Measuring the Useful Field of View During Simulated Driving With Gaze-Contingent Displays

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Objective: We aimed to develop and test a new dynamic measure of transient changes to the useful field of view (UFOV), utilizing a gaze-contingent paradigm for use in realistic simulated environments.

Background: The UFOV, the area from which an observer can extract visual information during a single fixation, has been correlated with driving performance and crash risk. However, some existing measures of the UFOV cannot be used dynamically in realistic simulators, and other UFOV measures involve constant stimuli at fixed locations. We propose a gaze-contingent UFOV measure (the GC-UFOV) that solves the above problems.

Methods: Twenty-five participants completed four simulated drives while they concurrently performed an occasional gaze-contingent Gabor orientation discrimination task. Gabors appeared randomly at one of three retinal eccentricities (5°, 10°, or 15°). Cognitive workload was manipulated both with a concurrent auditory working memory task and with driving task difficulty (via presence/absence of lateral wind).

Results: Cognitive workload had a detrimental effect on Gabor discrimination accuracy at all three retinal eccentricities. Interestingly, this accuracy cost was equivalent across eccentricities, consistent with previous findings of "general interference" rather than "tunnel vision."

Conclusion: The results showed that the GC-UFOV method was able to measure transient changes in UFOV due to cognitive load in a realistic simulated environment.

Application: The GC-UFOV paradigm developed and tested in this study is a novel and effective tool for studying transient changes in the UFOV due to cognitive load in the context of complex real-world tasks such as simulated driving.

Keywords: useful field of view (UFOV), driver distraction, gaze-contingent displays

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INTRODUCTION

As we go about our daily lives, we often have to rapidly respond to changes in our environment. For example, in order to safely drive a car, we must be aware of other vehicles and pedestrians that encroach on our car and respond to them accordingly. Importantly, the information we must be aware of in order to respond appropriately often first appears in our peripheral vision. Researchers use a theoretical construct to describe this aspect of situational awareness, called the useful field of view (UFOV). The UFOV comprises the visual field from which information can be extracted in a single eye fixation (i.e., without eye and head movements) (Ball, Beard, Roenker, Miller, & Griggs, 1988; Mackworth, 1965; Miura, 1986; Williams, 1985). There are several other commonly used terms that refer to the same theoretical construct, including the functional field of view (FFOV) (Crundall, Underwood, & Chapman, 1999; Park & Reed, 2010; Williams, 1989), the perceptual span (Gildman & Underwood, 2003; Greene, Simpson, & Bennion, 2012), and attentional breadth (Pringle, Irwin, Kramer, & Atchley, 2001). In addition, there is the trade-marked measure, the UFOV®, developed by Ball and colleagues (Ball et al., 1988; Ball et al., 2006), which shares the same name as the theoretical construct. Importantly, the UFOV can vary as a function of changes in cognitive workload (Atchley & Dressel, 2004; Ball et al., 1988; Crundall, Underwood, & Chapman, 2002; Recarte & Nunes, 2003; Williams, 1985) and is amenable to training (Ball et al., 1988; Ikeda & Takeuchi, 1975; Roenker, Cissell, Ball, Wadley, & Edwards, 2003). From an applied perspective, measures of the UFOV have been shown to be predictive of negative outcomes in real-world tasks, such as crashes during driving (Ball, Edwards, Ross, & McGwin, 2010; Clay et al., 2005). This is purportedly because people with a narrow or degraded UFOV fail to perceive safety-critical information in their environment that falls outside the bounds of their UFOV (Pringle, Kramer, & Irwin, 2004).

A large number of previous studies, including those of Ball and colleagues using the UFOV®, have measured the UFOV using tachistoscopic displays (i.e., briefly flashed while the viewer was forced to maintain fixation) with simple stimuli, such as letters, numbers, or simple shapes (Atchley & Dressel, 2004; Ball et al., 1988; Mackworth, 1965; Motter & Simoni, 2008; Rantanen & Goldberg, 1999; Williams, 1985; Wolfe, O'Neill, & Bennett, 1998). These targets are presented at different retinal eccentricities, while the observer is instructed to maintain fixation on the center of the screen. However, a drawback to the nature of these measures' design is that they cannot be used to measure transient changes in the UFOV in realistic stimulated driving environments. First, using tachistoscopic displays with enforced fixation is antithetical to the possibility of allowing viewers to freely look around a complex display such as a driving simulator. Second, if one were to overlay the UFOV® measure on the windscreen of a driving simulator, it would visually mask the scene beyond the windscreen. Thus, the UFOV® task and similar ones cannot tell us how the UFOV changes on a moment-to-moment basis during driving, for example when drivers encounter heavy traffic or become distracted. Being able to study such situation-dependent moment-to-moment changes in a person's UFOV provides important insight into the specific dangers caused by a narrow or degraded UFOV and can thus suggest ways to either avoid or counteract those dangers. Furthermore, studying the UFOV in context allows us to draw more detailed insights into the role of the UFOV in complex tasks than has been possible in previous correlational studies.

Other studies have investigated transitory changes in the UFOV due to cognitive load during either real or simulated driving (Bian, Kang, & Andersen, 2010; Crundall et al., 1999, 2002; Jahn, Oehme, Krems, & Gelau, 2005; Miura, 1986; Recarte & Nunes, 2003; Reimer, Mehler, Wang, & Coughlin, 2012; Seya, Nakayasu, & Yagi, 2013; Son, Park, & Oh, 2012). The most commonly used measure of the UFOV in these studies, the peripheral detection task (PDT), typically requires drivers to respond to the onset of LED lights at fixed locations across the vehicle windscreen and measures accuracy and/or reaction time on this task as a function of workload or driving task difficulty (Bian et al., 2010; Crundall et al., 1999, 2002; Jahn et al., 2005; Miura, 1986). However, there are important aspects of how the PDT has been implemented that limit our understanding of the UFOV. The most pressing of these concerns are that the PDT stimuli generally appear at fixed physical locations, relative to either the vehicle or the driver's head, and that they generally have fixed sizes and intensities. In order to measure moment-to-moment changes in the UFOV, one must analyze target detection rates as a function of retinal eccentricity. For example, Crundall et al. (1999, 2002) used luminance targets with fixed locations on the screen. Likewise, Jahn et al. (2005) used three LEDs reflected on the left side of the windscreen of a driving simulator, ranging from 11° to 33° of visual angle from the center of the steering wheel. A problem in using fixed target locations is that drivers are constantly moving their eyes and heads relative to the target stimuli in ways uncontrolled by the experimenter. Thus, a target's retinal eccentricity is uncontrolled, and therefore, no two targets will necessarily appear at the same retinal eccentricity. For this reason, the experimenter is unable to control the relationship between the independent variables of cognitive load and target retinal eccentricity, adding potential noise to the measured relationship between the two. A second related problem in PDT studies is that the targets generally also have a fixed size and intensity, whereas the distance between the center of gaze (the fovea) and the targets varies. This is a problem because it confounds (a) the fixed drop-off of acuity/sensitivity with increasing retinal eccentricity and (b) the effects of attentional breadth. Specifically, visual resolution rapidly decreases with increasing distance from the fovea, as does one's ability to distinguish objects from their neighbors (visual crowding) (for review, see Strasburger, Rentschler, & Juttner, 2011). Thus, as has previously been argued (Chan & Courtney, 1998; Williams, 1989), in measuring the UFOV, it is important to disentangle the effects of these hard limits from the pure effects of attentional breadth, which are more cognitive in nature (Ringer et al., 2014). Additionally, in order to more effectively measure the attentional state of the observer, one must provide a task that requires effortful processing. In this regard, the simple detection of visual features (i.e., presence vs. absence) is not as attentionally demanding as discriminating between similar stimuli (Carrasco, 2011; Correa, Lupianez, Milliken, & Tudela, 2004; Kowler, Anderson, Dosher, & Blaser, 1995; Sagi & Julesz, 1985).

Therefore, the primary goal of the present study was to overcome the previously discussed limitations by using gaze-contingent displays (GCDs) to measure moment-to-moment changes in the UFOV in a simulated driving environment. In doing so, we used the gaze-contingent UFOV (GC-UFOV) framework proposed by Ringer et al. (2014). This framework contains four components: (a) a dependent measure of attention, (b) a manipulation of attention, (c) GCDs, and (d) an adjustment of the discrimination threshold of the dependent measure of attention under fully attended conditions at each eccentricity.

The current study manipulated attention in two qualitatively different ways. First, we manipulated cognitive load by using the N-back task (Kirchner, 1958), an attentionally demanding working memory task. The cognitive load caused by the N-back task (at two-back) impairs dual task performance on visual tasks, such as the antisaccade task (Mitchell, Macrae, & Gilchrist, 2002), and visual performance during simulated driving tasks (Reimer et al., 2012; Son et al., 2012). This allowed us to manipulate attention in a rigorously standardized way. Second, we also manipulated cognitive load through simulated driving task difficulty. We did this by manipulating the presence of lateral wind in the driving simulator, which has been shown in previous studies to affect driving performance (Andersen & Ni, 2005; Medeiros-Ward, Cooper, & Strayer, 2014). This allowed us to manipulate cognitive load, and potentially visual attention, in a more ecologically valid way.

In the current study, we presented the Gabor patches on selected single fixations using GCDs (for reviews, see Duchowski, Cournia, & Murphy, 2004; Rayner, 1998; Reingold, Loschky, McConkie, & Stampe, 2003; van Diepen, Wampers, & d'Ydewalle, 1998). The use of GCDs to study the UFOV was pioneered by McConkie and Rayner as a way to investigate the perceptual span in reading (McConkie & Rayner, 1975, 1976; Rayner, 1975) and was later extended to investigate visual attention in scenes (e.g., Loschky & McConkie, 2002; Nuthmann, 2014; Rayner, Smith, Malcolm, & Henderson, 2009). By using eye tracking, GCDs can present dynamic imagery at fixed retinal eccentricities regardless of where the viewers move their eyes. In this way, we could overcome the PDT's previously noted problem of noisy measurement of eccentricity effects.

A secondary goal of the present experiment was to examine how retinal eccentricity, and more importantly, attention as manipulated by cognitive load, affects the UFOV in a driving simulator. Two competing possibilities exist to explain how cognitive workload affects the UFOV on a moment-to-moment basis in complex tasks. A tunnel vision account suggests that increased cognitive workload causes a narrowing of the UFOV (Greene et al., 2012; Ikeda & Takeuchi, 1975; Plainis, Murray, & Chauhan, 2001; Rantanen & Goldberg, 1999; Williams, 1988, 1989). The tunnel vision account predicts that discrimination at further eccentricities of the UFOV will show greater decrements under high workload, with discrimination at closer eccentricities remaining relatively conserved. Conversely, a general interference account holds that performance over the entire UFOV will be equivalently degraded under conditions of heightened workload (Bian et al., 2010; Crundall et al., 1999, 2002). The above listed studies have found evidence consistent with one or the other of these accounts. However, a vast majority of these studies did not control for the drop-off of visual acuity with eccentricity through use of adaptive thresholding or use of real-world images. Thus, the use of the GC-UFOV method described above provides an opportunity to investigate the "tunnel vision" and "general interference" accounts of the effects of cognitive load on the UFOV in a way that avoids the earlier mentioned problems.

METHOD

Participants

Twenty-five licensed younger adults (mean age = 22; age range = 19–30) with normal uncorrected near acuity (≤20/30 using a Snellen acuity chart) were recruited from Urbana-Champaign and paid for participating. Study procedures were approved by the University of Illinois Institutional Review Board, and participants provided informed consent prior to participating.

Apparatus

The apparatus consisted of several interconnected systems:

1. The core component was a DriveSafety™ desktop driving simulator (Figure 1). The simulator consisted of a 55-inch LED display. Scenarios were created using DriveSafety Hyperdrive. Steering and speed were controlled via a Logitech™ G27 steering wheel mounted on the desktop and pedals located under the desk. Driving data were collected at 60 Hz. Two buttons located on the steering wheel were used to collect driver responses to the gaze-contingent discrimination task. Custom HyperDrive code also ran a two-back working memory task, sending letters to a speech PC via transmission control protocol for audio playback and communicating with an EasyVR speech recognition module (http://www.veear.eu/products/easyvr-arduino-shield/) attached to another PC for gathering responses.

The projector screen display area measured 1.37 × 1.03 m and 1024 × 768 pixels, implying that the pixels were not square. All stimuli were differentially scaled in X and Y in order to have the correct metric dimensions on the display. Nominal viewing distance (participants' heads were not constrained) was 1.6 m, so the display measured approximately 46° × 36°.

Figure 1. Experimental setup of the DriveSafety simulator and SmartEye tracker.

2. A SmartEye Pro 5 (Smart Eye AB, Sweden) gaze tracker consisting of four stationary desktop-mounted IR cameras was used to reconstruct head and gaze position at 60 Hz. Data were output to the overlay PC via user datagram protocol (UDP).
3. The overlay rendering PC accepted two inputs: (a) the video output from the driving simulator using an Epiphan video capture card (http://www.epiphan.com/products/frame-grabbers/vga2pcie/), and (b) the gaze position from the SmartEye via UDP. A Python program collected the inputs, performed fixation identification, and used OpenGL Shader Language and an NVidia GeForce GTX 480 GPU to render the HyperDrive input image with or without a stimulus overlay.

Procedures

Overview. Figure 2 shows a schematic of the order of tasks in the experimental session. The order of the experimental drives, including driving difficulty and cognitive workload conditions, was counterbalanced across participants.

Gabor stimuli. Stimuli consisted of four brightness-clipped Gabor patches centered on fixation and tangentially spaced 90° apart with a random angular offset. At each of the three possible retinal eccentricities (5°, 10°, and 15°), the

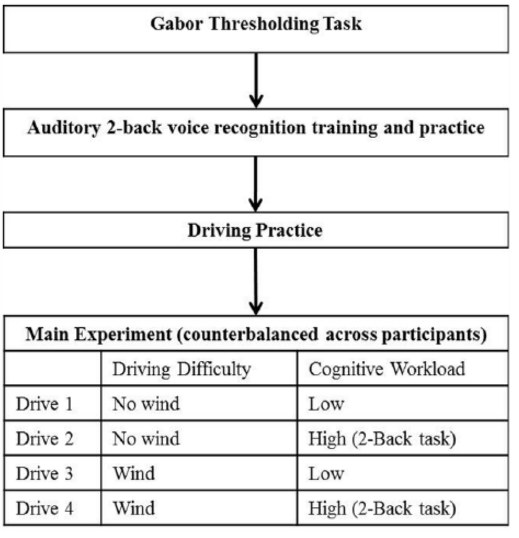

Figure 2. Order of tasks in the experiment.

Gaussian sigma parameter was equal to (eccentricity in degrees / 10) and the sinewave frequency in cycles per degree (cpd) was equal to (15 / eccentricity in degrees). Gabor patch size was always 4 * sigma, which at the largest size corresponded to 133 × 128 pixels. Even at this largest size, rendering time for the entire frame was ~1.7 milliseconds; as rendering was synchronized to vertical sync, patch size did not affect rendering frame rate.

In each video frame, the Gabor mean or baseline value for each of the four patches was taken as the Gaussian-weighted average of the pixel values around the same location in the underlying image. The Gaussian weighting function had the same sigma parameter and pixel size as the Gabor itself. The Gabor amplitude of each patch in pixel value steps was set to the maximum of (mean) and (255 – mean). Thus, the Gabors were always clipped either at the white or black end of the scale, unless the mean happened to be equal to 127.5.

Gabor thresholding. Prior to the main experiment, we pretested participants to determine their individualized Gabor orientation discrimination thresholds that would produce 80% accuracy at each of three retinal eccentricities (5°, 10°, or 15°). Participants fixated a white cross in the center of the screen while viewing a playback of an image sequence generated using the driving task described above. Gabor patches appeared randomly every 5 to 10 seconds at 5°, 10°, or 15° eccentricity from the white cross. The minimum eccentricity of 5° was chosen based on the limits of our SmartEye eye tracker's accuracy, and the maximum eccentricity of 15° was the farthest we could present our Gabors based on their size and that of the screen without having them go off the screen. Gabors were presented within a subset of the screen such that all four could clearly appear. The absolute value of the Gabor's deviation from vertical was varied between presentations based on participants' responses using the psychometric slope method (Kontsevich & Tyler, 1999) to find the 80% correct orientation threshold. These orientation values (one for each eccentricity) were then used for all Gabor stimuli presented in the main experiment for that particular participant. The thresholding procedure lasted approximately 25 minutes.

Gaze-contingent Gabor orientation discrimination. During each of the four experimental drives, participants completed an occasional gaze-contingent Gabor orientation discrimination task, hereafter referred to as the "discrimination task." Gabor patches appeared randomly every 6 to 10 fixations and had presentation durations of 67 milliseconds. As shown in Figure 3, the stimulus overlay consisted of four Gabor patches in random radial positions equally spaced around fixation at a constant distance of 5°, 10°, or 15° from fixation. Gabor orientation offsets (from vertical) at each eccentricity were set to each individual participant's threshold, calculated separately for all three eccentricities. Gabor size and spatial frequency covaried at each eccentricity to account for retinal size to ensure equal discriminability at each eccentricity and were consistent across participants. Participants identified the left/right orientation of near-vertical Gabor patches by pressing a corresponding button on the steering wheel. A video example of the discrimination task (with a circle to represent the driver's gaze) is accessible in the online supplemental material (available at http://hf.sagepub.com/supplemental).

Cognitive workload manipulation. During two of the experimental drives (high cognitive

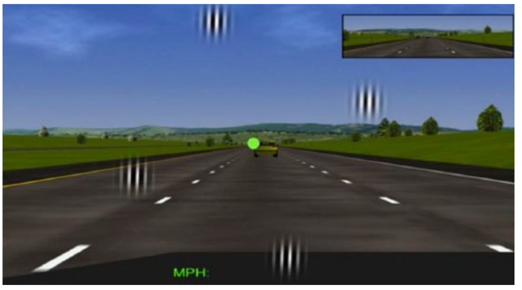

Figure 3. Example screenshot of the Gabor stimuli overlaid on the driving simulator image. The green dot represents the participant's current fixation location (note that this dot did not appear during the actual experiment). The participant's goal was to determine the direction of the vertical offset; in this case, the Gabors are offset to the right.

workload), participants completed a concurrent auditory two-back working memory task. We chose to present an auditory N-back task so that it would not directly interfere with the visual Gabor orientation discrimination task. On each trial, one of 26 letters (comprising the entire alphabet) was selected randomly. There was a 25% chance that the selected letter would match the letter two spaces before. Participants heard a letter every 3 seconds and were instructed to respond as quickly as possible, by saying "yes," if they detected a two-back repeat. In the other two drives (low cognitive workload), participants drove without doing the auditory two-back task. Prior to the actual experiment, participants were given training and practice with the auditory two-back task so that they both understood how to do it and were familiar with the task.

Driving task and task difficulty manipulation. Participants followed a lead vehicle (LV) in the center lane of a three-lane highway and were instructed to maintain a 50-meter gap from the LV while staying in the center of the lane. Driving difficulty was manipulated by adding lateral wind to two of the four drives, which was generated using the combination of a constant wind and the sum of three sine waves (Andersen & Ni, 2005; Medeiros-Ward, Cooper, & Strayer, 2014). Each drive lasted approximately 15 minutes, and participants were allowed to rest between drives. Prior to the experiment, participants practiced following behind the lead car and received visual feedback during the drive about their headway distance and lateral lane position.

RESULTS

Gabor Orientation Discrimination Accuracy

Of primary interest in the present study were the effects of task difficulty and cognitive workload on Gabor discrimination. Such effects, if found, would be evidence of attentional costs measured by our GC-UFOV measure. In addition, a second point of interest was whether these factors interacted with eccentricity, which would enable us to determine whether the experimental conditions produced either tunnel vision or general interference. Specifically, if Gabor discrimination accuracy were disrupted, either by task difficulty or cognitive workload, more at near eccentricities than far eccentricities, this would provide evidence for a visual tunneling effect. Conversely, if Gabor discrimination accuracy were impaired equivalently across eccentricities, this would provide evidence in favor of general interference.

Gabor discrimination accuracy values were compared using a repeated-measures ANOVA with wind condition (no wind, wind), cognitive workload (low, high), and eccentricity (5°, 10°, 15°) as within-subjects factors. Figure 4 presents Gabor discrimination accuracy at each eccentricity for each combination of driving difficulty and cognitive workload. Critically, cognitive workload had a negative impact on Gabor discrimination accuracy, as indicated by a main effect of workload condition, $F(1, 24) = 4.54$, $p = .04$, $\eta_p^2 = .16$. Thus, the GC-UFOV measure was sensitive to transitory attentional fluctuations due to cognitive load. Though nominally in the expected direction, the effect of wind was not statistically significant, $F(1, 24) = .09$, $p = .77$, $\eta_p^2 = .004$. Thus, the driving difficulty manipulation did not create a sufficient cognitive load to be registered by the GC-UFOV measure. Similarly, the main effect of eccentricity was not significant, $F(2, 48) =.2$, $p = .70$, $\eta^2_p = .02$. Importantly, the interaction between workload and eccentricity was not statistically significant, $F(2, 48) = .72$, $p = .49$, $\eta_p^2 = .03$, nor was the interaction between wind condition and

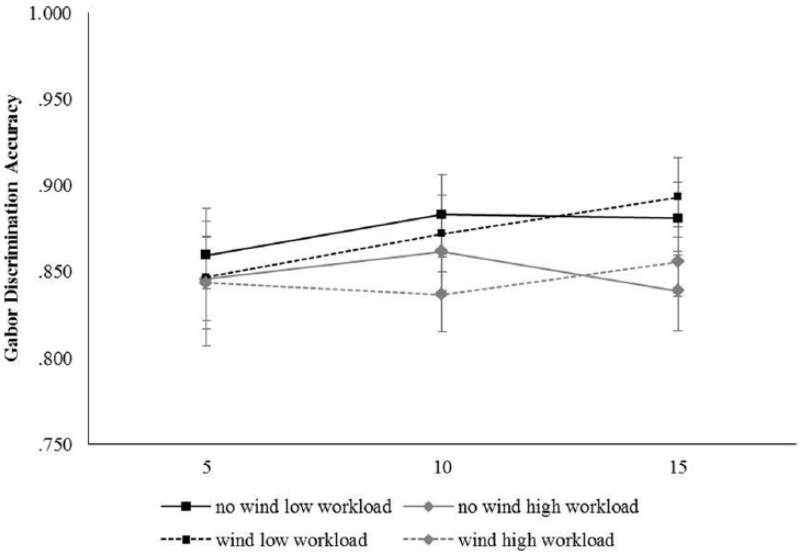

Figure 4. Gabor discrimination accuracy (proportion correct) at 5°, 10°, and 15° as a factor of driving difficulty and cognitive workload. Error bars represent ±1 standard error of the mean.

eccentricity, $F(1, 24) = .79$, $p = .46$, $\eta_p^2 = .03$. This indicates that one cannot reject the null hypothesis that cognitive workload impaired Gabor discrimination accuracy equivalently across all three eccentricities. This is consistent with a general interference account of the effects of cognitive load on the UFOV.

Driving Performance

The wind manipulation did not affect the discrimination task. Thus, to confirm whether the wind and cognitive workload manipulations affected driving performance, driving performance measures were analyzed with repeated-measures ANOVAs with wind (no wind, wind) and cognitive workload (low, high) as within-subjects factors. Lateral vehicle control was defined by the standard deviation of lateral lane position (SDLP) based on the distance (in meters) from the center of the driver's vehicle to the center of the lane. Larger SDLP was interpreted as poorer lane-keeping performance, indicating that a driver had greater difficulty keeping the vehicle in the center of the lane and thereby would be more likely to exit the lane unintentionally. As expected, wind increased SDLP compared to the no wind conditions, $F(1, 24) = 133.93$, $p < .001$, $\eta_p^2 = .85$. Somewhat contrary to expectations, lateral lane keeping was significantly less variable under cognitive workload, $F(1, 24) = 7.57$, $p = .01$, $\eta_p^2 = .24$. This is, however, consistent with previous simulator studies that have found that SDLP decreases with the addition of a nonvisual secondary task (Atchley & Chan, 2011; Becic, et al., 2010; He & McCarley 2011; Horrey, Wickens, & Consalus, 2006; Liang & Lee, 2010; Medeiros-Ward et al., 2014; Reimer, 2009). Importantly, however, the interaction between wind and cognitive workload was not significant, $F(1, 24) = 0.00$, $p = .99$, $\eta_p^2 = .00$ (Figure 5).

We also examined an additional measure of driving performance, longitudinal control, which was defined as the standard deviation of following distance (SDFD) from the LV (in meters) from the driver's vehicle's front bumper to the LV's rear bumper. Larger SDFD values indicate that drivers are more variable in maintaining a consistent gap from the vehicle in front of them. As shown in Figure 6, there was a nonsignificant trend for wind to increase SDFD, $F(1, 24) = 3.78$, $p = .06$, $\eta_p^2 = .14$. Similarly, there was a nonsignificant

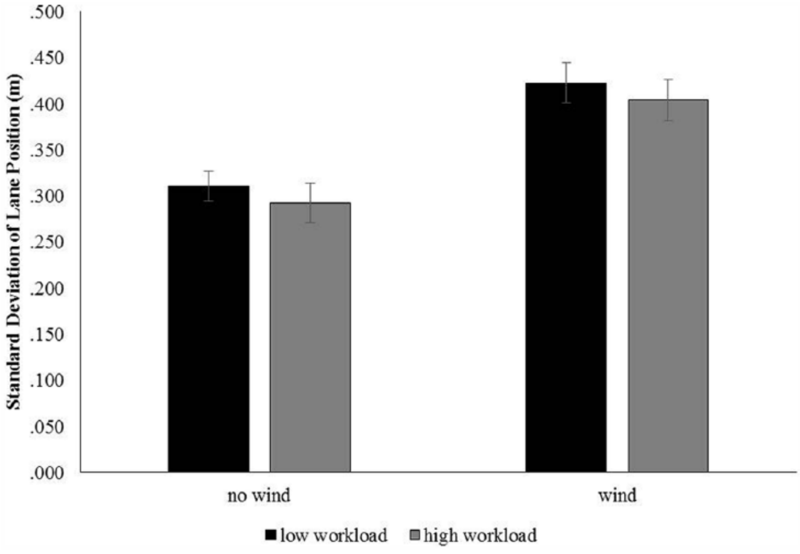

Figure 5. SDLP in the driving task. Error bars represent standard error of the mean.

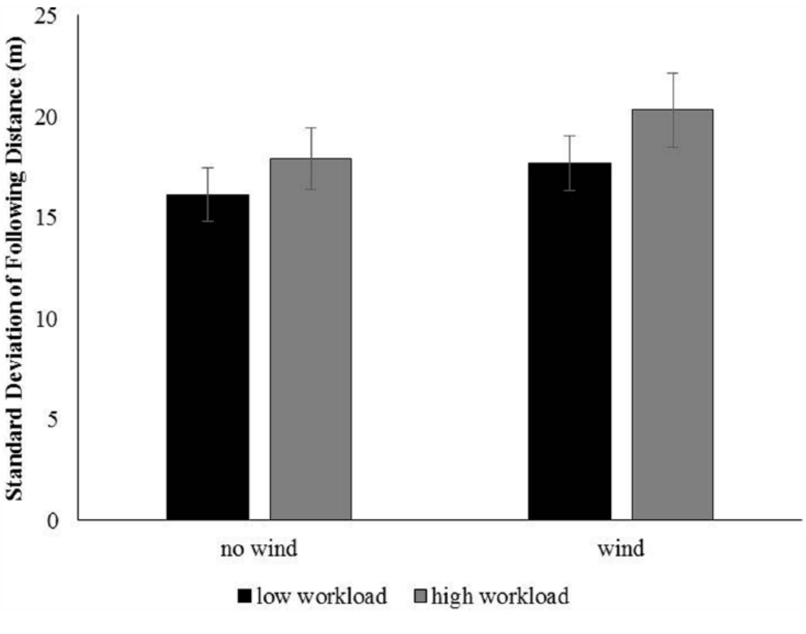

Figure 6. Standard deviation of LV following distance. Error bars represent standard error of the mean.

trend for cognitive workload to increase SDFD, $F(1, 24) = 3.60$, $p = .07$, $\eta_p^2 = .13$. As with the lateral lane position measure, there was no interaction between wind and cognitive workload on longitudinal position, $F(1, 24) = 0.17$, $p = .68$, $\eta_p^2 = .01$.

DISCUSSION

The present study involving the GC-UFOV validated a dynamic measure of transient changes to the UFOV for use in realistic simulated environments, which carefully controls for the retinal eccentricity of target stimuli and disentangles the hard limits of visual resolution with retinal eccentricity from purely attentional effects of retinal eccentricity.

The results of the current study showed that Gabor discrimination was clearly affected by cognitive workload, thus validating the GC-UFOV as a measure of transitory fluctuations in visual attention. Specifically, when drivers performed the two-back working memory task while driving, Gabor discrimination was significantly impaired. Furthermore, the GC-UFOV measured attention at three distances into the visual periphery, from 5° to 15° eccentricity. The results in the low cognitive load condition showed equivalent Gabor discrimination results across eccentricities, indicating that we were successful in factoring out the fixed drop-off in visual resolution with eccentricity through our size scaling and thresholding the orientation of the Gabors. More interestingly, the fact that the results also showed no difference in the cost of cognitive workload across all three eccentricities provides support for the general interference hypothesis. This result is interesting in that previous research evaluating driving ability during a dual-task (auditory N-back) manipulation found what seemed to be a tunneling of gaze (i.e., a more narrow distribution of fixation locations) with increasing levels of the N-back task (Reimer, 2009), which one could infer was evidence in favor of tunneling visual attention. Despite using a testing environment quite similar to the Reimer (2009) study, the Gabor discrimination results from this experiment demonstrate that, when the drop-off in visual resolution with eccentricity was factored out, the distribution of attention was reduced uniformly across the visual field, rather than as a function of retinal eccentricity.

Nevertheless, a different explanation for the general interference found in our study was the fact that we did not include an explicit foveal load. Williams (1985, 1988, 1989) has argued that a foveal load is a necessary condition for producing tunnel vision. Similarly, studies using the UFOV®, or similar measures, include concurrent foveal and peripheral tasks and produce results consistent with tunnel vision (e.g., Ball et al., 1988; Ball, Owsley, & Beard, 1990; Sekuler, Bennett, & Mamelak, 2000), though such studies have generally not used size scaling to eliminate effects due simply to cortical magnification. This would suggest that if the current study had included a foveal load, we might have found evidence of tunnel vision. Recent work using the GC-UFOV framework has indeed shown just this result, though not in the context of a driving simulator (Ringer, Throneburg, Johnson, Kramer, & Loschky, 2016). Nevertheless, one might consider the car-following task to comprise a foveal load (Horrey et al., 2006; Summala, Lamble, & Laakso, 1998). However, although we manipulated the degree of driving difficulty through lateral wind, we did not find an interaction with the retinal eccentricity of the Gabor discrimination targets, suggesting that attending to the LV may not have constituted a significant foveal load for our participants.

A study by Summala, Nieminen, and Punto (1996) showed that drivers could maintain their lane position using only their peripheral vision, while their focal attention was engaged with a demanding visual task below the dashboard. Thus, it seems that the global position of one's car relative to the road cues the driver when to correct the position without the need of large investments of attentional resources. However, under the same focal attentional load conditions, Summala et al. (1998) found that drivers were far slower to respond to unexpected hazards, such as a LV suddenly decelerating, especially when their brake lights were disengaged (see also Horrey et al., 2006). Thus, the UFOV may be much more necessary for the less predictable aspects of driving, namely the other drivers or hazards that violate the participants' expectancies and require them to quickly react to their environment. It is also possible that, in terms of single task difficulty, our wind manipulation was not as attentionally demanding as our N-back task. The fact that we did not independently measure such single task difficulty (e.g., using the NASA TLX), and equate it, is a limitation of the current study, and future studies should do so.

Other possible limitations of the current study regard some vagaries of performance on the Gabor task. The primary limitation is the fact that performance on the N-back task was somewhat above the 80% performance threshold set at the beginning of the study for each participant (ranging from roughly 83% to 88% accuracy across conditions). This can be simply explained in terms of participants gradually increasing their Gabor task performance over the course of the experiment, which is an unavoidable fact faced when using thresholded stimuli.

A future direction using the GC-UFOV is with older adults in driving simulator studies. In this way, we could extend the work using the UFOV® with older drivers to studies measuring moment-by-moment changes in the UFOV during simulated driving. Nevertheless, studies using driving simulators to test driving ability must take account of limits to the generalizability of their findings (e.g., incomplete fidelity relative to real-world driving, associated reductions in perceived risk, and the lower generalizability of results from stimulator studies to real-world driving for more impaired drivers) (e.g., Owsley, Wood, & McGwin, 2015).

In sum, the present study demonstrates a promising new approach, the GC-UFOV, to studying transient changes to the UFOV in the context of complex, real-world tasks. This approach overcomes previous limitations with other online measures of the UFOV and should yield important insight into the nature of visual attention in the context of driving.

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KEY POINTS

- This paper presents a new method, the gaze-contingent UFOV, for measuring the useful field of view in complex environments.
- This measure overcomes limitations with previous online measures of the UFOV in applied settings.
- Using this method, the present study showed evidence of general degradation of visual attention, not visual tunneling, in the presence of increased workload.

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