we used a predetermined sample size of 20 participants for each experiment or each group in the between-subject design experiment in Section 1 (Experiments 1-4), while a sample size of 30 participants for each experiment or each condition in the between-subject design experiment in Sections 2-4 (Experiments 5-10). The larger sample size used in Sections 2-4 is because in these experiments we split data to investigate the block effect where a relative larger sample size is needed to achieve a sufficient power. The sample size on each experiment/condition refers to the number of included participants, with some additional participants being excluded from analysis because of their poor performance on either target or cue report (overall accuracy < 40% for either target

or cue report, this criterion was set in advance based on our pilot data, and applies to all following experiments).

Participants. Sixty undergraduates from the Pennsylvania State University participated in this experiment and were divided randomly into three groups in exchange for course credit. All of them reported normal or corrected-to-normal visual acuity. Three additional participants were excluded from analysis because of their poor performance on either target or cue report (overall accuracy < 40%).

Apparatus. Stimuli were presented on a 17-in CRT monitor with a resolution of 1024×768 and refresh rate of 75Hz. Participants viewed the screen from 50 cm away, with their head being stabilized by a chin rest. They entered responses via a computer keyboard. The experiment was programmed by using MATLAB with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) on Windows XP computers.

Stimuli. Four placeholders (0.76° black circles) were displayed in a square formation ($7.69^\circ \times 7.69^\circ$, outer edge to outer edge), with a black central fixation cross (0.76°) appearing in the center of the invisible square. The cue was composed of two identical colored rectangle bars (0.18° height $\times$ 1.13° width), with each one being presented 1.53° above and below the placeholder. There were four different types of cue color (red: 227/34/12; blue: 58/199/252;

green: 84/249/19; and purple: 191/55/244). The targets were fifteen black English letters (A,B,C,D,F,H,J,K,L,N,P, R,T,V,X) printed in the Arial font size of 30, and their height and width subtended about 1.06° and 0.76° respectively. The target mask was generated by using two overlapped black symbols (@ and #, see Figure 1). All the stimuli were presented on a gray background (RGB: 150/150/150).

Procedure and Design. As depicted in Figure 1, each trial began with the simultaneous appearance of the central fixation cross and four placeholders. On 80% of trials, after a random interval (900-1900 ms), a colored cue flashed at the location of one of four placeholders for 80 ms, which was then followed by a blank screen until the appearance of the target letter. The duration of the blank screen varied in different Cue-target SOA conditions. Of these cue-present trials, the cue was uninformative about the target in that 75% were *Invalid* wherein the target was presented at a different location as the preceding cue, while 25% were *Valid* wherein the target and the cue were presented at the same location. The SOA between the cue and the target was evenly divided over the values 107, 201, 308, 508, or 709 ms. After 94 ms of the target presentation, a target mask appeared at each of the four placeholder positions for 107 ms. After a 415 ms blank screen, participants were asked to report the target letter by pressing corresponding

keys. On the remaining 20% of trials, the target letter was not preceded by a cue (*No Cue* condition). In addition, unlike in cue-present trials wherein the placeholders disappeared simultaneously with the cue, the placeholder screen remained on the screen until the presence of the target letter on these No-cue trials.

All instructions used for the experiments throughout the paper are published as an online supplemental. Participants were divided randomly into three groups of 20 which determined the experimental tasks they received: *Cue location report group*, *Cue color report group*, and *No-cue report group*. In the No-cue report group participants were asked to report only the target letter. In the cue location report group, participants were asked to report the location of the cue (five alternative force choice: four possible locations plus the “no cue” choice) after target report on each trial, while in the cue color report group they were asked to report the cue color (five alternative force choice: four possible colors plus the “no cue” choice) instead of its location. Participants from all three groups were informed before the experiment that the cue would be randomly displayed at one of the four possible positions and therefore would be uninformative with respect to the location of the subsequent target letter.

All participants completed 9 blocks, with each block containing 15 Invalid, 5 Valid, and 5 No Cue control trials, resulting in a total of 225 trials. The trials of different conditions were

randomly ordered within each block. Participants completed 10 practice trials before the experimental trials began.

Analysis. The cost effect was calculated by subtracting the target accuracy in the Invalid condition from that in the No Cue condition, while the benefit effect was calculated by subtracting the target accuracy in the No Cue condition from that in the Valid condition. To assess how cost and benefit effects were influenced by the amount of encoding information of the cue, several sets of planned comparisons were performed among three different groups (*Cue location report group*, *Cue color report group*, and *No-cue report group*) by using separate mixed repeated measures analysis of variance (ANOVAs).

Experiment 1

Figure 1. Schematic illustration of the trial sequence of 107 ms SOA condition in Experiment 1.

Results and Discussion

The overall accuracy of cue location and cue color report were .89 (SD = .07) and .94 (SD = .06) respectively. The accuracy of target⁴ report as a function of Cue-target SOA in Experiment 1 is depicted in Figure 2A. Preliminary analyses in this and following experiments showed that the cost effect was typically largest in the first two SOA conditions (i.e., 107 and 201 ms SOAs) and dissipated as SOA increased, which is the time window during which encoding-induced cost is predicted to occur. Thus, the analyses will focus on these two SOAs.

A 2 (SOA: 107 and 201 ms) $\times$ 3 (Trial condition: Invalid, No Cue, and Valid) $\times$ 3 (Group: Cue-location report, Cue-color report, and No-cue report) mixed repeated measures analysis of variance (ANOVA) was initially performed and the analysis showed a significant 3-way interaction ($F(4, 114) = 3.754, p = .007, \eta_p^2 = .116$). Thus, we conducted two separate 2 (SOA) $\times$ 2 (Trial condition) $\times$ 3 (Group) mixed repeated measures ANOVAs to evaluate the cost (Trial conditions: Invalid vs. No Cue) and benefit (Trial conditions: Valid vs. No Cue) effects respectively. The cost and benefit effects across conditions are depicted in Figure 2B.

Influence of cue encoding on the invalid cost effect

The ANOVA analysis for the cost effect involving just the No-cue and invalid conditions yielded a reliable effect of Trial condition ($F(1, 57) = 53.327, p < .001, \eta_p^2 = .483$),

⁴ For all of the experiments, we refer to the letter as the "target" for consistency even though the cue is also technically a target in the cue-report conditions.

such that target report was significantly worse in the Invalid condition than in the No cue condition (i.e., Invalid cost effect). More importantly, the trial condition interacted significantly with group, ($F(2, 57) = 8.291, p < .001, \eta_p^2 = .225$), indicating that the invalid cost effect was modulated by memory encoding of cue information, which is consistent with MEC theory.

Furthermore, this modulation effect was not different between 107 and 201ms SOA conditions in a non-significant 3-way interaction ($F(2, 57) = 1.016, p = .369, \eta_p^2 = .034$). The data of 107 ms and 201 ms SOAs were thus collapsed in the following further analyses.

Planned comparisons revealed that the cost effect in the cue color report group was substantially larger than the cost in the cue location report group ($F(1, 38) = 6.577, p = .014, \eta_p^2 = .148$) and the No-cue report control group ($F(1, 38) = 13.002, p < .001, \eta_p^2 = .255$), while the cost effects in the latter two groups were not significant different ($F(1, 38) = 2.791, p = .107, \eta_p^2 = .067$).

Influence of cue encoding on the validity benefit effect

An analogous ANOVA analysis for the validity benefit also showed a significant main effect of Trial condition ($F(1, 57) = 17.465, p < .001, \eta_p^2 = .235$), such that the target report was better in the Valid condition relative to the No cue condition (i.e., Validity benefit). Critically, there was a significant interaction between trial condition and group ($F(2, 57) = 3.619, p = .033, \eta_p^2 = .113$), suggesting that, as with the cost, the benefit was also influenced by memory

encoding of cue. Planned comparisons showed that, opposite to the invalid cost, the validity benefit in the Cue color report group was reliably smaller than in the No-cue report group ($F(1, 38) = 5.890, p = .020, \eta_p^2 = .134$). The Cue color and Cue location report groups were not significantly different ($F(1, 38) = 3.499, p = .069, \eta_p^2 = .084$) nor were the Cue location report and No-cue report groups ($F(1, 38) = .890, p = .351, \eta_p^2 = .023$).

Figure 2. The results of Experiment 1. (A): The mean accuracy of the target report as a function of Cue-target SOA on each group in Experiment 1. (B): The cost and benefit effects in the figure were generated based on the average data of 107 and 201 ms SOAs. The cost effect was calculated by subtracting the target accuracy in the Invalid condition from that in the No Cue condition, while the benefit effect was calculated by subtracting the target accuracy in the No Cue condition from that in the Valid condition. The error bars represent standard errors.

In summary, as predicted by the MEC, requiring participants to report some information of a cue that previous work suggested is not automatically encoded (e.g., color; Chen & Wyble 2015a) produced a larger invalid cost than not asking for cue report. In contrast, asking participants to report some information of a cue that should have been automatically encoded (e.g., location; Chen & Wyble 2015a) did not yield a noticeable additional cost. It could be argued that requiring cue report increased focus on the cues, and thereby increased their effects. However, this explanation would predict that cue report requirements would increase both costs and benefits, while Experiment 1 found increased costs and reduced benefits. It is worth noting that these findings might be accommodated by other cueing theories through the addition of extra factors or assumptions. However, MEC, can explain these effects without additional assumptions, and has additional explanatory power in the following experiments.

Experiments 2a

Experiment 1 showed larger cost and smaller benefit effects when increasing cue report requirements. Here we sought to increase the duration of cue encoding with a mask. This manipulation is inspired by AB studies which have shown the AB to be substantially strengthened if T1 is masked (e.g., Chun & Potter, 1995; Nieuwenstein, Potter & Theeuwes,

2009; Raymond et al., 1992; Visser & Ohan, 2007). If the invalid cost effect shares a common mechanism with the AB as suggested by our MEC theory, then the cost of an invalid cue should also be enhanced when the cue is masked. We also predict that the benefit of a valid cue should be reduced or even reversed by masking the cue since, according to the MEC model, the cost of encoding the cue occurs for the valid trials as well, though it can be obscured by the attentional facilitation caused by the cue. To test this prediction, we replicated the cue color report group of Experiment 1 with the addition of a cue mask.

Method

This experiment was identical to the cue color report group of Experiment 1 except as follows. A new group of twenty undergraduates participated in this experiment. Three additional participants were excluded with the criterion described before. The cue display was visible for 94 ms⁵ and was replaced by cue masks for 27 ms before the onset of the target. Thus, the cue-target SOAs were: 121, 228, 321, 522, 723 ms, which were slightly different from Experiment 1. Each cue mask consisted of colored small rectangles, of the same as four cue colors (see Figure 3A).

⁵ We initially planned to set the cue duration to be 80 ms as in Experiment 1, however the presentation of the cue mask inadvertently extended the cue exposure time.

Only the cued location was covered by the cue mask. As in Experiment 1, the cue was uninformative about the target location.

Results and Discussion

The accuracy of cue color response was .80 ($SD = .11$). The mean accuracy of the target report as a function of Cue-target SOA in Experiment 2a is depicted in Figure 3B.

For target accuracy, we compared the data of the current experiment with those from the cue color report group of Experiment 1. A 2 (SOA: 121 and 228 ms) $\times$ 3 (Trial condition: Invalid, No Cue, and Valid) $\times$ 2 (Group: masked-cue and unmasked-cue) mixed ANOVA was performed on target accuracy, with SOA and Trial condition as within factors and Group as a between factor. As there was a significant 3-way interaction ($F(2, 76) = 7.608, p < .001, \eta_p^2 = .167$), we conducted two separate 2 (SOA) $\times$ 2 (Trial condition) $\times$ 2 (Group) mixed repeated measures ANOVAs to evaluate how cost and benefit effects affected by cue mask respectively. The cost and benefit effects are depicted in Figure 3C.

Influence of cue mask on the invalid cost effect

The ANOVA analysis yielded a reliable cost effect ($F(1, 38) = 149.372, p < .001, \eta_p^2 = .797$), and more importantly, this cost was significantly larger when the cue was masked in comparison with when the cue was unmasked ($F(1, 38) = 5.383, p = .026, \eta_p^2 = .124$). The 3-

way interaction did not reach significance ($F(1, 38) = .569, p = .455, \eta_p^2 = .015$), suggesting a similar masking effect on cost between the two SOA conditions.

Influence of cue mask on the validity benefit effect

The analysis revealed a reversed benefit effect ($F(1, 38) = 28.895, p < .001, \eta_p^2 = .432$), suggesting that masking the cue produced such a large encoding cost that the spatiotopic attentional facilitation was overcome. Critically, the benefit effect was considerably reduced when the cue was masked compared to when the cue was not masked ($F(1, 38) = 34.061, p < .001, \eta_p^2 = .473$). The effect of the mask on the benefit was stronger in the 107ms than the 201ms SOA condition, as revealed by a significant 3-way interaction ($F(1, 38) = 13.184, p < .001, \eta_p^2 = .258$).

Figure 3. (A): Schematic illustration of the trial sequence of cue mask display in Experiments 2a and 2b. (B): The mean accuracy of the target report as a function of Cue-target SOA in Experiment 2a (Left figure, Cue masked) and color report group of Experiment 1 (Right figure, Cue unmasked). (C): The cost and benefit effects in Experiment 2a (i.e., blue bars) and color report group of Experiment 1 (i.e., orange bars), which were generated with the average data of 107 and 201 ms SOAs. The error bars represent standard errors.

These results support our prediction that masking the to-be-reported cue will increase the cost effect, which is similar to the effect of T1 masking in the AB (e.g., Visser & Ohan, 2007).

This finding provides further evidence that the invalid cost and AB are driven by a common

underlying mechanism. The observation of the reversed benefit supports our hypothesis that memory encoding of cues not only contributes to the cost effect, but also reduces the benefit effect even to the point of reversing it.

Experiment 2b

Experiment 2a showed that masking the cue substantially reduced target report accuracy in both valid and invalid conditions, as would be predicted by our hypothesis that the AB and cueing effects share an underlying mechanism—Encoding induced suppression. However, an alternative explanation is that the presence of the cue masks impaired the processing of the subsequent target through a forward masking effect or some other low-level mechanism (e.g., the presentation of cue mask in Experiment 2a extends cue exposure time slightly as compared to Experiment 1), in particular for the valid condition wherein the cue mask and target were presented closely in space. To distinguish between these possibilities, we replicated Experiment 2a but without the requirement to report the cue color. If our memory encoding hypothesis is correct, target report performance should improve dramatically at short SOAs relative to Experiment 2a. Otherwise, if the forward masking/low-level mechanism hypothesis is true, then a similar result should be observed in this experiment.

Method

This experiment was identical to Experiment 2a except that participants were no longer asked to report the cue color. A new group of twenty undergraduates completed the experiment. No participants were excluded. As in Experiments 1 and 2a, the cue was uninformative about the target location.

Results and Discussion

The mean accuracy of target report as a function of Cue-target SOA in Experiment 2b is depicted in Figure 4A. We compared the data of Experiments 2a and 2b in a 2 (SOA: 121 and 228 ms) $\times$ 3 (Trial condition: Invalid, No Cue, and Valid) $\times$ 2 (Group: Experiment 2a-cue report and Experiment 2b-no cue report) mixed ANOVA on target accuracy, with SOA and Trial condition as within factors and Group as a between factor. The 3-way interaction did not reach significance ($F(2, 76) = 1.606, p = .208, \eta_p^2 = .041$), but as in previous experiments, we conducted two separate 2 (SOA) $\times$ 2 (Trial condition) $\times$ 2 (Group) mixed repeated measures ANOVAs to compare the cost and benefit effects between Experiments 2a and 2b respectively. The cost and benefit effects of Experiments 2a and 2b were depicted in Figure 4B.

Influence of cue report on the invalid cost effect

The analysis revealed a significant cost effect ($F(1, 38) = 164.969, p < .001, \eta_p^2 = .813$), and critically, as expected, this cost effect was substantially larger in Experiment 2a (wherein participants were required to report the color of the masked cue) than in the current experiment (wherein participants were no longer required to report the cue color), ($F(1, 38) = 61.403, p < .001, \eta_p^2 = .618$). The 3-way interaction was not significant, ($F(1, 38) = 3.789, p > .05, \eta_p^2 = .091$).

Influence of cue report on the validity benefit

Similarly, the analysis showed a reliable benefit effect ($F(1, 38) = 26.415, p < .001, \eta_p^2 = .410$) that was noticeably smaller in Experiment 2a than in Experiment 2b. ($F(1, 38) = 34.755, p < .001, \eta_p^2 = .478$). The 3-way interaction was not significant, ($F(1, 38) = 1.223, p = .276, \eta_p^2 = .031$).

Figure 4. (A): The mean accuracy of the target report as a function of Cue-target SOA in Experiment 2a (Left figure, cue color report) and Experiment 2b (Right figure, no cue report). (B): The cost and benefit effects in Experiment 2a (i.e., blue bars) and Experiment 2b (i.e., orange bars), which were generated with the average data of 107 and 201 ms SOAs. The error bars represent standard errors.

In conclusion, Experiment 2b showed that the mere presence of the cue mask was not responsible for the poor target report in the valid and invalid conditions of Experiment 2a. Without the need to report cue color, the data more closely resembled those of the No-cue report group in Experiment 1, indicating that the requirement to report information about a cue was crucial for the magnified effect caused by the cue-mask. This result supports our memory-encoding hypothesis but argues against the aforementioned forward masking or other low-level mechanism possibilities.

Experiment 3

Previous experiments demonstrated that the invalid cost was enhanced either through increasing the amount of information to be reported or by partially masking the to-be-reported cue so as to slow down the memory encoding process. The current experiment attempted to further test the MEC theory by manipulating cue visibility. The logic here is that, if the MEC theory is correct, then the invalid cost effect should be nearly eliminated when the cue is effectively invisible due to strong masking. Critically, despite of a lack of invalid cost, the benefit effect might still be present because previous studies have demonstrated that attention can still be triggered by an invisible cue (Mulckhuyse & Theeuwes, 2010). In addition, this experiment would also include a visible-cue condition which allows the comparison of cueing effects as cue visibility is manipulated.

Method

This experiment was run at Zhejiang University, China, and a new group of twenty undergraduates from Zhejiang University completed the experiment. Three additional participants were excluded with the same criterion as previous experiments. Stimuli were presented on a 17-in CRT monitor with a resolution of 1024×768 and refresh rate of 85Hz. As depicted in Figure 5A, there were two placeholders appearing at 5.77° from each side of fixation.

The cue consisted of two black rectangles (0.19° height $\times$ 1.92° width), and the cue mask was a black hollow square, with the composed lines subtending 0.31° height $\times$ 1.92° width. Each trial began with 500-1000 ms placeholder display, which was followed by the cue display. The cue appeared only for 12 ms. In the invisible-cue condition the cue was covered by a mask for 35 ms, while in the visible-cue condition there was no cue mask following the cue. There were two cue-target SOA conditions: 118 and 1024 ms. The target was an English letter from the same set as in previous experiments and the distractor was a digit (1-9). Participants were asked to report the target letter first, and then the location of the cue (left, right, or no cue).

Thus, the experimental design was 2(SOA: 118 and 1024 ms) $\times$ 3 (Trial condition: Invalid, No cue and Valid) $\times$ 2 (Cue type: visible cue and invisible cue). All participants completed 8 blocks, and each block contained 36 trials dividing equally among all conditions. For cue-present trials, the cue validity was 50% and thus was uninformative about the target location given that there were two locations. There were 36 practice trials before the formal experiment.

Results and Discussion

The average accuracy of cue location response in the invisible-cue condition was .335 (SD=.02), which is almost equal to chance ($1/3=.333$), indicating that the cue mask was effective in making the cue invisible (the cue location report accuracy was only .048 in cue-present trials

since participants reported “no cue” on almost all invisible cue trials). The average cue report accuracy was .92 ($SD = .06$) in the visible-cue condition. The mean accuracy of the target report at different conditions in Experiment 3 is depicted in Figure 5B.

A $2(\text{SOA: 118 and 1024 ms}) \times 3(\text{Trial condition: Invalid, No cue, and Valid}) \times 2(\text{Cue type: visible cue and invisible cue})$ repeated measures ANOVA was performed on target accuracy. As there was a significant 3-way interaction ($F(2, 38) = 21.468, p < .001, \eta_p^2 = .530$), we conducted two separate $2(\text{SOA}) \times 2(\text{Trial condition}) \times 2(\text{Group})$ repeated measures ANOVAs to evaluate cost and benefit effects respectively. As expected, preliminary analyses showed that neither cost nor benefit effect was observed in the long SOA condition (all $ps > .09$). Thus, the following analyses only focus on the short SOA condition. The cost and benefit effects at short SOAs are depicted in Figure 5C.

Invalid cost effect

As predicted, the cost effect differed between invisible-cue and visible-cue conditions, as confirmed by a significant Trial condition $2(\text{Invalid and No cue}) \times 2(\text{Cue type: Invisible cue and Visible cue})$ ($F(1, 19) = 36.282, p < .001, \eta_p^2 = .656$). Planned comparisons showed that the invalid cost effect was present in the visible-cue condition ($t(19) = 6.356, p < .001, \text{Cohen } d = 1.421$), but not in the invisible-cue condition ($t(19) = .170, p = .867, \text{Cohen } d = .038$).

Valid benefit effect

As with the cost effect, the benefit effect also differed between the invisible-cue and visible-cue conditions, as confirmed by a significant Trial condition (Valid and No cue) $\times$ Cue type (Invisible cue and Visible cue) ($F(1, 19) = 33.093, p < .001, \eta_p^2 = .635$). A planned comparison showed that the benefit effect was obtained in the invisible-cue condition ($t(19) = 2.559, p = .019, \text{Cohen } d = .572$). However, in the visible-cue condition, as in Experiment 2a, a reversed benefit effect (better performance in the No cue condition than in the valid condition) was observed ($t(19) = 5.101, p < .001, \text{Cohen } d = 1.141$).

Figure 5 (A): Schematic illustration of the trial sequence of invisible-cue, short SOA (118 ms) condition in Experiment 3. (B): The mean accuracy of the target report in different conditions. (C): The cost and benefit effects in invisible-cue and visible-cue conditions at short SOA.

Experiment 3 showed that the invalid cost effect was only present when the cue was visible, but not when the cue was invisible. This result directly supported the MEC theory that the invalid cost was driven by memory encoding of the cue. Furthermore, despite the lack of an invalid cost, the benefit was still present in the invisible-cue condition, suggesting that attention can be triggered by a spatial cue without necessarily needing to encode that cue. The benefit-

without-cost effect observed here strongly argues against traditional attentional limitation theories, and fits well with the MEC theory. In addition, as in Experiment 2a, a cost for a valid cue was obtained, this time in the visible-cue condition. This supports the MEC theory's assumption that the benefit effect reflects a net effect of both memory encoding induced cost and attentional enhancement.

It remains possible that participants have a residual perception of the masked cue (despite not being aware of the cue) in the invisible condition, which might enable them to achieve a performance better than chance if given a two-alternative-force-choice task (i.e., forcing participants to report the location of the invisible cue). Were this true, the results of this experiment would suggest that such a residual processing of the masked cue is insufficient to produce a noticeable cost effect. This is an interesting point, despite not being the focus of the current study, and is worth considering and exploring in the future.

Experiment 4

The MEC theory of cueing posits that cueing costs and the AB are driven by a common mechanism, which is encoding the first item into memory, whether that be a T1 or a spatial cue. The preceding experiments supported this by showing that increasing the requirements of cue-encoding (either by increasing the amount of encoding cue information or by masking the cue)

alters the depth of the cueing effect, even to the point of reversing the cueing benefit in the case of a masked cue. However, the AB's characteristic U-shape is typically found when two targets are presented in the same location, which is the equivalent of a valid cue trial. This U-shape includes a data point known as *Lag-1 sparing*, in which performance is better at shorter SOAs (i.e., Lag1) than longer ones (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992).

However, there has been no reliable Lag 1 effect in the preceding experiments (Cue color report group of Experiment 1 revealed a small but not significant Lag-1 effect).

If our hypothesized link between spatial cueing and the AB has some basis, then it should be possible to exhibit Lag-1 sparing in a spatial cueing task as well. That is, if the cue is effectively treated as a T1, there should be a short window of time in which it is easier to report a subsequent target (i.e., T2). We hypothesized that the lack of Lag 1 sparing effect in the previous experiments was due to the placeholders, which were small circles that were contained within the spatial extent of the cue. This arrangement may have enhanced the visual representation of the cued placeholder, such that it interfered with processing of the following target at short SOAs only in valid trials⁶. Only in valid trials did the cue, placeholder and target occur at the same location and in rapid succession. Such a competitive interference has been found to occur at

⁶ This possibility was suggested to us by the phenomenal experience that the cued placeholder seemed to pop out of the display quite strongly.

very short SOAs (50-100 ms; Potter, Staub & O'Connor, 2002; Wyble, Potter, Bowman & Nieuweinstein, 2011), leading to tradeoffs in processing of the two targets. This competitive tradeoff is maximal at SOAs prior (50-100 ms) to the peak of the AB (200-300 ms).

Therefore, in this experiment we replaced the circle placeholders with bigger squares such that the cue bars occurred inside the placeholder, rather than outside it. We predicted that we would now observe Lag-1 sparing in the valid condition wherein the target letter appeared at the same location as preceding cue, since previous studies demonstrated that Lag 1 sparing typically only occurred when T2 and T1 were presented at the same spatial location (c.f. Visser, Zuvic, Bischof, & Di Lollo, 1999).

In addition, in previous experiments the placeholders disappeared simultaneously with the cue on cue-present trials but remained on the screen until the presentation of target on no-cue trials, we speculate this might cause the better performance on the invalid trials than no-cue trials at long SOAs. Although the long SOAs are not the focus of MEC theory, this potential issue slightly complicates the interpretation of the current findings. To eliminate this potential issue, the placeholders on this and following experiments remained on the screen until the onset of the target stimulus on all trials. In addition, we increased the encoding demands of the cue to increase the strength of memory encoding induced cost.

Method

This experiment was identical to the color report group of Experiment 1 except as noted below. A new group of twenty undergraduates completed the experiment. Five additional participants were excluded with the same criterion as previous experiments. As depicted in Figure 6 A, placeholders were black square outlines ($3.46^\circ \times 3.46^\circ$) instead of small black circles, which remained on the screen until the onset of the target on all trials. The cue consisted of two lines with the same color (red: 200/0/0, blue:0/200/200; yellow:200/200/0; or purple: 190/45/200), and there were four different types of cues basing on the length of two lines: short-short (1.15° length in degree), long-long (3.46° length in degree), above-short-below-long, and above-long-below-short, see Figure 6 A. The cue and target durations were 54 ms and 40 ms respectively. Another difference is that we added one new trial condition, namely the central cue condition, in which the cue was presented near the central fixation, with each bar being 1.53° degree above and below the fixation. This Central-cue condition was intended for future work comparing the effects of different kinds of neutral cues but a revision of the paper has prompted us to include these analyses in Section 4. There were three cue-target SOA conditions: 107, 214, and 709 ms. On each trial, participants were asked to report target letter, followed by the color of cue, and then the cue type. For the cue type report, participants were required to select the cue (or No-cue choice if no cue) they had just seen in a five-alternative-force-choice task (four

different types of cue plus the No-cue choice). There were 5 blocks, with each block containing 36 trials (9 Invalid, 9 No cue, 9 Valid, and 9 Central cue trials), resulting in a total of 180 trials.

The cue was informative about the following target location. There were 12 practice trials before the experiment.

Results and Discussion

The accuracy of cue color and length response were .92 (SD = .09) and .73 (SD = .14).

The mean accuracy of the target report as a function of Cue-target SOA in Experiment 4 is depicted in Figure 6B.

As the main purpose of the present experiment is to investigate whether Lag 1 sparing can be obtained on valid trials, here we compared the target performance of valid trials among three SOAs. The results showed that the target performance of valid trials dropped from 107 to 214 ms SOA, and then recovered at 709 ms SOA, with the performance being significantly different between 107 and 214 ms SOAs ($t(19) = 3.347, p = .003, \text{Cohen } d = .749$), and between 214 and 709 ms SOAs ($t(19) = 3.535, p = .002, \text{Cohen } d = .790$), but not between 107 and 709 ms SOAs ($t(19) = .110, p = .914, \text{Cohen } d = .025$). These results showed a classic Lag 1 sparing effect on valid trials. As predicted, there was no Lag 1 sparing on invalid trials, with target performance being comparable between 107 and 214 ms SOAs ($t(19) = .328, p = .746, \text{Cohen } d$

= .073). In addition, target performance on invalid trials at 709 ms SOA was significantly better than 107 ms SOA ($t(19) = 5.907, p < .001$, Cohen $d = 1.321$), and 214 ms SOA ($t(19) = 5.007, p < .001$, Cohen $d = 1.120$).

In addition, in contrast to some of previous experiments showing worse performance in the No-cue condition than in the Invalid condition at the long SOAs, here this effect was eliminated, with the performance in the No-cue condition being even numerically (although not significant) better than that of Invalid condition (No-cue: 0.72 vs. Invalid: 0.69, $t(19) = 1.057, p = .304$, Cohen $d = .24$).

Figure 6. (A): Four different types of cue display. (B): The mean accuracy of the target report as a function of Cue-target SOA in Experiment 4.

In summary, the current experiment showed a Lag 1 sparing effect on valid trials, but not on invalid trials, which is in accordance with the prediction of the MEC theory. This finding further supports our assumption that cueing costs and the AB share a common mechanism. In addition, this observation argues against the possibility that the effects of cue encoding on target report reflect a simple resource tradeoff. This is because this resource depletion hypothesis would predict a reversed result pattern relative to the Lag 1 effect, such that the target performance should be worse at 107 ms SOA than 214 ms SOA, since less resource should be

available for subsequent target at shorter SOA condition when the processing of prior cue was still ongoing. Moreover, the cue encoding requirement was increased in this case because of adding an additional feature (i.e., cue length).

Another finding is that the reversed cost effect at long SOAs (i.e., better performance in the Invalid condition than in the No-cue condition) was absent in this experiment when the placeholders no longer disappeared prior to target onset. Thus, this finding supports our assumption that the reversed effect was driven by the disappearance of the placeholder. It is crucial to note that this placeholder issue does not affect the key findings supporting the MEC from previous experiments (Experiments 1, 2a, and 2b), which is that the invalid cost increased (and the valid benefit decreased) as the increment of cue memory encoding across experiments, since any influences from this placeholder issue would be cancelled when doing comparisons across these manipulations. Furthermore, the findings of the current experiment are still in favor of the MEC model even after the potential placeholder issue was removed. The remaining experiments will also not involve the disappearance of placeholders.

Section 2: How do spatial cueing effects vary across blocks?

In the previous section, cueing costs increased and cueing benefits decreased as the requirements to encode the cue into memory were increased, which supports Prediction 1 of the

MEC. In this section we tested the MEC using a more typical cueing paradigm, in which participants never have to report the cue. In such cases we predict that the amount of cue-encoding decreases with experience in the task as subjects become more efficient at remembering only the information that must be reported. We assume therefore that information about the cue will be encoded into working memory at the start of an experiment and steadily decrease across trials⁷. If our assumption is correct and the cost is linked to memory encoding, then the cueing cost should also decrease across trials when participants are not required to report the cue.

Furthermore, according to the MEC account, even as costs decrease, the benefit effect should not decrease across trials, since attention is triggered by a cue irrespective of whether it is encoded into memory. In fact, according to the MEC, since the observed benefit of a valid cue reflects the sum of attentional enhancement and encoding costs, if attentional enhancement remains constant while encoding is reduced, the observed benefit should increase. In this section we test these predictions with a series of experiments.

Experiment 5

⁷ We assume this for now, but this assumption is tested in the next section of the paper.

In this experiment participants only reported the target on each trial. The aim of the experiment was to explore whether and how cost and benefit effects vary across trials within an experiment.

Method

This experiment was identical to the No Cue report group of Experiment 1 with the exception noted below. A new group of thirty undergraduates completed the experiment. Three additional participants who completed the experiment were excluded according to the criterion reported for Experiment 1. The target duration was shortened to 67 ms, to provide more sensitivity for detecting benefit effects. The cue duration was 94 ms. Another change to increase the power is to remove the 308 and 508 ms SOA conditions, leaving only 107, 201, and 709 ms SOAs. The 709 ms SOA serves as a control condition that we predict should not reveal a cost effect in any cueing condition. As in Experiment 4, there was a Central-cue condition in this experiment which will be discussed in Section 4. As before, the placeholders remained on the screen until the presentation of the target in all conditions. The cue was uninformative about the target location, as in Experiment 1.

Results and Discussion

The mean accuracy of the target report as a function of Cue-target SOA in Experiment 5 is depicted in Figure 7A.

The experiment consisted of 9 counterbalanced blocks to distribute the conditions evenly across the experiment. We divided the trials into three groups: Blocks 1-3, Blocks 4-6, and Blocks 7-9. As predicted, preliminary analysis showed that there was no cost effect ($t(29) = .878, p = .387$, Cohen $d = .165$) in the long SOA control condition (i.e., 709 ms SOA), and the data of this SOA did not enter into the following block analysis. A 2 (SOA: 107 and 201 ms) $\times 3$ (Trial condition: Invalid, No Cue, and Valid) $\times 3$ (Block: Blocks 1-3, Blocks 4-6, and Blocks 7-9) repeated measures analysis of variance (ANOVA) was performed on target accuracy, with all three factors as within factors. Significant main effects were found for SOA ($F(1, 29) = 14.988, p < .001, \eta_p^2 = .341$), Trial condition ($F(2, 58) = 26.747, p < .001, \eta_p^2 = .480$), and Block ($F(2, 58) = 3.181, p = .049, \eta_p^2 = .099$). Significant 2-way interactions were observed for Trial condition $\times$ Block ($F(4, 116) = 3.435, p = .011, \eta_p^2 = .106$), which was the crucial test and also SOA $\times$ Trial condition ($F(2, 58) = 6.873, p = .002, \eta_p^2 = .192$), but not for SOA $\times$ Block ($F(2, 58) = 2.038, p = .140, \eta_p^2 = .066$). The 3-way interaction was not significant ($F(4, 116) = .305, p = .874, \eta_p^2 = .010$).

Below we will unpack the Trial condition $\times$ Block interaction to examine the costs and benefits separately. In addition, as the 3-way interaction was not significant, the data were

collapsed across 107 and 201 ms SOA conditions while analyzing block effects for the cost and benefit. Consequently, two separate 2 (Trial condition) $\times$ 3 (Block) repeated measures ANOVAs were conducted to illustrate the block effects of the cost and benefit.

Block effect of Cost

The analysis of the cost effect (No-cue - Invalid) yielded a significant main effect of Trial condition ($F(1, 29) = 41.789, p < .001, \eta_p^2 = .590$), such that the overall target performance was significantly worse in the Invalid condition than in the No cue condition (i.e., Invalid cost effect). Critically, the analysis showed a significant interaction between Trial condition and Block ($F(2, 58) = 5.791, p = .005, \eta_p^2 = .166$), suggesting that the cost effect varied across blocks (Blocks 1-3: 21%, Blocks 4-6: 10%, Blocks 7-9: 7%, see Figure 7B). Planned comparisons showed that the cost at Blocks 1-3 was significantly larger than those at Blocks 4-6 ($F(1, 29) = 7.448, p = .011, \eta_p^2 = .204$) and Blocks 7-9 ($F(1, 29) = 9.394, p = .005, \eta_p^2 = .245$), whereas the cost did not significantly differ between the latter two blocks ($F(1, 29) = .565, p = .458, \eta_p^2 = .019$).

Block effect of benefit

The analysis of the benefit (Valid – No-cue) showed a significant main effect of Trial condition ($F(1, 29) = 4.515, p = .042, \eta_p^2 = .135$), indicating that the overall target performance in the Valid condition was better than in the No Cue condition. However, there was no

significant block effect of benefit, as confirmed by a non-significant interaction between Trial condition and Block ($F(2, 58) = 1.381, p = .260, \eta_p^2 = .045$).

In summary, the current experiment revealed a clear block effect for cost, such that the cost dropped across the experiment duration, as we had predicted. In contrast, the benefit did not reduce over trials, and actually increased numerically (Blocks 1-3: 2%, Blocks 4-6: 9%, Blocks 7-9: 7%) although this effect was not significant. Consequently, this experiment revealed novel observations that costs and benefits of spatial cueing effects vary differentially across blocks,

which, to the best of our knowledge, has not been reported in previous cueing studies. These findings are of great importance for our understanding of the nature of spatial cueing effects, since they might be able to explain why costs and benefits analyses can be inconsistent across studies. Trial count often varies dramatically between experiments, and our findings here suggest that trial count should affect the ratio of costs to benefits.

Experiment 6

It might be argued that the block effect observed in Experiment 5 reflects the fact that participants learn to ignore the cue as the experiment progresses because the cue was uninformative (the cue validity is 25% for four locations) and thereby useless in predicting the location of the subsequent target. To test this possibility, here we replicated Experiment 5 except with an informative cue by setting the cue validity as 50%.

Method

This experiment was identical to Experiment 5 except as follows. A new group of thirty undergraduates participated in the experiment. One additional participant completed the experiment but was excluded based on the criterion reported before. The cue validity was 50% instead of 25%, and thus was informative about the target location.

Results and Discussion

The results of Experiment 6 are depicted in Figure 8 and were almost the same as Experiment 5. The ANOVA analysis showed a significant main effect for Trial condition ($F(2, 58) = 44.494, p < .001, \eta_p^2 = .605$), but not for Block ($F(2, 58) = .644, p = .529, \eta_p^2 = .022$) or SOA ($F(1, 29) = 3.784, p = .061, \eta_p^2 = .115$). Critically, the Trial condition $\times$ Block ($F(4, 116) = 5.664, p < .001, \eta_p^2 = .163$) was significant. No other interactions reached significance (all $ps > .15, \eta_p^2 < .07$).

As in Experiment 5, we conducted two separate 2 (Trial condition) $\times$ 3 (Block) repeated measures ANOVAs to evaluate the block effects of the cost and benefit respectively.

Block effect of cost

Consistent with Experiment 5, the cost effect was variant across blocks (Blocks 1-3: 21%, Blocks 4-6: 12%, Blocks 7-9:5%, see Figure 8B), as confirmed by the significant Trial condition $\times$ Block interaction ($F(2, 58) = 9.199, p < .001, \eta_p^2 = .241$). In addition, there was a significant main effect for Trial condition ($F(1, 29) = 20.706, p < .001, \eta_p^2 = .417$), but not for Block ($F(2, 58) = .709, p = .496, \eta_p^2 = .024$). Planned comparisons showed that the cost at Blocks 1-3 was significantly larger than those at Blocks 4-6 ($F(1, 29) = 6.442, p = .017, \eta_p^2$

= .182) and Blocks 7-9 ($F(1, 29) = 17.571, p < .001, \eta_p^2 = .377$), and the cost did not significantly differ between Blocks 4-6 and Blocks 7-9 ($F(1, 29) = 3.306, p = .079, \eta_p^2 = .102$).

Block effect of benefit

As in Experiment 5, the block effect of benefit did not reach significance, as confirmed by the nonsignificant interaction between Trial condition and Block ($F(2, 58) = 2.723, p = .074, \eta_p^2 = .086$). However, the main effect of Trial condition was highly significant ($F(1, 29) = 24.274, p < .001, \eta_p^2 = .455$), such that the target performance was significantly better in the Valid than in the No cue condition.

Figure 8. (A): The mean accuracy of the target report as a function of Cue-target SOA in Experiment 6. (B): The cost and benefit effects across blocks in Experiment 6 which were generated with the average data of 107 and 201 ms SOAs. The error bars represent standard errors.

Consistent with Experiment 5, this experiment revealed a strong block effect of cost, such that the cost declined with blocks, even though the cue was now informative in predicting the location of the following target. Despite non-significance, the benefit numerically increased across blocks (Blocks 1-3: 6%; Blocks 4-6: 10%; Blocks 7-9: 14%). More importantly, the overall benefit was reliable, suggesting that the cue was effective in triggering attention, especially at late blocks, which argues against the possibility that participants learn to simply ignore the cue as the experiment progresses. Collectively, Experiments 5 and 6 indicate that

participants learn to avoid the negative effects of an invalid cue without losing the facilitative benefits of a valid cue. This finding is difficult to accommodate with a capacity theory of attention, which predicts that reductions in the invalidity cost would be mirrored (in direction if not exactly in lockstep) by changes in the validity benefit.

Experiment 7

Experiments 5 and 6 showed that spatial cueing effects were not invariant across blocks, with the cost decreasing while the benefit remaining consistent across blocks. These results support our memory variation hypothesis; that is, participants automatically encode some aspects of cue information (e.g., location) at the beginning of experiment and then learn to no longer encode that information as they repeatedly experience the task, thereby leading to the observed block effects. To further test this hypothesis, we asked participants to report only the target during the first half of the experiment, and then in the middle of the experiment we unexpectedly switched the task by asking them to report the cue color as well as the target. We predicted that the cost effect should drop across the first half of the experiment and then immediately increase when participants were asked to report cue color. Furthermore, this strengthened cost effect should remain through the second half of the experiment wherein participants were continually asked to report cue color, rather than declining as in the first half of experiment.

Method

The experiment was identical to Experiment 5 with some changes as noted below. A new group of thirty undergraduates participated in this experiment. One additional participant was excluded with the criterion as before. The experiment included 8 blocks to distribute counterbalancing, with each block consisting of 12 Invalid, 4 Valid, and 4 No Cue trials, totaling 160 trials. Only 107 and 709 ms SOA conditions were employed, with the 709 ms SOA being a control condition as in Experiments 5 and 6. In the first half of the experiment (i.e., Blocks 1-4), participants were asked to report only the target letter, while in the second half of the experiment (i.e., Blocks 5-8) they were unexpectedly asked to report the cue color after the target report. As in Experiment 1, the cue was uninformative about the target location.

Results and Discussion

The results of Experiment 7 are depicted in Figure 9. We split the data into four block groups: Blocks 1-2, Blocks 3-4, Blocks 5-6, and Blocks 7-8. A 3 (Trial condition: Invalid, No Cue, and Valid) $\times$ 4 (Block: Blocks 1-2, Blocks 3-4, Blocks 5-6, and Blocks 7-8) repeated measures analysis of variance (ANOVA) was performed on the target accuracy, with both factors as the within factors. Significant main effect was obtained for Trial condition ($F(2, 58) = 82.111$, $p < .001$, $\eta_p^2 = .739$), but not for Block ($F(3, 87) = 2.002$, $p = .120$, $\eta_p^2 = .065$). Critically, the

interaction between Trial condition and Block was significant ($F(6, 174) = 3.959, p < .001, \eta_p^2 = .120$).

As before, we conducted two separate 2 (Trial condition) $\times$ 4 (Block) repeated measures ANOVAs to evaluate the block effects of the cost (Trial conditions: No-cue vs. Invalid) and benefit (Trial conditions: No-cue vs. Valid) respectively.

Block effect of cost

The analysis revealed a reliable cost effect ($F(1, 29) = 91.763, p < .001, \eta_p^2 = .760$), and more importantly, this cost effect significantly varied across blocks ($F(3, 87) = 7.136, p < .001, \eta_p^2 = .197$, see Figure 9B). A planned comparison showed that the cost significantly declined from Blocks 1-2 to Blocks 3-4 (Blocks 1-2: 35% vs. Blocks 3-4: 18%, $F(1, 29) = 13.967, p < .001, \eta_p^2 = .325$), in which participants were asked to report the target only. Furthermore, as expected, the cost increased in Blocks 5-6 wherein participants switched to report both target letter and cue color, in comparison with that in Blocks 3-4 (Blocks 3-4: 18% vs. Blocks 5-6: 39%, $F(1, 29) = 16.502, p < .001, \eta_p^2 = .363$). This increase in cost did not significantly drop from Blocks 5-6 to Blocks 7-8 (Blocks 5-6: 39% vs. Blocks 7-8: 32%, $F(1, 29) = 2.002, p = .168, \eta_p^2 = .065$), where participants were continually asked to report the cue color as well as the target.

Block effect of benefit

An analogous analysis for the benefit showed that the interaction between Trial condition and Block was not significant ($F(3, 87) = 1.598, p = .196, \eta_p^2 = .052$), indicating that there was no reliable block effect of benefit. In addition, neither the main effect of Trial condition ($F(1, 29) = 1.526, p = .227, \eta_p^2 = .050$) nor the Block ($F(3, 87) = .032, p = .992, \eta_p^2 = .001$) reached significance. As participants were required to report the cue color on the second half of the experiment, but not at the first half of experiment we split the data into two groups, and found that there was a significant benefit effect on the first half of experiment (No-cue: 0.87 vs. Valid: 0.93, $t(29) = 2.186; p = .037$, Cohen $d = .399$), whereas the benefit effect was absent in the second half of experiment (No-cue: 0.91 vs. Valid: 0.90, $t(29) = .441; p = .662$, Cohen $d = .081$).

Figure 9. (A): The mean accuracy of the target report as a function of cue condition at different blocks in Experiment 7. (B): The cost and benefit effects across blocks in Experiment 7 which were generated with the data of 100 ms SOA. The error bars represent standard errors.

As predicted, the current experiment showed a decline of cost from early blocks (Blocks 1-2) to middle blocks (Blocks 3-4) when participants were not required to report any information of the cue, again supporting our memory variation hypothesis. The cost increased once participants were switched to report the cue color in Blocks 5-6 and did not significantly decrease in Blocks 7-8. This is consistent with the findings of Experiment 1 showing that requiring participants to report cue color would boost the cost effect. In addition, the benefit effect was only present in the first half of the experiment wherein participants were not asked to report any information about the cue, but not in the second half wherein participants were required to report the cue color. This replicates the distinction in benefits between the No-cue-report and Cue-color-report

conditions of Experiment 1. This result is also in line with the MEC theory suggesting that the observed benefit effect is a net effect of attentional facilitation and memory encoding cost.

Generally, these findings showed clear changes in the cost and benefit effects as the result of changes in memory encoding within the same experiment, thereby providing stronger and more direct evidence that memory encoding of the cue plays a crucial role in yielding cueing effects.

Section 3: Probing the memory of the cue with surprise tests

In section 2 we confirmed Prediction 2 by demonstrating that spatial cueing effects varied across blocks, which we assume reflected a change in memory encoding of the cue with experience in the task. Namely, cueing costs change because participants automatically encode some information from the cue (e.g., location) at the beginning of the experiment and then learn to avoid encoding that information across trials. In the third section, we tested Prediction 3, which suggests a link between block-wise changes in spatial cueing costs and the ability to remember the cue's location. In these experiments we directly probed participants' memories of the cue location at the early and late blocks by using surprise tests developed in studies of inattention blindness (e.g., Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005; Simons & Chabris, 1999), change blindness (e.g., Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1998) and attribute amnesia (Chen, Carlson, & Wyble, in press; Chen & Wyble, 2015a,

2015b, 2016; Chen, Swan, & Wyble, 2016; Huhn, Chen, Wyble, & Dennis, in press; Swan, Wyble, & Chen, 2017). The core prediction is that the decline of cost effects across blocks would be accompanied by a corresponding decrease in the ability to report cue location information. These experiments could provide more direct evidence that the cost effect is linked to memory encoding of the cue.

Experiment 8

This experiment tested participants' memories of the cue location at early and late blocks. Experiment 6 was replicated with the addition of a surprise question asking participants to report the location of the cue they had just seen. The surprise question was placed in either the very first block or in the last block of the experiment, and of interest here is to compare participants' memory performance of the cue location in these two conditions (early vs. late surprise questions). According to the aforementioned assumption, we predicted that participants' memory of cue location would be better when it was probed on an early surprise question than when it was probed at a late surprise question. The results of this experiment confirmed our prediction.

Method

This experiment was identical to Experiment 6 except as noted below. A new group of sixty undergraduates completed the experiment. These participants were randomly assigned to two groups: Early-surprise test group vs. Late-surprise test group. Four additional participants were excluded according to the criterion reported before. As depicted on Figure 10A, on the Early-surprise group participants received a surprise question in the first block (i.e., Trial 17), whereas on the Late-surprise group participants got the surprise question at the last block (i.e., Trial 323). The surprise question on these two groups read “This is a surprise memory test, where were the purple bars on the last trial? Press a number (1-4) to indicate the location of the purple bars” with 4 alternative force choice location report options as in Experiment 1. Note that the cue color was purple on every trial. After reporting location, participants were asked to report the target identity as usual. After the surprise trial, all participants continued to be asked to report the cue location. These post-surprise trials served as control trials, since the trial structure was exactly like the surprise trial with the only difference being that participants now had an expectation that they might need to report the cue. On both early and late surprise groups, the surprise and first control trial (i.e., the trial immediately followed the surprise trial) were always invalid with 107 ms SOA, which enables the direct comparison of cue location report between the surprise and first control trial. However, for the other following control trials of the early

surprise group, there were three different SOA conditions (107, 201, and 709 ms) as in pre-surprise trials.

Participants from the Early-surprise group completed 7 blocks, with the first block containing 18 trials (16 pre-surprise trials, 1 surprise and 1 control trial), and the other 6 blocks containing 36 post-surprise/control trials each. Participants were asked to report cue location after the target report on all post-surprise trials. In the Late-surprise group participants completed 9 blocks, with each block containing 36 trials (12 Invalid, 12 No cue, and 12 Valid trials), resulting a total of 324 (36×9) trials. The surprise (i.e., Trial 323) and control trials (i.e., Trial 324) of the Late-surprise group were the last two trials of the experiment. As in Experiment 6, the cue was informative about the target location.

Results and Discussion

The results of this experiment are illustrated in Figure 10B and 10C.

Block effects of cost and benefit. The same analyses were performed to examine the block effects as in Section 2. We replicated the block effect of cost in 322 pre-surprise trials of the Late-surprise test group wherein participants were asked to report the target letter only, with the cost declining over blocks (Blocks 1-3: 33%; Blocks 4-6: 17%; Blocks 7-9: 14%, $F(2, 58) = 19.464$, $p < .001$, $\eta_p^2 = .402$). By contrast, the cost effect did not significantly change across

post-surprise blocks in the Early-surprise test group wherein participants were asked to report cue location on every trial after the surprise trial (Blocks 2-4: 33%; Blocks 5-7: 28%, $F(1, 29) = 1.430$, $p = .241$, $\eta_p^2 = .047$). For the benefit, however, there was no block effect on either of these two groups ($ps > .339$, $\eta_p^2 < .037$). These results generally replicated the findings in Section 2.

Surprise memory test on cue location. Of more importance is that, for the Late-surprise group, participants' memory of the cue's location was substantially worse on the surprise trial relative to the post-surprise/control trial, 53% vs. 87%, $\chi^2(1, N = 60) = 7.937$, $p = .005$, $\phi = .36$). However, for the Early-surprise group, participants' memory of cue's location on the surprise trial was numerically worse than the first post-surprise/control trial but the difference did not reach significance (83% vs. 97%, $\chi^2(1, N = 60) = 2.963$, $p > .085$, $\phi = .22$). High performance on the control trials also demonstrates that participants were able to rapidly alter their task set to encode the cue location once they had an expectation that it would be probed. Crucially, a direct comparison of cue location memory on the surprise trial between these two groups showed that participants' memory performance was significantly worse in the Late-surprise group than in the Early-surprise group (53% vs. 83%, $\chi^2(1, N = 60) = 6.239$, $p = .012$, $\phi = .32$). Note that, the surprise questions on these two groups were exactly the same, and thus the observed memory

performance decline provides more direct evidence favoring the memory variation hypothesis, such that participants automatically encode cue location at the beginning of the experiment and then reduce the probability of encoding that information into memory as the experiment progresses.

Figure 10. (A): The illustration of experimental design in Experiment 8. (B): The cost and benefit effects across post-surprise blocks in the Early-surprise group of Experiment 8. (C): The cost and benefit effects across pre-surprise blocks in the Late-surprise group of Experiment 8. The data in all these figures were generated with the average data of 107 and 201 ms SOA. The error bars represent standard errors.

The current experiment not only replicated the block effects of cueing from Section 2, but more importantly, it showed that the decline of cost across blocks was accompanied by a corresponding drop in memory of cue location. This provided more direct evidence for the close link between cueing effects and memory encoding of cue as claimed by the MEC theory.

Experiment 9

In most of the previous experiments the benefit effect was small relative to the cost effect. One possible reason for this asymmetry is that the target letter was presented alone, which gave it an extremely large salience. A high salience target may have been able to trigger attention by itself, overwriting the weaker attentional configuration set by the cue. Another possibility is that, as the target was presented alone, there was relatively little noise that a valid cue could mitigate, since previous studies suggested that the benefit effect might arise from noise reduction (e.g., Shiu & Pashler, 1994). Both of these possibilities imply that a larger benefit effect could be obtained if the target is presented simultaneously with distractors, either reducing the attentional capture by the target or by increasing the amount of noise to be suppressed.

More importantly, it could be possible that increasing the benefit of valid cueing could change the encoding strategy such that participants might continue to encode such a beneficial

cue, thus leading to stable cost effects across time. If this is the case, unlike Experiment 8 in which subjects could not report the cue location accurately towards the end of the experiment, they should now have relatively robust memories of the cue location through the entire experiment even without being probed for cue location. To test this possibility, we adopt the exactly same cue as previous experiments but presented the target with three simultaneous distractors.

Method

This experiment was identical to Experiment 8 except as noted below. A new group of sixty undergraduates completed the experiment. Four additional participants were excluded based on the same criterion reported in previous experiments. On each trial the target letter was always presented together with three randomly selected distractor digits (2-8) without repetition. In addition, in the Early-surprise group, participants only received one single post-surprise trial (i.e., control trial) and the experiment ended. There were three cue-target SOA conditions: 80, 161, and 696 ms. For cue-present trials the cue was 50% valid and thus informative about the target location (there were four possible locations).

Results and Discussion

The results of this experiment are illustrated in Figure 11. The same analyses were conducted as in Experiment 8. Contrary to Experiment 8, the cost effect was constant across blocks in pre-surprise trials of Late-surprise group (Blocks 1-3: 24%, Blocks 4-6: 26%, Blocks 7-9: 24%; $F(2, 58) = 0.148, p = .863, \eta_p^2 = .005$). Furthermore, participants could usually correctly report the cue location when given a surprise question, irrespective of whether the surprise question was placed on the first block (24/30= 80% correct) or last block (22/30= 73% correct), with their performance being not significantly different ($\chi^2(1, N = 60) = .373, p > .54, \phi = .08$). In addition, neither group showed a significant difference on cue location report between the surprise and control trial (Early-surprise group: 24/30=80% vs. 26/30=87%, $\chi^2(1, N = 60) = .480, p > .48, \phi = .09$; Late-surprise group: 22/30=73% vs. 26/30=87%, $\chi^2(1, N = 60) = 1.667, p > .19, \phi = .17$).

As predicted, unlike in previous experiments which produced a small benefit effect, here the benefit effect in pre-surprise trials of Late-surprise group was consistently large (Blocks 1-3: 21%, Blocks 4-6: 17%, Blocks 7-9: 18%; $F(2, 58) = 0.806, p = .452, \eta_p^2 = .027$). This supported our assumption that the small benefit effect observed in previous experiments was due to the fact that the target was presented alone, which reduced the effectiveness of the cue. Furthermore, the relative ineffectiveness of the cue contributed to a decrease in encoding.

Figure 11. The cost and benefit effects across pre-surprise blocks in the Late-surprise group of Experiment 9. The data in all these figures were generated with the average data of 80 and 161 ms SOA. The error bars represent standard errors.

These results showed that, unlike previous experiments in which there was a robust decline of cue encoding across blocks, participants in the current experiment continued to encode the cue location into memory throughout the experiment. These results suggest that it is the *effectiveness* of the cue (i.e., the effectiveness of the cue in facilitating target performance on valid trials) that determines whether participants will automatically encode the cue into memory or not.

Section 4: Extending the scope of the MEC model

In this section we test Prediction 4 which is that the MEC model will generalize to a broader set of cueing cases, including central-cue baselines and reaction time measures. First, the costs and benefits reported in previous sections were measured against a No-cue baseline (i.e., we compared the Valid and Invalid cues against a No-cue baseline), which leaves an open

question of whether the MEC model could account for the data of other kinds of spatially neutral baseline conditions, such as a centrally presented cue. As mentioned before, several of the preceding experiments (Experiments 4-6) not only contained a No-cue baseline, but also included a Central-cue baseline condition, similar to what is frequently used in the cueing literature. Such cues are useful because they provide equivalent temporal information about the arrival of a target, but do not provide a spatial bias towards one of the locations. However, they are not suitable as baseline conditions for testing the MEC because those central cues could potentially be encoded into memory, just as an invalid cue is. Here we analyzed the data from these Central-cue baseline conditions to examine whether and how these data can be accounted for by the MEC model.

Second, the previous experiments described here used accuracy-based paradigms and thus focused only on measures of accuracy for masked targets. Here we tested whether the MEC model's predictions generalize to reaction time measures.

Part 1: Generalizing the MEC account to Central-cue paradigms

According to the MEC model, the central cue would also be encoded into memory and thus should produce an encoding-induced cost in a similar manner as an invalid cue. To test this prediction, we used the Central-cue condition in Experiments 4-6. As shown in Figure 12, the results of the Central-cue condition were almost identical to that of Invalid-cue condition in

Experiment 4 wherein participants were asked to report some information (i.e., color and length) of the cue. For instance, the cost (i.e., No-cue – Central-cue) triggered by the central cue was comparable to the cost yielded by the invalid cue (22% vs. 22%, $t(19) = .043$; $p = .967$, Cohen $d = .01$). Thus, when using a central cue as a baseline, Experiment 4 would reveal no cost. However, if cue effectiveness were determined as the difference between valid and invalid trials, as is often done, a validity effect would be observed.

Figure 12. The mean accuracy of the target report as a function of Cue-target SOA in all four conditions (Invalid, Valid, No-cue, and Central-cue condition) of Experiment 4.

In contrast, for Experiments 5 and 6, in which subjects had no requirement to report the cue, the Central-cue-triggered cost was significantly smaller than the Invalid-cue-triggered cost (Experiment 5: 5% vs. 13%, $t(29) = 4.00$; $p < .001$, Cohen $d = .730$; Experiment 6: 1% vs. 13%, $t(29) = 5.953$; $p < .001$, Cohen $d = 1.087$). The smaller cost evoked by the central cue, compared to an invalid cue can be explained by the MEC if we assume that it is faster to encode a cue at

fixation, or that subjects are better able to ignore such a cue. The superior performance for the central cue compared to the invalid condition would cause a measurable cost when a central-cue is used as a baseline.

More importantly, the results of Experiments 5-6 showed that the cost triggered by the central cue showed a similar block effect as that triggered by the invalid cue, with the cost being significantly reduced across blocks (Experiment 5 (Figure 13A): Blocks 1-3: 12%, Blocks 4-6: 4%, Blocks 7-9: 1%; $F(2, 58) = 3.170$, $p = .049$, $\eta_p^2 = .099$; Experiment 6 (Figure 13B): Blocks

1-3: 7%, Blocks 4-6: 1%, Blocks 7-9: -3%; $F(2, 58) = 4.484$, $p = .015$, $\eta_p^2 = .134$).

A Experiment 5: Central cue

B Experiment 6: Central cue

Figure 13. The central-cue related results of Experiment 5. (A): Left figure: the mean accuracy of the target report as a function of all four cue conditions of Experiment 5; Right figure: the cost effect triggered by a central cue (No-cue – Central-cue) across blocks in Experiment 5, which were generated with the data of 107 and 214 ms SOA. (B): The Central-cue related results of Experiment 6, which are essentially the same as those of Experiment 5 depicted in (A). The error bars represent standard errors.

In summary, the findings of the Central-cue baseline condition from Experiments 4-6 suggest that a central cue was also encoded into memory and produced an essentially similar (though smaller) cost as an invalid cue. This result provides further converging evidence in favor of the MEC model.

Part 2: Generalizing the MEC account to RT measures (Experiment 10)

Here we sought to replicate key findings supporting the MEC model using reaction time instead of accuracy. Unlike in all previous experiments, in Experiment 10 we adopted an RT-based measure of target processing. The purpose of this experiment is to demonstrate a similar block effect of cueing as in Experiments 5 and 6.

Method

The experiment was identical to Experiment 5 except as follows. A new group of 30 undergraduates from Zhejiang University participated in this experiment. Stimuli were presented on a 17-in CRT monitor with a resolution of 1024×768 and refresh rate of 60Hz. As this is a RT-based experiment, the target stimulus remained on the screen until participants made a response and there was no mask stimulus following the target. There were two different target letters: S and F. Participants were instructed to report whether the target letter was ‘S’ or ‘F’ as quickly and accurately as possible before the experiment using keys S and F on the keyboard (All participants were required to use their left finger to press the S key while using their right finger to press the F key). As in Experiment 5, the cue was uninformative about the target location.

Results and Discussion

The accuracy was near ceiling on all conditions and did not yield any notable differences. The mean response time (RT) of the target report as a function of Cue-target SOA in Experiment 10 is depicted in Figure 14A.

The RT outliers (2SD above and below the mean) were removed. In addition, those trials in which participants were incorrect in target report were also excluded from analysis. An ANOVA analysis showed a significant main effect for Trial condition ($F(2, 58) = 86.621, p < .001, \eta_p^2 = .749$) and SOA ($F(1, 29) = 17.623, p < .001, \eta_p^2 = .378$), but not for Block ($F(2, 58) = .023, p = .977, \eta_p^2 = .001$). Critically, the Trial condition $\times$ Block ($F(4, 116) = 2.905, p = .025, \eta_p^2 = .091$) was significant.

As in previous experiments, we conducted two separate 2 (Trial condition) $\times$ 3 (Block) repeated measures ANOVAs to evaluate the block effects of the cost and benefit respectively.

Block effect of cost

Consistent with previous accuracy-based Experiments (Experiments 5-8), the cost effect was variant across blocks (Blocks 1-3: 7.14 ms, Blocks 4-6: -0.40 ms, Blocks 7-9: -10.31 ms, see Figure 14B), as confirmed by the significant Trial condition $\times$ Block interaction ($F(2, 58) = 3.587, p = .034, \eta_p^2 = .110$). Planned comparisons showed that the cost at Blocks 1-3 was significantly larger than those at Blocks 7-9 ($F(1, 29) = 6.517, p = .016, \eta_p^2 = .183$), but not

than those at Blocks 4-6 ($F(1, 29) = 1.234, p = .276, \eta_p^2 = .041$), and the cost did not significantly differ between Blocks 4-6 and Blocks 7-9 ($F(1, 29) = 2.776, p = .106, \eta_p^2 = .087$).

Block effect of benefit

The block effect of benefit did not reach significance, as confirmed by the nonsignificant interaction between Trial condition and Block (Blocks 1-3: 37.64 ms, Blocks 4-6: 35.75 ms, Blocks 7-9: 30.51 ms; $F(2, 58) = .396, p = .675, \eta_p^2 = .013$). However, the main effect of Trial condition was highly significant ($F(1, 29) = 125.196, p < .001, \eta_p^2 = .812$), such that participants' response was consistently faster in the Valid than in the No cue condition.

Figure 14. (A): The mean response time (RT) of the target report as a function of Cue-target SOA in Experiment 10. (B): The cost and benefit effects across blocks in Experiment 10 which were generated with the average data of 117 and 217 ms SOAs. The error bars represent standard errors.

This RT-based experiment revealed a significant block effect of cost, with the cost declining across blocks as in Experiments 5-6. Despite there being no significant block effect of benefit (Blocks 1-3: 6%; Blocks 4-6: 10%; Blocks 7-9: 14%), the benefit effect was reliable through the experiment, which again argues against the possibility that participants learn to completely ignore the cue as experiment progresses. Thus, this experiment provided further evidence supporting the MEC model and suggests that the MEC model does not only apply to the accuracy-based cueing studies, it could also explain some results of RT-experiment.

Section 5: Simulation of cueing effects using a model of the Attentional Blink

The final prediction that we will address is that the central results of the experiments supporting the MEC theory can be accommodated by a model of the attentional blink in which the primary parameter manipulation corresponds to memory encoding of the T1. This would correspond to our direct and indirect manipulations of cue encoding across the experiments. For this purpose, we adopted the eSTST model (Wyble, et al., 2009), which simulates the AB as the consequence of a set of neural mechanisms that suppresses the deployment of attention to a T2 while a T1 is being encoded into memory. This particular model is ideal for our purpose because it distinguishes between attentional enhancement triggered by a stimulus, and inhibition caused by encoding that stimulus into memory. Thus it can simulate how a stimulus is able to trigger attention without leaving a memory trace. This model also allows us to simulate the cue, the placeholders and the target as stimuli with varying encoding demands and levels of stimulus strength, presented at different spatial and temporal offsets. These simulations demonstrate that many of these spatial cueing effects and the AB can be explained by a common underlying theory. It is important to note also that the eSTST model, originally published 2009 was not created with this goal in mind, nor were these data available when the model was initially created. Therefore, the fit of these simulations is imperfect, and made more so because few

parameters were manipulated. In theory, many models could be fitted, post-hoc to new data, but in this case the model can accommodate the manipulations in this paper with changes to only a single free parameter and several other heavily constrained parameters (e.g. SOA, presence of the placeholders).

For our purposes, the key parameter in eSTST specifies the amount of information to be encoded for each stimulus. We attempted to fit all of the preceding experiments by adjusting only this single parameter, and left all of the other parameters fixed either at values used in the original publication (Wyble et al., 2009), or modified just to reflect the cueing paradigm (e.g. target strength was reduced from the published value to match the no-cue baseline. See the appendix for a more thorough description of the parameter values.

Note that we elected not to do a model comparison. There are only two computational models of the AB that specifically simulate encoding costs: the eSTST (Wyble et al., 2009) and the Threaded Cognition model (Taatgen, Juvina, Schipper, Borst, & Martens, 2009). Since both of these models are essentially similar as far as MEC is concerned, little would be gained by proving that one is a better fit than the other. Other AB models that do not incorporate encoding load of the T1 (e.g., Olivers & Meeter, 2008) could not easily represent changes in encoding load according to task instruction, or block effects.

For full details of the eSTST model, the original manuscript can be consulted (Wyble et al., 2009). In brief, the model consists of three major components: a *type* processing layer which represents the identification of individual stimuli, an attentional system, which reacts to the presence of salient or task-relevant stimuli by enhancing their processing, and a memory consolidation system, which stores copies of those stimuli in working memory as *tokens* using a *binding pool* of simulated neurons. For each target in an experiment, the model simulates how memory encoding and attention interact to produce patterns of successful working memory storage. Successful storage of a target occurs when simulated neural activity within the binding pool reaches a sufficiently high level of activation to form a robust attractor state.

The original model was only intended to simulate attention to a single stream of items, as is canonically used in AB tasks. However, modifying the model to represent different discrete locations requires only that the attentional mechanism is replicated for each different location, since Lag-1 sparing is mediated by spatial congruence (Visser et al., 1999; Wyble & Swan, 2015; Shih, 2000). However, memory consolidation is simulated in a single pool of neurons that is shared across all locations since perceiving a T1 produces inhibition of attention across multiple locations, regardless of where the T1 was located (Shih, 2000; Visser et al., 1999; Wyble & Swan, 2015). Figure 15 depicts the revised model, with a shared set of type nodes for different locations that are subserved by two independent attentional nodes. This figure illustrates two

separate mechanisms that cause a reduction in target report accuracy (Wyble et al., 2009; 2011).

The first is a weak form of interference that occurs whenever two or more stimuli are simultaneously active at the type layer (Figure 15, bottom). This interference reflects the difficulty of representing multiple pieces of information within a single cortical region at the same time. This interference is necessary to simulate the competition between two targets that occurs only at short latencies (i.e. Lag-1) in the AB (Potter, Staub & O'Connor, 2002). The second mechanism is a suppression of attention during memory encoding, such that whenever the T1 is currently being consolidated into memory, the attentional system undergoes some amount of suppression. Thus, the AB reflects the temporal footprint of memory consolidation of the T1. See Taatgen et al., (2009) for another model in which memory consolidation of the T1 invokes a protective mechanism that retards processing of the T2. These models are informed and supported by a diverse set of empirical constraints (Dux & Marois, 2009; Lagroix et al., 2012; Martens & Wyble, 2010; Nieuwenstein et al., 2009; Nieuwenstein, Potter, & Theeuwes, 2009).

Figure 15. Illustration of eSTST model (Wyble, Bowman & Nieuwenstein 2009) with a modification to allow for multiple spatial locations. All highly salient or task relevant stimuli (i.e. Types in the terminology of eSTST) are encoded in a common memory store, which suppresses attention to the two spatial locations equally. Attention can be allocated separately to the two locations causing multiplicative enhancement of feed-forward connections. The red inhibitory link at the bottom reflects a weak form of interference that occurs when multiple types are active concurrently, as explained in Wyble et al. (2009). The inhibitory links between memory encoding and attention are the source of the memory encoding cost that we posit is the invalidity cost in spatial cueing paradigms.

In these simulations, the cue, the placeholders and the target are each simulated as distinct stimuli that trigger attention and have varying encoding demands. Validity of the cue is simulated by activating type nodes for the cue and the target at either the same location or different locations. We assume that the onset of the cue and the placeholders can activate both attention and memory encoding, just as a target does in an AB experiment, and the degree of activation varies according to whether those stimuli will need to be reported or indicate useful

information about the target. To simulate the manipulations in the previous experiments, the amount of information encoded about the cue is varied. In cases where the cue location needs to be reported, the amount of information encoding is small. This value is incremented for experiments in which more information about the cue must be reported. To simulate cases where the cue has no report requirement, we set cue encoding at a small value to reflect the MEC's hypothesis that subjects encode information about the cue on some trials, particularly at the beginning of the experiment. This distinction is made explicit in simulations of early vs late blocks (Experiment 6), where the cue encoding is set to zero in the late block. Figure 16 illustrates simulations of each of the core data sets from these experiments as well as the corresponding empirical data. In each pane of the figure, we indicate the amount of information to be encoded about the cue and other parameter variations. See the appendix for more specific details.

Figure 16. Simulations of core manipulations from the current study with corresponding empirical data. In each panel the parameter E_{cue} indicates the amount of information that will be stored about the cue, with a greater amount corresponding to a longer duration of attentional suppression. The parameter $S_{placeholder}$ indicates that the activation value of the placeholder type node in the simulation was set to 0, reflecting the fact that the placeholder in this experiment was not placed inside the cue and thus could not be selected by attention. The parameter S_{cue} represents the strength value of the cue which is fixed for the invisible cue simulation.

A notable deviation between the model and the data is in the cue-visible condition of Experiment 3, in which valid trials produce a simulated validity benefit at 120 ms while the data revealed a substantial cost for the same condition. Nevertheless, the model does simulate the

finding that the accuracy in the invisible cue condition for valid trials is higher at the short SOA condition than for the visible condition. In the model, this reduction in accuracy for the visible cue condition is due to the cost imposed by encoding the cue and the cued placeholder.

Another deviation is that the data reveal a cost of cue encoding in the valid condition of Experiment 2a, while the model simulates valid trials as essentially at parity with the no-cue baseline under this encoding load. However, the model is capable of simulating a cost in the valid trials by imposing an even higher encoding load on the cue, which is essentially the attentional blink. This is shown in the simulation of Experiment 4.

General discussion

In the current paper we provided five lines of evidence in support of the theory that memory encoding plays a crucial role in yielding spatial cueing effects (both benefit and cost). These lines of evidence can be summarized as follows: (1). Increasing the report requirements of the cue changed the cueing effect by increasing cost while reducing benefit at short SOAs. (2). When benefits and costs are broken down by blocks in experiments in which cue report is not required, costs decline across blocks while benefits numerically increase across blocks (note that the block effect of benefit was significant in a combined analysis across experiments, which is

discussed below). (3). Surprise memory tests delivered at various points in an experiment supported the predictions of the MEC theory, such that subjects reliably report information about the cue in cases where invalidity costs were high, and have difficulty reporting information about the cue in cases where the invalidity cost is very weak. (4). A central cue also produced a smaller, but essentially similar cost as an invalid cue that also dissipated across trials. In addition, the RT-based experiment also showed a decline of invalid-cost across blocks as in the accuracy-based experiments. (5). Most of the observed effects in support of the MEC theory could be simulated by an existing AB model using manipulations of the model's memory encoding parameter. These lines of evidence collectively suggest the influence of encoding costs in visual cueing data, as predicted by the MEC model. While some previous cueing models could be modified to include an encoding cost, most of the typical cueing models (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Posner, 1980; Posner & Petersen, 1990) would still have difficulty explaining how benefits can be observed without costs in the later blocks of a cueing experiment. Also, these models have difficulty accounting for findings of divided attention without substantial cost (e.g., Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; White, Lunau, & Carrasco, 2014), while the MEC model has little difficulty explaining such findings, given that attention is not a limited quantity. Furthermore, the MEC model has additional

explanatory power in that it extends to the AB and thus in terms of total explanatory power, parsimony favors the MEC account.

Interpretation of findings from the current study

Evidence from Section 1: Spatial cueing effects varied as the requirement of cue encoding changed.

In the first line of evidence, the cue encoding requirement was manipulated by asking participants to report its location, color, or shape. The results showed a systematic increase in the invalidity cost when the cue-encoding requirements were increased (Experiment 1) and this cost was enhanced by masking the to-be-reported cue (Experiment 2a), as would be predicted from studies of the AB. Also, the cost effect was completely eliminated when using a cue masked so strongly that participants had no memory of seeing it (Experiment 3). Furthermore, Experiment 4 revealed that Lag-1 sparing could be obtained in valid trials when the placeholders were placed outside the cue, which further strengthened the putative similarity between the AB and visual cueing.

These results dovetail with recent results indicating that in visual cueing experiments subjects encode information about the cue's location into memory, even when they have no need to report it (Chen & Wyble, 2015a). Color, on the other hand, is not automatically encoded to

the same degree, and was well remembered only when subjects had an expectation to report it.

Thus, we conclude that in typical visual cueing experiments, where there is no expectation to report the cue, subjects automatically encode the cue's location for at least some portion of the trials in the experiment, and this encoding produces the invalidity cost when averaged across the experiment. This non-spatiotopic encoding-induced cost is also present on valid trials of course, but it is often countermanded by the beneficial effect of spatial attention recruited by the cue.

Asking participants to report the cue location on every trial has no clear effect on target report performance because subjects were presumably automatically encoding the target location already. However, asking them to encode additional attributes (e.g., cue color) causes an increase in the invalidity cost. When the cue is masked, the encoding cost increases to the point that it overwhelms the enhancement provided by spatial attention in valid trials, which eliminates or even reverses the validity benefit. This crucial finding confirmed another key principle of MEC, which is that the validity benefit reflects a net effect of attentional facilitation and memory encoding cost.

Another core assumption of the MEC is that cueing effects share a common mechanism with the AB, which is the encoding cost imposed by processing of the cue/T1 on the second stimulus. These experiments provided two additional effects supporting this hypothesized link. First, masking a to-be-reported cue dramatically reduced the ability to report the target

(Experiment 2a), and this was not a result of visual interference or forward masking (Experiment 2b). Similarly, it is well known that the AB is dramatically affected by having a post T1 mask (Chun & Potter, 1995; Nieuwenstein et al., 2009). Second, Experiment 4 revealed that Lag-1 sparing, which is a characteristic of the AB, could be obtained in an attentional cueing paradigm. The mechanisms underlying the AB and spatial cueing effect have been exhaustively investigated separately and a variant of models/theories have been proposed to explain these effects respectively. To our knowledge, the MEC model is the only single model that is able to explain the fundamental effects of these two seemingly distinct phenomena.

Evidence from Section 2: Block effects of spatial cueing effects.

This section provided another line of evidence in favor of the MEC theory. Over the course of many trials in a typical cueing experiment, in which subjects *do not report the cue*, the invalidity cost decreases dramatically, to the point of being difficult to measure (Experiments 5 and 6). However, when subjects were asked to report the cue halfway through the experiment, the cost returned, and then remained for the rest of the experiment (Experiment 7).

Over the same time course, there is a slight increase in the validity benefit, which was opposite to the trend in the cost effect. While the increase in the benefit was small, it was significant when collapsed across all of the experiments/conditions in which the cue did not need

to be reported (Experiments 5, 6 and 8-Late surprise test group, Mixed ANOVA with the experiment (5,6,8) as a between factor; $F(2, 174) = 3.171, p < .05, \eta_p^2 = .035$). There was no significant interaction between the block effect and experiment factors ($F(4, 174) = .338, p > .852, \eta_p^2 = .008$), indicating that the block effect of benefit was consistent among experiments.

The inverse relationship between the block effect on the cost and benefit (i.e., decrease in cost but increase in benefit across blocks) is incompatible with previous models of cueing. For instance, according to capacity models of attention, the decline of cost suggests that fewer resources were deployed to the cued location and thus should result in a decrease, instead of an increase in benefit effect at the cued location. Similarly, the noise exclusion model would also predict a decline of cost together with a decrease of benefit, since a smaller cost indicates the cue produced a weaker filtering/exclusion for uncued areas, which should yield a smaller benefit at the cued area.

It could be argued that the observed block effects (i.e., an increase in benefit and a reduction in cost across blocks) were caused by the alerting effect associated with the cue, and this effect might increase over the course of an experiment. That is, the non-spatiotopic alerting caused by a cue increased the target performance in both valid and invalid conditions across

blocks at short SOAs, which yields an increment of benefit and decrement of cost across blocks.

However, this possibility is challenged by two points. First, although it is clear that alerting can influence response time, it is debated whether it can also affect response errors (e.g., Rolke, 2008; Rolke & Hofmann, 2007). Second, previous studies demonstrated that alerting effect usually attenuated, rather than increased with repeated exposure, and thus the current results go in the wrong direction (Kraut & Smothergill, 1978; Kraut, Smothergill, & Farkas, 1981). Finally, an alerting explanation would not explain the other manipulations.

Evidence from Section 3: Relationship between spatial cueing costs and cue memory.

If the MEC theory is correct that the reduction in invalidity cost of the previous experiments is due to a loss of cue encoding, then there should be a drop in the ability to report the cue location in a surprise question, which was found in the results of Experiment 8. On the other hand, Experiment 9 illustrated that participants' memory of cue location did not drop in a situation wherein the invalid cost was constant through the whole experiment. Thus, Experiments 8 and 9 suggest a link between the spatial cueing effects and the memory of cue, which provided more direct evidence favoring the assumption that the invalidity cost was at least primarily, if not entirely caused by memory encoding of the cue.

However, as mentioned before, a possible alternative explanation could be that participants learn to ignore the cue after repeated exposure to the cue stimulus, which would result in a decrease in both invalid cost and the memory performance of the cue. This hypothesis is unlikely because the cueing benefit increased across trials in a combined analysis across experiments. This is consistent with earlier studies showing that it is hard to ignore an abrupt peripheral cue, which triggers a reflexive form of attention (e.g., Yantis & Jonides, 1990). Our studies clarify this finding by revealing that participants could learn to avoid encoding the cue after repeated exposure, although it still triggered attention. In other words, this finding suggests that attentional deployment by a peripheral cue could occur without encoding the cue. This is in line with many previous studies showing cueing effects even when participants could not encode/consciously perceive cues (Mulckhuyse & Theeuwes, 2010).

Another plausible factor causing the loss of cue information across trials is proactive interference (Keppel, & Underwood, 1962). However, this explanation has difficulty explaining why performance was so high on the control trial immediately after poor performance on a surprise trial in the late block of Experiment 8. Also Experiment 9 illustrated that memory for the cue location was still quite accurate at the end of a long series of trials, in contrast to Experiment 8. Proactive interference should have caused a decline in both experiments if it were the primary cause of poor memory on the surprise trial.

Evidence from Section 4: Generalization to central-cue baseline and RT measures

To ensure that these effects apply to a broader set of cueing paradigms than are used here, we considered first how the MEC account explains performance with a central cue rather than no cue. The MEC predicts that, at least in the initial trials of an experiment, all onsets would be encoded, even a cue presented in the middle of the display that could not possibly be valid. The prediction is therefore that such cues would behave in a similar way to invalid cues, causing a cost relative to a no-cue baseline, and furthermore that this cost would dissipate across trials. An analysis of central cue conditions from Experiments 4-6 confirmed this prediction. To further generalize our results, we tested whether reaction time measures would exhibit similar characteristics with regard to changes in costs and benefits across trials. The last experiment showed that RT costs for invalid cues do indeed decline across trials. In fact at the end of the experiment, the alerting benefit produced by the cue is so strong that even invalid trials are faster than no-cue trials. In the same experiment, the benefit effect was stable across trials, replicating the results for accuracy in Experiments 5 and 6.

Section 5: Linking cueing effects to the attentional blink

This section attempted to map the observed cueing effects onto an existing computational model of the attentional blink (Wyble, Bowman, & Nieuwenstein, 2009). The

prediction was that most of the observed effects in support of the MEC theory could be simulated by this model using manipulations of the model's memory encoding parameter. While these simulations are not evidentiary in nature, they do illustrate how readily core findings from attentional cueing experiments can be explained by a model that was originally designed to illustrate the mechanisms underlying the attentional blink. This should not be taken as evidence that cueing effects are mini-attentional blinks, since the two phenomena have a variety of crucial differences. Rather, the simulations highlight the possibility that there could be a commonality in the mechanisms underlying the phenomena.

Interpretation of findings from prior studies

Attentional enhancement can be deployed without limit

A core assumption of the MEC model is that the costs associated with invalid cueing are not due to a lack of attentional resources. In fact, like the gradient model (Cheal et al., 1994; LaBerge & Brown, 1989), the normalization model (Reynolds & Heeger 2009), FeatureGate (Cave, 1999), and the attentional shroud model (Fazl, Grossberg, & Mingola, 2009), the MEC model places no assumptions on the number of distinct locations that can be attended at a given time. In the strongest version of MEC, the costs of invalid cueing (and even costs associated with valid cueing in Experiment 4) are entirely the result of memory encoding. The idea that

attention might not be the core bottleneck goes against the grain of many years of cognitive theory (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Posner, 1980; Posner, Snyder, & Davidson, 1980), and makes an important distinction between attentional enhancement and processing. The argument is not that the brain's processing capability is unlimited. Rather, attention is used here in a more specific sense to refer to enhancement of processing at one or more locations within the visual field. After being attended, stimuli could then be encoded into memory, or used to drive speeded decisions, or processed in any other cognitive function. There has in fact been considerable empirical support for this idea within the behavioral and electrophysiological literature in recent years (e.g., Ansorge, 2004; Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; Dubois, Hamker, & VanRullen, 2009; Eimer & Grubert, 2014; GoodBourn & Holcombe, 2015; Kawahara & Yamada, 2006; Kyllingsbæk & Bundesen, 2007; Shiffrin & Gardner, 1972). For instance, several studies used simultaneous-sequential presentation paradigm and found that participants' performance was comparable between reporting two simultaneous and sequential stimuli (e.g., digits or letters). These results indicated that attention can be deployed to two separate locations simultaneously. Furthermore, some recent studies showed that attention cannot only be triggered by multiple cues at different locations simultaneously, but critically, doing so did not necessarily yield a corresponding attenuation of attentional effects at each of these cued locations (e.g., Bay & Wyble, 2014).

Such findings present a challenge to some of the well-established theories of cueing, since, if attention can be divided across multiple locations, it remains to be explained why anchoring attention at one location causes an invalidity cost at other locations. The MEC model, on the other hand, is compatible with such findings, since it explains invalidity costs as the result of cue encoding rather than limitations in attention.

Asymmetrical relationship between cost and benefit

According to many traditional capacity models of attention (e.g., Cheal, Lyon, & Gottlob, 1994; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Posner, 1980), directing attention to a particular location would produce improved performance at that location (i.e., benefit), which would be accompanied by corresponding impairments at any unattended locations (i.e., cost), in comparison with a neutral baseline condition in which attention was distributed across all possible locations. Such a trade-off in target performance between attended and unattended locations is a hallmark of those capacity limitation models of attention. However, this assumption, in spite of being supported by many previous studies, was nonetheless challenged by some other studies showing an asymmetrical relationship between cost and benefit effects, with the evidence deriving from both *cost without benefit* and *benefit without cost*.

Cost without benefit

Several studies have shown an invalid cost effect of precuing without being accompanied by a validity benefit (e.g., Folk & Hoyer, 1992; Hawkins et al., 1990; Shiu & Pashler, 1994, 1995), in particular when the target followed a cue in a close temporal window (i.e., shorter cue-target SOAs). For instance, Shiu and Pashler (1994) presented a single target digit which was preceded by an abrupt peripheral cue (a black square) and found a large and reliable invalidity cost effect (as opposed to a no cue neutral) when all possible target locations were masked, despite of lacking a noticeable benefit effect of a valid cue. In a follow-up study (Shiu & Pashler, 1995) the effect was replicated and extended by showing the cost-without-benefit result pattern again when the target was presented simultaneously with three dissimilar distractors, although this effect dissipated when the target was accompanied with similar distractors. Folk and Hoyer (1992) also found the cost-without-benefit pattern using RT at short cue-target SOAs in both young and old groups, regardless of the use of peripheral or central cues.

The cost-without-benefit pattern was also consistently found in several of the experiments described here, in particular at early blocks of the experiments. This finding is compatible with the MEC model, since the memory encoding cost was maximized at short cue-target SOAs when the encoding process of cue was still ongoing. A stronger encoding cost could override the effect of attentional facilitation in the valid condition, thereby resulting in an

absence or even reverse of benefit. Note that the pattern of cost-without-benefit observed in Shiu and Pashler (1995)'s studies could also be explained as the consequence of noise exclusion or forward masking by the cue at the cued location. However, neither of these two hypotheses could explain why the cost-without-benefit was only present at early blocks of current experiments, but not at late blocks in which a reversed pattern (i.e., benefit without cost) was typically obtained. Thus, we argue the MEC model could provide the best explanation for cost-without-benefit findings.

Benefit without cost

In comparison with the cost-without-benefit, the pattern of benefit-without-cost was rarely reported in previous studies, especially for those using peripheral cues. Posner and Snyder (1975) reported large benefit effects but almost no cost effect when adopting central cues (not to be confused with the spatially uninformative central cues used above). Another study showed the pattern of benefit-without-cost came from Friesen & Kingstone (1998), which used nonpredictive gaze cue as a cue. However, we are not aware of such an effect when using peripheral cues. The rarity of finding benefit-without-cost is consistent with many of the experimental results reported here and is explained by the findings of Chen & Wyble (2015a), which showed that the location of the peripheral cue was typically automatically encoded into

memory even without a requirement to report it. According to MEC, such encoding would yield costs and also restrict the magnitude of benefits. This is also in agreement with Jonides' (1981) finding that exogenous attention triggered by peripheral cues usually produced greater inhibition than the endogenous attention triggered by central cues.

Nonetheless, the present study showed that the benefit-without-cost pattern can be observed at late blocks of experiment, even when the cue was a peripheral cue. According to the MEC, this is because at late blocks the memory encoding induced cost was minimized since participants would learn to filter out irrelevant memory encoding as experiment progresses. This implies that the more trials used in an experiment, the more likely to obtain such a benefit-without-cost result pattern. Another observation of benefit-without-cost comes from Experiment 3 which manipulated cue visibility. This finding provides stronger evidence for the MEC theory that the cost effect was driven by memory encoding of cue. As discussed before, these novel findings in the current study can hardly be interpreted by existing models.

Mechanisms of memory-encoding cost: attentional suppression and interference

According to the MEC model, memory encoding costs play a key role in producing both invalid cost and limiting the magnitude of validity benefits. What are the mechanisms underlying this cost? Based on previous modeling work (Wyble, et al., 2011), we suggest that the memory

encoding cost results from two mechanisms: interference caused by mutually active stimuli and encoding-induced attentional suppression.

The former of these reflects the hypothesized interference that occurs whenever multiple representations of sensory stimuli are coactive within the visual system. This is not hypothesized to be a strict bottleneck, since evidence from the AB suggests that multiple pieces of information can be co-active (e.g. Lag-1 sparing; Potter, Chun, Banks & Muckenhoupt, 1998). However, accuracy in reporting targets is typically reduced whenever two pieces of information are temporally proximal (Wyble & Swan, 2015). In previous work, we argued that this weak form of stimulus-stimulus interference is necessary to explain the drop in T1 performance during the AB, when the two targets are presented at lag-1 (Wyble et al., 2011). Similarly, in these experiments we think that strong interference from a cued placeholder might reduce target accuracy slightly in the valid condition at lag-1. This was supported by the results of Experiment 4 in which changing the placeholders so that they were not located inside the cue, reversed the slope of accuracy with SOA.

The second and likely more influential mechanism from Wyble et al. (2011) that might be causing a memory encoding cost is the encoding-induced attentional suppression. In the AB literature, attentional inhibition has been proposed as a means to parse the continual stream of

visual input into distinct episodes (Bowman & Wyble, 2007; Wyble et al., 2009; 2011). In this model, encoding of a T1 suppresses the ongoing deployment of attention, thereby producing impaired ability to report a subsequent T2. A similar mechanism is used in the threaded-cognition model of visual target processing by Taatgen et al. (2009), although the role of the suppression in that model is to protect the first target from interference. In either case it can be predicted that the cue, and perhaps also the placeholders, in a visual cueing paradigm could affect target report if they are encoded into memory. The encoding cost is not spatially specific in these models. Encoding a cue at one location would impair the processing of a target presented at a different location. Note that this suppression is also present at the location of the first target (in the canonical AB task, T1 and T2 are typically at the same location) and therefore also has a limiting effect on benefit of a valid cue.

The encoding-induced attentional suppression/inhibition mentioned above essentially differs from spatially localized forms of inhibition (Cepeda, Cave, Bichot, & Kim, 1998; Hopf et al., 2006; Klein, 2000; Mounts, 2000a; 2000b), because the form of inhibition used to explain the attentional blink is non-spatiotopic, and thus is thought to extend across the whole field including the target location. On the other hand, there is evidence that targets also elicit highly selective forms of inhibition that reduce processing in the spatial vicinity of a target (Hopf et al., 2006; Mounts, 2000a; 2000b) and at the location of distractors presented simultaneously with a

target (Cepeda, Cave, Bichot, & Kim, 1998; Gaspelin, Leonard & Luck, 2015). It is an open question as to what role these phenomena play in visual cueing paradigms and the attentional blink. For example, while target-surround inhibition is found in some cases (e.g. Mounts, 2000a; 2000b), it is not a ubiquitous finding (e.g. Chastain, 1992). Furthermore, the paradigm used here has cue-target separations sufficiently far apart that they would fall outside of typical measures of spatial-surround effects (roughly 4-5 degrees, Mounts, 2000a), and yet robust cueing effects are observed. As regards distractor-centered inhibitory effects, it is conceivable that they could have contributed to cost effects measured here, but this phenomenon does not explain why the costs would be affected by cue encoding, or why they would reduce over the course of a block of trials. Moreover, since the attentional blink occurs even when the T2 appears at a location that had not previously been occupied by another stimulus (Visser, Zuvic, Bischof & Di Lollo, 1999), the mechanisms causing distractor-localized inhibition would have to exist in parallel to the mechanisms underlying the attentional blink.

Another most well-known component of spatially localized attentional inhibition is inhibition of return (IOR; Klein, 2000). The phenomena associated with MEC occur primarily at short SOAs and thus occur prior to the onset of IOR effects. IOR would be considered a complementary form of attentional control, although there was little evidence of it in these particular experiments.

Additional research will be required to elucidate more clearly whether localized inhibitory phenomena reflect distinct mechanisms, and to clarify the boundary conditions under which they occur. Though unparsimonious, it would not be surprising if all of these mechanisms of attentional selection co-exist within the brain, and are expressed differentially according to experimental method.

In summary, in the MEC theory, the performance of reporting the target is the sum of three distinct effects (Figure 17). 1. A weak form of interference between competing sensory representations that is spatiotemporally locked to the cue and placeholder. 2. Suppression of attention that is caused by encoding of the cue. 3. A transient, spatial form of attention that is evoked by the cue, which accelerates processing of the target.

Figure 17. A conceptual illustration of the hypothesized effects on target report within the MEC model. In these diagrams, the observed accuracy is the sum of the unobservable internal mechanisms that act to enhance or diminish target processing.

When and what information of a cue will be automatically encoded?

Chen and Wyble (2015a) demonstrated that participants automatically encoded the location but not the attributes (color, identity) of a spatial cue into working memory during a classical spatial cueing paradigm. The current study replicated and extended this finding by showing that the automatic encoding of cue location is affected by the number of pre-surprise trials and also the cue *effectiveness* (i.e., the magnitude of the benefit effect triggered by a valid cue). To be specific, when the cue is not very effective at increasing target report, cue encoding can drop off over the course of a long experiment as shown in Experiments 5-8, 10. In these experiments participants automatically encoded the cue location at the beginning of the experiment, but subjects who were not probed about the cue location learned to filter out that encoding as experiment progressed. By contrast, when the cue was very effective at enhancing

target report in Experiment 9, participants could report the cue location in a surprise probe at the end of the experiment, which suggests that cue information was still being encoded. Importantly, the experiment with the effective cues did not exhibit a reduced invalidity cost over trials.

Note that the effectiveness of a cue was, at least on the basis of the current findings, not sensitive to the statistical predictivity of the cue, since a similar decline of invalid cost and/or cue location memory across blocks was observed in Experiments 5-8, irrespectively of whether or not the cue was informative in predicting the upcoming target location (Experiments 5 and 7(first half of Experiment 7): uninformative cue, 25% validity, Experiments 6 and 8: Informative cue, 50% validity). Instead, in our paradigm the effectiveness of the cue was increased when the target was presented simultaneously with three distractors in Experiment 9, despite the fact that the cue was exactly the same as in the other experiments. These findings imply that the effectiveness of the cue can be more a function of the difficulty of locating the target than its validity, and essentially replicates the findings of Shiu & Pashler (1994), who showed that isolated targets experienced only a modest benefit from a valid cue. Future studies are needed to systematically explore the factors that can affect the cue effectiveness.

Limitations of the MEC theory

Despite the benefit of the MEC in simplifying our theoretical understanding of attentional effects by linking the attentional blink and spatial cueing costs to a common mechanism, it is important to clarify the limitations of this theory.

First, as mentioned before, effects that happen at longer time scales, such as endogenously cued forms of orienting and inhibition of return (Klein, 2000; Posner & Cohen, 1984) are outside of the scope of the MEC model. The mechanisms underlying the benefits and costs (i.e. transient attention and memory encoding suppression) explained by the MEC model occur most clearly within a few hundred milliseconds of stimulus onset. This is particularly true because the cue is typically a simple stimulus that subjects are trying to ignore which means that encoding times would be brief in a typical cueing paradigm.

Second, the effects explained by the MEC model are cases in which stimuli are spread far enough apart that there is a minimal role for surround inhibition, which is true of the classic cueing paradigms using only two locations, each several degrees from fixation. There are additional localized suppression/inhibition effects such as proximity graded inhibition and selective inhibition (Cepeda, Cave, Bichot, & Kim, 1998; Hopf et al., 2006; Klein, 2000; Mounts, 2000a; 2000b) that would be additive to the effects that we address in this paper. It is left to future work to integrate these additional forms of inhibitory control.

Third, the MEC theory argues that visuospatial attention might not necessarily be capacity limited, in contrast to the classic notion of a spotlight. Rather, MEC proposes that it is memory encoding that limits the amount of information acquisition at each moment by suppressing attention. This theory suggests that multiple locations can be attended at the same time, and suggests that invalidity costs in many cueing paradigms may not necessarily be indicative of attention's limitations. One boundary condition of this perspective, however, is that limits in spatial attention may manifest when stimuli are placed relatively near to one another. In such cases, surround inhibition effects may provide a limitation on concurrent attentional deployment at multiple locations or extended regions.

Conclusion

The present study proposed a new theory of how memory and visual attention interact in an attempt to provide better explanations for spatial cueing effects (i.e., benefit and cost). Unlike previous models of cueing phenomena, the new model, in conjunction with the experimental results, argues that the observed invalidity costs in exogenous cueing studies with well-separated stimuli may be largely, if not entirely driven by memory encoding induced cost, which shares a common mechanism as AB. On the other hand, the observed validity benefit was caused by the

combined effects of attentional facilitation at the cued location and the non-spatial memory encoding cost that exists through the whole visual field.

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Appendix

Across all simulations, the *blasterdelay* parameter was set to 10 ms instead of 40 ms, which is what previous simulations used when we switched from RSVP to onset targets (Wyble, Potter, Bowman & Nieuwenstein, 2011). In addition, except for the invisible cue condition, the duration of the cue, and the target were each 100 ms. The cue strength and target strength both varied uniformly across the range [.2 to 1.2] in 21 steps for a total of 441 combinations. The strength value of the placeholder was fixed at .70 when the circular placeholder inside the bars was used and was 0 when the large placeholder outside the cue was used. In simulation, the placeholder appeared coincident with the cue, representing the phenomenology of the

placeholder being thrust into awareness by the attentional response to the cues. Cue masking was implemented by changing the rate of decay of the cue's type node from .06 to .12. In the case of the invisible cue, the cue duration was set at 10 ms, the strength of the cue was fixed at .65 and the placeholder strength was set to 0, since subjects were unable to discern which of the placeholders had been cued and therefore had no memory representation of it. The SOA for the short SOA condition was set to 120 ms, to mimic the SOA of Experiment 3. The visible cue condition used the same parameters as the invisible cue condition except that the cue was unmasked (i.e., it decayed at .06 instead of .12) and the strength of the placeholder was set at 1, matching the value used in the other experiments where the placeholder was inside the cue bars.

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