

# Impairing the useful field of view in natural scenes: Tunnel vision versus general interference

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A fundamental issue in visual attention is the relationship between the useful field of view (UFOV), the region of visual space where information is encoded within a single fixation, and eccentricity. A common assumption is that impairing attentional resources reduces the size of the UFOV (i.e., tunnel vision). However, most research has not accounted for eccentricity-dependent changes in spatial resolution, potentially conflating fixed visual properties with flexible changes in visual attention. Williams (1988, 1989) argued that foveal loads are necessary to reduce the size of the UFOV, producing tunnel vision. Without a foveal load, it is argued that the attentional decrement is constant across the visual field (i.e., general interference). However, other research asserts that auditory working memory (WM) loads produce tunnel vision. To date, foveal versus auditory WM loads have not been compared to determine if they differentially change the size of the UFOV. In two experiments, we tested the effects of a foveal (rotated L vs. T discrimination) task and an auditory WM (N-back) task on an extrafoveal (Gabor) discrimination task. Gabor patches were scaled for size and processing time to produce equal performance across the visual field under single-task conditions, thus removing the confound of eccentricity-dependent differences in visual sensitivity. The results showed that although both foveal and auditory loads reduced Gabor orientation sensitivity, only the foveal load interacted with retinal eccentricity to produce tunnel vision, clearly demonstrating task-specific changes to the form

of the UFOV. This has theoretical implications for understanding the UFOV.

## Introduction

### General

Imagine the following real-world scenario: While driving, you are talking on a cell phone and looking at the car in front of you when you fail to notice a pedestrian entering the road in your peripheral vision. If you had not been talking on the cell phone, then you might have been more likely to notice the pedestrian (for review, see Horrey & Wickens, 2006). This real-world example raises several important theoretical questions regarding the nature of visual attention that we address in the current study. Is your attention actually narrower due to the cognitive load (i.e., *tunnel vision*), or is it generally worse across your entire visual field (i.e., *general interference*)? If your attention is narrower, is it because you are attending to something important in your center of vision (i.e., a *foveal load*), or could a general cognitive load—such as in the auditory modality—be sufficient to produce the same effect?

As we search our visual landscape, we are bombarded with information. As we explore our environ-

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ment, we experience the world as a continuous flow of information although it is actually acquired discretely on separate fixations, the information from which is integrated to create a coherent whole. Furthermore, there is a complex relationship between perceptual input and central processing, which seamlessly produces moment-by-moment awareness during our everyday activities. Because we cannot actively encode every piece of information in our visual field at a single time, we must limit the scope of our processing in a way that optimizes our responses and decisions—a set of mechanisms collectively called *visual attention*. The area of visual space from which visual attention selectively processes information within a single fixation is called the *useful field of view* (UFOV; Mackworth, 1965).<sup>1</sup> The UFOV has been shown to be modulated by factors such as age (Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Sekuler, Bennett, & Mamelak, 2000), divided attention and task complexity (Atchley & Dressel, 2004; Chan & Courtney, 1998; Miura, 1986; Motter & Simoni, 2008), and training (Ball, Edwards, & Ross, 2007). Yet despite its flexibility, the UFOV is still reliant on perceptual information, which is limited by the structure of our sensory organs.

We typically interpret our environment as being clear and not distorted or blurred as information is presented further away from the center of our gaze. In reality, there are a number of low-level physiological changes that occur between central and peripheral vision, and they necessarily reduce visual performance with increasing retinal eccentricity, referred to here collectively as eccentricity-dependent sensitivity limits. Although the literature detailing the nature of attention and central versus peripheral vision both have been rigorously investigated in parallel, the issue of how attention changes independently of eccentricity-dependent sensitivity limits is still unresolved. In particular, the effects on the UFOV caused by visual versus auditory dual tasks have not been directly compared with one another, nor have their effects been teased apart from the effects of eccentricity-dependent sensitivity limits.

## Central versus peripheral vision

Fundamental differences between central and peripheral vision are well established with the earliest quantitative modeling being described by Aubert and Foerster (1857; Strasburger, Rentschler, & Juttner, 2011). They found that, as retinal eccentricity increased, letter acuity decreased. Although the experimental rigor of psychophysical estimations of spatial visual abilities continued over the next century, a more unified model of the response properties of central and

peripheral vision at a neural level was not developed until the pioneering work of Anstis (1974), Rovamo, Virsu, and Naesaenen (1978), and Virsu and Rovamo (1979). These studies determined that the sensitivity for a stimulus with fixed spatial properties (size, spatial frequency, contrast) would decrease monotonically as the stimulus appeared farther away from the center of vision. This is due, in part, to the decrease in cone density from central to peripheral vision (Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987) as well as the reduced ratio of cones to the retinal ganglia (which project to the lateral geniculate nucleus), which diminishes with eccentricity after approximately 10° of retinal eccentricity (Perry & Cowey, 1985).

The reduced cellular representation at these early sensory stages of processing translates to further central vision biases of information representation in the primary visual cortex with more cortical cells responding to information in central vision than in peripheral vision. This central vision bias in the visual cortex was termed “cortical magnification” by Daniel and Whitteridge (1961) and modeled in terms of its relationship to the contrast sensitivity function by Virsu and Rovamo (1978; Rovamo & Virsu, 1979). As a consequence, the bias in signal processing across visual space can be mitigated by scaling the stimuli to be more salient in terms of their perceptual attribute, thus eliciting a response from an equal number of cortical cells across retinal eccentricity (Daniel & Whitteridge, 1961). Nevertheless, the precise cortical magnification factor ( $M$ ) varies across a wide range of factors, including the target stimulus (e.g., Landolt C vs. Gabor patches), species, individual differences, and the azimuth position of the stimulus (Strasburger et al., 2011). Therefore, although it is possible that one could estimate  $M$  from neurological data, if the goal of the researcher is to mitigate low-level visual differences across retinal eccentricity, one may be more precise by setting the scaling factor on the basis of individual observers’ psychophysical data.

The structural/perceptual differences between central and peripheral vision have real-world effects in terms of the types of information that they are best suited to processing. The high spatial resolution of the fovea makes it ideal for tasks that require one to discriminate fine-detailed information, such as objects (Henderson & Hollingworth, 1999; Nuthmann, 2014), words (McConkie & Rayner, 1975), and faces (Walker-Smith, Gale, & Findlay, 1977). Although peripheral vision has lower spatial resolution, it is generally sufficient to guide attention to to-be-fixated objects (Deubel & Schneider, 1996; Henderson, 1992; Henderson & Hollingworth, 1998; Schneider, 1995) and even to identify or discriminate peripheral stimuli if they are large enough to be resolved (Thorpe, Gegenfurtner, Fabre-Thorpe, & Bulthoff, 2001).

## Attention

Attention is a key factor that can at least partially allow the observer to compensate for the reduced sensitivity in the visual periphery (Posner, 1975). However, the term “attention” is itself a contentious construct with no clear answer on precisely what attention is or precisely how it improves visual performance (Anderson, 2011; Carrasco, 2011; Posner, 1975; Rosenholtz, Huang, & Ehinger, 2012). The association between attention, working memory (WM), and executive control (Cowan, 1988; Engle, 2002; Ericsson & Kintsch, 1995) has strong construct validity; however, it is not clear whether these functions are independent of each other or if they are merely subsets of a more complex latent variable.

Nevertheless, a vast body of research has shown that, for a given stimulus, tremendous differences in the perceptual experience can result from the attentional state of the observer. From this literature, two key assumptions regarding attention seem to be well supported (reviewed in Carrasco, 2011). First, the brain has limited neural resources to accomplish any given task or set of tasks and must therefore selectively allocate its resources. Second, the activation of irrelevant information can interfere with processing relevant information (Posner, Snyder, & Davidson, 1980; Remington, Johnston, & Yantis, 1992; Theeuwes & Godijn, 2002). Putting these two assumptions together, selective attention can be understood as the set of processes by which task-relevant information is amplified while task-irrelevant information is suppressed (Carrasco, 2011).

## Measures of attention

Most research on attention has measured it using arrays of artificial stimuli, such as in attentional cueing paradigms (Posner et al., 1980), feature/conjunction search tasks (Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989), multiple object tracking (Pylyshyn & Storm, 1988), and orientation-discrimination tasks (Nachmias, 1967). Despite the artificiality of these paradigms, their simplicity allows for careful control of the stimuli and allows one to draw inferences regarding attention in a more general sense. An attentional measure of particular relevance to the current study, which uses such artificial stimuli, is the Useful Field of View<sup>®</sup> (UFOV<sup>®</sup>) task (Ball et al., 1988; Ball et al., 1993), which has been shown to successfully predict real-world driving performance. This measure contains three tasks: foveal object identification (called the *processing speed task*), foveal object identification concurrent with peripheral object localization (called the *divided attention task*), and foveal object identification concurrent with

peripheral object localization among distractors (called the *selective attention task*). In the *processing speed task*, the amount of time needed to identify the foveal object with 75% accuracy is calculated. Using the presentation duration determined in the processing speed task, peripheral targets are presented at retinal eccentricities ranging from 10° to 30° eccentricity in the divided and selective attention tasks (Ball et al., 1993). Increases in error rates for more peripheral targets suggest that the participant’s UFOV has been reduced, which can indicate that the individual has a reduced speed of processing or that there is reduced sensitivity to peripheral information regardless of time. Nevertheless, reduced peripheral processing in the UFOV task has correlated relatively strongly ( $r = 0.52$ ) with the likelihood of being involved with a car collision over the following 3-year span (Ball et al., 1993; Ball et al., 2006; Edwards et al., 2005). However, these studies demonstrate that a substantial amount of the explained variance in predicting car collision likelihood is shared by simple eye health ( $\approx 25\%$ ), and these measures are limited to correlations between reductions in attention and overall collision risk. The design of the UFOV task also prevents it from being implemented within the boundaries of a simulated real-world environment, such as a driving or flight simulator. Thus, the UFOV<sup>®</sup> cannot be used experimentally to measure transitory attentional variations within real-world contexts, such as simulated driving. Therefore, if an important goal of attentional research is to measure attention in meaningful, real-world contexts and in a dynamic fashion, then measures of attention involving real-world stimuli and allowing natural eye movements must be used.

Measures of attention often rely on measuring the spread of attention by using overt attentional behaviors (e.g., eye movements) to infer the spread of covert attention in space (Loschky et al., 2014; Reimer, Mehler, Wang, & Coughlin, 2012). This allows one to see moment-to-moment changes in attention as differences in saccade targeting, amplitude, and fixation densities. The assumption here is that attention must be allocated to an area or object in space prior to the eye movement by being made (Deubel & Schneider, 1996). When an observer is under higher cognitive load, he or she has fewer attentional resources to distribute over visual space, which affects what peripheral information he or she can localize and orient toward (Loschky et al., 2014; Pomplun, Reingold, & Shen, 2001; Reimer et al., 2012). Thus, the breadth of attention is more constrained. Likewise, artificially limiting the span of covert attention using gaze-contingent displays can result in changes to overt attention. The “moving window” paradigm pioneered by McConkie and Rayner (1975) in the context of reading used eye tracking to present a gaze-contingent “window” of normal text centered on the fixation point, surrounded by masked (i.e., randomized) letters in the

periphery, and varied window size to determine the threshold beyond which masking produced no significant difference in saccade amplitudes compared to a normal text condition. Results showed asymmetries in window size (i.e., needing more letters to the right of fixation than to the left), thus establishing a link between covert and overt attention during dynamic reading, such that one attends to a particular region in space before a saccade can be made to that particular target region. The moving window method has also been extended to visual search of artificial stimulus arrays (Elihipanah, Christensen, & Reingold, 2011; Pomplun et al., 2001; Rayner & Fisher, 1987) and search for objects in scenes (Loschky & McConkie, 2002; Nuthmann, 2013; see also Cajar et al., 2016; Nuthmann & Malcolm, 2016). Nevertheless, there are some general limitations of the moving window paradigm. One is that the window itself may create artifactual effects on eye movements (the dependent measure of attention). For example, if the window suddenly appears relatively late during a fixation, this can systematically produce longer fixation durations, a phenomenon known as *saccadic inhibition* (Reingold & Stampe, 1999).<sup>2</sup> A related question is whether attention may also be drawn to the edge of the window due to the sharp resolution contrast there, thus also affecting attentional breadth. However, if so, saccade length distributions in window conditions should cluster around the window radius, but an analysis of gaze data in a moving window study found no evidence for this (Loschky & McConkie, 2002). Finally, one could argue that it is preferable to study covert attention by having the experimenter preselect items to probe during fixations rather than depending on the viewer to select which items will be targeted by overt attention.

Other studies have measured covert attention more directly by having viewers make an explicit response to peripherally presented information. One method of doing so, often used in driving simulator studies, is the peripheral detection task (PDT), in which participants must detect targets that are presented at random intervals, at fixed positions, often appearing in peripheral visual locations (e.g., near the edges of a computer display; Crundall, Underwood, & Chapman, 1999, 2002). As we discuss later, although this method has the advantage of requiring explicit responses to peripheral stimuli, it has also had two important limitations. Specifically, in the PDT, target stimuli are usually not size-scaled to control for eccentricity-dependent sensitivity loss; thus, doing so would be an improvement. Furthermore, in the PDT, the retinal eccentricity of the target presentations are generally not controlled, thus adding measurement noise.

More recently, a framework has been developed for dynamically measuring covert attentional breadth in real-world scene photographs, videos, or simulations, called the gaze-contingent UFOV (Gaspar et al., in

press; Loschky et al., 2014; Ringer, Johnson, Gaspar, et al., 2014). This framework attempts to solve the various problems discussed above in other measures of attention in scenes. The gaze-contingent UFOV framework has four basic components: (a) a dependent measure of covert attention (e.g., a discrimination task), (b) the gaze-contingent display of target stimuli in order to control the retinal eccentricity of targets during single fixations while allowing free eye movements, (c) size-scaling of target stimuli as a function of retinal eccentricity in order to mitigate low-level limits on visual resolution that would otherwise be confounded with attention (as discussed in the next section), and (d) a manipulation of attention. This framework has been used in Experiments 1 and 2 and is described in greater detail in the Methods section.

## Dual tasking and changes in the UFOV

Current understanding of visual attention is inconclusive with regard to how attentional breadth changes with reduced processing resources. In general, two primary effects have been observed: *general interference* and *tunnel vision*. When a secondary task produces equivalent decrements in visual performance regardless of retinal eccentricity, this is called general interference (Holmes, Cohen, Haith, & Morrison, 1977). When a secondary task produces greater decrements in visual performance with increasing retinal eccentricity, this is called tunnel vision (Ikeda & Takeuchi, 1975; Webster & Haslerud, 1964). Williams (1988), however, drew a sharp distinction between these two phenomena and laid out three requirements for producing tunnel vision in a visual task: (a) there must be a sufficiently difficult foveal task, (b) the foveal task must be given priority over all other tasks, and (c) the observer must make a speeded response to both tasks.

We argue that an additional factor must also be considered when discussing the existence or not of tunnel vision. These are the well-known, eccentricity-dependent limits of visual sensitivity due to cortical magnification, which are logically independent of any effects of attention. Williams (1988) found that a difficult foveal load (e.g., vowel/consonant matching) produced a steeper decline in peripheral letter identification than an easy foveal load (e.g., same letter matching). However, Williams (1989) realized that such a result could potentially be explained in terms of the above-noted, eccentricity-dependent sensitivity limits. Therefore, in a follow-up study, Williams (1989) first size-scaled his stimuli (based on pilot testing) such that under single-task conditions performance was equivalent at all tested eccentricities (experiment 2). Importantly, it was only under dual task conditions that he found tunnel vision, providing strong evidence of tunnel vision based purely on attention. The only other

study to our knowledge to have combined a manipulation of foveal load with size-scaling of peripheral stimuli was that done by Chan and Courtney (1998). That study used a size-scaling equation based on the reciprocal of the cortical magnification factor, called *m-scaling*, to equalize performance across eccentricities in the absence of a foveal load. The results showed no evidence of tunnel vision but something much closer to general interference.<sup>3</sup>

Similarly, a small number of studies of visual search have investigated whether *eccentricity effects*, as an attentional phenomenon, are eliminated by using *m-scaling* to control for the drop-off in visual sensitivity with eccentricity due to cortical magnification. Importantly, such *eccentricity effects* in visual search are similar to *tunnel vision* in that both are generally assumed to be attentional phenomena, and both show a precipitous drop-off in visual performance with increasing eccentricity—as also found with the UFOV®. On the one hand, Wolfe, O’Neill, and Bennett (1998, experiment 4a) found that *m-scaling* their stimuli did not eliminate eccentricity-dependent reductions in search efficiency. They therefore concluded that the UFOV in visual search is limited based on attention, not cortical magnification. On the other hand, an extended series of experiments by Carrasco and colleagues (Carrasco & Frieder, 1997; Carrasco, McLean, Katz, & Frieder, 1998) found that through careful *m-scaling* of their stimuli along various stimulus dimensions, including combinations of size, orientation, and spatial frequency, they could eliminate the eccentricity effects generally found in visual search, which share much in common with tunnel vision. Thus, the previous literature is unclear as to whether tunnel vision actually exists when one first carefully controls for the eccentricity-dependent reduction in visual sensitivity due to cortical magnification.

Given the tenuous nature of finding the tunnel vision effect when a foveal load is manipulated, it seems even less likely that such an effect would occur in the presence of an auditory WM load. Nevertheless, in one study evaluating the effects of an auditory WM load on a visual match/mismatch visual search task (Pomplun et al., 2001), participants’ UFOV size was reduced by increasingly difficult auditory dual task loads as measured by reduced saccade amplitudes between target locations and increased reaction time (RT) when mismatched clusters were presented at greater retinal eccentricities. Similarly, Atchley and Dressel (2004) found that conversations in which the participant has no control over when he or she is able to receive or transmit information produces a smaller UFOV as measured by the UFOV® task. This implies that, as long as there is a visual task, the added cost of any secondary load, even a purely auditory one, can produce tunnel vision. Nevertheless, neither of the above studies controlled for eccentricity-dependent reductions in visual

sensitivity, and the UFOV® task itself contains an implicit foveal load in all three of its tests. Furthermore, two key questions are whether these attentional effects would necessarily translate to more realistic contexts and whether the narrowing of attention is further exacerbated by increasingly difficult auditory attentional demands.

In order to titrate the cognitive load of an auditory WM task, the *n*-back task is useful as it can incrementally increase the level of load experienced by the participant in dual task situations (Jaeggi et al., 2003; Reimer, 2009; Reimer et al., 2012; Ringer, Johnson, Neider, Kramer, & Loschky, 2014). As an auditory WM task, participants typically listen to recordings of lists of letters and must respond whenever an item repeats one that was *n* items back in the list. As *n* increases, so does the number of items that must be held and updated in WM.<sup>4</sup> Specifically, the *n*-back task’s main interfering effect seems to reside in its ability to reduce executive attentional resources. With a growing public safety emphasis on the dangers of distracted driving, a growing number of studies have sought to answer a very important and practical question: What is the effect of an auditory WM load on the UFOV in driving situations? In simulator studies of the UFOV, the driving task itself is usually quite straightforward. It requires participants to navigate through various degrees of traffic density in single or dual task conditions (e.g., with the *n*-back task) often while maintaining a set distance from a lead vehicle. Dependent measures of attention usually involve measuring lane variability, brake RT, and assessing saccade scan paths while the vehicle is on the road. Despite Williams’ (1988; 1989) proposed requirement of a foveal load to precipitate tunnel vision, driving studies using the *n*-back task have found that increasing the level of *n* increased brake RT to peripheral hazards and caused fixation patterns to become more tightly clustered around the center of the display (Reimer, 2009; Reimer et al., 2012). Thus, the latter authors concluded that reduced attentional resources produce a narrowed scope of attention, namely tunnel vision. We note, however, that these conclusions were drawn from saccade distributions, which may miss the subtle effects found by measures of covert attention.

Indeed, there is other evidence from simulated driving environments that auditory cognitive loads produce general interference when using measures of covert attention. Strayer, Drews, and Johnston (2003) found that cell phone conversations (i.e., an auditory WM load) caused equally substantial decrements to both central and peripheral vision as measured by braking RTs to foveal (e.g., stopped vehicle) and peripheral (road sign) hazards, suggestive of general interference. Similar conclusions have been drawn from two recent driving simulator studies that used an auditory *n*-back task for their cognitive load (Gaspar et al., in press;

Ringer, Johnson, Neider, et al., 2014). Those studies found that the auditory *n*-back task caused equal reductions in covert attention (measured by Gabor orientation discrimination) over the measured visual field (from 5° to 15° eccentricity), again providing evidence of general interference. These latter two studies were unique in including two important controls to help differentiate tunnel vision from general interference, which have been missing from previous studies that measured covert attentional breadth in natural scenes (e.g., Crundall et al., 1999, 2002; Miura, 1986). First, they used size-scaled stimuli to control for eccentricity-dependent loss of sensitivity, thus eliminating possible spurious evidence of tunnel vision. Second, they presented the target Gabor patches gaze-contingently at precisely determined eccentricities, thus increasing measurement sensitivity, helping to differentiate tunnel vision from general interference. Thus, using direct tests of covert attentional breadth in simulated real-world environments, there is fairly consistent evidence that auditory WM loads cause general interference in visual tasks, which is consistent with Williams' (1988; 1989) claim that a foveal load is necessary to produce tunnel vision.

## The current study

The purpose of the current study is to determine what effects differing task modalities (auditory vs. foveal visual) have on attentional breadth, independent of fixed properties of the retina and early visual processes and as they apply to real-world environments. We did this using a particular instantiation of the gaze-contingent UFOV framework described earlier (Ringer, Johnson, Neider et al., 2014). Specifically, we utilized eye tracking to present stimuli gaze-contingently at controlled distances from the center of vision during a given fixation. Because the target eccentricities were predetermined, we could also scale them to be equally discriminable over visual space under single task conditions. This allows one to attribute any changes in visual performance across the visual field in a dual task condition as being unique to attention. We chose two tasks to evaluate whether increased task demands reduce the extent of attentional breadth (i.e., tunnel vision) or produce overall reductions in attentional strength (i.e., general interference) and whether these effects are unique to foveal and auditory WM loads, respectively.

Each experiment required participants to freely view images of natural scenes while performing a gaze-contingent Gabor orientation discrimination task. In Experiment 1, we manipulated attention by foveally presenting a rotated L versus T discrimination task (Beck & Ambler, 1973; Bergen & Julesz, 1983; Egeth & Dagenbach, 1991; Kwak, Dagenbach, & Egeth, 1991;

Wolfe et al., 1989) at the same time as the peripheral Gabor patches. Based on prior research showing that a foveal load will induce tunnel vision, the addition of a foveal load was predicted to reduce extrafoveal Gabor orientation sensitivity whereas single task performance (i.e., only peripheral or foveal stimuli within a given fixation) was predicted to produce relatively flat accuracy across retinal eccentricity (after having controlled for eccentricity-dependent sensitivity through size-scaling). To further test the importance of a foveal load in producing tunnel vision, in Experiment 2, we did not use a foveal load, but instead used an auditory *n*-back task to manipulate attention (Gaspar et al., in press; Jaeggi, Buschkuhl, Perrig, & Meier, 2010; Loschky et al., 2014; Ringer, Johnson, Gaspar et al., 2014) at the same time as the Gabor dual task. If a foveal load is necessary to produce tunnel vision, then the auditory *n*-back would instead be predicted to produce general interference. Conversely, there is other data to suggest that auditory WM loads (Atchley & Dressel, 2004; Rantanen & Goldberg, 1999) and the *n*-back task in particular (Reimer, 2009; Reimer et al., 2012) produce tunnel vision. However, these latter studies did not measure attentional breadth in a way that controls for the eccentricity-dependent loss of visual sensitivity due to cortical magnification.

Thus, the current study investigated this issue while controlling for the effects of cortical magnification through size-scaling using nearly identical methods between attentional manipulations. *General interference* would be evidenced by consistent reduction in orientation sensitivity that occurs across the visual field (i.e., a statistical main effect of single vs. dual task) whereas *tunnel vision* would be evidenced by reductions in orientation sensitivity that occur with increasing retinal eccentricity (i.e., a statistical interaction of the single vs. dual task factor and eccentricity). Of course, as the statistical reasoning outlined above suggests, these two outcomes are not necessarily mutually exclusive. Therefore, a further question for these two experiments was to determine whether a foveal load and an auditory WM load produce tunnel vision, general interference, or both.

## Experiment 1

### Methods

#### *Methodological overview*

In this experiment, participants completed four 1.5-hr sessions over 4 days: day 1, visual and cognitive screening and practice; day 2, Gabor task stimulus onset asynchrony (SOA) thresholding across eccentricities; days 3 and 4, single and dual task testing. More specifically, on day 1, participants were screened

for visual and cognitive acuity and given a brief practice with the gaze-contingent discrimination task. The gaze-contingent discrimination task was adapted from Ringer, Johnson, Gaspar et al. (2014), and in it, participants were told to freely view an image of a natural scene for a picture memory task that would occur at the end of a block of trials. During the memorization task, a gaze-contingent stimulus would appear, followed by a mask. After the discrimination task, participants' memory for scenes in the previous block was tested. On day 2, the SOA between the target and a mask was thresholded to determine the amount of time needed to provide equal accuracy across different retinal eccentricities. On days 3 and 4, the participants were given two blocks of trials, one in which only one retinal eccentricity was presented at a given point in time (combined single task) and another block in which a foveal stimulus was presented simultaneously with a peripheral stimulus (dual task). The ordering of single and dual tasks on days 3 and 4 was counterbalanced both within and across participants.

### Participants

Ten Kansas State University students (six females; mean age = 24.35,  $SD = 3.45$ ) responded to an online university posting for a paid, multiday study lasting approximately 4 days. Participants were compensated \$5 per hour at the end of each session with the promise of an additional \$5 per hour for each hour completed if they completed all sessions. Before being admitted into the study, participants were screened for normal vision (20/30 Snellen acuity) using the Freiburg Acuity and Contrast Sensitivity Test (FrACT; Bach, 2007) and for normal cognitive acuity using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). All auditory stimuli (i.e., digit lists, sentences, etc.) were prerecorded to ensure that the stimuli were identical across participants. Informed consent was given at the beginning of each session.

### Materials

#### Apparatus

Experiments were performed on a custom PC running Microsoft Windows 7 with an Intel Core i7 970 processor (3.4 GHz) and 16 GB of DDR3 RAM and a 2-GB nVidia GeForce GTX 760 video card. Stimuli were displayed on a 19-in. View-Sonic Graphics Series monitor (Model G90fb) with a refresh rate of 85 Hz and a display resolution of  $1024 \times 768$  pixels. A chin and forehead rest was used to stabilize head position with a viewing distance of 60.33 cm from the screen, providing a viewing angle of  $33.67^\circ \times 25.50^\circ$  for all images. The monitor was calibrated using a Spyder3-

Elite photometer with a maximum and minimum luminance of  $91.3 \text{ cd/m}^2$  and  $0.40 \text{ cd/m}^2$ , respectively, and a gamma of 2.2.

Eye movements were recorded monocularly using an Eyelink 1000 desktop mounted eye tracker with a sampling rate of 1000 Hz. Participants were calibrated on a 13-point grid with a maximum average error rate of  $0.5^\circ$  and a maximum error rate of  $1^\circ$  of visual angle. The eye tracker was also used to present Gabor and L/T stimuli gaze-contingently on the screen at a rate of approximately every seven fixations. The experiment structure was programmed using Experiment Builder (version 1.10.1247), and the functional aspects of the experiment (e.g., gaze-contingent stimulus drawing, SOA settings, etc.) were implemented through custom coding in Python (version 2.7). A fundamental concern for the gaze-contingent displays is that the onset of the gaze-contingent stimuli to the screen should occur relatively quickly following the onset of a fixation (e.g.,  $<80 \text{ ms}$ ; Loschky & Wolverton, 2007). All of the stimuli presentation times were checked prior to analyses and were found to range from 19 to 51 ms ( $M = 41.25 \text{ ms}$ ,  $SD = 3.56$ ) after the onset of a critical (stimulus present) fixation. Responses to the discrimination tasks and the memory task were made using a Cedrus RB-834 response box.

#### Stimuli

Scene images were randomly selected from the SUN database. The image categories included a large number of indoor and outdoor scenes. Stimuli for the foveal task, the "L/T" patches (Figure 1A), were black letters on circular neutral gray patches (grayscale value = 127), subtending  $2^\circ$  diameter, which contained two letters: either two Ls (catch stimulus) or an L and a T (target stimulus). The characters in the foveal stimulus were rotated to  $90^\circ$ ,  $135^\circ$ ,  $180^\circ$ ,  $270^\circ$ , or  $315^\circ$  to ensure that the L/T stimuli required serial processing (Egeth & Dagenbach, 1991; Kwak et al., 1991). Additionally, the pairs of letters were oriented either vertically or horizontally. To increase the difficulty of the foveal task, the junction of the L was offset by two pixels to make the difference between the Ls and Ts more subtle (Jiang & Chun, 2001). The foveal patch was presented for a thresholded duration and then followed immediately by a mask containing four black squares (Figure 1A), which covered the potential locations for the L and T target features. The maximum mask duration was always equal to that of the L/T patch duration.

The Gabor stimuli used as the peripheral targets (Figure 1B) were generated using MatLab (2009b), including the image processing and signal processing toolboxes. Four Gabor patches were presented, each equidistant from the point of gaze and each other. This was done so that, even if the participant's gaze landed in a corner of the image, at least one Gabor patch

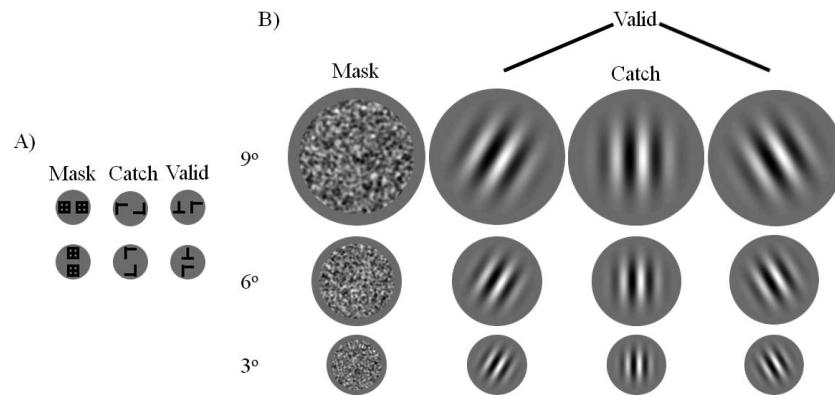


Figure 1. Sample stimuli for Experiment 1. (A) Foveal targets and masks for the L versus T discrimination task showing examples of target and catch stimuli, masks for foveal stimuli. (B) Examples of Gabor patches and masks at 3°, 6°, or 9° of retinal eccentricity.

would be visible. The size-scaling of the patches was estimated from earlier pilot studies in which the Gabor patches were size-thresholded to be equally discriminable under unmasked conditions. The individual 3°, 6°, and 9° eccentricity Gabor patches subtended 4.1°, 5.8°, and 7.7° diameter, respectively. Because the Gabor patches were presented on top of natural scene images, there was the potential for simultaneous masking of the Gabor patch by the background scene information. Thus, in order to remove any variability caused by the Gabor patches being presented in structurally sparse versus complex backgrounds, a neutral gray annulus surrounded each patch, creating a gap of 0.5° between the patch and the scene background (Saylor & Olzak, 2006). In order to control for the amount of processing time available for the Gabor patches, they were presented for varying durations, and were immediately followed by a filtered Gaussian noise mask, which was the same size as the patch (Figure 1B). The noise masks had the same mean luminance (0.5), RMS contrast (1), and peak spatial frequency as the Gabor patches and were presented up to the maximum duration of the Gabor patch.

## Procedure

### Procedural overview

Within a trial, participants carried out two different tasks: (a) memorization of the scene image, for a later (relatively easy) picture recognition task—this was done to encourage participants to actively explore the image with many eye movements—and (b) discrimination tasks, involving either Gabor patch orientation or rotated L versus T discrimination, which only occurred occasionally for single fixations. The trial continued until the participant made the requisite number of fixations, producing the requisite number of discrimination (target and catch) presentations for every trial. Processing times for the stimuli were initially thresholded in single task conditions. On the

final 2 days of testing, discrimination sensitivity was compared between combined single task (separate presentations of foveal and extrafoveal stimuli on different fixations) and dual task (simultaneous presentations of foveal and extrafoveal stimuli on the same fixation) conditions. Below we describe each of these components of Experiment 1 in greater detail.

### Memory task

In order to facilitate eye movements during the discrimination tasks, participants were encouraged to remember the details of the scene images in preparation for new/old picture recognition memory tests that would occur at the end of each block of trials. The recognition memory tests consisted of half of the images from the previous block (*old* images), and the other half were *new*. Participants would start each memory test trial using the same drift check and fixation fail-safe procedures as the discrimination task. The image would appear for 3 s, followed by a response screen on which the participants were asked if they had seen the image in the previous block of trials, to which they gave a yes/no response using the response box. The results of the recognition memory tests also provided an alternative measure of the effects of the cognitive load on attention as assessed by picture encoding into long-term memory.

### Discrimination tasks

In order to measure moment-to-moment changes of attentional breadth, participants performed gaze-contingent Gabor orientation and/or rotated L/T discrimination tasks while freely viewing natural scenes for a later memory task. Each trial was run with a particular scene image that was viewed only once throughout the discrimination phase of the experiment. When a participant was ready to begin a trial, they pressed a button while looking at a fixation fail-safe target at the center of the screen. If the participant failed to fixate



within a 1° invisible box around the target or his or her calibration was no longer valid, the trial was aborted; otherwise, the trial began. While they viewed the images, the peripheral Gabor or the foveal L/T stimuli would appear at varying distances from fixation, followed by a mask. The SOA between the target and the mask was set at an individually thresholded value for each participant with his or her longest SOA value among the four target eccentricities being used for all eccentricities. If the participant moved his or her eyes prior to the onset of the mask, the stimulus presentation was deemed a “nil patch” and rerun at the end of the trial. In order to avoid having trials go on indefinitely, if a participant generated too many nil patches, a total of three nil patches per trial could be accumulated before the experiment would simply move on to the next trial. The gaze-contingent stimuli were presented after every seven fixations with the first presentation occurring on the participant’s seventh fixation for that image. Participants could make a response to the stimuli any time before the next presentation (i.e., within the following seven fixations).

The stimuli for the foveal and peripheral discrimination tasks differed in order to create a more difficult foveal load as well as to prevent participants from making a simple same/different judgment for the central and peripheral stimuli during the dual task condition. For the (foveal) L/T discrimination task, the participants were required to respond with a button press from their left hand when a T was present in the patch but not when both characters were Ls. For the (peripheral) Gabor discrimination task, participants were required to make a response with their right hand when the patches were oriented diagonally ( $\pm 30^\circ$ ) but not when the patches were vertically oriented. Each trial contained at least two presentations of each stimulus (one target, one catch) at each level of retinal eccentricity.

### SOA thresholding

In order to further control for eccentricity-dependent sensitivity losses due to cortical magnification and to mitigate individual differences in processing speed among the participants, the SOAs between the onset of the target and the following mask were tailored to the ability of each individual participant. Following the screening procedures from Day 1, participants completed the *simple single task*, consisting of 20 practice trials of the L/T discrimination task, followed by 20 trials of the Gabor orientation discrimination task. Because only two L/T patches were presented to the participants per trial in this first phase of thresholding, in each trial, the L/T stimuli in this block could be all targets, all catch trials, or half target and half catch trials to prevent participants from using a memory strategy to make their responses. Changes in SOA were

incremented using the single interval adjustment matrix (SIAM; Kaernbach, 1990) adaptive threshold estimation algorithm. The target accuracy was set at 82.5%, and the SOA step size was 23.5 ms (two monitor refresh cycles). Feedback (percentage correct) for each target eccentricity was given every five images.

On day 2, which was the second day of thresholding, participants completed 80 trials of what we refer to as the *combined single task*, in which *both* the L/T discrimination task *and* the Gabor discrimination task were presented within the same trial but on separate fixations, separated in time by seven fixations (Supplementary Movie 1). This was followed by 80 picture memory test trials. Importantly, on day 2, the initial SOA values were set at the thresholded values from Day 1. The step sizes for the SIAM were set at 23.5 ms for the first 40 trials and 11.76 ms (one monitor refresh cycle) for the last 40 trials. Feedback was given after every five trials. The threshold estimates were then calculated and applied to the dual versus combined single task trials on days 3 and 4.

The longest SOA value that was used from the estimation session on day 2 was used as the SOA for all retinal eccentricities on days 3 and 4. In the combined single task condition, the L/T stimuli and Gabor stimuli were always presented on separate fixations with presentations separated in time by seven intervening fixations. Conversely, in the dual-task condition, the L/T task and the Gabor task were presented on the same fixation. Therefore, if we had used separate SOAs for the L/T task and the Gabor task, it would have resulted in masks appearing on the screen at different times within a single fixation for the L/T and Gabor stimuli. Whichever task was easier would have had a shorter SOA, and its mask would onset earlier than the mask for the more difficult task. The motion transient caused by the earlier mask onset could exogenously capture attention to that location (Remington et al., 1992; Theeuwes, Kramer, Hahn, & Irwin, 1998), disrupting performance in the more difficult task. Therefore, in order to avoid this, it was necessary to use a single SOA for both the L/T and Gabor tasks (across all three Gabor eccentricities), applying the longest SOA across both tasks and eccentricities to both tasks and all eccentricities.

### Combined single task versus dual task testing

On days 3 and 4 of the experiment, the participants completed a block of 60 trials each of combined single task and dual task trials. In the combined single task condition, the participant saw two presentations for each eccentricity with only one target eccentricity presented during a given fixation. In the dual task condition, the L/T task was presented at the same time, on the same fixation, as the Gabor patches

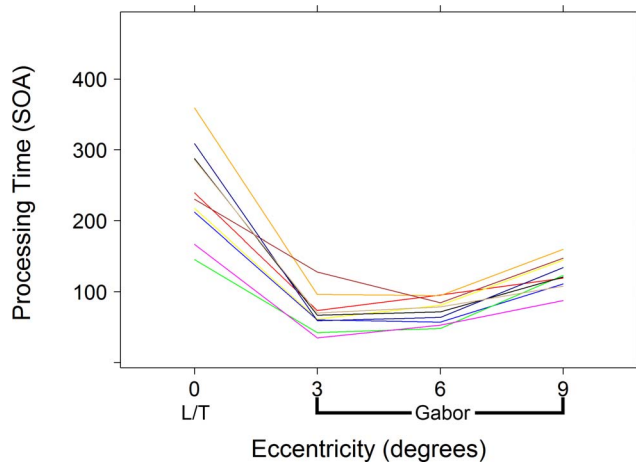


Figure 2. SOA thresholds (in milliseconds) for individual subjects as a function of retinal eccentricity with each line representing an individual subject's stimulus threshold.

(Supplementary Movie 2). Thus, in the dual task condition, the L/T task served as a foveal load, during which time attention must be divided between central and peripheral vision. Feedback was given after every five images, but *only for the foveal L/T task*. This implicitly encouraged participants to prioritize the foveal task, a requirement for producing tunnel vision according to Williams (1988, 1989). Each block of the discrimination tasks was followed by a picture memory test. The order of the combined single task and dual tasks was counterbalanced across days for each participant and across participants to account for practice and learning effects.

## Results

### Precursors

**SOA estimation:** As noted above, in order to eliminate eccentricity-dependent sensitivity loss and to control for individual differences, masking SOAs were thresholded for all participants. Prior to analyzing a participant's thresholding results, the data were filtered to remove any patch presentations in which a saccade occurred before the mask could be presented (i.e., a "nil patch"). Next, the thresholding data were filtered to contain only *reversal trials*, namely, trials in which the direction of SOA progression changed (i.e., increasing to decreasing SOA or decreasing to increasing SOA). Finally, the first four reversals (by participant and eccentricity) were removed to reduce noise in the data (Kaernbach, 1990). In order to calculate reliable threshold estimates, approximately 12 reversals are necessary. Participants averaged 17.68 ( $SD = 4.94$ ) reversals for each eccentricity, which was well above the minimum suggested number (Kaernbach, 1990). Nevertheless, out of the total of 40 threshold estimates, four

	Mean SOA (ms)	SE	$t$ value	$p(t)$	Cohen's $d$
0° (L/T)	245.18	20.69	11.85	<0.0001	
3°	70.38	18.96	-9.22	<0.0001	-2.92
6°	74.08	18.42	-9.29	<0.0001	-2.94
9°	125.06	18.37	-6.54	<0.0001	-2.07

Table 1. Mean SOA estimates (in milliseconds) obtained on the second day of SOA thresholding. *Notes:* The statistical test for the L/T task is compared against 0 ms whereas the tests for 3°, 6°, and 9° are compared against the L/T SOA.

individual SOA values were found to have insufficient numbers of reversals (<12). In each of these cases, this was due to a floor effect on the SOA scale (i.e.,  $SOA = 11.74$  ms). Thus, the participants were significantly practiced, and their performance was neither highly variable nor unpredictable, and thus their data was included in the final analysis.

As shown in Figure 2 and Table 1, the SOA thresholds to produce the target level of equivalent performance across tasks (82.5% accuracy) were significantly higher for the foveal L/T task (at 0°) than those for the peripheral Gabor task (at 3°, 6°, and 9°). Furthermore, for the Gabor patches, the SOAs necessary to reach the criterion level of accuracy tended to increase from 3° to 9°,  $t(9) = 8.31$ ,  $p < 0.001$ , although there was no difference between 3° and 6°,  $t(9) = 0.672$ ,  $p = 0.52$ , n.s. Thus, the size-scaling of the stimuli did not completely remove all eccentricity-dependent loss of Gabor orientation sensitivity, further validating our use of SOA thresholding for each eccentricity. Nevertheless, the mean SOA for the furthest eccentricity tested (9°) was still well below the SOA threshold for the foveal task. As noted above, on days 3 and 4, for the Gabor orientation task, this meant that the participants were allowed a considerably longer processing time in the periphery than was needed to achieve the criterion level of accuracy, which provided an even more stringent test of the tunnel vision hypothesis.

### Discrimination

The complete results from 10 participants were analyzed using a probit mixed-effects modeling approach to signal detection (DeCarlo, 1998; Jaeger, 2008; Wright, Horry, & Skagerberg, 2009) with R statistical software (version 3.1.3) using the *lme4* package (Bates et al., 2015). This modeling method calculates the likelihood of a response as a function of the type of stimulus (catch vs. target), task type (combined single vs. dual task), and retinal eccentricity (0°, 3°, 6°, 9°). The predictor of stimulus type as the first step in the model provides an estimate of sensitivity ( $d'$ ) because it is determining the slope of the response likelihood between target and foil stimuli, and thus it is

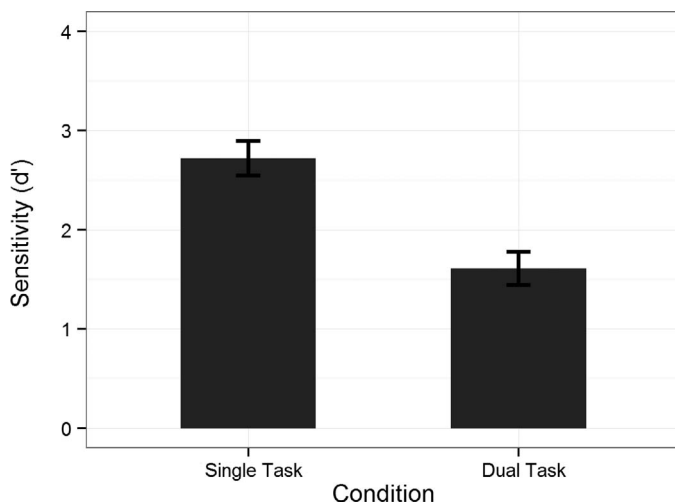


Figure 3. L/T discrimination task sensitivity ( $d'$ ) as a function of task type. Error bars = 95% CI.

the estimate of the difference between hits and false alarms, respectively. Therefore, any reference to sensitivity with regard to our predictors of task type and eccentricity will be the result of its interaction with stimulus type (DeCarlo, 1998; Wright et al., 2009). Any interaction that does not include stimulus type (catch vs. target) provides an estimate of bias given that it represents the likelihood of responding “yes” to both catch and target trials (DeCarlo, 1998; Wright et al., 2009). Note, however, that unlike the signal detection bias measure,  $c$ , the interaction B in this case represents a “yes” bias with positive values.

Prior to evaluating any fixed effects among the three tasks in Experiment 1 (i.e., L/T discrimination, Gabor orientation discrimination, and picture memory), multiple models were generated, in which each model was identical in its fixed effects structure, and the random effects structure was permuted for singular effects of task type and eccentricity (peripheral Gabor task only) as well as additive and interactive effects of task type and eccentricity (peripheral Gabor task only). Model selection was on the basis of Bayesian inference criteria (BIC) values, in which the model with the lowest BIC value was selected, and its fixed effects were used for hypothesis testing. This procedure was carried out for all other mixed effects models.

**Foveal sensitivity: L/T discrimination:** A total of 9,800 foveal observations were recorded across 10 participants. This was on the order of twice as many observations as any other eccentricity, which is due to the fact that foveal presentations occurred with every Gabor eccentricity in the dual task condition whereas all other Gabor patch eccentricities were presented only once. Two models were generated and tested prior to analyzing the fixed effects of task type on sensitivity. In one model, the random effects structure included only subject intercepts as a random effects variable whereas

another model included task type as the sole random effects variable. An assessment of BIC values demonstrated that the added random effect of task type was not warranted in the model (BIC = 8,129.4), and the simplest model was chosen for analysis of fixed effects tests (BIC = 8,118.9). The fixed effects of the model (see Appendix A in Supplementary Materials) indicated a significant liberal (“yes”) bias overall in foveal responses ( $B = 0.436$ ,  $z = 4.15$ ,  $p < 0.001$ ) in the combined single task condition; however, this effect seemed to be attenuated in the dual task condition ( $B = -0.123$ ,  $z = -2.89$ ,  $p = 0.004$ ). Analysis of sensitivity ( $d'$ ; Figure 3) showed a significant effect of task with participants’ performance at a much higher degree of sensitivity to the L/T task in the combined single task condition ( $d' = 2.70$ ,  $SEM = 0.08$ ) relative to the dual task condition ( $B = -1.07$ ,  $z = -12.59$ ,  $p < 0.001$ ). However, in terms of comparing foveal performance to the thresholded accuracy from the simple single task estimation portion (i.e., 82.5% accuracy), dual task and combined single task accuracies equate to approximately 81.8% and 91.5% correct, respectively. Therefore, it appears that over the course of the experiment, participants’ performance increased from the initial simple single task SOA estimation to the combined single and dual task conditions. However, addition of the dual task brought participants’ performance back to roughly their original simple single task estimation level of performance.

**Peripheral task sensitivity: Gabor orientation discrimination:** A total of 14,926 observations were used to compare the effect of the presence of a foveal load on peripheral orientation sensitivity. The data for the Gabor orientation discrimination task were analyzed similarly to the method used for the foveal discrimination task but with the added effect of retinal eccentricity. Response likelihood was computed as a function of the type of stimulus (target vs. catch), task type (dual task vs. combined single task), and retinal eccentricity. Random effects structures (effects that varied across participants) varied as a function of task type, eccentricity, task type + eccentricity, and the task type  $\times$  eccentricity. From these models, BICs were compared (see Appendix B for the full list of BIC values in Supplementary Materials), and the optimal model was found to be one that allowed model flexibility in terms of task type (BIC = 9920.4) compared to the nearest model that included the additive random effects of condition and eccentricity (BIC = 9931.2).

In the combined single task condition, participants were well beyond chance at discriminating Gabor orientations (Figure 4; but see Appendix C for the full model in Supplementary Materials) with sensitivity being quite high ( $d' = 4.33$ ,  $z = 55.53$ ,  $p < 0.0001$ ). This was not surprising given that participants’ SOAs for the Gabors were well beyond what was needed to produce their criterion level of accuracy in the combined single

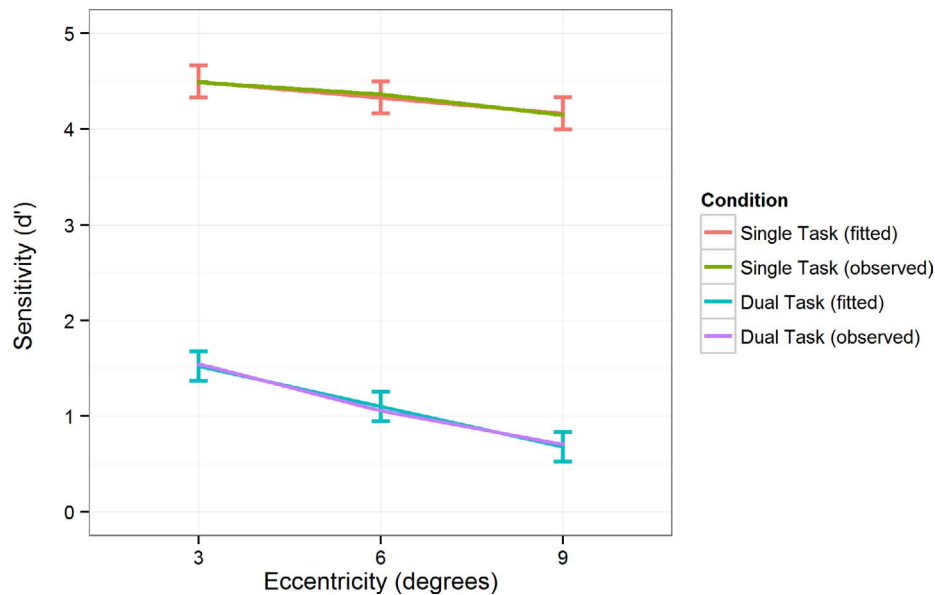


Figure 4. Gabor orientation sensitivity as a function of task and eccentricity. Lines are overlaid between observed and fitted results. Error bars = 95% CI. “Fitted” results reflect the linear fit of Gabor discrimination sensitivity predicted by the model, and “observed” data reflects the raw Gabor discrimination sensitivity at each categorical level of retinal eccentricity.

task in order to prevent asynchronous mask onsets between the foveal and peripheral tasks. The single value of SOA produced relatively constant combined single task sensitivity as a function of eccentricity ( $\Delta d' = -0.055^\circ$ ,  $z = -1.77$ ,  $p = 0.077$ ). The fact that the values for the combined single task are approaching the upper limit of the distribution for  $d'$  would normally be troubling for traditional measures of sensitivity (Macmillan & Creelman, 2005); however, a major benefit of fitting the data to a generalized linear mixed model for signal detection is that such modeling is robust to finding differences between values at extreme ends of the binomial distribution (Dixon, 2008). As expected, the dual task condition produced a significant decrease in Gabor discrimination sensitivity compared to the combined single task condition ( $B = -3.23$ ,  $z = -38.35$ ,  $p < 0.0001$ ), which would potentially provide support for general interference. However, the crucial question was not *whether* performance with the single versus dual tasks would be different, but rather *how* performance in these two tasks conditions would differ as a function of eccentricity. Figure 4 shows clearly that there was a significantly more negative slope as a function of eccentricity for the dual task condition than in the combined single task condition ( $\Delta d' = -0.085^\circ$ ,  $z = -2.52$ ,  $p = 0.012$ ), which supports the tunnel vision hypothesis. We can then ask whether this interaction invalidates the interpretation of the main effect for single versus dual task as support for general interference. Here, that does not seem to be the case as the main effect of single versus dual task has a  $z$  value ( $-38.35$ ) that is  $>15$  times larger than the interaction  $z$  value ( $-2.52$ ) as can be seen in Figure 4. Therefore, the

results seem to strongly support general interference but nevertheless also show support to a lesser degree for tunnel vision.

### Picture memory

Results from the picture recognition memory tests were analyzed using a probit mixed model to determine whether participants' memory for pictures was affected differentially by the combined single task versus dual task conditions. Two models were generated with the identical fixed effects of picture identity (new vs. old) and task condition. These two models differed in that one model included only each subject as a random effect whereas the other model included task type (single vs. dual) as a random effect. A comparison of BIC values indicated that the simpler model was sufficient to account for variability across subjects (BIC = 1492.6) and that the addition of task type was not warranted (BIC = 1504.7). The fixed effects from the model (see Appendix D for all model estimates in Supplementary Materials) show that there was no significant response bias for the combined single task condition ( $B = -0.060$ ,  $z = -0.56$ ,  $p = 0.573$ ), nor was there a significant change in bias for the dual task condition relative to the combined single task condition ( $B = -0.030$ ,  $z = -0.41$ ,  $p = 0.680$ ). The participants were quite sensitive to the picture memory task in the combined single task condition ( $d' = 2.887$ ,  $z = 28.103$ ,  $p < 0.001$ ), and there was no difference in sensitivity between the combined single task and dual task conditions ( $B = -0.273$ ,  $z = -1.86$ ,  $p = 0.064$ ; Figure 5). Thus, it does not seem that the addition of simulta-

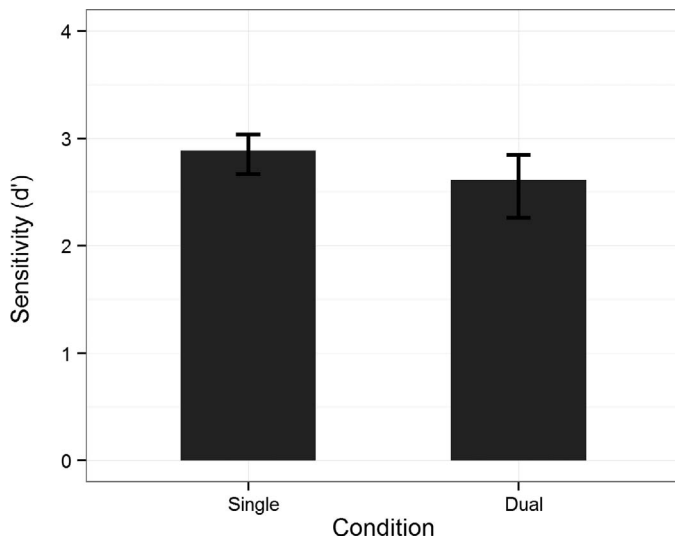


Figure 5. Picture memory sensitivity as a function of task type. Error bars = 95% CI.

neous foveal and peripheral tasks affected the encoding of the scene images into long-term memory.

## Discussion

The results from Experiment 1 confirm previous findings that attentional breadth is significantly reduced in the presence of a difficult foveal load (Greene, Simpson, & Bennion, 2012; Ikeda & Takeuchi, 1975; Kramer, Sirevaag, & Hughes, 1988; Williams, 1988, 1989), but importantly, this was shown after carefully controlling for eccentricity-dependent loss of sensitivity due to cortical magnification, reducing noise in the sensitivity measures by presenting stimuli gaze-contingently at precisely determined eccentricities and within the context of freely viewing natural scenes. Task difficulty for the foveal load can be inferred by the substantially longer SOAs that were necessary for the foveal load (245 ms) compared to the most eccentric Gabor patch (125 ms). An even more convincing aspect of these results is that the peripheral Gabors were given a much longer amount of processing time (masking SOA) than necessary to reach their criterion level of accuracy, but they still showed evidence of tunnel vision. Sensitivity for the Gabors in the single task condition was very high and completely flat across all retinal eccentricities. However, when the foveal load was presented simultaneously with the Gabors, orientation sensitivity became increasingly worse with increasing levels of retinal eccentricity. Importantly, this occurred even when more time than necessary was provided, which, if anything, would have reduced the tunnel vision effect.

As noted above, the large main effect of the single versus dual task factor in the Gabor task performance

provided strong evidence of general interference. Likewise, there was also a decrease in foveal L/T task sensitivity in the dual task condition, which is further evidence of overall attentional costs to dual task performance that extended over the entire visual field including the fovea (i.e., general interference). Although the added cost to the L/T task was not as substantial as for the peripheral Gabor task, the loss of foveal processing power in the L/T task was both significant and meaningful. The fact that the evidence for general interference was considerably larger than that for tunnel vision may have been due to the fact that we carefully controlled for the eccentricity-dependent loss of resolution due to cortical magnification by size-scaling our Gabor stimuli and SOA thresholding them for each participant.

Interestingly, however, the drops in foveal L/T task and peripheral Gabor sensitivity did not translate to an impairment in scene memory encoding. These drops in foveal and peripheral processing seemed to be only at the point in time at which the foveal and peripheral targets were present as opposed to being continuously interfering. Picture memory was unaffected between the two task conditions, which means that the encoding of the picture into long-term memory was not significantly affected by the added foveal load. Thus, the interference was likely at a feed-forward level of processing and not at later stages of processing.

## Experiment 2

Experiment 1 showed that a foveal load produced a strong degree of general interference together with a milder degree of tunnel vision after controlling for eccentricity-dependent loss of sensitivity due to cortical magnification. Importantly as well, this was shown within the context of a naturalistic environment (i.e., freely viewing natural scenes). Experiment 2 sought to determine whether an auditory WM load would produce tunnel vision or general interference of attention while using similar methodological controls in the same natural scene-viewing environment.

## Method

### Methodological overview

The methodology for this study was similar to Experiment 1 with the primary difference being the cognitive load manipulation: namely, an auditory  $n$ -back task rather than the L/T foveal load. Day 1 contained the same screening procedures as in Experiment 1, but participants completed 20  $n$ -back lists to determine the appropriate level of  $n$ -back to produce roughly equal performance to that in the Gabor

discrimination task. On day 2, the participants completed 66 trials of the Gabor discrimination task, which estimated the SOAs to be used during the following days of testing. Days 3, 4, and 5 contained the single versus dual task testing sessions. The testing sessions were split up into three blocks: Gabor single task,  $n$ -back single task, and dual task conditions.

### Participants

Twelve Kansas State University students (nine females; mean age = 24.3,  $SD = 5.04$ ) responded to an online university posting for a paid, multiday study lasting approximately 5 days. Participants were compensated \$5 per hour at the end of each session with the promise of an additional \$5 per hour bonus for each hour completed if they completed all sessions. Participants were also screened for normal vision (20/30 Snellen acuity) using FrACT (Bach, 2007) and cognitive ability using the MoCA (Nasreddine et al., 2005). Informed consent was given at the beginning of each session.

### Materials

#### Apparatus

The apparatus used in Experiment 2 was identical to that in Experiment 1. The delays between the onset of a fixation and updating of the Gabor stimuli to the display were analyzed and found to have a range of 22–51 ms ( $M = 41.21$ ,  $SD = 3.52$ ), which was well below the 80 ms updating threshold prescribed by Loschky and Wolverton (2007).

#### Stimuli

The Gabor stimuli used in Experiment 2 were identical to those of Experiment 1; however, the foveal stimulus was changed from an L/T patch to a Gabor patch subtending  $2.2^\circ$  of visual angle. The auditory stimuli used in the  $n$ -back task were audio recordings of seven letters (H, J, K, L, R, S, and T), which were played every 2 s.

### Procedure

#### $N$ -back thresholding

Following the vision testing and MoCA screening on day 1, the participants completed 20 trials in which they freely viewed images of natural scenes for a picture memory task that would occur after the  $n$ -back block had ended. In the trials, participants were told to memorize the images while they carried out the auditory  $n$ -back task. Given that  $n$ -back levels can only be changed in discrete increments, the SIAM

thresholding algorithm was not used in this case. Instead, if participants scored an accuracy level of less than 77.5% correct, the  $n$ -back level would be reduced by one, and if they scored greater than 87.5% correct, the  $n$ -back level would be increased by one. Then, the  $n$ -back level that provided a performance level closest to the criterion accuracy level (82.5%) was used for the first dual versus single task blocks of trials on day 3.

#### Gabor SOA thresholding

On day 2, participants each completed 66 Gabor discrimination task trials with two presentations (one target, one catch trial) of each Gabor patch eccentricity ( $0^\circ$ ,  $3^\circ$ ,  $6^\circ$ , and  $9^\circ$ ) per trial (Supplementary Movie 3). Based on the results from Experiment 1, in order to avoid artificially inflated SOAs early on in the experiment, the SOA for all Gabors was set at 200 ms for the first six trials in the experiment. After the first six trials, the participants were given feedback on their accuracy for each eccentricity, and the SIAM algorithm began to manipulate the SOAs for the Gabors. Feedback was provided every six trials until the participant reached the memory task.

#### Memory task

The memory task for Experiment 2 was identical to Experiment 1.

#### Single versus dual task testing

On days 3, 4, and 5, the participants completed three blocks of 30 trials during each session: Gabor single task,  $n$ -back single task, and dual task (Supplementary Movie 4). However, to account for learning and fatigue effects that could occur across and within each session, respectively, the order of each of these tasks was counterbalanced both within and across participants. At the beginning of each session, the experimenter set the  $n$ -back level and Gabor SOA values (within the nearest monitor refresh increment) based on the threshold values from the previous session. The participant was given feedback on the  $n$ -back task every six trials to ensure that they were sufficiently engaged with the attentional manipulation. However, because the subjective WM load of the  $n$ -back task has been shown to be significantly reduced with practice, the  $n$ -back level was monitored during each session. If the participant's average  $n$ -back accuracy exceeded 90% correct for a given day, the  $n$ -back level was increased by one for the next day. For sessions in which the  $n$ -back level had increased, the participant began the next day's experiment by completing five  $n$ -back practice

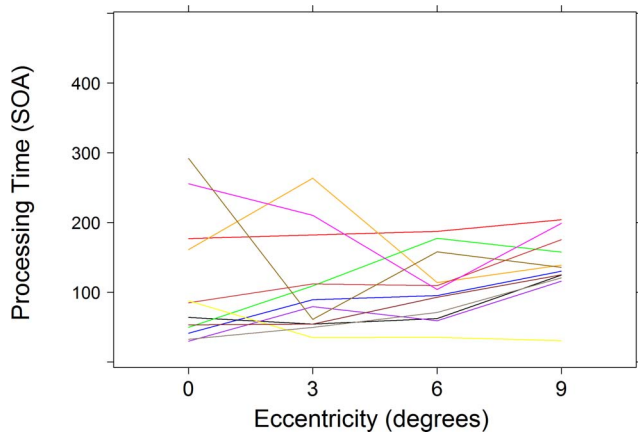


Figure 6. SOA thresholds (in milliseconds) for individual subjects as a function of retinal eccentricity with each line representing an individual subject's stimulus threshold.

trials with the new level before starting the experimental trials for that day.

## Results

### Gabor SOA thresholding

The data cleaning procedures for the Gabor SOA thresholding data for Experiment 2 were the same as those in Experiment 1. One participant had difficulty with the estimation task on day 1, which resulted in SOAs of more than 400 ms and thus created the strong likelihood of frequent nil patches in the following 3 days of testing. However, after a second thresholding session, the SOA estimates were below 200 ms and were considered acceptable. Participants averaged approximately 11.46 reversals ( $SD = 3.71$ ) for each retinal eccentricity, which is slightly lower than what was prescribed by Kaernbach (1990). However, in the cases in which less than 12 reversals were obtained, the SOA values were usually approaching floor levels of processing time. Thus, the results were not contaminated by inconsistent SOAs across eccentricity.

The thresholded Gabor SOAs for Experiment 2 (Figure 6) were approximately equivalent to those obtained in Experiment 1.<sup>5</sup> Nevertheless, the statistically significant trend for larger SOA thresholds at greater target eccentricities that was found in Experiment 1 was not significant in Experiment 2.

### Gabor discrimination: Single versus dual task

A total of 17,217 observations collected from 12 participants were used to generate five competing models in a similar fashion to Experiment 1. These models had identical fixed effects of stimulus type

(target vs. catch trial), task type (single vs. dual), and retinal eccentricity ( $0^\circ$ ,  $3^\circ$ ,  $6^\circ$ , and  $9^\circ$ ) and varying degrees of random effect complexity. The models (listed in Appendix E in Supplementary Materials) were compared, and it was found that the best model was one that included additive random effects of task and eccentricity ( $BIC = 11,400.9$ ) when compared to the nearest best-fitting model, which included eccentricity as the sole random effect ( $BIC = 11,408$ ). Fixed effects tests (detailed in full in Appendix F in Supplementary Materials) revealed that single task Gabor sensitivity was significantly above chance for all participants ( $d' = 2.97$ ,  $z = 68.79$ ,  $p < 0.0001$ ; Figure 7) but that there was a significant reduction in orientation sensitivity with increasing target retinal eccentricity ( $\Delta d' = -0.049^\circ$ ,  $z = -3.92$ ,  $p < 0.0001$ ). Additionally, there was a significant difference in sensitivity for the Gabor orientation task in the dual task condition relative to the single task condition ( $B = -0.733$ ,  $z = -13.02$ ,  $p < 0.0001$ ), showing potential support for the general interference hypothesis. However, as was the case in Experiment 1, the critical question was not *if* the two tasks would be different, but *how* they would be different across retinal eccentricities. The dual task condition did not show a significantly more negative slope compared to the single task condition ( $\Delta d' = -0.023^\circ$ ,  $z = -1.43$ ,  $p = 0.154$ ), which is inconsistent with the tunnel vision hypothesis for an auditory dual task load but is consistent with the general interference hypothesis.

### N-back task: Single versus dual task

To assess whether participants were engaged in the cognitive load manipulation between the single and dual task conditions, a probit mixed model was used to analyze the sensitivity to the  $n$ -back task between single versus dual task conditions. Two competing models were generated, in which the fixed effects of stimulus type (target vs. catch trial) and task type (single vs. dual) were held constant, and the random effects of the model included overall participant performance and performance between single and dual tasks. The model fits were assessed using BIC values, which demonstrated that the simpler model that only included the overall subject differences as a random effect ( $BIC = 14,612$ ) was the better fit compared to the model that included variability between single versus dual task performance ( $BIC = 14,629$ ). Analysis of the fixed effects (detailed in full in Appendix G in Supplementary Materials) from the model demonstrated that participants' sensitivity to the  $n$ -back task was significantly above chance in the single task condition ( $d' = 1.75$ ,  $z = 78.56$ ,  $p < 0.0001$ ; Figure 8) but that there was a significant decrease in sensitivity to the  $n$ -back task in the dual task condition ( $B = -0.22$ ,  $z = -6.64$ ,  $p < 0.0001$ ). Despite the differences in

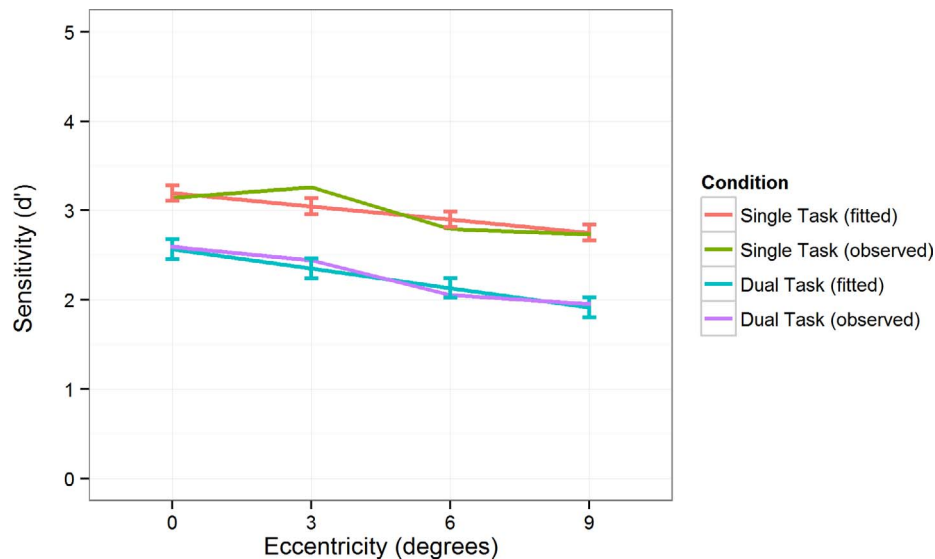


Figure 7. Gabor discrimination sensitivity as a function of task type and retinal eccentricity. Error bars = 95% CI. Fitted results reflect the linear fit of Gabor discrimination sensitivity predicted by the model, and “observed” data reflects the raw Gabor discrimination sensitivity at each categorical level of retinal eccentricity.

performance, however, participants were still well above chance in both conditions, which supports the assumption that participants were sufficiently engaged in the  $n$ -back task when simultaneously engaged in the Gabor orientation discrimination task.

### Picture memory

To determine the effect of the  $n$ -back task on the encoding of picture information during the learning phases of each block, two probit mixed models were generated in a similar fashion to the picture memory results from Experiment 1 but now with three levels of task (Gabor single task,  $n$ -back single task, and dual task; Figure 9). The optimal random effects structure was one that allowed slopes to vary by subject

intercepts (BIC = 2317.2) compared with one that allowed slopes to vary as a function of task across subjects (BIC = 2354.9). Fixed effects tests (detailed in Appendix H in Supplementary Materials) showed that participants were very sensitive to the picture memory task in the Gabor single task condition ( $d' = 2.99$ ,  $z = 25.37$ ,  $p < 0.0001$ ), which was significantly higher than both the  $n$ -back single task ( $B = -0.68$ ,  $z = -4.43$ ,  $p = 0.0001$ ) and the dual task conditions ( $B = -0.865$ ,  $z = -5.75$ ,  $p < 0.0001$ ). However, there was no difference in picture memory between the  $n$ -back single task and dual task conditions ( $B = -0.186$ ,  $z = -1.338$ ,  $p = 0.181$ ), both of which were lower than the Gabor single task condition. Thus the presence of the  $n$ -back task, which required participants to hold letter items in WM while also memorizing the information held within the image, interfered with encoding picture information into long-term memory.

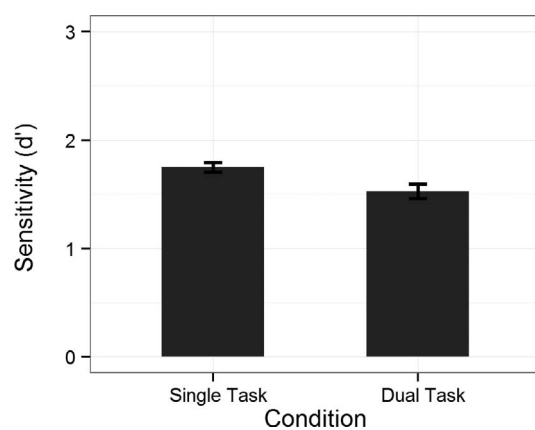


Figure 8.  $N$ -back task sensitivity as a function of task type. Error bars = 95% CI.

### Discussion

The results from Experiment 2 showed that an auditory WM load did not produce tunnel vision. It should be noted that the effect of the foveal load on the Gabor discrimination task ( $\Delta d' = -0.085^\circ$ ) in Experiment 1 was more than three times steeper as a function of retinal eccentricity than the auditory WM load ( $\Delta d' = -0.023^\circ$ ) in Experiment 2. One explanation for the fact that an auditory WM load failed to narrow the UFOV (i.e., the auditory WM load produced shallower changes in attentional breadth between single and dual tasks), whereas the foveal load did, is in terms of



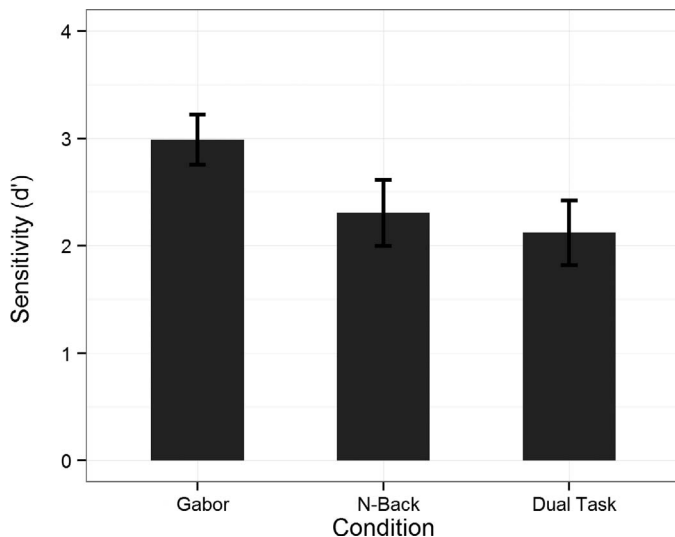


Figure 9. Picture memory sensitivity as a function of task type. Error bars = 95% CI.

reduced competition at the visual perceptual level of processing. That is, the foveal load in Experiment 1 pitted two visual tasks against each other whereas the auditory WM load in Experiment 2 did not.

A second possible reason for the lack of difference in Gabor sensitivity slopes as a function of eccentricity across the single versus dual tasks is that the *n*-back task auditory stimuli only occasionally occurred during the trial whereas the foveal load dual task from Experiment 1 always appeared simultaneously with the peripheral Gabor discrimination task. To evaluate this hypothesis, a hazard analysis on the dual task condition was conducted to determine if there was any change in Gabor sensitivity across retinal eccentricities as a function of the temporal distance from an *n*-back stimulus. Five logit mixed models were computed with fixed effects of Gabor eccentricity and the distance in time from an *n*-back stimulus with both serving as singular, additive, and interactive mixed effects. Time was fitted with a natural spline to account for potential nonlinearity among retinal eccentricity slopes. Model fitness indices found that a model that varied only in terms of overall subject means was the best fitting model (BIC = 7623.4; listed in full in Appendix I in Supplementary Materials) compared to the next best model, which included differences across the previous time from an *n*-back target. Although fixed effects tests (see Appendix J for full details in Supplementary Materials) revealed a replication of a significant negative slope for eccentricity ( $B = -0.06$ ,  $z = -3.11$ ,  $p = 0.002$ ), there was no main effect of time ( $B = -0.07$ ,  $z = -0.308$ ,  $p = 0.757$ ), nor was there any interaction of retinal eccentricity and time ( $B = -0.008$ ,  $z = -0.123$ ,  $p = 0.902$ ). Thus, given that the time between *n*-back stimuli and Gabor stimuli had no effect on Gabor

	Mean SOA (ms)	SE	<i>t</i> value	<i>p</i> ( <i>t</i> )	Cohen's <i>d</i>
0°	110.81	25.95	4.27	0.001	
3°	108.68	24.42	-0.09	0.93	0.025
6°	106.66	23.09	-0.18	0.86	0.052
9°	140.77	23.22	1.29	0.22	0.372

Table 2. Mean SOAs (in milliseconds) for Gabor stimuli in Experiment 2. Notes: *t* values are in comparison to the 0° eccentricity, and the 0° *t* value is compared to 0.

sensitivity, we cannot explain the lack of a tunnel vision effect in the current experiment based on the only occasional occurrence of the *n*-back auditory stimuli. In fact, a task analysis of the *n*-back task shows that the “empty time” between the occurrence of *n*-back auditory items is far from cognitively empty. Rather, the time between auditory items is filled with a series of cognitive processes (Chen, Mitra, & Schlaghecken, 2008; Jaeggi et al., 2010), including “matching the newest item with the one *N*-back in the list, deciding whether to make a response (including resolving interference from distractors), either making or inhibiting a response, then shifting the *N*-1 back item to the *N*-back list position, replacing the previous *N*-back item with the new one, and possibly also rehearsing the relevant section of the new list” (Loschky et al., 2014, p. 530). Thus, if anything, it seems likely that the participants in Experiment 2 were under a more continuous cognitive load than the participants in Experiment 1, who only dealt with the rotated L versus T task every 2–3 s (i.e., every seventh fixation). At a central processing level, there was reduced picture memory with the *n*-back task, in which picture memory was highest for the Gabor single task and significantly lower for the *n*-back single task and the dual task conditions. The lack of difference between the *n*-back single task and dual task conditions, however, confirms the conclusion from Experiment 1 that the occasional, gaze-contingent stimulus presentations do very little to interfere with the encoding of visual information. Conversely, the relatively continuous cognitive load caused by the *n*-back task clearly disrupted encoding visual information into long-term memory.

## General discussion

The objective for these two experiments was clear. To date, no study had thoroughly evaluated the moment-to-moment changes of attentional breadth that occur (a) in the presence of differing task modalities, (b) independent of eccentricity-dependent loss of sensitivity due to cortical magnification, and (c) in naturalistic contexts. The results presented here suggest that a demanding foveal load is necessary but

also sufficient to significantly reduce the size of the useful field of view in natural scene viewing even when controlling for eccentricity-dependent loss of sensitivity.

Nevertheless, the results across the two experiments showed substantial main effects of task type (single vs. dual), which is consistent with general interference. To reiterate, evidence of tunnel vision does not necessarily negate evidence of general interference in a dual task paradigm. In Experiment 1, despite the significant interaction between task and eccentricity, there was a far more pronounced main effect of dual task interference across all eccentricities. This predominance of general interference may be explained by our use of size-scaling and SOA thresholding to control for eccentricity-dependent loss of resolution due to cortical magnification in the fully attended (single task) condition. If correct, this suggests that much of the usual reduction of the UFOV with eccentricity that is labeled as tunnel vision may be due to cortical magnification rather than attentional tunneling per se. From this perspective, it is perhaps surprising that we were able to find evidence in Experiment 1 of tunnel vision at all once eccentricity-dependent loss of sensitivity had been controlled for under single task conditions. Thus, these are the first results to demonstrate tunnel vision using a covert visual attention measure in real-world scenes after accounting for eccentricity-dependent visual differences.

In Experiment 2, we also observed clear evidence of general interference with an auditory WM load, which produced no interaction between the single versus dual task and eccentricity factors. Those results are consistent with other recent results using the same methodological framework but in driving simulator studies (Gaspar et al., in press; Ringer, Johnson, Gaspar, et al., 2014). These results are most easily explained by the lack of a foveal load but may also reflect our efforts to control for the effects of cortical magnification. One can ask further why the foveal load caused such strong general interference in Experiment 1 relative to the effect found in Experiment 2. Specifically, the foveal load in Experiment 1 produced greater dual task interference with the Gabor task (single vs. dual task,  $\Delta d' = -3.23$ ) than the *n*-back task did in Experiment 2 (single vs. dual task:  $\Delta d' = -0.733$ ). Having said that, we must be cautious in interpreting these differences because methodological constraints necessitated the use of different SOA thresholds between Experiments 1 and 2. Nevertheless, it is noncontroversial that visuospatial/visuospatial dual task interference should be stronger than audio WM/visuospatial dual task interference in line with predictions from multiple resource theory (Wickens, 2002). In Experiment 1, participants completed a visual–visual dual task with central processing resource competition occurring within the spatial

domain (i.e., the spatial configurations of junctions in the L/T task and the spatial orientation of the Gabor patches). Conversely, Experiment 2's dual task paradigm was an auditory WM load with central processing resources divided between auditory versus visual resources and also WM versus perceptual resources. Thus, the different magnitudes of the single versus dual task effects across Experiments 1 and 2 is not surprising despite the fact that the difficulty for the primary tasks in Experiments 1 and 2 (i.e., L/T discrimination and auditory *n*-back task, respectively) was thresholded to be approximately equal across both experiments. Despite these efforts to equalize the difficulty of the primary tasks, what is particularly interesting is that when comparing single task performance on the visual L/T and auditory *n*-back tasks themselves, the L/T task ( $d' = 2.7$ ) was clearly a much easier task than the *n*-back task ( $d' = 1.75$ ). Nevertheless, as shown by a comparison of Figures 3 and 8, the drop in performance from single to dual task was much greater for the visual L/T task than the auditory *n*-back task. This clearly shows that the relative difficulty of a single task does not determine its relative difficulty when used as a dual task manipulation.

The results from these two experiments are consistent with Williams' (1988, 1989) claim that producing tunnel vision requires a sufficiently difficult foveal load. Interestingly, however, although Williams (1988, 1989) also argued for the necessity of a speeded response, in the current study we did not have that, yet we produced tunnel vision. On the other hand, our study did limit stimulus processing time through the use of visual masking that was tailored to each participant through adaptive threshold estimation. This is similar to Ball et al.'s (1988) method for measuring the UFOV, which included a foveal load, and both used visual masking to limit processing time, which is varied with an adaptive threshold estimation procedure. Ball et al.'s (1988) method and measure strongly imply the existence of tunnel vision in their task, which is inferred through increased processing time thresholds for localization targets with increasing retinal eccentricity (although the UFOV<sup>®</sup> does not control for low-level, eccentricity-dependent loss of resolution and thus cannot rule out that simple explanation for the apparent tunnel vision in their task). In fact, having limited stimulus processing time seems like a reasonable alternative to Williams' (1988, 1989) requirement of a speeded response as a critical factor for producing tunnel vision.

Indeed, a simple explanation for our evidence of tunnel vision in Experiment 1 crucially invokes limited processing time. Specifically, if viewers' attention was initially focused at the fovea by the L/T foveal load and if processing of the foveal load required considerable processing time (as shown in Figure 2, L/T task), viewers may not have had enough time to then switch

their attention to the peripheral targets before they were masked. Furthermore, if attentional switching times increase with retinal eccentricity (as shown in Figure 2, Gabor task at 3°–9°), then difficulties caused by limiting processing time would be more severe for more eccentric targets, thus producing tunnel vision. Interestingly, we found this result despite giving participants considerably more processing time than they needed to do the Gabor task by itself (Figure 2, comparison of L/T vs. Gabor task SOAs) by setting the SOA for both tasks, for each participant, to their longest SOA across tasks (i.e., the L/T). By doing so, we therefore made it more difficult to find evidence of tunnel vision if our above argument based on processing time is correct. Thus, our evidence of tunnel vision is, if anything, an underestimate.

The above argument is also consistent with previous results showing that limiting processing time differentially affects perception in central versus peripheral vision with longer processing times needed to process information in the periphery—suggesting that attention moves outward from the fovea to peripheral vision over the course of a fixation. Larson and Loschky (2009) investigated rapid scene categorization and found that they could divide circular scene images into mutually exclusive central and peripheral regions (a circular center and a surrounding annulus divided by a *critical radius*) that produced identical performance when briefly flashed but unmasked. Then, in a later experiment using such critical radius stimuli, Larson, Freeman, Ringer, and Loschky (2014) used visual masking to investigate the effects of processing time on rapid scene categorization based on information from central versus peripheral vision. In one experiment, a probability manipulation biased participants to expect either the central or peripheral portions of natural scenes, which were shown on 80% versus 20% of trials. When participants were biased to expect centrally presented portions of the image, they were significantly worse at categorizing information in the periphery at early (e.g., <70 ms SOA) levels of processing time. Conversely, when participants were biased to expect peripheral information, there were no differences between central and peripheral scene categorization at either early or later processing times. These results suggested an outward expansion of attention over processing time within a single fixation. Comparing the central processing bias found in Larson et al. (2014) with the results of the current experiment suggests that a foveal load slows down the rate at which attention moves from the fovea into the periphery.

The progression of attention from central to peripheral vision over the course of a single fixation is consistent with *serial attentional shift* models (Henderson, 1993), which have been supported by gaze-contingent studies of both reading (Henderson, 1992;

Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003; for a comprehensive comparison of models, see Reichle, Rayner, & Pollatsek, 2003) and scene perception (van Diepen & d’Ydewalle, 2003). Generally, these models assume that after a saccade ends, early in a fixation, attention is devoted to processing the foveal target, assumedly because that is the information used to update our understanding of the visual array. Having done that, attention expands (or is allocated) to the area in the visual periphery that is potentially most informative (Eckstein, Drescher, & Shimozaki, 2006; Najemnik & Geisler, 2005). Related research has shown a systematic spread of covert attention from central to peripheral vision that maps onto the time course of single fixations (Motter & Simoni, 2008). Nevertheless, Experiments 1 and 2 did not directly manipulate the temporal properties of our Gabor and L/T stimuli (initial SOA thresholding notwithstanding), and therefore, we cannot claim with certainty that tunnel vision is a consequence of the sequential spread of attention over space during a fixation. An alternative parallel processing account would be that applying fewer attentional resources to the periphery simply produces slower peripheral processing.

To our knowledge, in scene perception, there are currently no fully implemented computational models of attentional distribution during each fixation between the fovea and the periphery. However, in reading, the saccade-generation with inhibition of foveal targets model (SWIFT; Engbert, Nuthmann, Richter, & Kliegl, 2005) provides a computational approach to measuring the effects of foveal, lexical processing on delaying the transition between serial and parallel processing. Later versions of SWIFT (i.e., SWIFT 3; Engbert, Longtin, & Kliegl, 2002; Schad & Engbert, 2012) integrate theories of parallel processing and the “zoom lens” model of attention (Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Mueller, Bartlett, Donner, Villringer, & Brandt, 2003; Seiple, Clemens, Greenstein, Holopigian, & Zhang, 2002). In it, the programming and execution of a saccade is dependent upon the degree of foveal load but not the degree of extrafoveal load. Greater foveal loads (e.g., difficult lexical processing) reduce the size of the attentional window, which interferes with the ability to process peripheral information before the next saccade and fixation. Because attention is a limited resource, if greater attentional gain is devoted to foveal information, then less is available for the parafovea and the periphery, leading to attentional tunneling. This is broadly consistent with the results of Experiment 1, which showed that a foveal load led to tunnel vision in scene perception. This suggests that a computational model of attentional distribution during fixations in scene

perception could have a number of parallels with the SWIFT model for reading. However, in the context of scene viewing, such a model would need to incorporate changes based on crucial differences due to the nature of scene versus reading stimuli, their respective diagnostic information sources (Schyns, 1998), and related processing routines (Ullman, 1984). For instance, text has a far less varied structure than scenes, and attentional shifts in reading are normally unidirectional whereas, in scene viewing, attention is not nearly so spatially and directionally constrained, and this is evidenced in a number of differences in eye movement parameters although not in the underlying processes (see Nuthmann & Henderson, 2012).

An important remaining question is why the current study showed that tunnel vision only occurred with a foveal load and not with an auditory WM load as other studies have shown that an auditory cognitive load produced tunnel vision. Several studies have inferred that increasing levels of an auditory cognitive load produce progressively greater tunnel vision as indicated by reduced saccade amplitude and increased fixation distribution densities (Loschky et al., 2014; Pomplun et al., 2001; Reimer et al., 2012). In an ingenious example, Pomplun et al. (2001) made careful use of eye-movement metrics to estimate the size of the covert window of attention. To do this, they used a gaze-contingent moving window to limit the scope of visible information in such a way that the window was sufficiently large to not interfere with the search task. However, the narrowing of the perceptual span in all of the above-cited studies could have been affected by the eccentricity-dependent loss of resolution due to cortical magnification, which could have degraded visual information at a faster rate under divided attention conditions even if covert attention was being reduced at a constant rate across the visual field. If so, then our use of size-scaling and SOA scaling to equalize performance under single-task conditions may explain why we found evidence for general interference from an auditory WM load while these other studies found eye movement–based evidence of tunnel vision. Of course, for practical purposes, one could argue that the UFOV does result in tunneling when measured under any dual task condition—after all, the real world is not m-scaled. However, if one wants to understand how *covert attention* varies across the field of view, the answer can become muddled if it is confounded with a priori eccentricity-dependent sensory limitations. By using size-scaling and SOA thresholding to ensure that this alternative explanation could be eliminated, the data from the two experiments in the current study demonstrate a clearer association between a foveal load and narrowing of covert attention.

The current study provides an important step toward understanding the fundamental nature of the spread of

attention across the field of view, aka the UFOV, and it does so within the context of naturally viewing real-world scene images. In doing so, the current study raises new questions, for example, regarding the independent or interacting effects of m-scaling, processing time, and attentional prioritization in producing tunnel vision or general interference, which further research will be needed to answer. However, the current study provides both a strong foundation and much-needed guidance on which to base such further research.

*Keywords:* eye tracking, gaze-contingent displays, dual tasking, divided attention, useful field of view

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## Footnotes

<sup>1</sup> Other similar terms are the *functional field of view*, *perceptual span*, or *attentional breadth*. We will primarily use the terms UFOV or attentional breadth.

<sup>2</sup> This concern can be avoided by updating the gaze-contingent display continuously. However, that can produce a different artifact; namely, if perceptible

jitter is introduced by intrafixational movements, attention can be drawn to the edge of the window.

<sup>3</sup> The results of Chan and Courtney (1998) are rather complicated by the fact that there were opposing ceiling and floor effects at the largest retinal eccentricity ( $5^\circ$ ) in the size-scaled and non-size-scaled conditions, respectively. For the size-scaled stimuli, performance actually increased with eccentricity, suggesting that the size-scaling was somewhat overly effective.

<sup>4</sup> Studies using fMRI measurements to evaluate the locus of interference in the  $n$ -back have generally found a relationship between the level of  $n$  and activation of Broca's area although this effect attenuates with increased training (Cohen et al., 1997). A more reliable effect of the  $n$ -back task is that the dorsolateral prefrontal cortex (known to be heavily involved in executive WM tasks) increases its level of activity as  $n$  increases with a significant difference between zero and one back compared to two and three back (Cohen et al., 1997). Other fMRI data has also shown increases in the right and left inferior frontal gyri and superior parietal lobe in the two- and three-back tasks, an effect carried over to the one-back task during simultaneous visual and auditory  $n$ -back tasks (Jaeggi et al., 2003).

<sup>5</sup> The only notable difference was the substantially shorter threshold SOAs to discriminate Gabor patches at the fovea (Table 2) than the rotated L/T task in the fovea in Experiment 1. However, given the larger differences between the tasks, such a difference is not surprising.

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